Generic Electric Propulsion Drive

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ABSTRACT

Considerable resources worldwide are invested in the research and development of future transportation technology. The foreseen direction and therefore research of future personalised transportation is focused on Battery Electric Vehicles (BEV) or hybrid combinations that use hydrogen fuel cells. These new transport energy systems are consider most to replace the current vehicles powered by the internal combustion engine (ICE).

The research work presented in this thesis mainly focuses on the development of a software control system for future BEV prototype vehicles - a generic intelligent control system (GICS). The system design adopts a modular design concept and intelligent control. The whole system consists of four modules being communication, power supply, motor driver and transmission module. Each module uses a microcontroller as the brain and builds an embedded control system within the module. The control and communication between the modules is based on a group of specific parameters and the status of a state machine. In order to effectively implement intelligent control and simplify the system structure and programming, a generic intelligent fuzzy logic model that can be configured to a specific application with a near real-time buffered communication methodology is developed. The tests made on the fuzzy control model and the near real-time buffered communication gave a very positive outcome. The implementation of the fuzzy control and the communication methodology in each of the modules results in a communication between the modules with a steady speed, better reliability and system stability. These modules link together through the communication channels and form a multi-agent collaborative system (MACS). As the controllers are designed based on the parametric concept, the system is able to be implemented to future new modules and therefore allow prototype vehicle control systems to be developed more efficiently. The MACS is based on the core components of the control system - fuzzy logic controller (FLC), Serial Communication and Analogue input control software modules. Further work is carried out as an attempt to integrate the control software with a hardware design for a generic electric propulsion drive (GEPD). This thesis therefore outlines the design and considerations in software and hardware integration in addition to the GICS. The output from this thesis being the construction of soft programming modules for embedded microcontroller based control system has been accepted and presented at two international conferences; one in Wellington, New Zealand[1] the second in Acireale, Italy[2].

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LIST OF ABREVIATIONS

BEV: Battery Electric Vehicles

CPLD: Complex Programmable Logic Devices

COG: Centre Of Gravity

COS: Centre Of Sums

CVT: Continuously Variable Transmission

DCT: Dual Clutch Transmissions

EPA: Environmental Protection Agency

FBC: Full Bridge Converter

FLC: Fuzzy Logic Controller

FVC: Frequency to Voltage Converter

GEPD: Generic Electric Propulsion Drive

EPD: Electric Propulsion Drive

CLCS: Close Loop Control System

GICS: Generic Intelligent Control system

HBC: Half Bridge Converter

HEV: Hybrid Electric Vehicles

ICE: Internal Combustion Engine

MACD: Multi Agent Collaborative Design

PCA: Programmable Counter Array

PWM: Pulse Width Modulation

SMPS: Switch Mode Power Supplies

VDP: Variable Diameter Pulley

CHAPTER 1 INTRODUCTION

1.1 The Research Topic

The aim of this research is to develop a soft generic intelligent microcontroller-based control system (GISC) that has the capability to quickly and easily integrate with prototypes of electric propulsion drive (GEPD). The GEPD is the central unit to battery electric vehicles (BEVs). The research into developing a GISC has two objectives. The first is to search and develop a generic software solution that is capable of being configured to the application specifics. The GICS is to produce a user friendly package for the development and updating of embedded control systems. The second objective is to reduce the development time for generating application instances when implementing the GISC. The presented GISC is developed for a hardware platform that consists of three modules; power supply, motor drive and transmission. The GISC is designed with a set of standardised core operations and an effective methodology that is able to configure the system and generate application programs for the hardware and operations. Each hardware module has a microcontroller as the control unit. These control units communicate with the central control system that operates in an industrial computer. A multi-agent collaborative system (MACS) is formed using this distributed network arrangement. . The modulated MACS design makes the realisation of the two objectives possible by designing a same software interface but with different parameters with each hardware module. Utilization of such a MACs allows change without major redevelopment. The completion of the generic intelligent control system design stimulates an interest in the development of a low cost electric propulsion drive. A set of initial designs of the circuit boards for the hardware modules have been completed. Future work is to make the physical modules and integrate them with the software to have a complete control system for an electric propulsion drive.

1.2 The Scope of Research

The research undertaken in this thesis focuses on developing a control system that is to aid in the development of prototype BEVs. The developed control system seeks to provide a solution that allows the rapid integration of updated hardware components or new technologies. This solution is to provide a core of common software components for control systems using mixed signal microcontrollers. These common components are to be configured to the designer's requirements to allow the common core to be used over a range of possible BEV systems.

The system developed in this thesis involves the development of dynamic or soft coded software components. These components are to be placed directly in the control system program or configured to application specifics before inclusion.

In parallel to the development of the GISC is the design of an electric propulsion drive. The design of the EPD is to provide a future system to test the full operation of the GISC. The manufacturing of the EPD is not addressed in this research however provides a valuable approach to identifying the needs of the GICS. The investigation and design for the EPD covers three hardware modules. The three hardware modules are a power supply, motor driver and transmission.

1.3 Organisation of Dissertation

This dissertation is arranged as follows:

Chapter 2 deals with the background information that is of use for developing the generic intelligent control system. Chapter 2 includes information about electronic automotive control systems, automotive network communication systems, battery and hybrid electric vehicles, power electronics to be used in the hardware design and background of automotive transmissions.

Chapter 3 focuses on the body of the research and covers the development of soft modules for the generic intelligent control system. Chapter 3 explains the GICS as a unit; then explains and details the operation of the three software components that are identified to be needing improvement. Chapter 3 details the operation of the following soft modules: ADC, Serial communication and a Fuzzy logic controller.

Chapter 4 outlines the development of a prototype electric propulsion drive. Covered in this chapter is the description of the overall operation of the EPD and proceeds to be an introduction for the detailed design that is split into individual hardware modules.

Chapter 5 covers the design process for the switch mode power supply of the EPD. In chapter 5 the options for the control and hardware are considered.

Chapter 6 details the identification of possible methods to produce a low cost motor control module for an EPD. Within chapter 6, possible control options for the induction motor are examined and the development of a control system around these options is proposed.

Chapter 7 investigates the option of inserting a mechanical transmission between the output of the electric motor and a final drive for a future vehicle. Within chapter 7, two viable options of transmission are examined. The chosen option is then further developed to a mechanical design to be manufactured at a later stage. The chapter explains the electronic controls that are to operate the designed transmission and integrate with the developed GICS.

Chapter 8 is the discussion and the conclusion for the research carried out in this thesis. The discussion details both the GICS and the hardware design for the EPD. The GICS discussion outlines the workings and the success of the developed soft modules; then forms recommendations for future work. The discussion detailing the hardware design gives a status of the work and forms an in-depth recommendation for future development. The conclusion in chapter 8 focuses on the main objective of the research that being developing the GICS.

Appendix A includes information about battery technology for electric vehicles. The information in Appendix A does not have direct use within the research but may be of some interest to the reader.

Appendix B contains the explanation of the methods utilized for testing the software developed for the GICS. The methods are contained within the appendix because of the nature of software development. Placing the methods in the appendix is done to keep the content within chapter 3 focused.

Appendix C contains the voltage traces captured by an oscilloscope. In appendix C are traces that cover the testing of the ADC, Serial communicaton and FLC. Serials communication voltage traces are located in this chapter in addition to the text; this is to display the results in central location.

Appendixes D, E, F contain the electronic hardware designs for the power supply, motor driver and transmission modules.

CHAPTER 2 LIATURE REVIEW

2.1 Background

General BEV background and trends

Electric vehicles have a number of challenges to overcome before they can replace the existing internal combustion (ICE) powered vehicles. The introduction of battery electric vehicles (BEVs) is being delayed by the lack of cost effective batteries and manufacturing of permanent magnet synchronous motors. Current high-end battery and motor technologies are capable of providing the necessary performance for electric vehicles. However, the cost of such systems is not feasible for mass marketing. To provide a suitable replacement for current ICE vehicles BEV are required to provide a similar capability of operation with the same cost. The public perception of electric vehicles in the past has been associated with poor performance and high cost. Commercially developed BEVs have attempted to be a vehicle that outperforms the current ICE vehicles. Currently BEVs are still expensive and have not become more than a niche product. Hybrid electric vehicles (HEVs) are beginning to have significant market in certain countries such as Japan and the USA. These vehicles provide the means of introducing the electric vehicle to consumers without considerable cost of a large battery pack. The appearance of hybrid vehicles has made a technology push for the development of battery, motor and control systems. Up until now, there have been a number of attempts to produce electric vehicles that have been too expensive for consumers. The technologies developed for HEVs have provided mass produced components that could allow BEVs to become economically feasible in the near future.

GICS Purpose

It is highly likely that within two decades BEV's will become a commonplace reality. With current "state of the art" research demonstrating that the technology is now available for BEVs to become technically feasible, other areas of the BEVs are required to begin the development stages. The GICS is to improve the efficiency of this secondary stage by providing a method of rapid development and testing of prototype systems. A significant advantage of the MCAD is that it will allow new components to be included in a system without extensive reworking.

2.2 Investigation

The investigation of GICSs did not locate a source of research that corresponds directly to the aim of the desired system. The most relevant source of prior work to this research aim is a patent granted to Mercedes Benz[3]. The patent outlines a microcontroller test unit that provides an embedded control system to test automobile hardware systems. The patented test unit provides digital and analogue I/O ports, an embedded control system and a communication link. Outlined in the patent is the description of the hardware layout and operation. The patent however does not provide the reader with a description of the software. Figures within the patent document demonstrate the layout of the device and provide the reader with an assessment of what is required for such a system.

In the absence of corresponding work, the investigation for this research is to investigate the perceived necessary components for the development of a GICS. The investigation includes an assemblage of information from the following areas.

- Automobile control systems, were possible electric vehicles.
- Fuzzy logic control in automotive systems.
- Automotive communication.
- Battery Electric Vehicles (BEV).
- Hybrid Electric Vehicles (HEV).
- Power electronics.
- Automotive transmissions.

The first three sections listed above provide the reader with a background knowledge of the controls systems used in the automobile industry. The sections allocated to battery and hybrid electric vehicles are to demonstrate the history and direction of the targeted vehicle type. Finally the investigation provides an understanding of hardware systems necessary for BEVs.

In addition to the topics listed, information about the research and development path for battery technologies is included in the appendix.

2.3 Automotive Control Systems

Embedded control systems became common in North American produced automobiles during the 1980s. This technology had been available since the 1970s but was not utilised until US government legislation made conventional systems unworkable[4].

The earliest located source explaining embedded control systems (ECS) in automobiles states that these systems were to introduce electronic controlled fuel injection systems. ICEs originally operated using a carburettor then later mechanical/ hydraulic fuel injection systems. These mechanical systems were not capable of meeting low emission standards as pollution controls became more stringent.

The ECS solved this problem by allowing a more precise control of the fuel and air mixture. Initially the ECS only controlled the air fuel mixture however; within a short time the units included control for the ignition. At this stage the external control of an ICE was covered fully by electronic devices, however internals used for the timing were still mechanically driven.

The controls for ICEs became increasing more complicated and eventually became a fully integrated control unit that senses and controls many variables within ICEs.

Figure 2-1 The ECU from a late model Nissan vehicle[5].

The control system within modern automobiles can be described as a distributed network with remote control units based around the vehicle. High end models may include a number of different controls units. Typical examples of control units are listed as follows

- Engine Control Unit (ECU).
- Chassis Control Unit (CCU).
- Transmission Control Unit (TCU).
- Hydraulic Control Unit (HCU).
- Power-train Control Module (PCM).

The control units are often separate in electrical paths but contained within the same physical case. This case containing the control units is often known as an electronic control unit and given the same acronym as the engine control unit. The control unit tasks vary from manufacturer to manufacturer and deferring models however, typically each unit is identified by its function and named accordingly. The ECU controls all functions relating to the engine, this includes not the only engine itself but secondary systems such as controlling fuel supply and cooling mechanisms. The CCU is often responsible for braking and suspension systems, this includes systems such as ABS brakes (from German; Antiblockierbremssystem commonly known as anti lock brakes), differential torque displacement, active suspension and steering. TCU controls the operation of the transmission and the torque couple (either clutch plate or torque converter). Controlling the transmission and torque couple involves sensing shaft speeds and mechanical positions. The TCU then acts by the operation of hydraulic or mechanical systems. Some vehicles may instead have dedicated ECUs, CCUs and TCUs have HCU or PCM. HCU provides a control unit that guides the operation of the vehicles hydraulic systems this may include the brakes and some transmission control (common with older automatic transmissions). PCM is a control device that integrates an ECU and TCU in one unit.

The use of ECS has led to the widespread development and research of concepts that have not been practical in the past. These concepts and developed systems improve automobile safety and/or performance. The use of ABS, Traction control systems (TCS), Supplementary Restraint Systems (SRS, commonly known as airbags) are common with modern automobiles. All of these systems began becoming popular in the 1980s and it is now common for countries to legislate for the inclusion of such systems[6, 7]. During the past decade it has became increasingly common for manufactures to include even more advanced systems[8]. Increasingly common, is the inclusion of systems such as electronic stability control, collision avoidance and the early beginnings of guidance systems such as lane following and parking assistance.

2.3.1 Antiblockier System (ABS)

ABS systems adjust the braking force applied to each wheel to avoid wheels “locking up.” Avoiding locking up the wheels provides two safety benefits. Firstly a tyre provides less braking force once locked. The second advantage is that a rotating tyre still allows a driver to steer the vehicle. ABS works by measuring the speed of each wheel during braking; these readings are then used to adjust the force applied to each wheel. The electronic control unit identifies the wheels that are rotating considerably slower than the others. A wheel rotating slower is often a forewarning that wheel is about to “lock up.” The electronic control unit takes preventative action by reducing the hydraulic pressure to the offending wheel. Reducing pressure to the offending wheel reduces the braking force applied to the tyre and aims to stop the wheel from locking.

The early systems had difficulties with slippery surfaces and during tight cornering. Slippery surfaces such as ice and gravel can cause two problems. With loose surfaces, the locking of the wheels forces the tyre to dig into the surface and this increases traction. On very slippery surfaces ABS can be overcome if more than one wheel locks. With less intelligent systems this can fool the ECU into concluding that wheels are not locked. Advanced ABS braking systems use a variety of advanced model techniques to avoid this problem and achieve greater response[9]. Petersen’s[9] work on using non linear modelling techniques based on the Ricciti solution has shown to improve the accuracy of the braking force. ABS has been shown by statistics and testing to greatly improve the safety of the vehicle in normal conditions. ABS however has had varying test results in slippery conditions. Some tests have shown stopping distances increased and others decreased, however all tests note improved controllability during stopping[10, 11].

2.3.2 Traction Control System (TCS)

The intension of TCSs is to maintain a vehicle’s traction with the road surface when the user is attempting to apply torque to the driving wheels[12, 13]. There are two distinct methods of TCSs; in normal production vehicles, the system stops any wheel spin. In performance applications such as “supercars” or motorsport, the system attempts to maintain wheel spin at the optimum point to gain the maximum performance using a tyres dynamic response[14]. TCSs can achieve traction control using a variety of approaches. The most common in normal production vehicles shares the hardware with the ABS system. The control units in these systems identify the loss in traction and simply corrects by applying the brakes to wheels that are about to loose traction. The ICEs in higher performance production vehicles have the ability to over power their braking systems, therefore these higher performance vehicles use additional methods to combat the possible loss in traction. The TCSs in high performance applications reduce the torque output from the engine; this reduces the torque at the wheels which is causing the loss in traction[15]. The TCS modifies the operation of the ICE's ignition and fuel supply[13]. Early systems simply retarded the ignition timing; modern systems now in addition to retarding the ignition, change the ignition duration, fuel/air mixture and variable cam systems change the movements of the cylinders valves. Finally TCS systems have been developed that control the vehicle's drive train and suspension to maximise use of a vehicle's potential traction.

2.3.2.1 Electronic Controlled Torque Disruption

With mechatronic drive lines, control units can direct the torque distribution to each wheel individually[16]. Individually controlling the torque applied to each wheel allows the control unit to provide the vehicle with the maximum possible drive force by achieving the greatest efficiency from each wheel. This system has been utilised for many years in world rally cars (now banned) and is now found in sportcars and off-road vehicles. Such systems can be found in Audi models fitted with the Quadratto AWD system[17] and Land Rover[18] has offered the systems in their vehicles since 2004.

2.3.2.2 Adaptive Electronic Suspension

Electronic controls systems have been used to produce reactive suspension systems that respond to the change in balance of the vehicle depending on a wide range of possible behaviour changes. Adaptive electronic suspension is in the category of electric stability control systems, however one factor of SCS is traction control. A documentary episode from 'Discovery Channel[19] demonstrates a competition between two off-road vehicles; one with electronic suspension, the other had a traditional mechanical system. The documentary does not take into account driver abilities however it demonstrates the clear advantage that vehicle with electronically control traction system (Land Rover Discovery 3) had over the vehicle with mechanical system (Jeep Wrangler).

2.3.3 Electronic Stability Control

ESC systems bring together the numerous distinct control systems found in early technology vehicles[20]. ESC forms a distributed control system that together acts to control the vehicle as a single entity. The operation of ESC systems vary depending upon the vehicle manufacturer; the systems however have the same function[21]. ESC systems attempt to provide a control structure that maintains the stability of the vehicle across a wider range of operational conditions than was possibly using the previous technology. In essence the ESC indentifies the user's objective of controlling the vehicle and then aids in the process. The simpler systems are built on top of ABS systems using the brakes as the control response; more advanced systems provide additional components to provide corrective action. The ESC system reads sensor values that measure lateral acceleration, yaw rate[1] and individual wheel speeds of the vehicle; these values are used to model the current path of the vehicle. The vehicle is skidding and determined as such; in the event that the modelled path of the vehicle does not match the desired path; the ESC in this case produces corrective action. The simpler systems depend upon identifying that the vehicle is skidding and use the ABS system to individually control the braking force of each wheel; the aim of this is to stop the skid and return the vehicle to the desired path. Advanced ECS systems in addition to the braking assistance may further include modifying the engine power output, torque distribution and suspension balance. ESC systems for commercial and sport utility vehicles include the above functionality with added sensors for measuring the pitch of the vehicle; these sensors are added to guard against the vehicle rolling over.

The control software for ESC systems decide upon the correcting action required from the actuators in the vehicles. The correct decision from the control system is difficult to produce because of the high dimensionality of possible vehicle movements and the dynamic nature of the vehicle's balance. These programs utilise a variety of methods. Early systems utilise a mapping technique that is commonly found in engine control units for governing ignition and fuel/air mixture. The mapping techniques used in early ESC software were produced with vehicle testing and mathematical modelling; these mapped responses are then stored in the ROM of the controller. Academic research for electronic stability control systems often investigates the use of intelligent controls to form the basis for corrective action. Commonly employed is the use of fuzzy logic control[22]; this provides a controller that is capable of reasoning similar to a human.

[1] A gyroscope device that measures the vehicles rotation around the vertical axis.

2.4 Research of Fuzzy Logic Control systems for Automobiles

Fuzzy logic controllers have been utilised in automobile research for a range of different control tasks. These controllers have been researched for use on control objectives such as cruise control, ABS brakes, Electronic stability control and transmission control.

Muller and Nocker[23] have investigated using fuzzy logic control for cruise control systems. Fuzzy logic control is applied in their research to improve the quality of control and to offer increased functionality. Their work uses infra red distance sensors in addition to conventional sensors in the vehicle for driver action and the environment; these sensors values are used in the fuzzy controller and are enacted using drive by wire communication to actuators. The experiments undertaken during their research has shown a system that acts similar in reasoning to decision that a human would take.

Mauer in his 1995 paper "A fuzzy logic controller for an ABS braking system" develops a fuzzy logic controlled ABS braking system[24]. Mauer applies fuzzy logic control in his research to provide a non linear controller in an environment that is unstable. The system uses the current and past readings of tyre slip to form a control signal to the vehicles brakes; the system is further adaptive for varying road conditions. He mentions in his work the use of parallelisation for the computing of the fuzzy logic control outcome; this provides a much reduced calculation delay and a reduction in the response time. The final system is tested on a examination arrangement this provides some good results; further the system is tested with bumpy surfaces that introduce rabidly change wheel speeds. His work has shown an improved level of performance of the ABS system in the highly unstable region of controlling tyre slip and maintaining operation over a wider range rough road surfaces.

The more recent research paper from Lin and Hsu introduces the idea of self learn fuzzy sliding mode for ABS systems[25]. The goal of such as system is to improve the response of the ABS braking in varying environmental conditions. The simulation results shown in the paper do demonstrate an improved performance and stability of the braking system; however the test is a simulation, not a real test.

Lee and Zak demonstrate a neural fuzzy ABS controller[26]. Their system uses a nonderivative fuzzy optimiser and a fuzzy logic controller. The nonderivative optimiser finds the optimum slip rate for the tyre with the road surface to generate the highest traction. The output from the optimiser is then feed as inputs to the fuzzy logic controller to generate a control response. The testing of the developed system is a comparison to both non ABS system and an ABS system when the slip rate is kept constant. The developed system provides a greater performance than the non ABS system and much improved response of varying road conditions compare to the traditional fix slip ABS system.

Wantabe, Emotor and Yoshimura 2003 work on an active suspension system using a fuzzy logic control demonstrates the use such systems to improve the stability in suspension and tyre deflections[27, 28]. The fuzzy controller in this system generates a model of the vehicle's operation; these are used as fuzzy inputs. The controller operates the fuzzy logic controller and outputs the control response to dynamic dampers in the suspension. There work has shown a large improvement in the oscillation of the vehicle, however the assumption of the vehicle is at steady state may limit the application in a production vehicle.

The 2005 work by B & M Boada and Diaz demonstrate the control of a vehicle's yaw rate achieved using a fuzzy logic controller adjusting the braking force to each wheel[29]. The system developed controls the yaw rate of the vehicle and the slip angle of the tyres. A fuzzy logic controller was chosen for this research because the methodology offers a system that is simple to implement and provides good control for non linear systems. The developed yaw rate controller is simulated with varying manoeuvres and road surfaces. The results show an improvement in the vehicles response and steady operation of the tyres slip angle. The control of the slip angle is important as this demonstrates the traction available to the vehicle.

Many researchers investigate the control of hybrid vehicles to offer the greatest efficiency by varying the power supplied form the ICE and the electric motor[30-35]. One such investigation is carried out by Schouten, Salman and Kheir in their 2002 publication "Fuzzy logic control for parallel hybrid vehicles[35]." The research presented utilises a fuzzy logic controller to optimize the operation of the vehicles systems. The controller uses varying inputs to the control system such as the driver action, motor operation and charge state. The inputs are used within a developed rule base to form the split output between the ICE and the electric motor. The simulation of the control system with respect to methods currently employed demonstrates the potential for an increase in efficiently of hybrid vehicles.

2.5 Automotive Control System Communications

Over the past forty years, the integration of electrical systems to ICE vehicles has greatly increased. With this increase of integration, a need has arisen in sophistication of inter-device operation and a means of system organisation. In 1955 a vehicle could expect to have 45m of wiring total, in comparison high-end luxury models today may have over 4km of wiring[36]. Originally, vehicle's electrical systems consisted of discrete wiring also known as "point-to-point." As one can imagine the wiring looms within automobiles were becoming increasing complicated. In the early 1980s, vehicle manufactures were replacing these discrete wired electrical systems with networked designs. The intension of the network was to allow increased function, however it also reduced the wiring required.

2.5.1 CAN (Control Area Network)

During the 1980s numerous automobile communication protocols were developed to allow greater functionality of automobile electronic systems. The most common today is the CAN (Control Area Network) protocol. The CAN protocol development began in 1983 by the Germany company Robert Bosch GmbH. Bosch was at the time developing electrical systems for automobile manufacturers Mercedes and BWM. Bosch Engineers were searching for a serial communication protocol that could be developed for use within their systems. The engineers were unable to find a suitable protocol and set about developing their own. Bosch's aim was to develop a safe, reliably and expandable communication protocol suited to automobiles. In 1986, the first CAN protocol was released at a SAE (Society of Automotive Engineers) conference. 1987 saw the first CAN controllers released by chip manufacture Intel.

CAN is an asynchronous serial communication protocol that operates on a multi-master bus communication channel. This operation is specifically developed for automotive applications to allow distributed control. CAN is a CDMA/CD based protocol (Carrier division multiple access with carrier detection), this means that multiple nodes could possibly transmit on the communication at the same time. The carrier detection within the protocol provides a methodology of avoiding communication clashes and this allow the use of a single communication bus to a practical limit. The CAN advantage is made possible because communications are sent with a command identifier that the intended nodes recognise. This is in contrast to many serial protocols that send using point-to-point connections or physical address. Each node on the bus receives all communication present, however only the node that recognises the identifier acts on the communication.

The identifier allows a single data bus to be used and this forms a more flexible design. Access points known as nodes on the data-bus can be added without a change in the overall electrical system layout. The CAN communication controllers at each node filter the messages on the bus and pass the desired command to the control unit the node serves. The communication design with a common bus and identifiers allow engineers to add or remove control nodes to the bus without modifying the entire system. This ability to remove or add nodes has given flexibly automotive engineers required for sophisticated electrical and control systems. According to ISO standards, CAN is capable of providing a data rate of up to 1Mb/s and SAE regards this rate as capable of real time control. Since the introduction of CAN 1986, the protocol has been standardised and further related protocols have evolved. As automobile systems became more complicated, difficulties began to arise from the high volume of traffic on the communication channel. The high traffic on the networks began to increase latency in the reception of the commands. Automobile manufactures nowadays typically use multiple CAN subnets in their vehicle's electronic system. CAN subnets are divided into groups depending upon their priority of control. Important nodes for controllers such as the engine control units, transmission control units, antilock brakes are located on high performance buses to allow real time control. Less important nodes responsible for communication for lights, user instrumentation and occupant comfort are located on lower cost and bandwidth busses.

As the involvement of electronics in vehicles has continued to grow, further needs have been required from automobile networks and communication channels. These different needs have produced the protocols specific to a family of common communication needs. These new protocols or on going developments can fall three categories. Automobile manufactures today require networks that provide low cost solutions or high bandwidth synchronous communication for multimedia applications. The most common form used for each case respectively is LIN (Local Interconnect Network) and MOST (Media-Orientated Systems Transport). Leen and Heffernan[36] also outline the research taken for X-wire systems. The X-wire systems researched are for use in future more advanced automobiles once legislation is changed. X-Wire systems will control "drive by wire systems "such as steering, braking.
Figure 2-2 demonstrates the layout of distributed control networks common to many production automobiles.

2.5.2 LIN (Local Interconnect Network)

The LIN protocol was developed as a low cost communication channel. LIN communication is used for devices that requires little intelligence and are not time critical. LIN is a basic broadcast network with a single master and up to 16 slaves. Instructions are in the form of an identifier and boolean command. The boolean command is the reason why some sources describe a slave device as simply a level shifter. A LIN network is typically a subnet within a CAN node and is used to control simple features in a local area of the vehicle[36]. LIN is commonly used within car doors, seats, roof lighting etc. As an example, a CAN node can provide a LIN network within a door to control the locks, mirrors and window. The low cost LIN option can be applied in this situation because all the actuators require only simple ON/OFF and directional control[36].

2.5.3 MOST(Media-Orientated Systems Transport)

MOST is a protocol developed by vehicle manufactures and leading suppliers to provide a way of connecting multimedia components in automobiles[36]. Unlike CAN, LIN and most other automobile protocols, MOST uses all seven layers of the ISO reference model for communication. The ISO reference model provides a standardised approach from physical hardware to software operation. Using all layers of the reference model aids the integration of multimedia devices and the automobiles entertainment system. MOST differs from conventional automobile protocols by using fibre optic communication mediums and synchronous transfer. The fibre optic medium allows high data rates, this is important for modern multimedia applications such as the MPEG standards. MOST is standardised to allow a bandwidth of $60Mbs^{-1}$; the equivalent of 15 MPEG2 channels[36]. Synchronous transfer is required in the multimedia applications to keep the media components (video, surround sound) in synchronisation. This synchronous transfer is not achieved in the traditional sense of the word with transfers occurring from an overall system oscillator. The synchronous transfer is still achieved with a common clock controller on the MOST bus. However, the synchronous connection is achieved with the data within the packets transmitted, not initiating transmission all at the same instant.

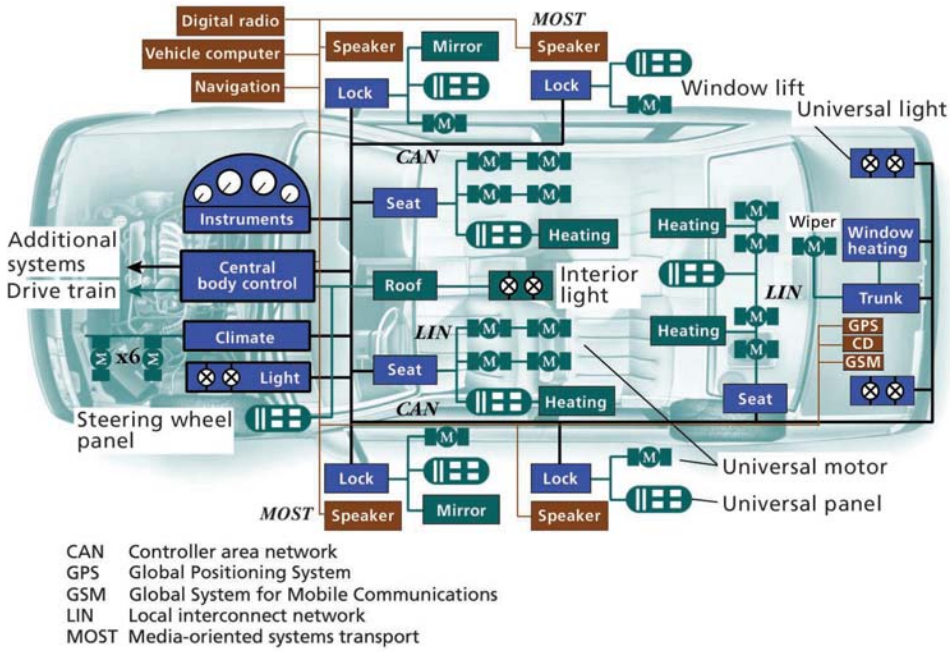

Figure 2-2 A typical CAN low priority sub system found in current production vehicles[36].

2.5.4 Battery Electric Vehicle Applications

Abdel Azzeh dissertation "CAN control system for an Electric Vehicle"[37] investigates the use of a CAN communication network specifically for Electric vehicles. Azzeh's work involves the development of CAN based control system for a Toyota MR2 being converted to an electric vehicle. A modulated control system communicating via the CAN protocol is used in his work to replace the original electrical system. The original electrical system is required to be replaced in the case of the Toyota MR2 for two reasons. Firstly the conversion to an electric powered vehicle will require different voltage levels to replace the hydraulic and mechanical systems with electromechanical systems. Secondly, the weight of the wiring harness in production vehicles is becoming a significant factor in their performance. Azzeh's work, while not controlling the EPD provides the reader with a good understanding of the control system structure in modern ICE vehicles and directions required for BEVs.

2.6 History of Battery Driven Vehicles

The first electric vehicle was invented in 1839[38, 39] and was the leading technology until the development of an efficient internal combustion engine (ICE) in the early 20th century. By 1881 battery technology had been developed that allowed electric vehicles to become a practical transportation for urban areas. 1899 saw the 100km/h mark broken[38] by an electric vehicle although production electric vehicles in the early 20th century had a max speed of approximately 32 km/h[39] due to non-existence of semiconductor devices. Electric vehicles were quite common for women and doctors (who required a reliable transport) as vehicles powered with ICEs were difficult to start[40]. In 1913 the automobile manufacture Cadillac introduced an ICE vehicle with an electric starter motor[38]. The addition of the starter motor gave ICE vehicle over the BEVS. The dominance of electric vehicles was gone and over time, BEVS disappeared as ICE performance grew at a faster rate.

In 1947 the transistor was invented, its devolvement laid the groundwork for the first efficient variable speed drives. In 1959 the Henney Kilowatt was first transistor based commercially produced. The vehicle originally used 18×2V PbA batteries in series but later switched to using a 12×6V arrangement. The later battery arrangement allowed a top speed of 100km/h with a 100km range[39]. The Henney Kilowatt was a short-lived production vehicle that was too expensive to sell and production stopped in 1961. The company made 100 units, only 47 were ever sold and unverified reports state that the majority of those sold were to the electrical utilities companies.

Following the production of the Henney Kilowatt vehicle there have been a number of attempts from small companies to introduce similar vehicles that would sell. Such vehicles were sold in low volumes but only over a short period. These vehicles were economically unpractical to sell on the mass market.

In the late 20th century some companies produced electric vehicles which targeted the niche market of expensive toy vehicles. Since the 1950s major automobile manufacturers have produced battery powered electric concept vehicles. The most successful concept program of an electric vehicle was the Chevrolet EV1 that was developed during the 1990s and lasted until the program ended in 2002[38]. Between 1998 and 2002 the US State of California required all the major vehicle manufacturers to produce zero emission vehicles[41]. The vehicles were provided on a lease only basis (expect some Ford models by a legal mistake) and at the time the actual cost of the vehicles was expensive in comparison to ICE models. The difference in price was however subsidized down to realistic a cost for consumers[38]. The vehicles produced by the major manufacturers for the State of California requirements are shown in the following table.

Manufacturer and	Motor	Battery	Vehicle Type

Model			
General motors EV1	100 kW 3 phase AC induction motor	26 ×12V PbA (18.7 kWh) Or 26×13.2V NiMH(26.4 kWh)	2 door Sedan
Honda EV Plus	49 kW Brushless DC	24 × 12V NiMH(27.4kWh)	Compact
Toyota RAV4 EV	49 kW Brushless DC	24 × 12V NiMH(27.4kWh)	Small Sports utility vehicle
Ford Ranger EV	67kW 3 phase 6 pole AC inductor motor	39×8V PbA (23 kWh) Or 25×12V NiMH(26KwH)	Pick up
Nissin Altra EV	62 kW permanent magnetic AC synchronous motor	96 Li-ion cells (about 32.7 kWh)	Minivan

Table 2-1 Full Electric vehicle produced by major automobile manufactures.

In 2001 the car manufacturers and oil companies sued the California state government in the federal court which forced California to relax the regulations on vehicle manufacturing. The car manufacture's case was that the public demand was too low to provide a market. Opponents argue that the car manufacturers did not promote their EV properly. A documentary has been produced called "Who Killed the Electric Car," follows the timeline of events and two sides to the story. After the mandate was changed, vehicle manufacturers started to recall and crush the electric vehicles. Public protests against the recall pushed Ford to sell a small percentage of the electric vehicles back to the original lessees. Toyota supported the public and offered the vehicles back to the lessees and continue to support the vehicles maintenance schedule though parts.

2.6.1 <u>Hybrid Vehicles</u>

A hybrid vehicle is a vehicle that uses two sources of power to propel the vehicle. The most common form of hybrid vehicle is a combination of electric motor and ICE although other types do exist. The early history of hybrid vehicles starts in 1890s were electric motors and ICE were combined to produce greater performance[39]. As ICE performance improved at a rate the electric technology slowly became phased out. With the invention of starter motors to start ICEs, companies that had been producing BEVs and HEVS experienced a fall in sales. A few of these companies at this point were actively advertising reduced fuel consumption although at this point the pollution effect of ICE was not of major concern (or any) and the improved fuel consumption did not overcome the cost difference and the lower performance of EVs.

In 1966, the United States Congress recognized the effect of air pollution, policies were changed and research into electric vehicles was encouraged. General Motors developed an experimental hybrid vehicle that had electric motor and small ICE. The vehicle named the GM 512 ran on batteries up to speed of 16km/h and then phased the ICE motor in and phased the electric motor out until 20km/h. The vehicle ran fully on the ICE from 20km/h up to a maximum speed of 65km/h.

After the 1973 oil embargo, the Environmental Protection Agency (EPA) ran a research program named the Federal Clean Car Incentive Program. The aim of the research program was the development of vehicles to produce reduced pollutions and the dependence on oil. Research grants were provided to ten applicants, one of these applications was to produce a hybrid petrol vehicle[42]. Over the next two years, two engineers named Dr Victor Wouk and Charlie Rosen developed a prototype HEV that used a Buick Skylark as a base vehicle[43]. During this period Wouk and Rosen continued to develop their prototype and by the time the prototype was ready for final testing, all the other applicants had dropped out. At this stage politics and lobbing started and the EPA refused to test the vehicle and threatened to stop the funding for the project. Further lobbing was done by the scientific community and the EPA agreed to test the vehicle upon the condition that if the prototype passed the requirements then the funding would continue. The vehicle passed the test and the fuel consumption was reportedly 9% of current vehicles at the time[43]. The EPA however rejected the test results due to concerns that the testing was rigged and dropped the funding. Wouk argued the EPA concerns and at later date it was discovered that the top bureaucrat at the EPA was against hybrid vehicles in principle and overrode technological advice from the agencies technical members. In 1976 the US government introduced a law to encourage research and demonstration of low emission vehicles through tax incentives to the automotive industry[39].

General Electric and Toyota both developed a concept HEV, General Motors had a research program on that were fully EV. Research continued until the 1990 in the United States and at that point further initiatives were undertaken and research increased with government funded projects working with American automotive manufacturers. At this time Toyota was left out of the research grants and begun their own secret research into high efficiency vehicles. 1997 saw the first hybrid vehicles were commercially produced from major automotive manufacturers. Toyota released the Prius and Audi released the Duo. The Audi

Duo proved too expensive to be sold in Europe and Audi quickly dropped production of the vehicle.

2.6.1.1 Toyota

The Toyota Prius was expensive and reportedly Toyota sold the Prius at a loss for the first few years. Toyota's intension when developing the Prius (Prius is a Latin word that can have the meaning "to go before") was to a produce a platform for the development of technology for future vehicles. Toyota stated through media communication that is considers the Prius successful in terms of gains in technology and marketing[44]. As of 2007 the Prius was the third generation of the model[45]. The first three generations of the Prius used NiMH batteries. Toyota's original plan was to use Li-ion batteries for the next generation of Prius but due to safety concerns the 4th generation will likely still use NiMH. Hybrids with Li-ion batteries are expected to be delayed by two years. Toyota's current hybrid production will introduce hybrid versions of conventional models. The Camry (medium sized passenger vehicle), and the Highlander (medium sized sports utility vehicle) are already in production. Toyota's research and development resources are currently working on plug in hybrid vehicles and introducing Li-ion batteries. Toyota's objective is to cover their entire range of models by 2011 with a plug in hybrid options.

The third generation Prius uses a single 450V 50 kW permanent magnet AC motor supplied by a 201.6V NiMH battery pack capable of a 21Kw power output[45]. The Toyota Camry hybrid was released in may 2006 and has the highest sales rate to date reached by a HEV. The Toyota Camry hybrid uses the same standard hybrid arrangement as the Prius. The Camry however uses high performance components. The Camry has a single 50 kW 650V permanent magnet AC synchronous motor though the power output is limited by the 30kW output from the battery[45]. The batteries pack used is 245V NiMH and 30kW output as mentioned.

The Highlander uses two 650V permanent magnet AC synchronous motors. The front motor is rated to 123 kW and the rear 50kW[45]. The battery pack in the Highlander is 288V NiMH with a power output of 45 kW[45].

Toyota uses oversized electric motors to achieve a greater efficiency with regenerative breaking. The larger motors allow larger energy recovery during engine braking.

2.6.1.2 Honda

Honda released the Insight in 1999 and at the time was the first hybrid vehicle into the US market. The insight was produced from 1999 to 2006 and during the period sold 13200 cars.

As with Toyota's first hybrid model, the Honda Insight was intended as a platform for proving new technology. The Insight used a small 1l 3 cylinder ICE coupled with 10kW AC synchronous motor. The energy storage in the Insight was a 144V NiMH battery pack with a storage capacity of 0.936 kWh. The Insight is not considered a full hybrid as the electric motor can not operate the vehicle by itself, the electric motor works as an assistant to the ICE and allow the ICE to be stopped when the vehicle is stationary. 2003 saw Honda introduce the Honda Civic hybrid. The Civic hybrid makes use of the same chassis as the conventional ICE version. The first generation Civic had the same type of transmission as the Insight and therefore was only a hybrid-assisted vehicle. The second generation was released in 2006 and allowed the vehicle to operate in a fully electric mode by switching off the ICE motor when at cruising speed. The Honda Civic uses a 140V NiMH 0.936 kWh battery as with the Insight but the size of the electric motor is a increased to 15kW. Honda released a hybrid version of it's Accord model in 2006. The Accord model followed a different school of thought. It was the most powerful yet the most economical version of the Accord. Honda has however dropped the hybrid version due to low sales.

2.6.1.3 Ford/Mazda/Mercury

Ford released the hybrid version of the Escape (small SUV) model in 2004. The Escape hybrid was the first production hybrid sports utility vehicle. The escape is powered by a 99Kw ICE and a 70Kw permanent magnetic AC synchronous electric motor[46]. The battery is an arrangement of 250 NiMH cells that produce an output voltage of 330V with 1.8kWh storage. The battery pack weight is 50 kg and is capable of propelling the vehicle on electric power alone for between 2.4 and 2.8 km. The hybrid system originally developed by ford was too similar to that developed by Toyota and required a patent sharing venture (Toyota received diesel direct inject rights in return) for Ford to use the system developed. The ford Escape is the same vehicle (chassis and drive line combination) as the Mazda Tribute and Mercury Mariner and both of these Ford owned companies began production of the hybrid.

Ford announced in June 2007 that the company had begun a research program into developing a plug in hybrid version of the Escape. A press release from the company on 11 December 2007 provided an update on the concept vehicle. The vehicle had produced fuel consumptions of 1.9L/100 km; this figure is approximately 20% of the estimated value for the similar ICE Escape. The specifications mention a 336V Li-ion battery that allows the vehicle to travel in the range of 40-50 km using only the electric motor.

2.6.1.4 GM

Chevrolet from 2008 will offer customers hybrid versions of some models. Hybrid options will be available on two models of vehicle including the compact, Malibu (mid sized 4 door sedan) and the Tahoe (medium sized SUV). The models offered by GM offer the same performance as the mid range ICE option.

2.7 Power Electronics

Power electronics is a general term given to systems that covert one type of electrical energy supply to another form of electrical supply. The generic electric propulsion drive is likely to include two forms of electrical energy conversion. The first is the conversion of a voltage input to the desired level. The second is the production of a three-phase AC voltage output to the motor.

The research is not focused on power electronics therefore will not contain more background than is required for the understanding of the project. The field of power electronics is too large to be fully explained and the required application specific information will be detailed in the body of this research under the relevant chapters. The engineering literature from Batarseh[47], Wildi[48] and Bose[49] has been useful in providing the background knowledge for the power electronics explained in the chapter.

2.7.1 DC-DC Converters

DC-DC converters fall into two categories, linear regulators and switch mode power supplies (SMPS). Linear regulators were the first device available and a work in very crude manor by effectively changing a series resistance with the output of the device to form a variable voltage divider.

2.7.1.1 Linear Power Supply

The linear power supply is a very simple circuit that allows a regulated DC voltage to be produced however it has two faults with the exception of small low power devices.

- Poor efficiency
- Can only regulate or lower a voltage

Poor efficiency

The use of a variable series load means that the linear power supply has a poor efficiency between the input and output of the device. This loss in efficiency is the outcome from the dissipation of excess voltage through the series resistance in the form of heat. For high power systems, this poor efficiency will result in a large financial penalty through large amounts of energy wastage. Secondly devices that operate from a stored finite amount of energy such as a battery, reduce the length of operation possible or require a larger storage deceive that increases cost and physical penalties such as size and weight.

Regulator Application

The linear power supply works by using a voltage divider to control the output voltage, as the device works as a voltage divider the output voltage must be less than the input voltage.

2.7.1.2 Switch Mode Power Supplies

Switch mode power supplies (SMPS) are a form of DC power conversion has been made possible by the introduction semiconductor switching devices. The devices operate using a pulse width modulation signal that operates the semiconductor device(s) in either on or off mode with the ratio between the two states (known as the duty ratio) controlling the output voltage. Theoretically, with perfect components SMPS supplies do not waste any energy, practically the devices do however dissipate some energy due to non ideal components that have series resistance, mutual inductance and the switching of the semiconductor devices is not instant.

There are three simple forms of SMPS converter

- Buck
- Boost
- Buck-boost

All the SMPS use an inductor with semiconductor devices for the switching and blocking of current for the control of current flow through the inductor. The control of the current through the inductor is the principle that is used to control the voltage output. The voltage across an inductor can be determined by Equation 2-1

$$v(t) = L\frac{di}{dt} \qquad (2\text{-}1)$$

v = Inductor voltage

L = Inductance value

t = time

i = current

2.7.1.2.1 Buck Converter

The Buck converter is the most basic form of a SMPS and allows voltage output between 0 and V_{out}. The basic layout can be seen in Figure 2-3

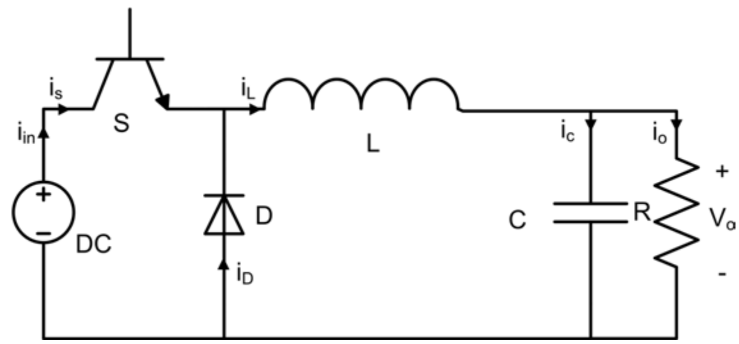

Figure 2-3 Buck converter layout.

The voltage of the buck converter is given by Equation 2-2.

$$V_{Out} = D \times V_{in} \tag{2-2}$$

V_{in} = Power Supply Input Voltage.

V_{out} = Power Supply Output Voltage.

D = Duty Ratio.

2.7.1.2.2 Boost Converter

The Boost converter is a SMPS that allows the voltage output from the power supply to range from V_{input} to infinity (in theory). The basic layout can be seen Figure 2-4

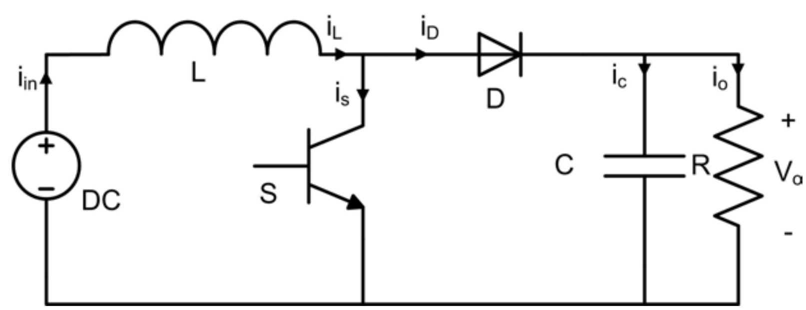

Figure 2-4 Boost converter layout.

The output voltage of the Boost converter is given by Equation 2-3.

$$V_{out} = \frac{1}{1-D} V_{In} \tag{2-3}$$

V_{in} = Power Supply Input Voltage.

V_{out} = Power Supply Output Voltage.

D = Duty Ratio.

2.7.1.2.3 Buck boost converter

The Buck Boost converter allows a voltage output be less or greater in magnitude than the output value but at the expense of being reverse polarity. The basic layout can be seen in Figure 2-5

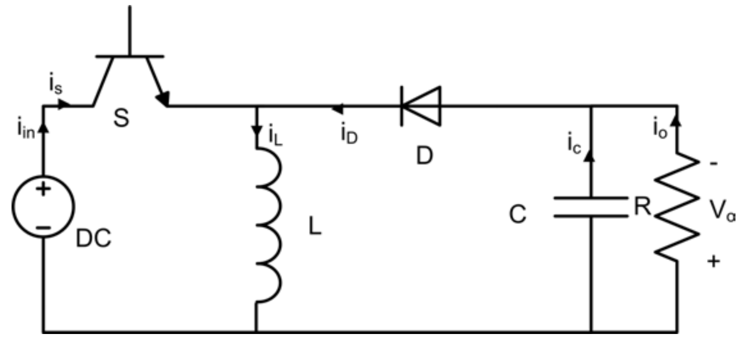

Figure 2-5 Buck-Boost converter layout.

The output voltage of the buck boost converter is given by the Equation 2-4

$$V_{out} = \frac{D}{1-D} V_{in} \quad (2\text{-}4)$$

V_{in} - Power Supply Input Voltage

V_{out} - Power Supply Output Voltage.

D - Duty Ratio

2.7.1.2.4 Complex SMPS

In addition to the three simple layouts explained above there is a vast amount of material available on more complex SMPSs.

2.7.1.2.5 Fourth order SMPS

The buck and boost converter layouts displayed above can be joined in series or parallel structures to combine the individual gains and form what is known as a high order converter. This is used to form two further common non isolated converters known as the SEPIC (single ended primary inductance converter) that allows a Boost Buck converter to be implemented without a reversion in polarity and achieved with only a single switching device. The Cuk converter has the same gain as the SEPIC but allows switching to occur at zero current (used for soft switching).

2.7.1.2.6 Isolated SMPS

Isolated SMPS use the AC wave form from the switching device to make use of a high frequency transformer that can be used as the primary means of a voltage ratio similar in AC to AC conversion. The high frequency transformer produces an isolation between the input and output supplies that add a degree of safety to the design when producing high output voltages.

2.7.2 Inverter

An inverter is a power electric system that converts DC supply voltage from the input to AC voltage on the output of the supply. The inverter uses the switching of semiconductor devices such as GTOs, MOSFETs or IGBTs to apply an alternating supply through a load. The layout of a simple single phase inverter is shown below using an H bridge configuration to reverse the polarity across the output terminals. The second common method is to use a variable DR PWM signal to the semiconductor devices throughout the period of the cycle. The DR is dependent upon the desired voltage output for each small period. At peak voltage, the DR is a high ratio. For a low voltage, the DR is a low ratio.

By having the voltage output from the inverter closely match a sinusoidal waveform the harmonics and switching stress on the semiconductors are reduced. Power electronic loads generally include an inductive load that forces large voltage spikes on the semiconductor devices during switching. By reducing the lower order harmonics which produce the greatest effect, the induced voltage across the semiconductor devices is reduced. The efficiency of the load is increased by less thermal and noise generation.

2.7.2.1 Three phase inverter for an AC motor

During the research, an inverter was used to produce a 3 phase variable frequency speed drive to an AC motor of either asynchronous or synchronous design.

To produce a three phase, supply an extra half bridge is added to the H-bridge layout. The same basic principles explained above can be applied to the three-phase bridge by switching with either a multiple semiconductor inverter arrangement or variable DR PWM signal. For a three phase induction motor, there are two possible phase configurations that can be used. The switching sequence implemented depends upon the configuration.

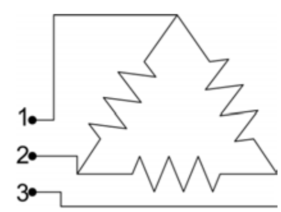

Figure 2-6 Delta phase configuration.

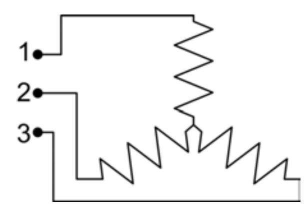

Figure 2-7 Wye phase configuration.

2.7.2.1.1 Asynchronous motors

Asynchronous motors generate torque to rotate by the rotor turning at a low frequency lower than that of the stator supply. Induction motors function using electromagnetic induction between the stator and rotor that is formed by a rotating magnetic field as the stator supply phase rotates. The induction caused by the rotating stator supply induces a current in the rotor winding which in turn produces another magnetic field. The interaction between the magnetic field of the stator and rotor produces a force and therefore a torque. There are two types of asynchronous AC motor, the squirrel cage rotor and wound rotor.

2.7.2.1.1.1 Squirrel Cage Induction Motor

The squirrel cage induction motor is the most common form of industrial AC motor and was first invented by Nikola Tesla in 1883. The first three-phase version was developed by Michail Osipovich Dolivo-Dobrovolsky in 1890. The motor type gets its name from the rotor design. The rotor consists of two rings, one at each of the rotor with bars running longitudinally to connect the two. The bars and rings are generally cast from highly conductive materials such as aluminium or copper with the remaining volume of the rotor filled with iron. The low resistance of the cage element results in a high current and therefore a greater magnetic field strength.

2.7.2.1.1.2 Wound rotor

Wound rotors were used in the past for applications that required variable rotor speed. Wound motors are now less common as semiconductor technology has replaced the need for this kind of motor design. The variable speed of the motor was accomplished using a series resistance with the rotor windings. Adjusting the series resistance of the rotor winding reduces the current through the winding and therefore reduces the magnetic field strength. The reduction in magnetic field strength reduces the torque applied to the rotor and the outcome is a change in the rotational velocity of the rotor output. The wound rotor was useful before the advancement in semiconductor technology, which in turn allows a method to change the frequency of rotation of the motor using a constant supply frequency.

Modern semiconductor devices allow the supply frequency to be controlled and therefore in most applications, the wound rotor system is now outdated.

2.7.2.1.2 Synchronous motor

Synchronous motors rotate at the same frequency as the supply in the stator and therefore have no slip factor involved. Synchronous motor differ to asynchronous motors in that the magnetic field of the rotor is produced by either an external source or a permanent magnet

The production of the magnetic field from the external supply of a current or a permanent magnet removes the need for a slip factor to induce a current flow in the rotor and therefore allows the rotor to operate at synchronous speed.

Synchronous motors generate torque by the phase difference between the stator and rotor magnetic fields. The torque produced by a motor is given by Equation 2-5

$$T = \frac{P}{n_s} \tag{2-5}$$

T - resulting torque per phase [Nm]

P - Mechanical power, per phase [W]

n_s - Synchronous speed in [rads^{-1}]

The mechanical power supplied to the rotor per phase is determined by Equation 2-6

$$P = \frac{E_o E}{X_s}\sin(\delta) \tag{2-6}$$

P - Mechanical power, per phase [W]
E - RMS value of the Stator Supply [V]
E_o - Exciter voltage [V]
X_s - Synchronous reactance per phase[Ω]
δ- Phase difference between stator and rotor magnetic fields[rad]

With fixed values of Xs, E,Eo, the theory demonstrates that the peak torque known as pull out torque occurs, at a phase angle of 90 degrees. Practically most AC synchronous motors have the pull out torque at approximately 70 degrees because of rotor shape[48]. Once the pull out phase angle is exceeded, the rotor falls out of synchronous speed because the torque is no longer sufficient to overcome the load.

Two types of synchronous motor exist. One is externally excited and the other uses a permanent magnet.

Externally Excited

Externally excited synchronous motors use slip rings on the rotor shaft to connect an external current supply though the rotor windings. This allows the exciter voltage to be changed which is easier in high power applications than to change the stator supply. The disadvantage of externally excited machines is the necessity of slip rings that require maintenance and further power electronic controls.

Permanent Magnet

Permanent magnet motors do not require an externally supplied exciter voltage because the permanent magnet generates the magnetic field from the rotor. The benefit of using the permanent magnet motor is the removal of the need to collect an exciter supplied current that reduces the magnetic requirement and simplifiers the rotor construction. The use of permanent AC motors is possible because of the advancements made in semiconductor technology that allow the improved control of the stator supply and improved processing capabilities of field programmable gate array (FPGA) type equipment.

2.8 Mechanical Transmission

There are a number of types of gearbox that are now used throughout the automotive industry. Automotive transmissions are grouped into either manual or automatic although these names no longer fit the current technology. Developments since the inceptions of manual and automatic transmissions now allow either type to be operated in a similar manor.

2.8.1 Automated Manuals

The introduction of microprocessors and embedded controllers into automobiles has allowed manual transmissions to become automated with the advantage of improving the performance and simplifying the operator's task. Semi-automated transmissions were first developed in the early 1950s using hydraulic and pneumatic systems although these never became more than a niche product. Advancements in computer and embedded control technologies allowed the transmissions to resurface. In 1993 the Formula 1 team Williams introduced a revolutionary design that took full advantage of electronic control systems. One of the developments was the first effective semi-automated transmission; the technology stayed and with time migrated to production vehicles. Modern control technology now allows gear changes to be performed that can not be matched by a human. Unverified statements in the media have mentioned the current gearboxes used in F1 can change gear in approximately 30ms.

The use of AMT in the last decade has become common in European automobiles. Asian companies have recently active in developing AMT technology.

2.8.2 Clutchless Manuals

Clutchless manuals were the first of the semi-automated manual transmissions to be developed for production vehicles. Clutchless manual transmissions still include a dry or wet plate clutch, however the engaging and disengaging of the clutch plate is operated by an embedded control system. The system works by the controller detecting the user selecting a gear. The controller then controls the clutch by actuators depending upon the operational conditions. Cltuchless manual transmissions derive their name from their mode of operation to the user.

2.8.3 Standard automated manual transmissions

Different vehicle manufactures adopt varying methods in the construction of standard automated manual transmissions. The basic principle is the same and is listed below. Essentially, a user initiates the gear change; a computer detects the gear change using a sensor then controls the operation of changing the gear ratios.

1. Engage clutch
2. Deselect first gear set
3. Synchronize second gear set with shafts

4. Select second gear set
5. Disengaged clutch

The technology has been developed to work with the different construction of manual transmissions which includes both traditional "H" pattern and sequential transmissions.

2.8.4 Dual clutch transmissions

Dual clutch transmissions (DCT) were developed by the Volkswagen group and first introduced in 2000. The concept of the dual clutch is to almost entirely remove the time required for a gear change and therefore allow a greater performance and smoother changing operation. With changing gear-sets the most time consuming procedure is synchronizing the next gear set with the current shaft rotation. This synchronization is required to avoid a sudden change in angular velocity that would produce high instantaneous torque that causes mechanical stress. The dual clutch systems works by preparing the next gear set while still transferring power though the first gear set; the transmissions then engages one clutch and disengages the other clutch. The advantage the DCT provides is that the time required for the second gear set to synchronise with the shafts is completely removed and the time period of no torque transfer is reduced to the time required for the clutches to switch operation.

The Dual Clutch transmissions offer the fastest gear changes developed to date however, the construction cost of the transmissions is high and the weight and size is an issue.

2.8.5 Seamless shift

Seamless shift transmissions a are new simple mechanical design that allows quick gear changes. To date no production vehicle uses the transmission and it was only introduced in Formula 1 during the 2007 season. The principle of operation is relatively simple although unverified reports from Formula 1 state that the Seamless shift system is was found to be difficult and unforgiving to operate.

The seamless shift works by allowing two gear sets to be selected at the same time, therefore reducing the shift period down to periods comparable to DCT. The working of Formula 1 gearboxes is unknown in the practical application; the patent owed by "Zeroshift" uses a ratcheting system that allows the second gear to be overrun, or under-run depending on the operation. Once the second gear has been synchronized the mechanical devices that selects gears is moved to lock the second gear and ratchets the first gear.

The seamless shift transmission does not switch between gear sets as fast as a DCT however; the advantage lies in the cost, weight, size comparisons. Seamless shift construction may not be the best performing system but it appears to be the choice of the future and the best comprise between performance and cost.

2.8.6 Automatic Transmissions

Automatic transmissions are known as such because the early versions allowed an automatic changing of gear ratios. The mechanical operation of an automatic transmission is very different that of a manual transmission. The selection of different ratios is achieved by a planetary gearbox and the torque coupling is achieved via a hydrodynamic couple known as a torque converter. The ratios of the automatic transmission are controlled by the locking of different shafts in the planetary arrangement thus changing the ratio between the input and output shafts. The advantage of the automatic transmission system is the simplicity of use. The transmission is easier to operate for the user because there is no requirement to operate a clutch pedal and the changing of ratios is automated. The disadvantage of the automatic transmission is other than its ease of use to the operator, is that it does not match manual transmissions in any other form of comparison. Automatic transmissions have poor efficiency and responsiveness and do not apply reserve torque. Compared to conventional manual transmissions they are more expensive, heavy and are prone to overheating.

2.8.7 Continuously Variable Transmissions (CVT)

Continuously variable transmissions are a type of transmission that theoretically allows an infinite selection of a ratio within a set range. The advantage of this system is that the engine can operate at a constant angular velocity, therefore can operate at an optimum point. There are two common forms of the CVT; variable diameter pulley and toroidal.

2.8.7.1 Variable diameter Pulley (VDP)

VDP continuously variable transmissions consist of two shafts connected by a Vee belt and Vee pulleys. The pulleys are in half sections to allow the diameter between the pulley faces to change. The diameters of half sections on the different shafts change in opposing directions. By changing the half sections in opposing directions the linear length of the belt remains constant and the contact radii with the pulley faces is modified. Changing the contact radii of the pulleys modifies the ratio between the shafts.

2.8.7.2 Toroidal

Toroidal systems consist of two conical wheels that are not physically connected to each other. To transfer torque from one conical wheel to the other, a set of rollers makes a frictional connection between the two conical wheels faces. To change the ratio of the system the rollers rotate on a separate axis. Rotating the roller changes the radius of the point of contact with the conical wheels, therefore changing the ratio between the two conical wheels.

2.8.8 Commercial Directions

For a number of years, European car manufacturers have been producing vehicles with automated manual transmissions, these transmissions are becoming increasing common. The larger automotive manufactures are more likely to offer the AMT as option. Mercedes-Benz, Volkswagen group, BWM, Citroën, Peugeot have automated manuals as options or standard.

The majority of the transmissions used in production vehicles are of conventional manual transmission design or either H or sequential transmissions with embedded controllers replacing the human operator. The Volkswagen group does offer the option of a DCT transmission in some models although performance is high, it has yet to take hold in the industry. Other European manufacturers are resistant to the use of DCTs because of the concerns of reliably, cost, weight and size. In 2003 Audi released the first adequate CVT transmission on a production vehicle. Even though the transmissions give a greater performance in torque transfer, concerns such as fuel economy and abnormal smoothness made the option unpopular and was not supported by the market. In Europe, the public erroneously perceives the CVT as an automotive transmission, in Europe this produces a marketing/sales problem as automatic transmissions are not favoured. The second issue is that vehicles with CVT are reported to be an unusual driving experience as the acceleration is so smooth with the engine staying at constant rpm.

2.8.9 Research Directions

Formula 1 has often set the path for future development for production vehicles. AMT has been used since 1993. Both CVT and DCT transmission technologies have been developed and a performance improvement was gained. The technologies were quickly banned in both cases to reduce the cost of the sport but the transmissions were shown to withstand arguably the most destructive application for automobiles. The focus on development of these transmissions needs to be on cost reduction and reliably to make them a viable option to replace conventional transmissions. The most recent transmission technology is the seamless transmission that is a low cost option and compares favourably to DCT performance. The system is a much simpler mechanical design that would transfer to lower production cost. The difficulty with the transmission as shown in Formula 1 is the difficulty in timing the gear changes which makes the technology currently unreliable. Transmission control research is concentrated on controlling the gear meshing sequence and the transient response of the clutch to minimise torque disturbances. This is shown in the study done for the automation of clutch operation as stated by Powers[4], Kluger[50], Duan[51], and Kulkarni[52].

CHAPTER 3 GENERIC INTELLIGENT CONTROL SYSTEM DEVELOPMENT

3.1 Purpose

This chapter covers the focus of the development GICS for this thesis. Within this chapter is the purpose and description of the GICS as a whole, then the description and design of the individual components.

The purpose of the GICS system is to improve the efficiency of developing electric propulsion drives. This improved efficiency is achieved by providing a package of common building blocks for a control system. These building blocks each have a set core that runs the general operation and a configurable skin to suit the application instance. Figure 3-1 below is a diagram that is used to mathematically model a closed loop control system (CLCS). This mathematical model is useful to demonstrate the requirement and the layout of a CLCS before implementation specifics.

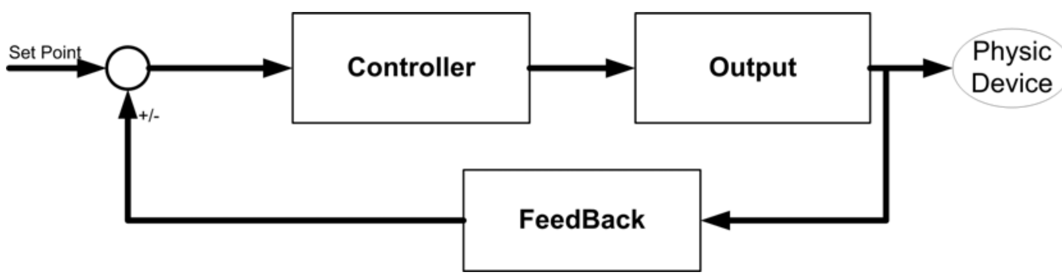

Figure 3-1 General model of a closed loop control system.

The diagram of the CLCS given contains the three distinct models, interaction paths between the models and the input and output to the system. The CLCS behaviour can be explained in-depth by the individual operation of the controller, system output and the system inputs.

Given the general layout of the CLCS, a microcontroller based control system has the same overview with the specifics set to suit the technology. Figure 3-2 demonstrates applying a CLCS with a microcontroller package. The microcontroller system is divided into two sections. The nodes of the control system within the dotted grey line are implemented within the microcontroller software. The nodes outside the marked area are peripheral components to form a bridge to the controlled device. The development of GICS is focused on the control system nodes that are located within the microcontrollers' software or elements with a strong link to software operation. This strong link will be discussed with the Analogue to Digital Conversion (ADC) process found later in this chapter. **Error!**

Reference source not found. provides a correlation between the model for mathematical CLCS representation and the applied control system to be developed.

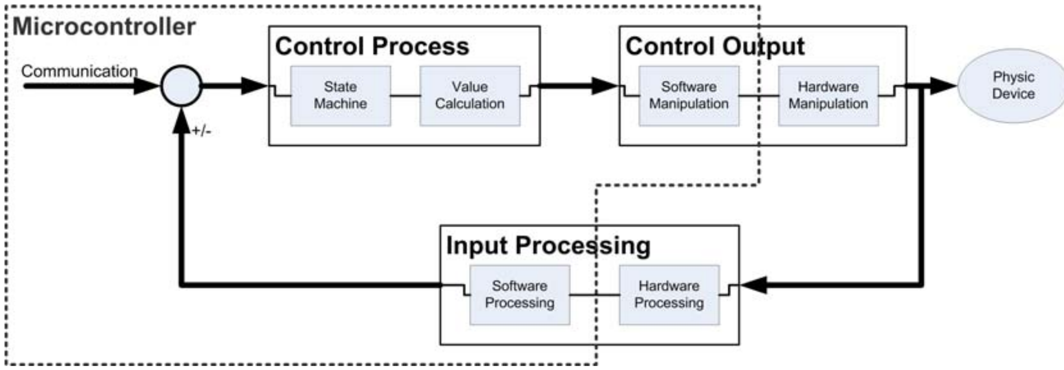

Figure 3-2 Microcontroller CLCS layout.

MATHEMATICAL MODEL	MICROCONTROLLER MODEL
Set point	Communication module that handles incoming commands
Controller	Central processing module that often requires a state machine and a means of numerical processing
Output Model	Combination of software and hardware to produce the desired result from the Central Processing module
Output	Usually Electromechanical device
Feed Back Model	Combination of software and hardware to process the controlled device's behaviour to a form required by the Central Processing Module

Table 3-1 Relationship between the General CLCS model and CLCS applied with microcontroller Technology.

With the layout of the GICS determined, the operational flow of the microcontroller software can be considered. The most general operation of a control system is a continuous loop of sensing the status and then executing adjustments to keep the desired action. In the application of GICS, the inputs to monitor the status and desired action correspond to the received commands and the feedback values from the device. Executing the adjustments is accomplished with the central processing module output components. Figure 3-3 displays the operational flow of the control system as explained.

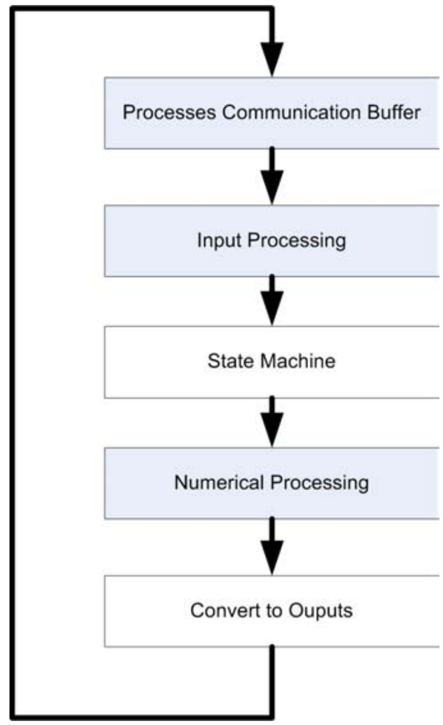

Figure 3-3 GICS software operational flow.

The operation flow diagram shows five software components that are required for most implementations of the GICS. These software components can be split into two distinct groups of development needs. The three components that often require simple but lengthy coding process are shaded in Figure 3-3. The unshaded components often require a complicated but short coding process. To improve the efficiency of developing implementations, the GICS building blocks developed are to reduce the coding process for the shaded components. Moving the focus towards the complex but short coding process, allows the developer to concentrate effort on software that is unique to the task.

Detailing the above, the shaded components that mange the communication input sample and numerical processing are unlikely to require significant modifications in core operation between implementations. The difference between implementations of these components is the parameters specific to the applied application. The problem these components cause the developer lay in the time investment required for each implementation. Once the basic core operation has been produced, the developer is forced into a long, tedious coding process. This tedious coding process for each implementation is time inefficient and error prone. The developer is modifying many simple lines of code to suit each instance and this is introducing another source of possible software bugs. Identifying the course of these software bugs is often time consuming and costly. This is because the software is legal to the development environment but causes an undesired operation. To locate the source of the bug the developer needs to estimate the location of the bug, then check each line of code.

In contrast to these three mentioned are, the components for the state machine and the output to the physical device. The development process for these components is likely to require even the core of the software to be highly modified between implementations. The process for these two components is however focused on the investigation and planning for the software rather than the coding.

The components responsible for communication, input processing and numerical processing are investigated and developed in this chapter. These three components have been indentified as requiring an improvement in the efficiency of development. The sections in this chapter from this point are detailed to specific components. The developed components are required to be easily integrated into the application control system with minimal coding. The developer interaction is similar to using dynamic linked libraries with PC software. The components are to be compiled, stored in the microcontroller's program memory then called from within the main application. In the case of the communication and numerical processing, the parameters of the module are dependent upon the application. For these two cases the component code is generated in automated approach then compiled. The inclusion of the input component is a fixed module that is configured on program start-up. Information passing between the main program and the input component is via methods which act as interfaces.

Microcontroller based CLCS contain the possibility of many desired actions. The range of actions available is too large for one project. The GICS is developed for use with prototype BEVs. With the purpose identified, it is possible to predict what functions are required from the software components. Communication to the microcontroller will use a standard protocol, the processing however is to be independent of the technology. Where possible the operation of the communication processing is independent of the technology. The Communication component developed is explained in section 3.3 .

Feedback inputs to the microcontroller are either digital or analogue values. Analogue to digital conversion is initially handled only within the input component. Handling ADC inputs streamlines applying the most common tedious input source. Defining digital inputs to the application that provide boolean information does not provide a major problem for the developer. In contrast, advanced digital inputs vary greatly in operation. Developing the interfaces within the component to handle advanced digital inputs requires a large time investment. Rather than investing large development times initially, these input interfaces can be developed on an as needed basis. The operation of the ADC component is detailed in section 3.2

The numerical processing core is the third component that is developed. Multiple input single output (MISO) fuzzy logic control (FLC) is realised within the core-processing component. Developing a MISO FLC provides the basis for an advanced control processing method that can be generic. The generic layout allows the developer to form the behaviour of the control without the requirement of coding. The development of the FLC component and development tools is explained in section 3.4.

The GICS components in this thesis are for use on the Silab 8051F020 mixed signal microcontroller and in the format required by complier SDCC. The device is a medium to high range microcontroller that offers a wide range of possible peripherals that cover a number of communication, analogue, digital and time critical interfaces. A large portion of the controller software can be applied to many different microcontroller packages with minor modification. Making the GISC available to other microcontrollers in the future will require modification of register definitions. The software is developed to work with the open source complier named SDCC. SDCC is used because of the free licence, continual development and access to help. Modification of the GICS may be required for use with other embedded C compliers.

3.2 ADC Conversion

The microcontrollers are required to gather physical information about the operation of their relevant modules. The microcontrollers' process information in digital format and the real world operates in analogue values therefore a conversion has to take place via an analogue to digital converter.

3.2.1 ADC Investigation

The analogue to digital converter has the three aspects of performance that are required to be considered

- Accurately read analogue values
- Constant sampling frequency
- Reduction in processing requirements

There are two options for the analogue to digital conversion with mixed signal a microcontroller, internal ADCs or external ADCs ICs.

3.2.1.1 Internal

The mixed signal Silab 8051F020 microcontroller applied for this research contains two internal ADC interfaces that can each access 8 analogue channels individually although only one at a time. The internal conversion of the analogue value is managed automatically by the hardware. The activation and processing of values is however required to be completed from software.

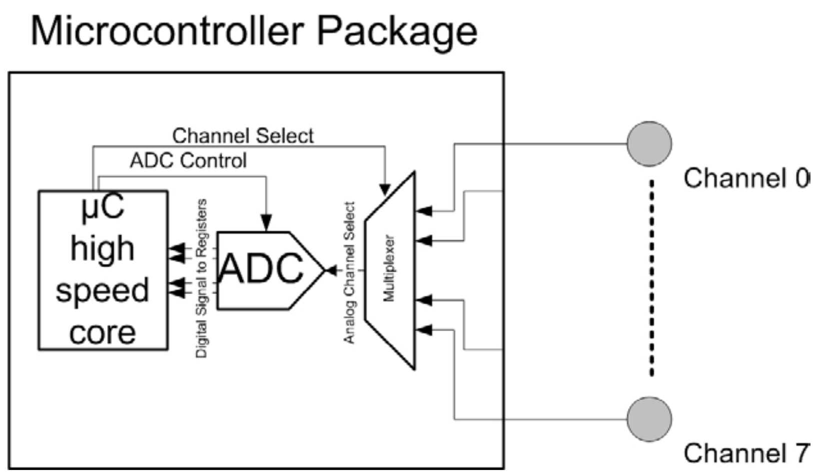

Figure 3-4 Internal ADC layout using embedded components.

The entire circuit for internal ADCs is contained within the microcontroller IC. The internals include the multiplexor, gain of the analogue channels; the necessary conversion hardware and the access to the microcontroller memory for the software to operate and process results.

3.2.1.2 External

Another option is to use external ADC ICs and communicate the digital values between the microcontroller and the IC. There are a number of different types of ADC ICs available with differing operational abilities. The general mode of operation is the setting of port pins to govern the configuration of the ADC IC and the start conversion on/off control is attained by control signals to the IC. Communication between the IC packages is possible through a wide range communication methods. Older legend ICs typically transfer digital values parallel to a microcontroller port (or other device) while newer ICs communicate using synchronous serial communication methods.

With external ADCs the ICs typically only contain the converter section of the required circuit. This requires the addition of gain for analogue inputs and either multiple circuits or multiplexers.

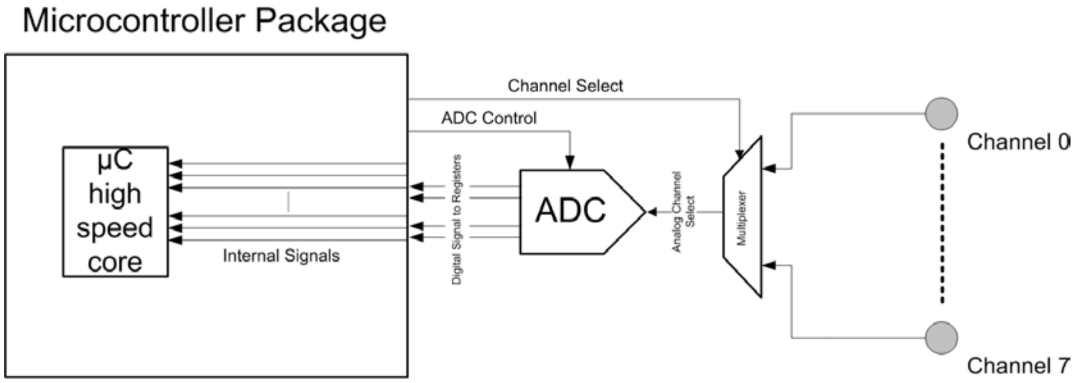

Figure 3-5 External ADC layout using parallel data transfer over a standard port I/O.

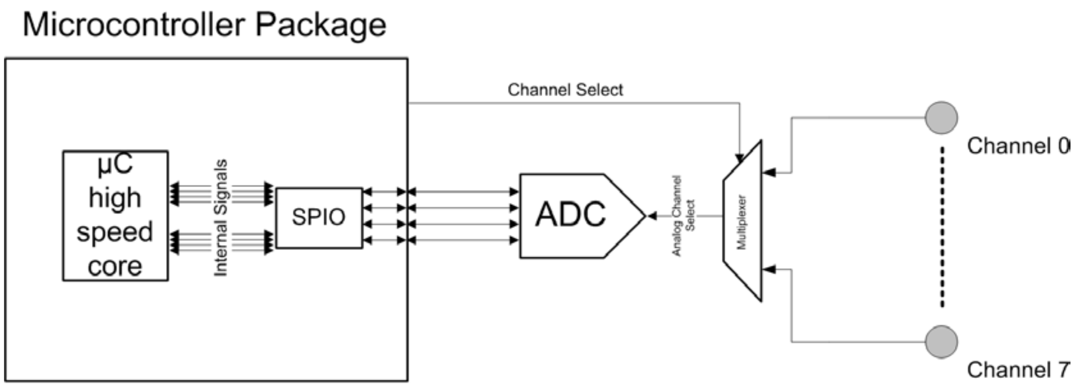

Figure 3-6 External ADC layout using synchronous serial communication.

3.2.1.3 Comparison

The internal ADC conversion provides a simple method of converting the analogue values without the need for complicated external designs. The external circuitry required is generally a gain and a filter. Both of these would be required regardless of any converter type. The disadvantage of the internal analogue conversion is the increased allocation of the microcontroller's processing capability. The microcontroller's high-speed internals are required to control the converter and the processing of the data requires either polling by waiting in software or the use of interrupt routines. Either of these processing methods require the microcontroller to stop its current control task for a period to deal with the ADC conversion.

The external ADC IC accomplishes the conversion with little processing from the microcontroller and presents the digital representation of the value to the microcontroller. This reduction of the microcontroller involvement theoretically allows greater system performance, which can be attributed to lowering the processing requirement of the processor. In reality the difficulties with the transmission of the digital values produce stability issues that require processor involvement that offset any gains by converting off package. With parallel transmission directly to the microcontroller's pins the processor is required to wait for pins on the output and inputs to become stable before the operation can be guaranteed. This waiting is typically been found in the range of 10-20 cycles per change, therefore for a process that requires a sent and received value the delay is at least double the settling time. Basic interrupt routines are carried out within 20 cycles so therefore the actual processing reduction theoretically achieved by external ADC ICs is not realised in practice.

External inter package communication that uses a synchronous serial method requires the processing of the received values, this produces an effect on the microcontroller similar to an interrupt routine triggered from the internal ADC operation. The realistic advantage of external converters is that multiple channels can be converted in parallel. The resulting higher sampling frequency of each channel produces a difficulty communicating the digital representation to the microcontroller.

To ensure data is not corrupted during transfer using parallel lines, ADC requires latches IC before input ports can be safely read. These latches introduce a further delay.Serial communicated ADC values require either high-speed communication or buffering and this still increases the processing cycles.

When evaluating the options between using internal and external ADCs, the internal option is the simplest, most cost effective and reliable method that does not require a realistic compromise for the majority of applications. The system to be developed is not expected to require abnormally high sampling rates and therefore the best option is to use the internal devices available. If at a later stage, high data rates are required then the hardware can be modified to suit the more demanding application.

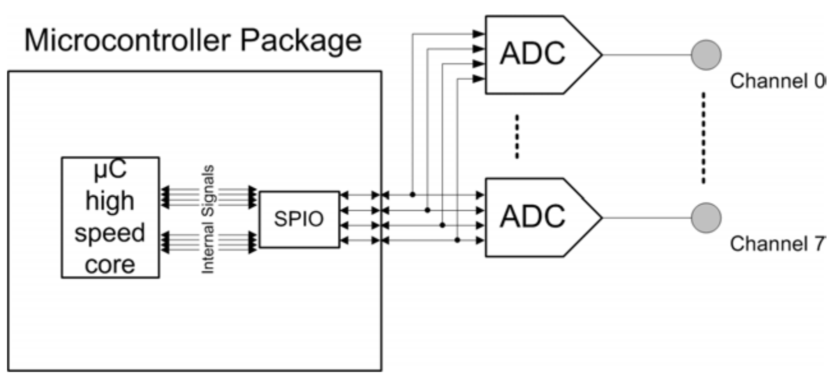

Figure 3-7 Parallel ADC conversion layout.

To achieve a stable system the best design outcome would be a constant sampling of the different channels and then present the results to the main controller program.

The sampling of the variables can be achieved with either polling or interrupt operation of the ADC.

3.2.1.4 Polling Operation

The polling approach is the simpler of the two control options and will provide a new analogue reading each cycle through the control algorithm. The downside to the polling method is that the control algorithm is paused while the conversion takes place. An additional fault is that because the sampling process depends upon the execution frequency of the control algorithm, the sampling rate can not be considered stable. The effect of this is that the derivative of input variables can not be considered accurate.

3.2.1.5 Interrupt Driven

The interrupt driven approach initiates the conversion of the analogue inputs at a set rate independent of the main program. The set conversion rate is generated using a timer programmed to interrupt at the desired sampling frequency. During the timer interrupt routine the conversion of the first channel to be sampled is initiated. Upon the ADC conversion complete interrupt the software vectors to the procedure that processes the converted value and then initiates the conversion of the next analogue channel. This procedure of initiating the next channel conversion continues until all the channels have been sampled. At that point the ADC becomes inactive until the next timer interrupt.

The sampling of the analogue values using a combination of timer and ADC interrupts provides a reasonably consistent sampling rate that is required for control variables that represent the derivative (with respect to time) of analogue inputs. The sampling timer is not strictly consistent due to the interrupt latency that may change depending upon the current operation of the microcontroller. Using the interrupt approach allows the controller to continue with the instructions of the main algorithm while waiting for the converter to complete the task. This allows the main algorithm to operate at a higher frequency. The interrupt operation of the ADC involves a more complicated program and the controller is at risk of unstable operation if not developed carefully. The advantage of using the interrupt routine however outweighs the disadvantages if implemented correctly. The requirements outlined at the start of this section stated the conversion to produce a high degree of accuracy in the sampling rate and reduced processing capacity if possible. Polling the ADC operation does not meet either of these requirements therefore the conversion has to be accomplished with an interrupt generated approach.

Mentioned above was the possibility of unstable operation when using interrupt driven software. The risk from using interrupt routines is the danger that an interrupt routine may change a common variable without the main control algorithm knowing. This can produce an undesired operation from the control algorithm because the changed value may require a different process or possibly be changed partway through a calculation. Excessive processing requirements for interrupts also have a negative effect on the other interrupt events because they can be delayed for a number of cycles and this could create timing issues.

The internal control systems in the modules require conversions of the different channels. This requires the microcontroller to cycle thought the required channels and convert each channel at a time. The task increases the difficultly in maintaining constant frequency of operation and the risk of unstable code. The options for timing the conversion process over multiple channels is either to operate each conversion as a separate clock event or use a single clock event to start the cycle and use the conversion complete interrupt to cycle though channels. Using the option of a single timer interrupt to start a conversion cycle provides a number of advantages

- Timing period is more consistent because the longer period averages out disturbances.
- Less disturbance to the main control algorithm by using less interrupts.
- Guarantee that the previous conversion was complete.

One fault with using a single clock interrupt to start the conversion cycle is that if the conversions are operating at a slower rate than the clock interrupt, the cycle does not finish the previous sample and this causes results and configuration registers to be changing without warning. The consequence of these undesirable actions can be unstable system operation and incorrect results. The problem however can occur with both methods and the simplest method is to make sure during the planning stage that the timer is not operating faster than the conversions can operate.

3.2.2 Software Development

The procedure for operating the ADC was developed to use a single timer interrupt to start the conversion then cycle through the required channels. The process is listed below and detailed flow charts of operation of the timer and ADC complete interrupts are shown in Figure 3-8 and Figure 3-9.

1. A timer interrupt sets the channel to the first channel and starts the ADC.
2. For each ADC complete interrupt of the cycle the result is stored in memory, the next channel is selected, and the ADC is then restarted.
3. On the final channel the process is stopped and a flag set that represents that information can be read safely.

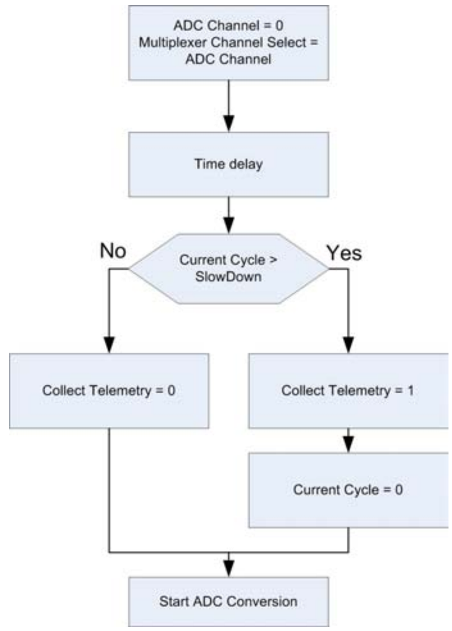

Figure 3-8 Flow chart of timer interrupt routine responsible for the ADC sampling rate.

The program involved using one of the general timers configured to operate at 1 kHz overload frequency. The converter has no effect on the operation of the timer, which is initiated on program start-up. Once it resets, the channel calls the procedure that operates the ADC; the timer is no longer involved. This makes the frequency of the timer constant and free from hazards interfering with its operation.

The procedure for operating the ADC handles switching between the channels and is called from both in the timer and the conversion complete interrupts. The procedure records the current reading and stores the value in the memory address for the current channel. The procedure then checks if there are more remaining channels to sample. If there are more channels to be sampled the procedure changes the current channel selection by switching the internal multiplexer then again initiates the conversion process. When all the channels have been sampled then conversion process is stopped and the flag changed that indicates the results are ready to be read. The flow chart demonstrating the operation of the ADC interrupt is shown in Figure 3-9.

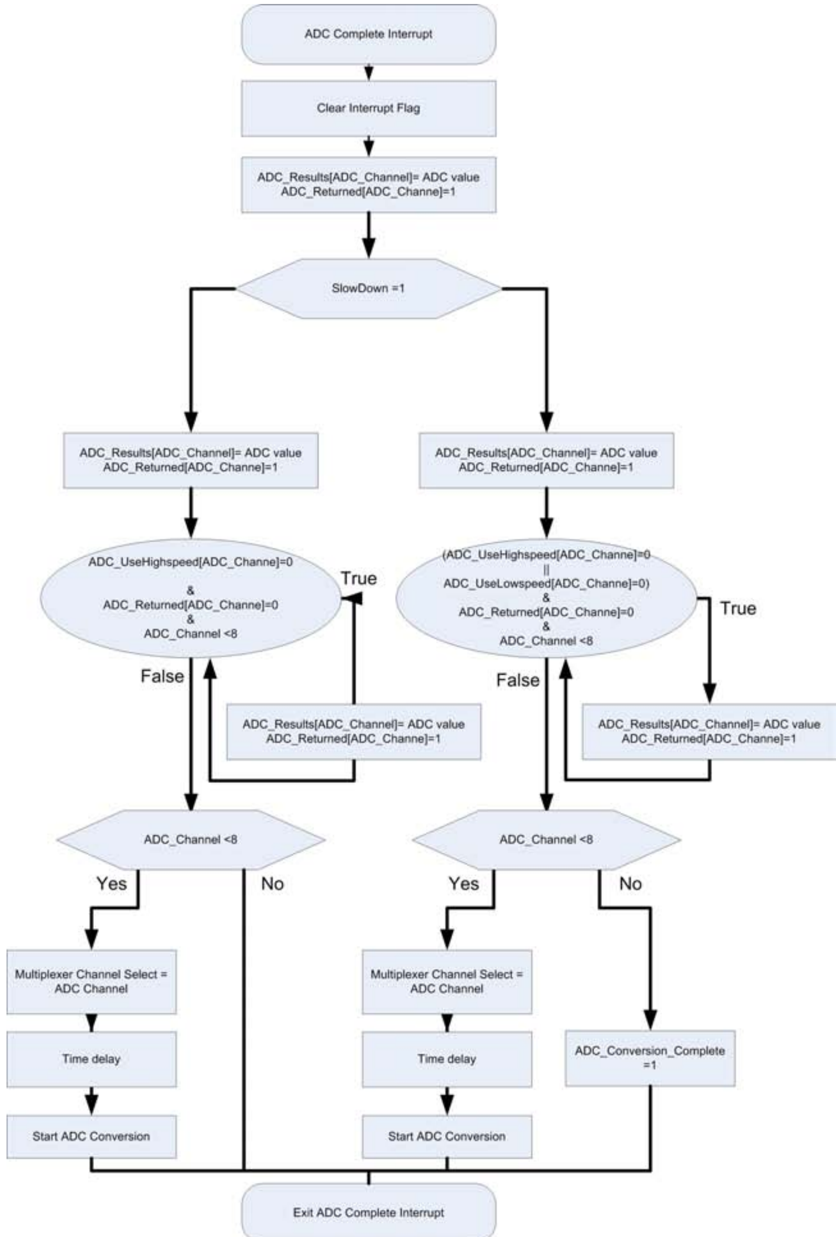

Figure 3-9 Flowchart of ADC interrupt routine.

3.2.3 Software Testing

The ADC process was tested initially by using voltage inputs that were then communicated to a PC that displayed the results. The first test was done with a simple algorithm that converted a single steady analogue channel then transferred the data by loading the result into the serial communication buffer. The results showed the accurate and linear conversion of the analogue signal. The next test was the introduction of using multiple signals to test the operation of cycling through the different channels. This showed that the channel cycling algorithm was working as planned however a problem was occurring that demonstrated an irregularity of the conversion. The converted values were often oscillating between the voltages connected to all the channels and not fixed to the single channel.

The problem was identified as a time constant in the internals of the microcontroller that resulted in the voltage level being sampled before the ADC input had reached a steady value. The converted voltage represented was therefore a mix between the previous channel and the current.

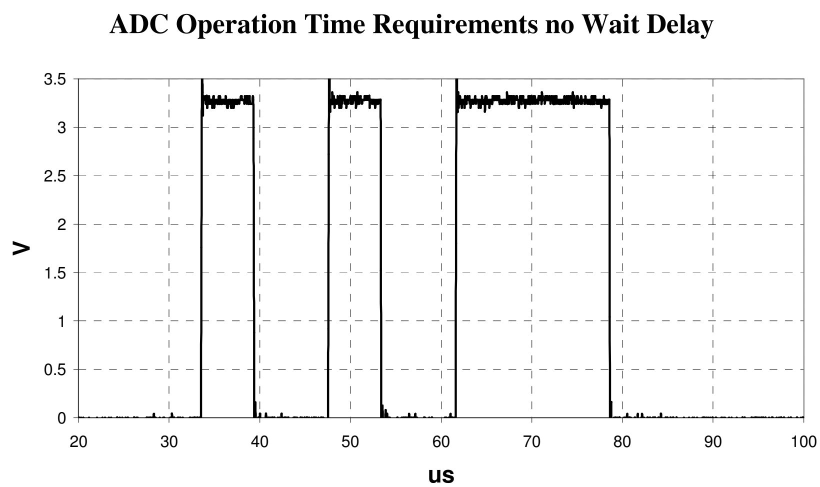

Figure 3-10 Voltage pulses demonstrating the ADC interrupt time requirement with no delay.

To delay the sampling of the input voltage the converter required a waiting period. This could be done with either a simple wait routine or interrupt routine. A simple wait routine of 10 clock cycles was added and the improvement was found to provide a result within 95% of the real value when tested using a full range difference (channel t-1 = 0, channel t = 2.5V). A delay of 20 cycles provided a value to a level of accuracy where faults could not be measured. Figure 3-10 and Figure 3-11 demonstrate the operation of the ADC without a time delay and with the time delay as found to be required.

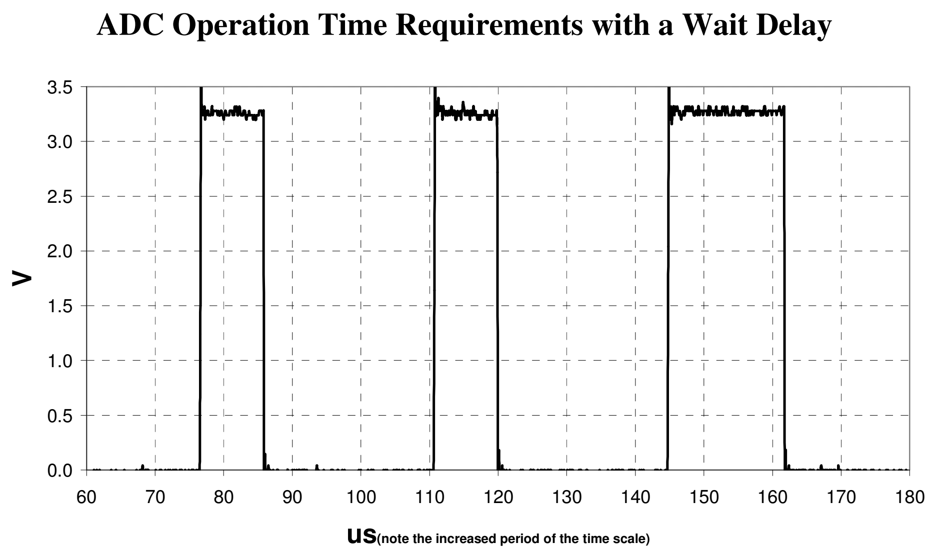

Figure 3-11 Voltage pulses demonstrating the ADC interrupt time requirement with a delay statement.

The option of a separate timer for the interrupt routine was ruled out as even a simple interrupt event was likely to cause 15-20 cycles of disruption to the main control program. Using an interrupt would provide little added performance increase if any because of an increase in code complexity, reduction in reliability and would require more microcontroller resources. Once the ADC operation focused testing had removed the faults of the conversion process, the ADC was tested to demonstrate the effects of the conversion with a high stressed control operation. The ADC operation was included into a controller that was running the initial prototype of a fuzzy logic controller. During this integration with a standard controller, development issues were found to be a challenging management aspect that left the code open to human error. The integration of the ADC required meticulous attention to the storage and management of passing information to variables. The problem was made difficult by the development code looking identical to the human eye with only minor differences of the indexing numbers. This made locating errors exceedingly difficult to identify. Load testing the control with ADC showed the controller functioning correctly without any major faults occurring. The timing of the sampling seemed consistent and was not having a large negative effect on the controller processing. Two minor improvements were found that could be made, the first was that the ADC conversion was operating at a frequency higher than required and the second was that operational cycle of collecting monitoring values occurred every 250 cycles required approximately a 50% longer execution period.

When the frequency of the control algorithm was monitored with an oscilloscope the frequency of operation was approximately 250 Hz as showed in Figure 3-12. This means that the analogue values were sampled at a frequency four times the required rate. The disadvantage of over sampling the values has the potential to produce both inferior conversion quality and unnecessary reduction in control frequency resulting from extra unused interrupt events.

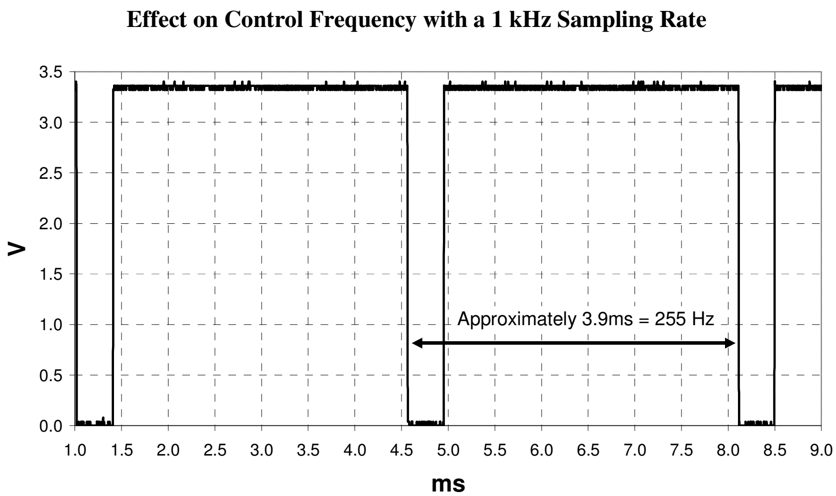

Figure 3-12 Effect of 1 kHz sampling on the frequency of the control algorithm.

Reducing the sampling frequency rate to 300Hz was tested and the result was an increase in the operational frequency of the controller to 295Hz. The operating frequency as recorded from oscilloscope is demonstrated in Figure 3-13.

To keep the sampling of the secondary values used for telemetry at 4Hz, the ratio between the standard cycles and transmission cycles decreased by a factor of 4. This resulted in a slower cycle approximately every 50 cycles and this may be a cause of problems in the future.

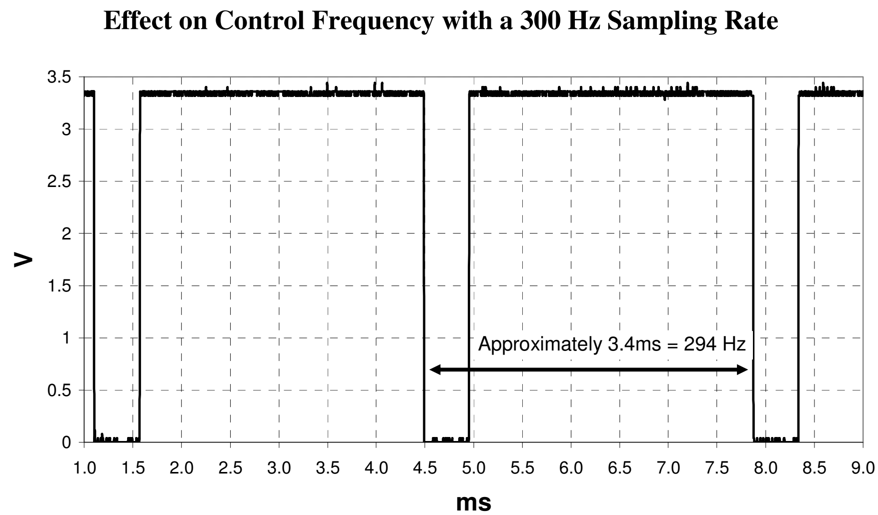

Figure 3-13 Effect of 300 Hz sampling on the frequency of the control algorithm.

3.2.4 Software Redevelopment

The aim of redevelopment of the prototype converter software was to investigate the possible reduction in the problems recognized during the later stages of testing. Improvements were sort to ease the difficulty in the addition of the ADC software and to reduce the increase in control period from the combined effect of sampling the telemetry inputs and the communication of system information.

3.2.4.1 ADC Software Module

The problem with the initial ADC software was the integration of the required software to work with the rest of the controller. As mentioned in section 3.2.3, the integration of the ADC code required meticulous programming to link the converted values and channel selection with variables to be used in the main control algorithm. The problem experienced with integration arose from many lines of similar looking code. The differences were so minute that they were extremely difficult to locate manually. The problems stemmed from coding faults that the human eye could not distinguish. This makes the coding process difficult, confusing and at risk of human error. Fault finding with such code is difficult as the errors can be difficult to spot in code form and the outcomes from the control often do not give a clear indication of the cause of the fault. Another problem that had been identified when trying to originally debug the software was caused by multiple points of access to information during different stages of the main control algorithm and the ADC software. Ideally the same ADC code would be used for every controller in the system. This allows the operation of the ADC to remain constant and updates to the operation could be easier applied with less likelihood of faults. This type of software is generally developed in PC software using object orientated software languages such as java, C++ or C#. The difficulty with software development for microcontrollers is that the languages are limited to procedure-based languages such as C, Pascal, Basic and these languages do not support object orientation.

The aim during the redevelopment was to produce a dynamic generic ADC software module that operated alone without any support from the main control algorithm. The configuration and passing of information was to be achieved with the minimum amount of interfaces between the ADC module and the main control algorithm. Reducing the pathways and allowing the ADC to operate with its own code separately would have a wide range of benefits.

- Allows the same code to be used across control systems.
    - Application of updates becomes easier and more reliable.
    - Standardized code allows easier understanding of operation.
- Development of safer code
    - Less interfaces provide safer control of variables.
    - Easier to locate faults as reduced number of possible sources.
    - Reduced risk of incorrectly modifying code during debugging.
- Main Control algorithm is easier to understand
    - Less detailed control coding is required in main control procedures.
    - Produces a recognised format in the main control algorithm.

The ADC module was developed to have start up options and have data passing of variables by a single function to be called in the controller initialisation or control loop. The initialisation start up function was to include the ADC converter, high or low speed, channels to be used by that activation and the timer reload value if this has not already been set.

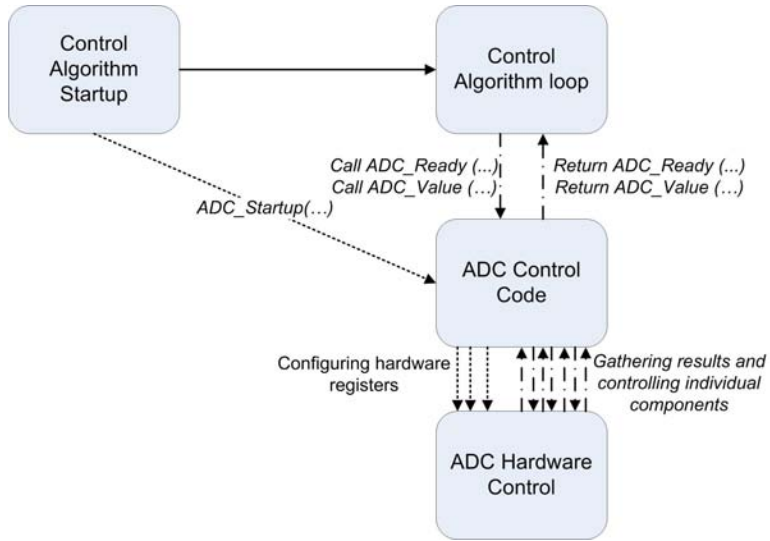

Figure 3-14 Modular view of the ADC software.

3.2.4.1.1 ADC module commands

The operation of the ADC software module consists of a group of functions and activated through the required commands and format. Following is an example of using ADC_startup function.

Format:

```
ADC_Startup( ADC_number, ADC_option, Channel_0_Used, Channel_1_Used,…, Channel_7_Used, Timer_reload);
```

Instruction 3-1 ADC start-up function (general).

An example of the desired operation using the instruction above should be similar too.

```
ADC_Startup (0, 0, 1, 1, 1, 0, 0, 0, 0, 1, 0xF800);
```

Instruction 3-2 ADC start-up function (example).

The instruction would run the procedure in the ADC software module to operate ADC0 with the sampling frequency specified by 0xF800 and apply the conversion to channels 0, 1, 2 and 7. The operation inside the ADC software module configures the timer for the required frequency of the operation, configures the array that governs the channels to be sampled and sets the initialisation of the storage of recorded values.

From the main control algorithm loop, the call to the function ADC_Ready checks the availability of a new ADC result for of specific analogue reading.

```
ADC_Ready (ADC_number, Channel_Select);
```

Instruction 3-3 ADC ready function.

The command ADC_Value returns the stored value from specified channel of the ADC converter and then resets the internal flag inside the ADC module that signifies a new value is available.

```
ADC_Value (ADC_number Channel_Select);
```

Instruction 3-4 ADC Value function.

3.2.4.1.2 ADC Software module outcome

The improvement of the ADC software module reduced the development complexity of the control software as originally intended. The integration of the ADC was simplified and required less lines of code in the main program. The program was easier to understand and the collection of variables has always been operationally reliable. Figure 3-15 and Figure 3-16 demonstrate two examples of the testing carried out on the ADC software operation. The examples shown below demonstrate the correct conversion of the input signal. The difference between the real input and the recreated voltage is explained by the resolution of the sampling and the latency of the software. Figure 3-15 demonstrates the latency of the conversion process caused by the delay in the microcontroller processing then recreating the input voltage. The 100Hz square wave input waveform measured is the worst case from all the measured traces. The 100Hz input reduces the resolution compared to the waveform period and the effect is most notable on the high-low-high of the square wave.

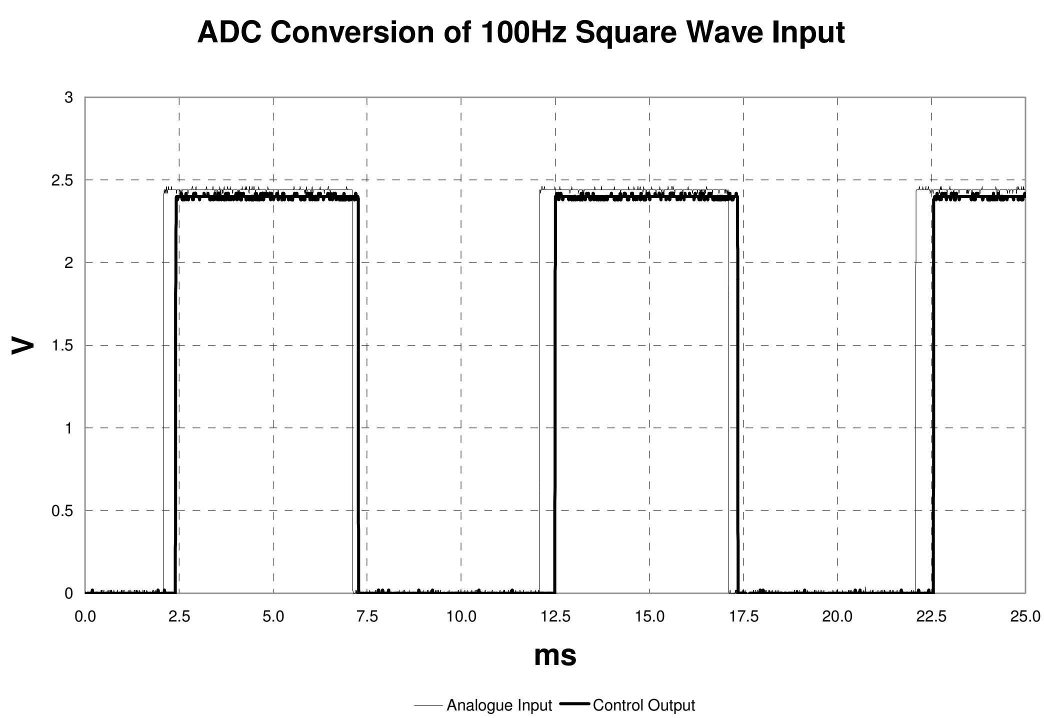

Figure 3-15 Oscilloscope trace from testing ADC operation with 100Hz square wave input.

Figure 3-16 shows the effect from the sampling resolution; this effect is most notable with the high frequency inputs. This resolution of the sampling can be increased to match the application; the increase however has a negative effect on the main control algorithm. Attempting to measure cross channel interference with final version of the ADC did not produce a result different to the above waveforms. The methods for testing the ADC software module are located within the appendix page B-1. The full results from testing the ADC are located in the appendix page C-1.

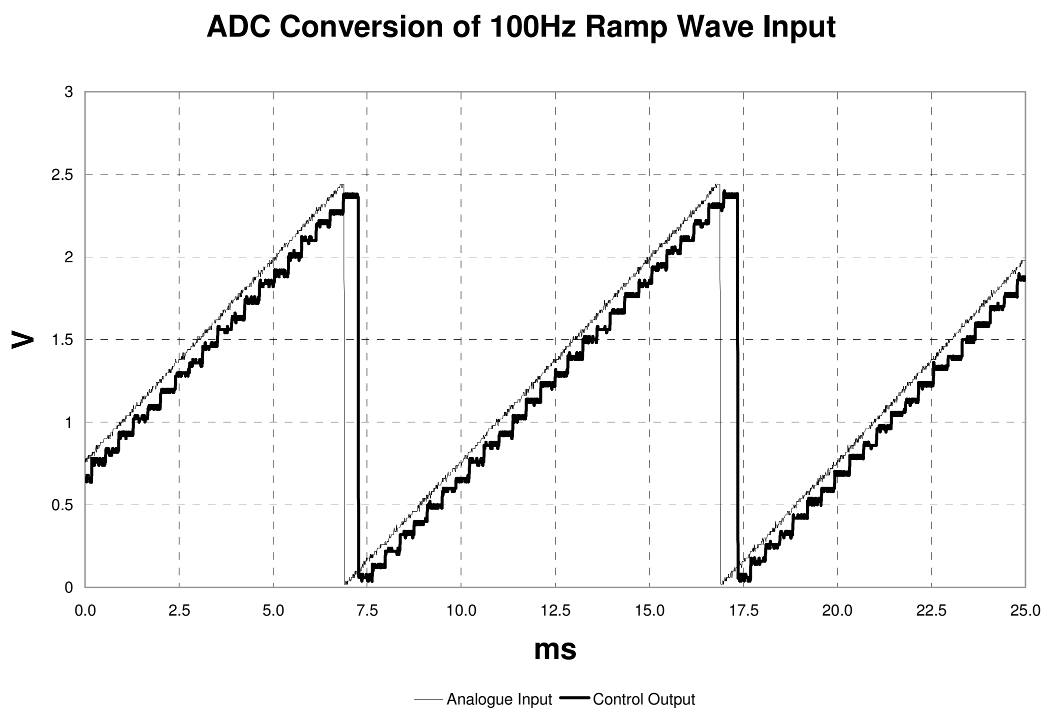

Figure 3-16 Oscilloscope trace from testing ADC operation with 100Hz ramp wave input.

3.2.4.2 Slow Telemetry Cycle

Every 50th cycle had been shown to be approximately 50% longer than the normal. The 50th cycle requires two extra tasks that could contribute to an increase in the control loop period, the extra ADC channels to be sampled and the loading of telemetry into the serial port buffer. To identify the cause of the increase in the cycle period, an oscilloscope was used with a pin to time the increased processing requirements. Both the increase in the analogue channels to be sampled and the loading of the communication buffer were shown to have an effect.

To solve the problem of slower cycle every 50th would involve distributing the added task over the entire 50 cycles. To distribute both tasks would involve more a complicated coding algorithm that would require more development time. The increase in the 50th cycle had not shown to be a fault at this stage and the therefore was concluded that further development time would not be useful until a problem was occurring at future stage.

3.3 Communication

The system layout is a multilevel hierarchy design with a system controller sending commands to the lower controllers that directly control the hardware. The reliance of the system controller sending commands requires the communication channel to provide reliable transmission and reception. The system controller is a PC based microprocessor that communicates to microcontrollers embedded in each hardware module. The Silab microcontroller used for the prototype system has a number of communication peripherals within the IC package.

The communication peripherals available are listed below.

- SOIC
- IC2
- SPI
- UART

The UART is the only communication peripheral available to the microcontroller that is compatible with standard PC communication options. The microcontroller's UART ports are capable of being interfaced with external ICs to attain the necessary protocols for a range of serial communication standards. Using an external IC would allow protocols such as RS232, RS485, USB (1.0, 1.1, and 2.0), fire wire, CAN and numerous wireless communication options. RS232 is the simplest of the standards that can be used to provide communication. The RS232 is however, a protocol that is outdated as it is limited to low data rates and transmission errors. Fire-wire could be used although this protocol is rarer because of economic constraints and the prototype has no foreseeable reason to use wireless communication between the hardware modules. The option of using a USB standard would reduce the rate of transmission errors and allow higher data rates. The high data rates available from of the USB standards are not able to be utilised because the microcontroller generates the timing for the communication channel and is not capable of rates above 256kbs^{-1}. The Silabs 8051F020 development board incorporates the external IC packages required for RS232 serial communication. This allows an easy implementation as the communication does not require additional hardware on either end of the communication channel. USB standards could be used as a means to improve communication; however, without the requirement of a large increase in performance, the investment in time to develop the required hardware outweighs the gains.

3.3.1 Communication requirements

The communication channel used between the system and module controllers is required to be bidirectional allowing operational commands to be sent to the module microcontrollers and the system controller to receive telemetry about the operation of the modules. The highest priority communication is the commands sent from the system controller to the microcontrollers. The microcontrollers' communications have a secondary priority that requires the transmitting of the operation of the module to the system controller for monitoring and means of providing telemetry to the user. The information sent through the communication channels is a set format that makes the processing of communication simpler by using a set standard.

"\&" + three character code word + information expressed 5 digit integer + "\n"

Instruction 3-5 Communication instruction format.

The characters "\&" and "\n" are the standard start and end of transmission character flags commonly used for communication. The addition of characters reduces the efficiency of the communication but gives a clear start and end of transmission which improves the reliability and reduces the complexity of the processing. The information stored in the instructions is given as the decimal representation of a 16 bit integer. Telemetry is simply given as the value gathered, for commands or warnings, set values represent the current state or command instruction.

The communication from microcontrollers has various ranges of priorities and events for transmitting the information to the overall controller.

3.3.1.1 Microcontroller communication instructions

System to Module Controller

High Priority

- Boolean Commands
  - *COMMAND CODEWORD + either 00000(off) or 65536(on)*
- Set Point Command
  - *SETPOINT CODEWORD + SET POINT*
- Information Request
  - *CODEWORD + 65536*

Module to System Controller

Automatic Communication

High Priority

- If a variable has been detected at a dangerous level.
  - *VARIBLE FAULT CODEWORD + 65536*

- Interlock has occurred
    - *INTERLOCK CODEWORD + 65536*

Medium Priority

- Variable is in a high area of allowable range and increasing
    - *VARIBLE FAULT CODEWORD + 32768*
- Variable was in a high or dangerous range however has returned to safe value.
    - *VARIBLE FAULT CODEWORD + 00000*
- Hand shaking of data transfer
    - *COMMAND CODEWORD + RECIVED COMMAND VALUE*

Lowest Priority

- Variable value for telemetry
    - *VARIABLE VALUE CODEWORD + VALUE*

Requested Information

Medium Priority

- Fault status request
    - For each possible fault → *VARIBLE FAULT CODEWORD + VALUE FOR FAULT STATUS*
- State of operation request
    - *CONTROL MODE CODEWORD + STATE*

The On/Off command gives the instruction for the module to either turn on or off. The overall controller gives the single command and the microcontroller runs through the required modes of operation until the desired mode is achieved. The reset commands are required after a variable has reached a dangerous level or an interlock has been triggered. The request fault state command is an instruction to the microcontroller to transmit back the status of all possible faults. This can be useful for the system controller to identify what is wrong with a module if the initial fault was missed. The request operational state command is to be used by the system controller to check the current state of the microcontroller. This is useful as it gives feedback to the system controller that the microcontroller has not missed a command and is in the desired state. Module operational information is provided automatically from the microcontroller in three levels of priority that relate to three levels of risk or if information is requested from the system controller. The highest level is used for faults that have occurred and the module has been shutdown. The second level of priority is used to communicate warnings of possible faults occurring if preventative action is not taken. The lowest level of priority is simply telemetry providing information about the operation of the system.

3.3.2 Simple Communication

The initial communication code was lifted from undergraduate projects. The structure of the communication as taught was a very simple approach that uses a polling method for transmission and received strings were processed within the communication interrupt routine. This simple method of serial communication is explained from "Embedded Programming with Field-Programmable Mixed Signal Microcontrollers"[53].

At undergraduate level, the described approach provided a simple solution that would generate a means of communication that allowed projects to work even though the communication channel was far from perfect.

3.3.2.1 Receiving

The processing of the received command is done during the UART interrupt routine. The character received is added to the end of a character array and the contents of the array are compared against known commands.

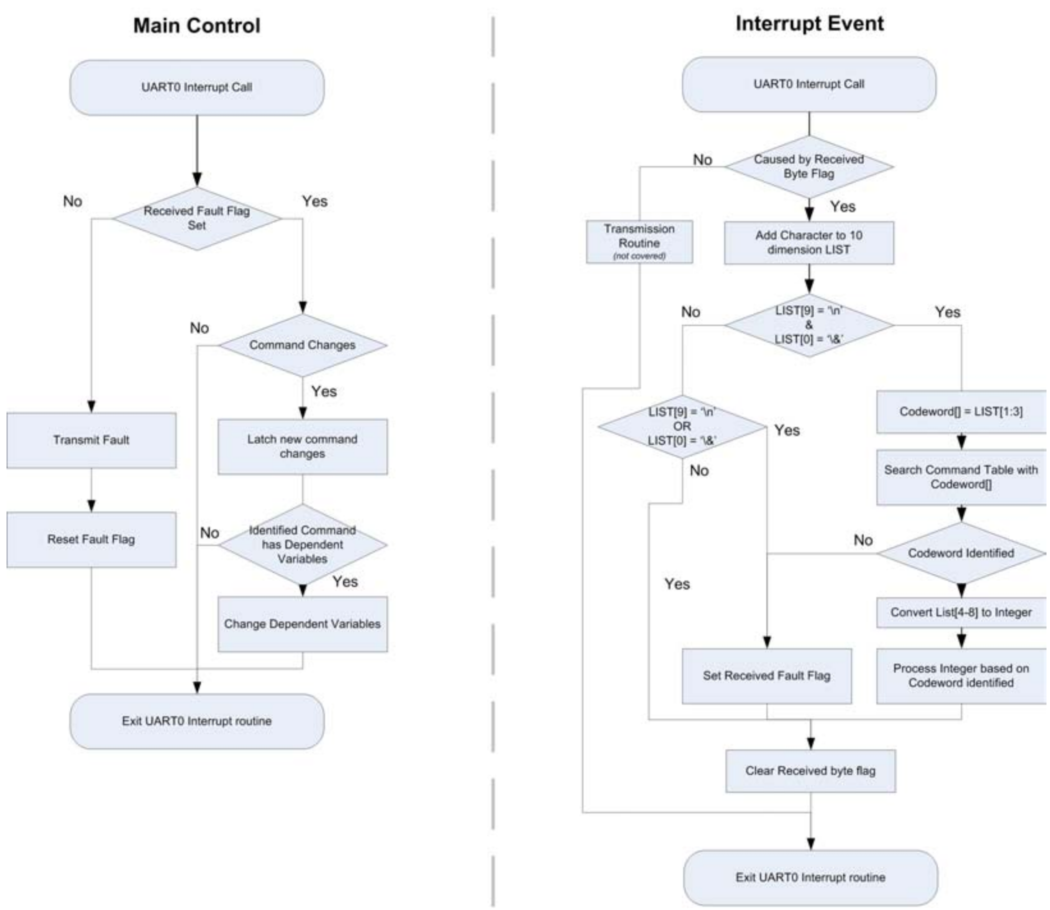

Figure 3-17 Simple receiving communication method using interrupt based communication approach.

3.3.2.2 Transmission

The transmission of information with the UART uses a polling approach to load each individual character into the single byte send buffer. The code uses C libraries that produce the character array representation for command and the software then moves through the character array sending each byte individually until the end of the array.

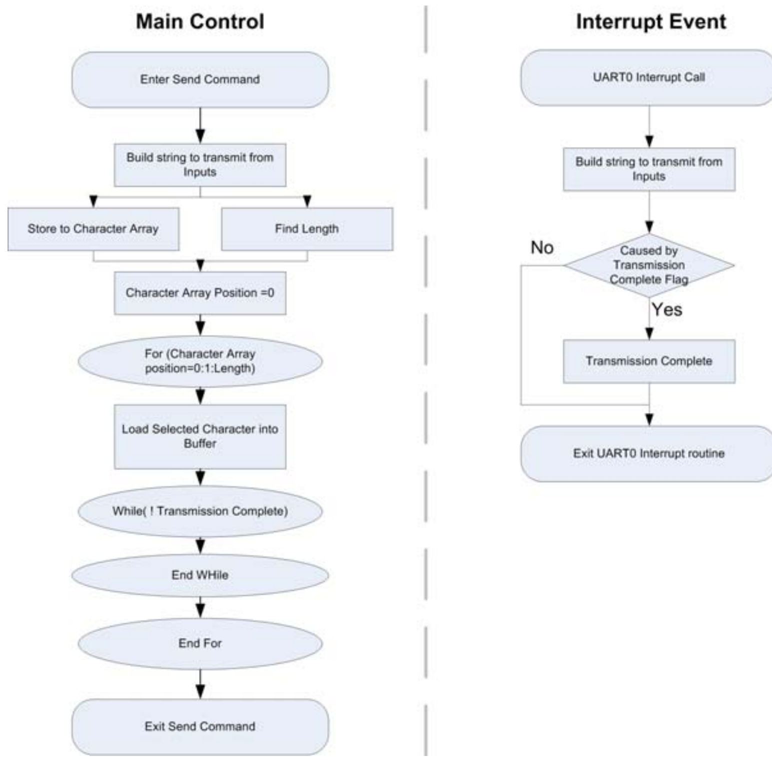

Figure 3-18 Simple transmission communication method using interrupt based communication approach.

The simple method of communication that was commonly used for applications was found not to provide a communication channel that met the requirement of high reliability and low processor time requirements.

3.3.3 <u>Software Development</u>

The receiving of the instructions had three problems that were required to be addressed.

- The long interrupt routines were causing instability in the main control routine.
- Lower priority interrupt routines were often subject to a latency that was considered be a possible source of problem in the future.
- Long interrupt routines were occasionally causing received bytes to be skipped that results in the entire string being processed incorrectly.

In basic programs these problems were not as serious because the simple nature results in shorter interrupt routines. The commonsense improvement was a reduction in baud rate. The reduction in baud rate had a positive impact on the errors listed however, the improvement was not great enough. Furthermore, the baud rate at the reduced rate was to a level that would not allow telemetry transmission from the microcontroller. Initial investigation through microcontroller textbooks and internet searches did not provide a suitable approach. To avoid the problems outlined above the new method for communication had to be operated from within the main code and the size of the interrupt routines reduced to a bare minimum.

The communication between computers using serial RS232 ports even at high data rates (1.2 Mbs^{-1}) is very robust. The improved method aimed at copying serial communication used with PCs. The communication method used for PCs is based around a buffered input and output method. The buffered communication method was therefore trailed for use with microcontrollers.

3.3.3.1 Receiving

Receiving commands from the overall controller is the most important part of the communication and was causing the greatest difficulty. The foremost aim of applying buffered communication was to solve the issues with the input communication. The method for the receiving of communications instruction works using a simple interrupt routine that enters the characters into a buffer that is then processed within the main control. The theoretical disadvantage to processing the received data in the buffer is that a time delay occurs between reading the communication channel and acting on the command. In practical terms, it was hoped that while there may be a small delay of 1-5ms before acting on the instruction this time delay would be consistent and be more reliable. The input buffer consists of a number of character strings. Each character string stores a possible command that is indexed while inside the interrupt routine using the identification of either a start or end of transmission character flag.

The characters have the following effect inside the interrupt routine

- "\&" instructs the command index to the next location it the buffer
- "\n" Sets the internal flag for the string that reception of for the command is complete. The interrupt routine also checks that the current position of the character is valid.
- Any other character is placed in the next character position for the current command string.

The processing of the string is done during the main control algorithm. The advantage of this is that the further time requirement for processing is not involved during the interrupt and therefore stopping the main control process.

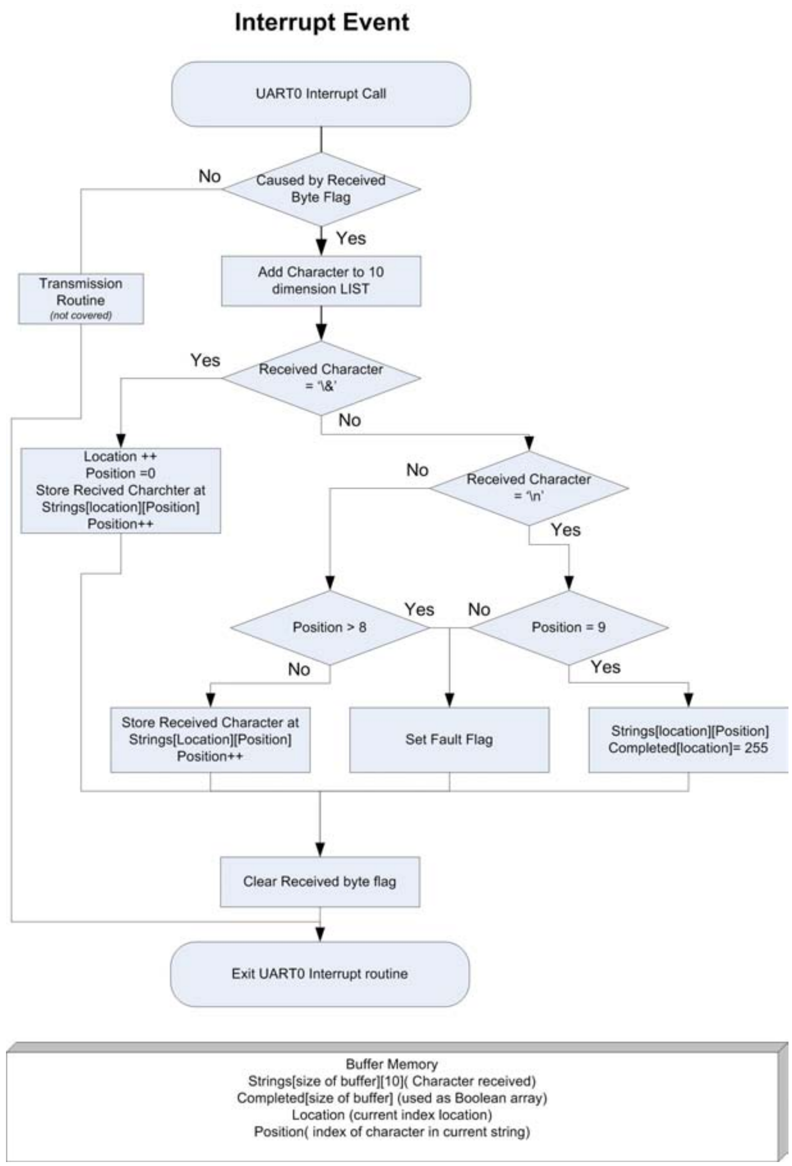

Figure 3-19 Interrupt routine for buffered communication.

The processing of the input buffer starts by searching for command locations that have had their command received flag set. Once a completed string has been identified, the processing of the command starts. The processing of the string begins with the substring of the characters in positions 1, 2 and 3 which corresponds to the codeword component of the command. The codeword is then compared to the possible commands for the system. Depending upon the identification of the codeword the processing of the numerical component of the command string is done using different methods. With commands that require a numerical value, the component is converted to an integer and then stored in the required location. For commands with a desired action, the value is converted to an integer then operated through a search table to match the number to the required action and the state of the action is stored.

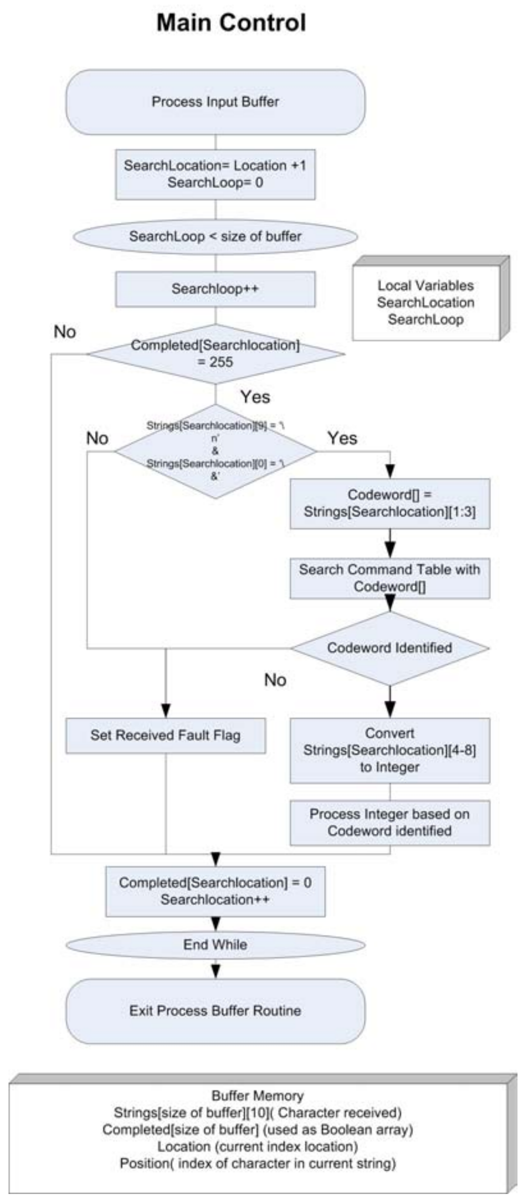

Figure 3-20 Processing input buffer routine.

A later advancement was to include a moving datum in the buffer that allows the buffer to be processed safely without having to stop the microcontroller from receiving characters. Effect on the reliability using the moving datum has reduced the errors in receiving commands to adequate levels when combined with handshaking for high priority communication.

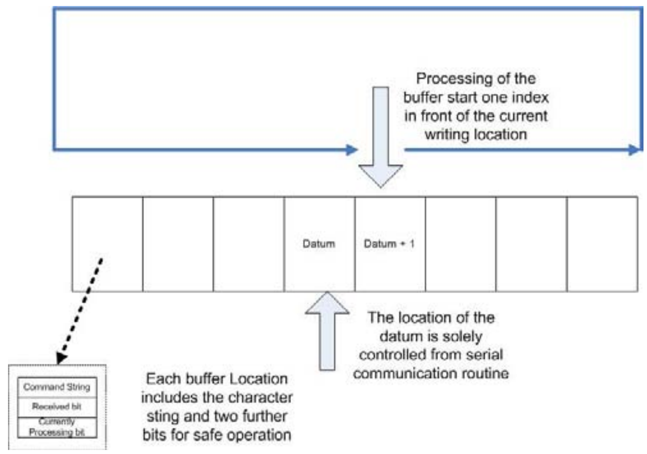

Figure 3-21 Moving datum relative to the communication buffer.

Once the improved approach of reception had been completed and debugged, an immediate improvement was noticed in stability even without the ability to fully test the approach by experimental means. Figure 3-22 and Figure 3-23 show the difference in the reliability and latency comparing the communication methods when sending a command from a PC at frequency of 10 Hz with a baud rate of 115200kbs^{-1}. The voltage pulses demonstrate the latency between the controller receiving the command and the processing of the received string. The pulse widths of the interrupt method demonstrate the reduced latency compared to the buffered approach, however a serious fault with the interrupt approach is shown that three out of the five communications were missed.

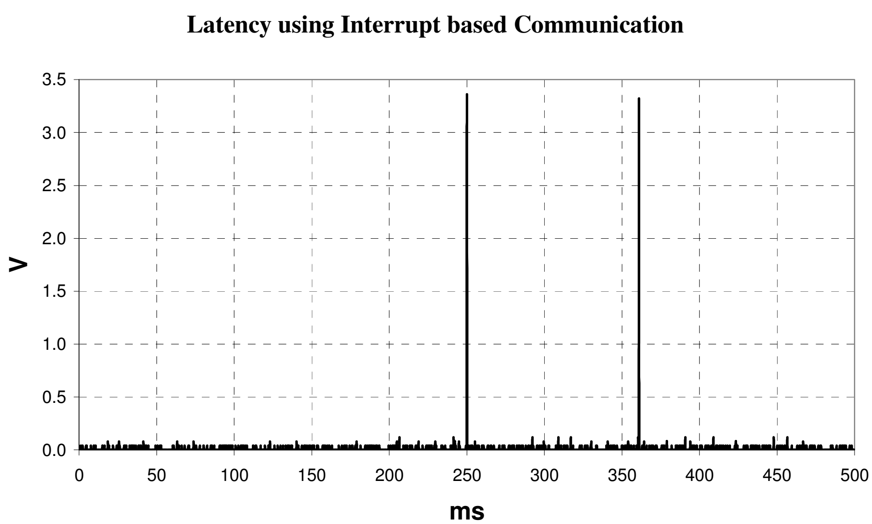

Figure 3-22 Latency of receiving commands using interrupt based communication.

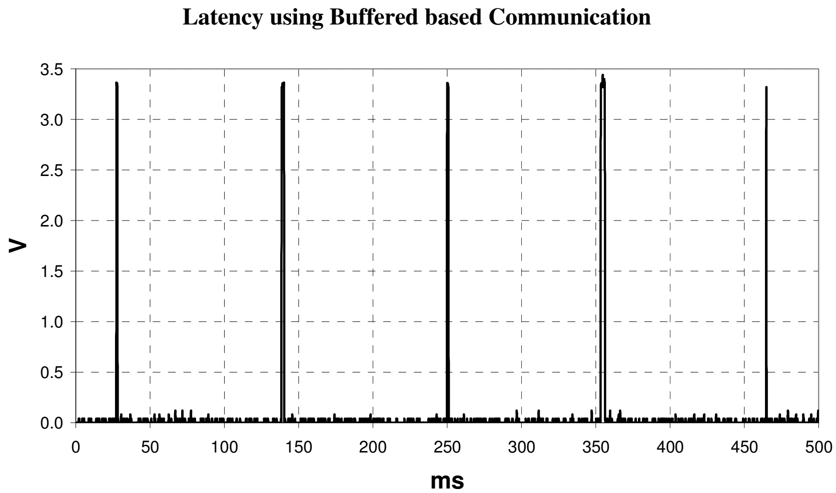

Figure 3-23 Latency of receiving commands using buffered communication.

3.3.3.2 Transmission

The original UART transmission method was discovered to have a negative effect on the controller operation by stopping the control process while the transmission was occurring. The polling method used for transmission became a problem once the microcontroller was programmed to provide telemetry. Telemetry used on the different modules consists of approximately ten communications sent every 200 program cycles. Stopping the controller to transmit the telemetry was not acceptable because the data rate of the communication channel required the equivalent period of approximately five control loops. The result of the polling method used, was that the controller waited every time it was transmitting and thus stopped controlling the hardware. To negate stopping the controller during transmission the buffered approach that successfully applied to the reception was introduced. The transmission was redeveloped to write commands to the buffer every 200 cycles then transmit these in the background over the next 199. The buffered method works by loading the commands to send into a buffer, the content of the buffer is then sent out of the UART in the background using the interrupt routines rather than making the microcontroller stop the control algorithm.

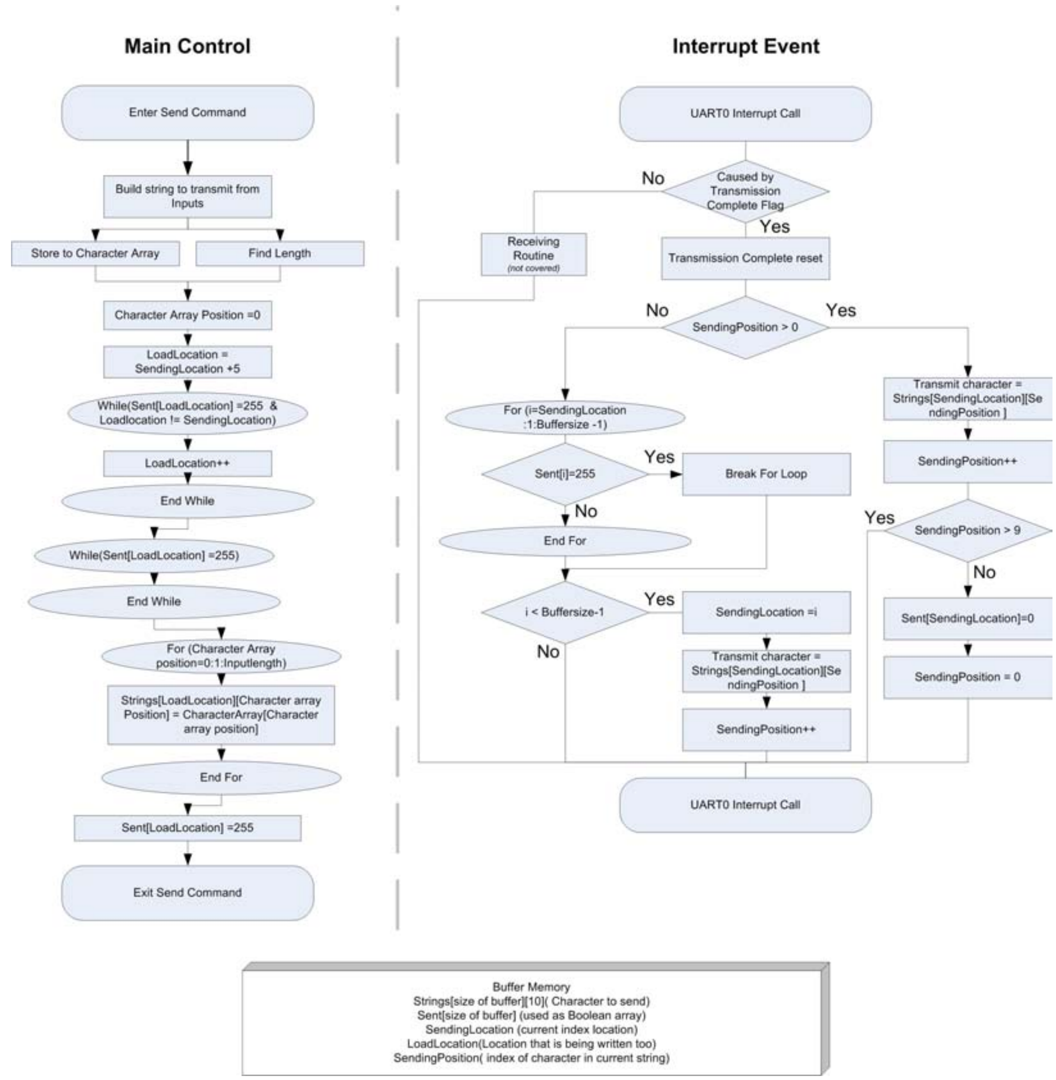

Figure 3-24 Flow chart of method employed for transmission using buffers.

3.3.3.3 Results

To compare the original method of communication and the buffered approach, a microcontroller was connected to a PC via a RS232 serial port. The PC program pseudo randomly chooses commands via the serial port to the microcontroller. The received strings are processed against a known table of commands and then transmitted the result. The PC program then compares the string received from the microcontroller to the string that was sent. The error rates of the differing methods of communication are shown in Table 3-2. The values shown are in relation to the entire string of the command, not individual characters. A single error in the string of 10 characters results in an error.

Communication Method	Command Received	Errors	Error Percentage
Original method	735	249	33.88
Buffer	1254	17	1.34

Table 3-2 Error rates from communication testing.

3.3.3.3.1 Effect on the Controller's Frequency of Operation

Figure 3-25 and Figure 3-26 demonstrate the effect of the methods of communication have on the control algorithm frequency. The original method of transmission that relied upon a polling technique stopped the controller when transmitting the data via the serial port. The effect of stopping the controller algorithm can be seen in Figure 3-25 that demonstrates the controller stopped for a few milliseconds before resuming control. The oscilloscope displays do show a lower frequency of operation for the buffered approach although the number is misleading. The fastest cycle of operation with polling communication method is faster than the buffered approach. It however allows more control cycles per second because there is no pause for transmission. The buffered control cycle is slightly slower for two reasons. Firstly, at the start of each cycle the received buffer is checked for new commands. Secondly, the transmission is carrying on in the background and the interrupt routine is having an effect on the execution time of the main control algorithm.

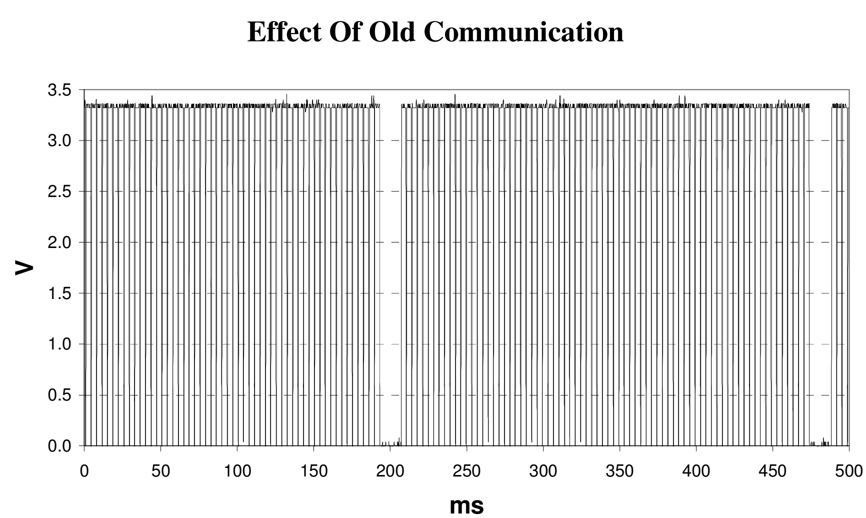

Figure 3-25 Captured waveform showing the execution frequency with the original transmission method.

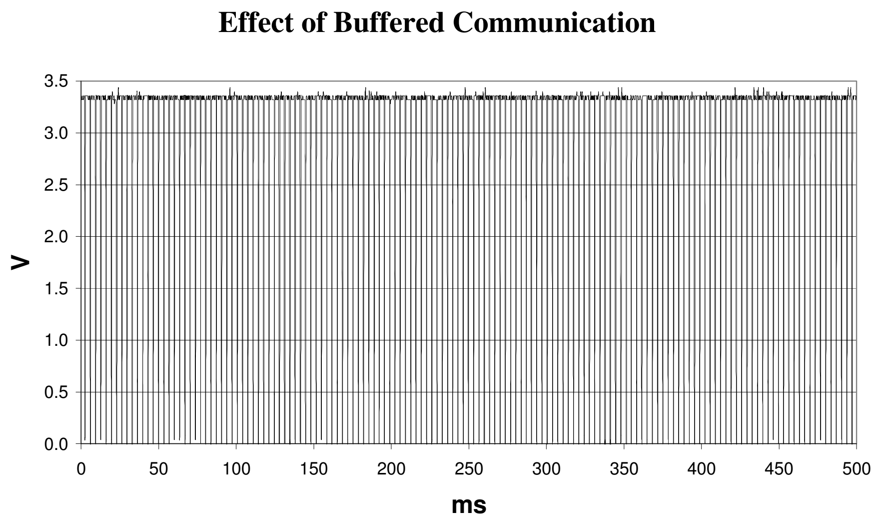

Figure 3-26 Captured waveform showing the execution frequency with the new transmission method.

3.4 Fuzzy Logic

The controllers within the system modules are assigned the task of controlling hardware that operates theoretically in a non linear fashion with several inputs variables required to determine a control response. Other than high performance examples, most microcontrollers do not allow real number representations nor do they provide a high clock frequency. This low processing ability of microcontrollers used in embedded hardware does not allow mathematical prediction models to be easily or reliably implemented for control purposes[54]. The prototype of the electric drive propulsion system developed is to operate over a wide range of operating conditions and so it is envisioned that multiple input variables will provide the means to accurately determine the controller response. The initial prototype will introduce a fuzzy logic controller that is adapted to be suitable for multiple input single output control with low processing requirements. This section will outline the development of the FLC processing of the generic control algorithm used in this research.

3.4.1 Difficulties

The application of fuzzy logic control to a microcontroller involves difficulties because of the limited ability of microcontrollers compared to PCs. Comparing the microcontroller to the application of a PC, the microcontroller suffers from the following.

- No floating point numbers.
- Reduced processing capacity.
- Limited Storage.

- Software developed by C code.

3.4.1.1 Floating point numbers

Most microcontrollers do not support the use of floating point numbers and this generates problems when implementing non-linear functions as the variables are forced to be represented by integers. Floating-point numbers provide a wider range of possible values compared to integers and can represent numbers of different powers to the same percentage of accuracy. When dealing with non-linear systems represented by low integers, the ± 1 error associated with integers can become a factor when performing integration type functions particularly when integers are of a low value. Using floating-point numbers maintains the number of significant places of variables and this allows accurate functions with small numbers and avoids the trouble with low values and integration functions.

3.4.1.2 Processing capacity

Microcontrollers operate at a clock cycle frequency many times lower than a PC and are not capable of parallel processing such as FPGAs. The Silab 8051F020 used is a 16-bit microcontroller therefore processing 32 bit integers requires more cycles compared to a 32 or 64 bit microprocessor. The reduced processing capacity of a microcontroller denotes that the control algorithm used must either operate at a lower frequency or be accomplished by a less calculation intensive procedure. Both compromises mentioned reduce the performance of the controller by either limiting the accuracy or increasing the period for corrective action.

3.4.1.3 Memory Storage

Memory storage is a useful element for fuzzy logic controllers as it reduces the need of live processing of information by allowing coordinate space mapping of the variables to a pre-processed controller response. If a device has no memory available, then for every control loop the device is required to carry out a mathematical operation to determine the activation of the membership functions within each fuzzy set. In comparison with other controller technologies, microcontrollers do not allow a high processing rate. This therefore means complicated mathematical instructions carried out on such devices have a large negative effect on the time required to operate a control algorithm loop. The longer a control loop takes to operate, the larger the delay before a correction can be made and therefore poorer control[54].

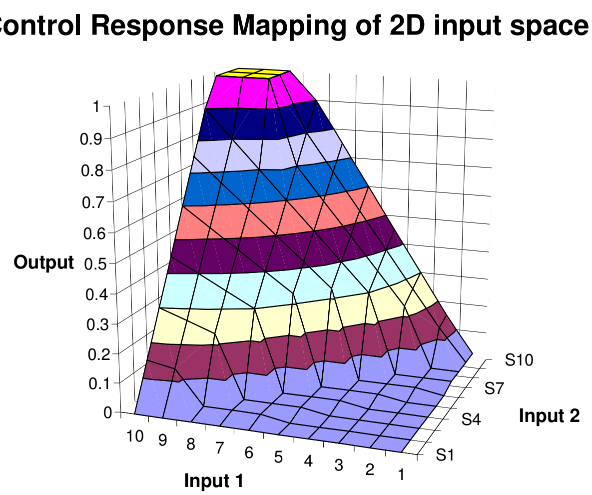

Figure 3-27 Control response mapping of 2D input space.

If a device had an infinite storage capacity, the entire mapping space of a controller could be pre-processed and stored in memory. The effect of pre-processed control output is that the controller operates at a higher frequency because the control algorithm is merely required to look up the required mapping coordinate and have the required output control available. The memory required to map a controller response can be given by Equation 3-1

$$m = \left(2^i\right)^v \times o$$

m – Required memory[B]

i – Input resolution[b] *(3-1)*

o – Output resolution[B]

v – Number of input variables

The impractical limitation of mapping an entire controller response with current technology can be demonstrated by a simple example. If a system controller used four input variables and a corresponding output value all with 16 bit resolution, the control device would require 32 Exa Bytes (~32×10^9 Giga Bytes) of memory storage. Equation 3-1 applied to the example given would form Equation 3-2

$$m = \left(2^{16}\right)^4 \times 2$$

$$m = 2^{65}$$

Answer in decimal representation (significant units are 1000s base) *(3-2)*

$$m = 3.689 \times 10^{19} B$$

Answer in digital system (significant units are 1024s base)

m = 32.79 EB

Mapping the entire system is therefore impractical as its size is not compatible with current or any near future memory technologies. No device has infinite memory storage however, there is large difference between a typical PC and a microcontroller. The memory in a PC can be commonly 2MB high speed or 8000MB medium speed memory. In comparison a good microcontroller may only have 512B or 64KB respectively. An example of this difference is that a PC based controller with 4000MB memory available is capable of entirely mapping a control output of a system represented by four variables of an 8 bit resolution each; in comparison a microcontroller could only represent the four variables with a 4 bit resolution ($1/16^{th}$ the resolution of a 8 bit variable) of the same system.

With current technologies mapping the entire input space for a control system becomes impractical when the resolution of the total control system becomes greater than approximately 40 bits (system resolution = number of variables × variables resolution). Such a method would require 1 TB of storage when using only a single byte controller response. From the examples above it can bee seen that the performance of a controller shown by the frequency of operation and resolution of information is limited by the economic and technology constraints of high-speed memory. Realistic memory mapping of complicated systems requires the mapping of individual areas rather than the entire system. The effect of mapping smaller areas reduces the required memory although this is at the expensive of increasing the processing requirements.

An effective method to reduce the processing requirements and use a reasonably small amount of memory is to map the input numeric variables to a fuzzy set representation. An example can be given below for the mapping of simple 8 bit numerical input variable to a fuzzy set consisting of 5 fuzzy membership functions. The mapping would directly map each of the 256 possible numeric input values to an activation representation of each of the five membership functions for any given input value as shown in Figure 4-23 to 4-35.

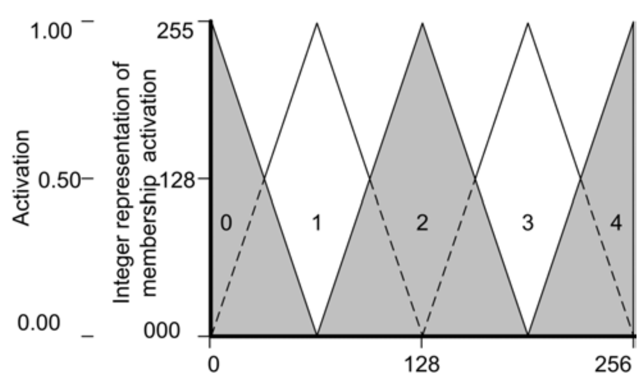

Figure 3-28 Graphical representation of membership needed to be implemented.

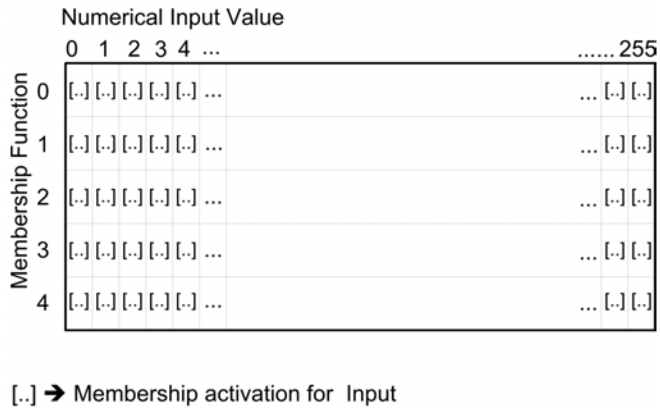

Figure 3-29 Array representation of mapping a fuzzy set.

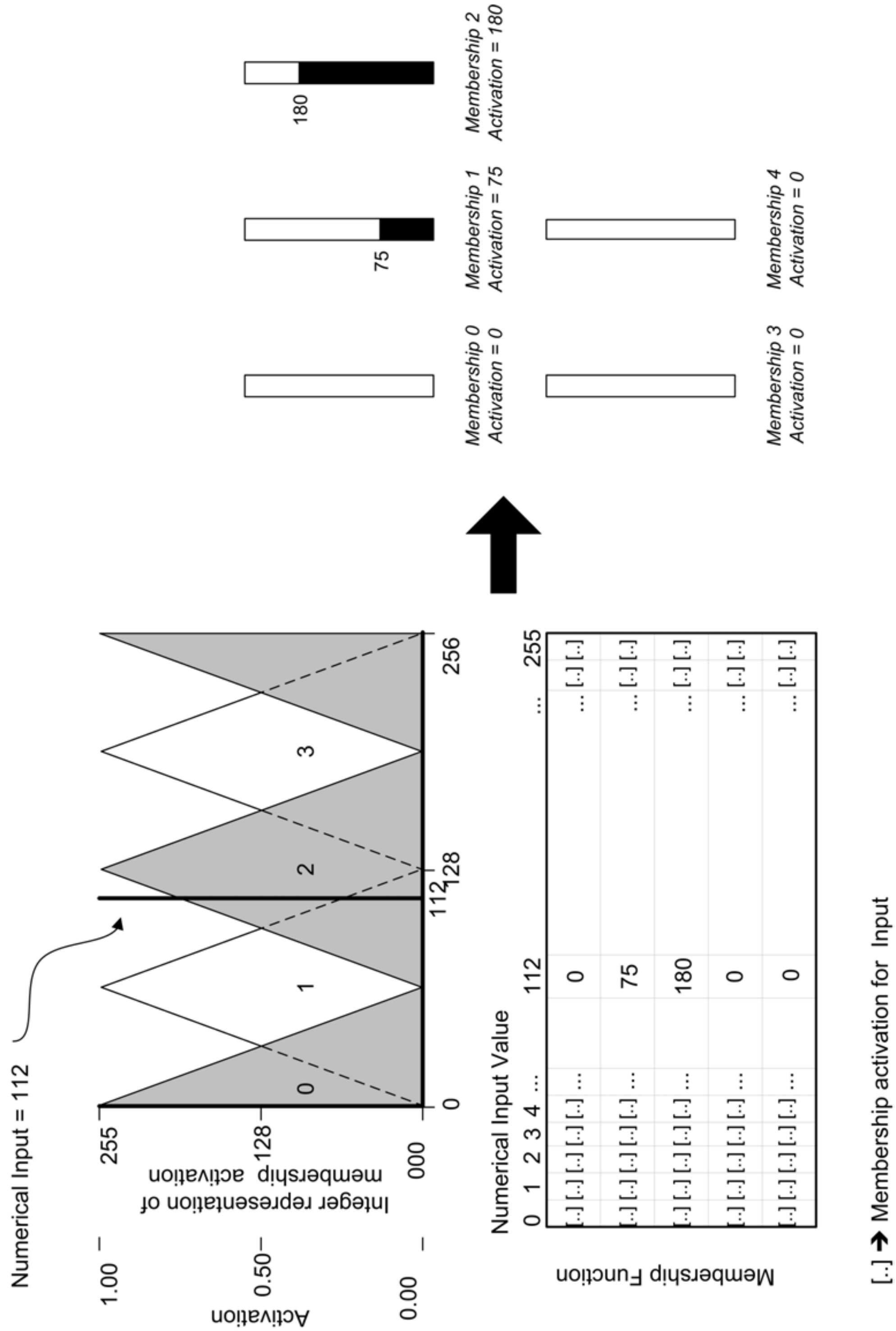

Figure 3-30 Example of looking up mapping of a fuzzy set.

The reduction in the required memory storage by individually mapping the numerical inputs to fuzzy set representation can be shown by a simple example. If a controller that has four input variables of 16 bit resolution and each is represented by a fuzzy set consisting of 7 membership functions then the memory storage requirement to map the entire range of possible inputs could be given by the Equation 3-3

$$m = v \times f \times 2^i \times o \tag{3-2}$$

m – Required memory[B]
i – Input resolution[b]
o – Output resolution[B]
v – Number of input variables
f – Number of memberships for each fuzzy set

The memory requirement used in this example would require 1792KB of memory and be able to provide the result in a small number of processor cycles. Mapping the input space is a useful method to reduce the processing requirement for the fuzzifier step on a PC because the process can be completed by simply looking up an address and the memory required for a realistic system as given is not a concern with modern memory technology. With a typical microcontroller the storage is limited to a range much lower than that of a PC and only a very basic mapping technique can be applied without a large percentage of memory usage. If non linear membership functions are required, a single generic membership function can be mapped and translated around the possible membership function centre points.

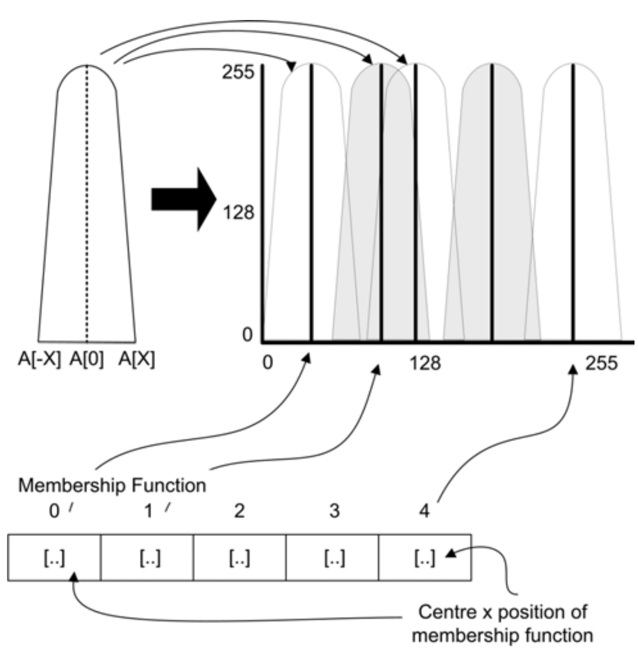

Figure 3-31 Mapping nonlinear membership using reduced memory requirements.

The advantage of this is that the very bare minimum memory is required for the mapping of variables at the expensive of further increased processing requirements and a fixed membership function applied to all variables.

Appling the same example with a controller that samples 4 input variables of 16 bit resolution to a generic membership model would allow the memory requirement to be reduced to approximately 10KB. This would require approximately 10KB (based on a membership function width of 10 000 points) for the membership map and only 72 bytes (4 variables ×9 memberships per fuzzy set × 2 byte representation of membership centre location) to store each membership centre. This figure of approximately 10KB is a considerable amount of a microcontroller's memory however; it is the most direct method of mapping numerical inputs that is capable of being achieved on a microcontroller.

3.4.1.4 Procedure based languages

The software development for microcontrollers is done with a procedure based language such as C, Pascal or basic. Procedure based languages allow a simple development of program code however for complicated software object orientation is a useful advantage that reduces the need for tedious repeated coding of the same general function and improves the readability of the code. Object orientation is useful for fuzzy logic controllers as objects can be produced to represent the fuzzy components and long sections of tedious code can be avoided by using generalised functions. Object orientation allows general functions to be imbedded in the produced fuzzy objects and applied to any instance of that object. Without object orientation, the function has to be hard coded to the specific variable.

3.4.2 Fuzzy Logic Controller Development

The fuzzy logic controller has three internal components in series that are used to produce a control output.

1. Fuzzification interference
2. Rule base
3. Defuzzification

The task of the fuzzification process is to convert the numerical input values into fuzzy representation. The rule base performs linguistic rules to govern the fuzzy output and the defuzzification process converts the fuzzy output to a numerical value that is then produced by the controller.

3.4.2.1 Fuzzification

The input variables in the controller are required to be converted to fuzzy sets in order to be used in the rulebase. The microcontroller has total a EEROM memory storage of 64KB that is required not only to store non volatile variables but also the entire program storage. The lack of program memory requires the fuzzification process to produce the membership functions using live processing of the numeric input variables. Using the live processing of the variables places increased processing strain on the microcontroller. In order to determine the fuzzy sets during the control algorithm simple processing is required and therefore limits the fuzzy sets to linear representations.

3.4.2.1.1 Fuzzy Set Generation

The process to determine the instantaneous activations of the membership functions within each fuzzy set is to be achieved within the main control algorithm. The boundary locations that govern the layout of the fuzzy set are required to be determined prior to processing of the numerical input values. The fuzzy set is created during the start-up of the controller or during a change in set point in desired operation. The membership functions used in the controller are linear in geometry therefore the information required to generate the memberships is minimal. Each membership is stored by recording the numerical position of the minimum and maximum integer locations. The Fuzzy sets are stored as a structure variable that consists of a multidimensional array and further information. The information stored in these sets is used to rebuild the fuzzy set quickly during live processing. These position points, with variables that govern general roll off slope for allow the control algorithm to determine the shape of the membership during live processing. The memory storage for each fuzzy set is shown in Figure 3-32 and an example demonstrating how the array values determine the location of the membership sets is shown in Figure 3-33.

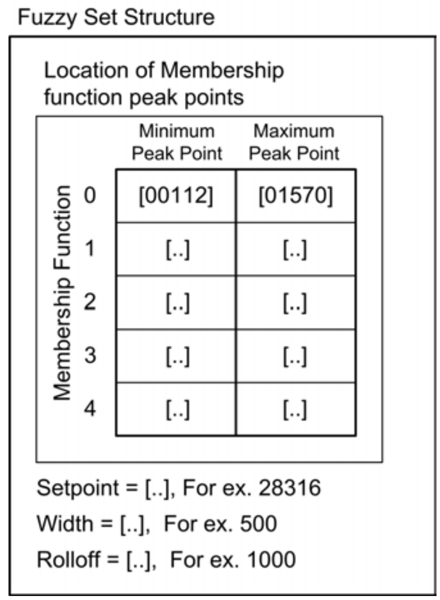

Figure 3-32 Microcontroller storage of fuzzy set.

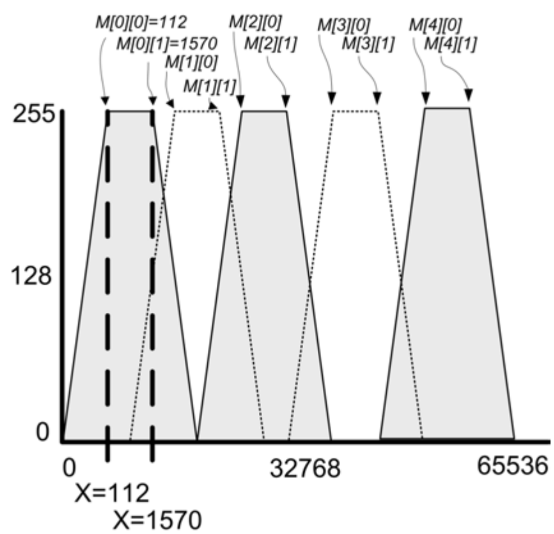

Figure 3-33 Method of storing membership in limited microcontroller memory.

Each input variable is to be represented by a fuzzy set of either 5 or 7 fuzzy membership functions.

- The extreme membership functions are to be shaped to run horizontally from the extremes and a then linear roll off towards the centre.
- The middle fuzzy variable to be represented by a triangular membership
- The remaining outer–centre variables are represented by triangular or trapezoidal shaped membership.

The fuzzy set constructor takes three inputs and from those inputs builds the shape of the fuzzy set. The constructor receives the values to govern the set point, roll off and variable width. From these values, the constructor builds the shape of the fuzzy set starting at the centre membership then building out towards each end. The lower and maximum peak points of each fuzzy variable are stored in an array as they are determined. These max points along with the roll off variable are used to locate the relevant activation of each membership function during the live processing of variables.

Constructor Process

Stage 1

Check to see if the variables are valid by ensuring the set point is far enough away from the end points using the given roll off and widths. If the values given are valid the standard process follows, otherwise the function will make adjustments to the values and this process will be explained in a later section.

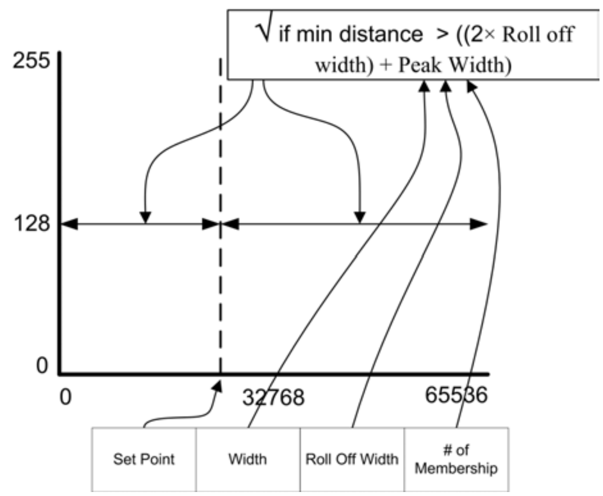

Figure 3-34 Stage 1 check if fuzzy set constants are valid.

Stage 2

The centre membership function is created. The shape of the membership is triangular therefore the minimum and maximum points are the same value. These points are represented by the set point value given to the constructor. The minimum points are not required to be calculated although they can be represented by the equation set point ± the roll off constant.

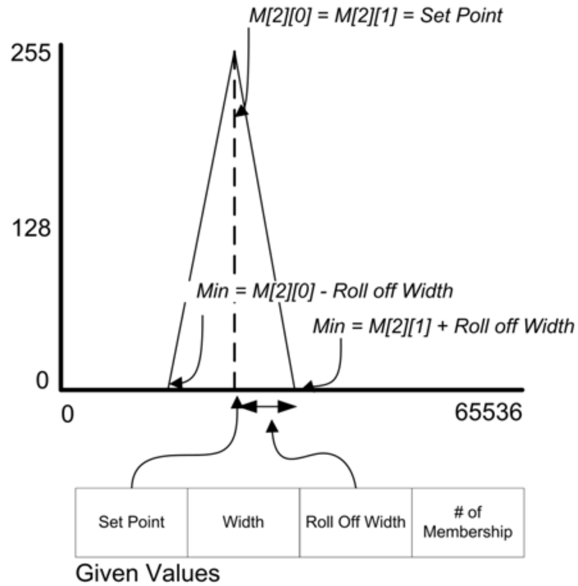

Figure 3-35 Stage 2 calculating the points for the centre membership.

Stage 3

The second stage of generating the fuzzy membership is locating the maximum and minimum high points for the outer-centre memberships. To find the membership functions within the fuzzy set higher than the centre membership can, be explained as follows.

1. The previous membership maximum high point is used as the min low point for the current variable.
2. The minimum low point plus the constant for the roll off gives the value for the min high point.
3. The minimum high point plus the width constant gives the value for the max high point.
4. The high points are then stored in the Fuzzy variable structure and the calculation for the current membership function is completed.

The maximum low point can be found using the maximum high point plus the roll off constant.

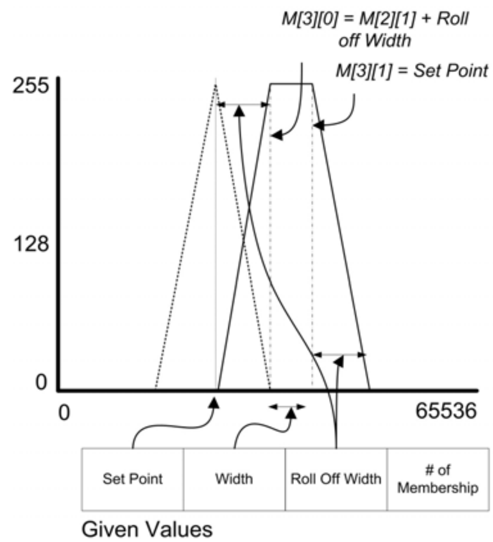

Figure 3-36 Stage 3 calculating the points for the outer centre memberships.

The process is repeated for the other remaining internal membership functions. For fuzzy variable below the set point, the process is mirrored and works downwards to the lowest membership function.

Stage 4

The final stage of generating the fuzzy membership is to locate the minimum and maximum high points of the outer membership functions. To find the point with high outside membership function, the process is as follows.

1. The maximum high point is the highest possible value of the inputs. In the case of the application, the input is 16 bit therefore the maximum high of the point is 65536.
2. The maximum high point of the second highest membership function corresponds to the min low point of the outer membership.
3. The min low point plus the roll off constant gives the value for the minimum high point.
4. The high points are then stored in the fuzzy variable structure and the calculation for the current membership function is completed.

There is no requirement for controller to calculate the min point outside the outer edge of either membership as the values are not possible.

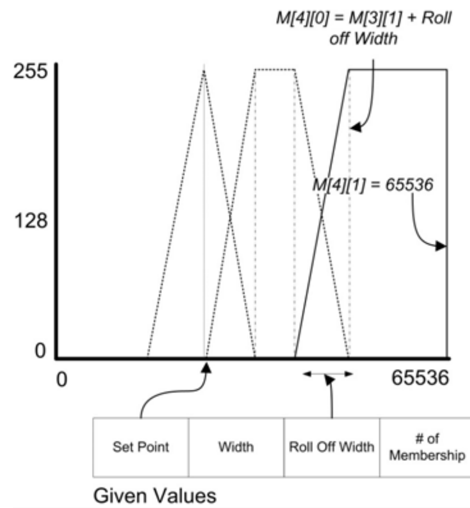

Figure 3-37 Stage 4 calculating the points for the outer memberships.

Non-Valid Input Variables

The construction process outlined above can not be directly used if the difference between the set point and the extreme range of the numerical input is too small to fit the desired membership functions. If the available distributions of possible values are too small then either the membership functions are required to be narrowed or one or more removed. Removing one or more membership function will produce problems with the necessity of different rule sets; this would require extra non volatile program memory, therefore because of the limitation of available program memory, removing a membership function is not a practical option. As membership functions can not be removed, the width of membership functions are required to be reduced. The widths of the memberships functions can be reduced by reducing the roll off and width constants for the effected memberships. The width can be compressed by either reducing the constants individually or together. Reducing the roll-off generates sharper transitions between fuzzy variables and therefore a sharper transition in control output. The sharp transitions are capable of increasing the controller's ability to correct for disturbance in the operation; however a sharp transition can lead to unstable control by generating large oscillations. Reducing the membership peak width reduces the dead zone between the changing of fuzzy representation of numerical variables. The effect of narrowing the width of a variable reduces the dead zone representation of a control variable. The benefit of reducing the dead zone is that the controller is capable of responding to small changes of system operation quicker without the necessary larger error. The only gain to memberships with dead zones is the reduction in the membership functions used for the variable and therefore a reduction in rules to represent the control space. If the variables used in the controller are a measure of only instantaneous proportion error then the dead zone is likely to be a destructive element, however if derivative or integral representation of measured values is also used, then the dead zone can allow the finer control to be allocated to the secondary variables. The reduction in the roll off and membership widths is reduced in two levels.

Level 1

The initial level is to reduce only the width of membership functions. The reason for doing so is that the dead zone is removed without amplifying the sharpness in output changes between membership functions[54],[33]. With the level one reduction the width of the high point of membership functions is recalculated for the short side so that memberships can fit within the available range. The calculated short side width value is then used in the construction process for the identified short side.

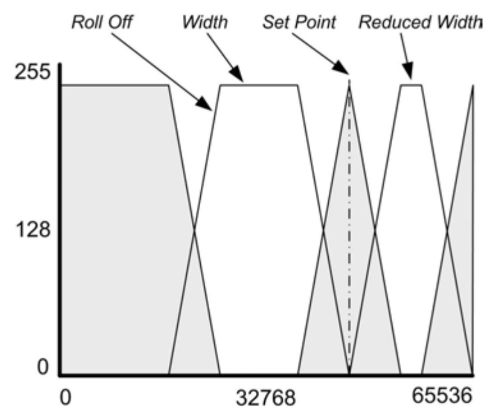

Figure 3-38 Shape of Fuzzy variable for set point moderately close to the limit of possible values.

Level 2

The second level of reduction reduces the roll off width and completely removes the width of membership functions. For the short side the width constant is set to 0, the calculated required roll off width is then used in the construction process of the short side.

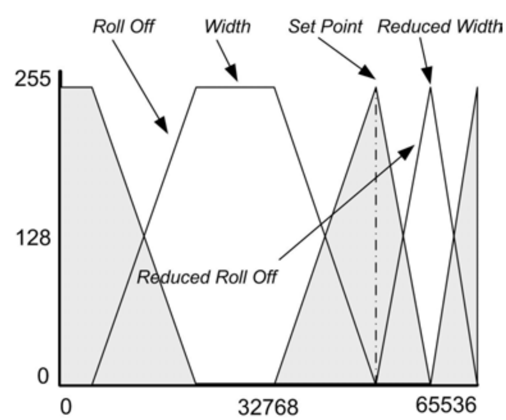

Figure 3-39 Shape of Fuzzy variable for set point very close to the limit of possible values.

3.4.2.2 Fuzzier Membership Activation

The input variables are represented by numerical values in the input to the fuzzy logic controller. The first part of the fuzzy logic processor is to convert the numerical values to fuzzy representations. The fuzzifier component in the controller applies the numerical variable representation to the model produced. Figure 4-35 to 4-38 are the graphical illustrations of the whole procedure.

1. Starting with the lowest fuzzy variable, the max high point is compared with the numerical input value. If the numerical value is higher than the max point the next variable is compared and this process continues until the numerical value is lower or equal to a max high point.
2. When a max high point has been found that is greater than the numerical value the numerical value is then compared to the min high point of the same variable. If the numerical value is greater or equal to the min high point then the fuzzy variable has a weighting of 1 and all others have weighting of 0. If the numerical value is less than the minimum high point then the numerical value lies between the previous variable's maximum high point and current variable's minimum high point. Therefore the fuzzy representation of the numerical value is a combination of both fuzzy variables. The weight of each variable is calculated using the location between the two points and then uses linear interpolation.

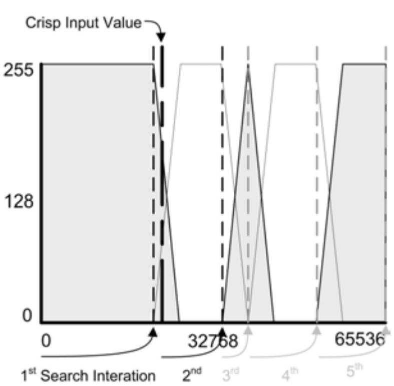

Figure 3-40 Locating the highest activated membership for single membership.

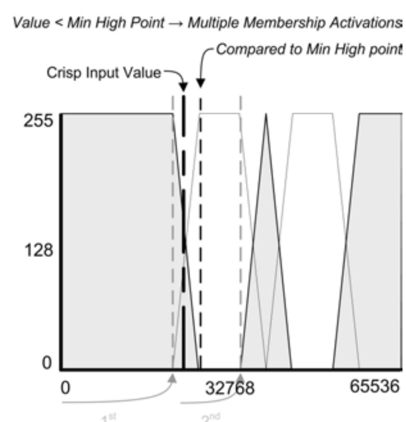

Figure 3-41 Decided upon activation of multiple memberships.

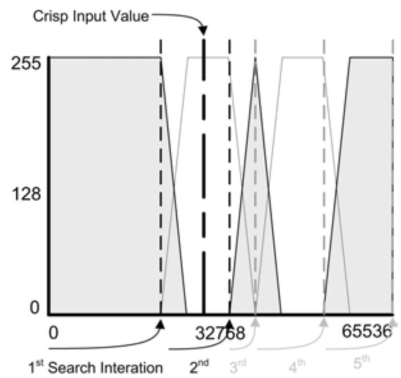

Figure 3-42 Locating the highest activated membership for single membership.

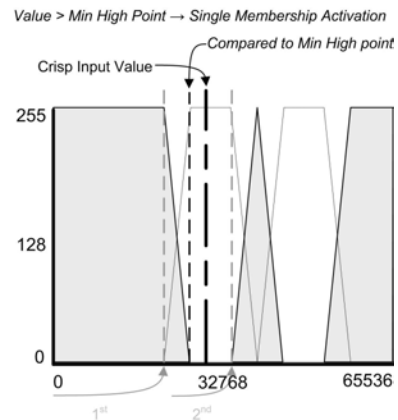

Figure 3-43 Found to only activate single membership.

The outlined method offers a compromise between processing complexity and processing requirement. On average, the position of the crisp value is located within fewer search cycles than checking each individual area of location with a linear method and the same required searching cycles as using a bisection method. The input variables are either 5 or 7 fuzzy variables therefore the worst case scenario would require 7 cycles to be carried out compared to the constant of 4 with a bisection approach. The worst case scenario using a linear searching method is a linear increase in the required cycles rather than a exponential increase; therefore it is not a critical problem. Implementing a bisection searching method would require the development of a more complex algorithm. The effect of the more complex algorithm is that it would result in an increase in program size and on average would require more clock cycles because of the overhead from the comparisons to determine the direction of searching.

3.4.2.3 Rule Base

The rule base of the control is produced by a series of linguistic rules. A linguistic rule can be demonstrated by the text below. Input condition is a fuzzy representation of the numerical input space. The output condition is the fuzzy representation of the desired rule outcome.

If *Input condition* then *output condition*

The control is developed to employ a number of the linguistic rules in an expert system to form the overall shape of relating inputs to the control output.

Rule weighting

The input conditions are the operational details that are met to determine the activation of the particular rule. Activation of each particular rule is determined by the weighting of the fuzzy variables specified in the condition. Low processing ability controllers are generally restricted to using either max or product operations for calculating the activation of each rule. Implementing the MAX operation is done with a sequence of comparisons that compare the weighting of fuzzy variables specified to locate the maximum value. The maximum weight located is then returned as the result. The product operation is done with multiplying the weighting of the variables mentioned. The product of the result is returned as the result of the operation. Comparing the two methods the MAX operation is the least processor demanding with only comparisons being made to determine the output; however using the MAX operation requires a normalisation function on the output of the controller that reduces the gains made in processing[54]. The product operation requires several multiplications for each rule and these multiplications are more demanding upon the microcontroller. The controller is required to process either three or four weights of 8 bit resolution. To ensure that there are no overruns in the multiplication, the variable type of the operation is required to be a 32 bit representation. The Silab 8051F020 microcontroller is a 16 bit device therefore a 32 bit multiplication in C instruction requires a substantial number of cycles to provide the result.

The product operation offers the best control as the outcome is dependent upon all the inputs rather than only the dominant weighted rule. The product operation was chosen for the controller as the control result from using the Max operation was to likely to result in poor control processing. If the microcontrollers were found capable of processing the product method then that would be the best technique to use. To produce a numerical value for the weight for each individual rule the equations shown below are used for the FLC algorithm. Figure 3-44 shows a pictorial demonstration of the evaluations of an individual rule’s activation. Equation 3-4 and Equation 3-5 give the calculation applied within the microcontroller for four and three variable fuzzy logic controllers respectively.

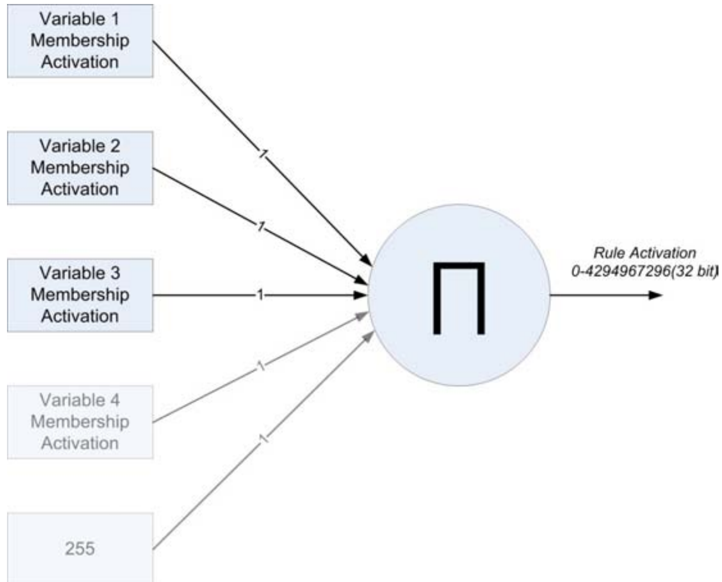

Figure 3-44 Pictorial view of calculating a rule activation.

$$R = V_a \times V_b \times V_c \times V_d \qquad (3\text{-}4)$$

R- Rule activation

Va- Actiovation of variable A's membership activation

Vb- Actiovation of variable B's membership activation

Vc- Actiovation of variable C's membership activation

Vd- Actiovation of variable D's membership activation

$$R = V_a \times V_b \times V_c \times 255 \qquad (3\text{-}5)$$

R- Rule activation

Va- Actiovation of variable A's membership activation

Vb- Actiovation of variable B's membership activation

Vc- Actiovation of variable C's membership activation

Rule base operation

The rule base is required to shape the overall response of the controller and to be considered stable, the output must be governed for the every possible input value of the system.

The required development resources for rule base increase exponentially as the number of possible rule space increase.

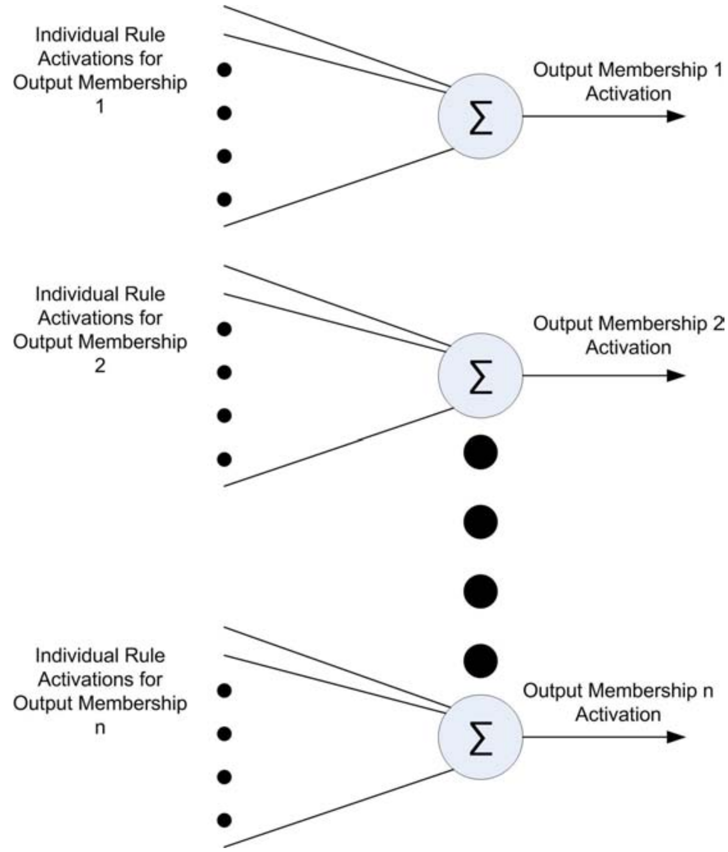

Figure 3-45 Diagram visualization of calculating output membership function.

The rule base is implemented in C code by listing each rule individually and summing the weighting results to each of the relevant output memberships. The coding process becomes difficult when used in this application because the code is required to represent either 125 (from 5^3) or 625 (from 5^4) rules depending upon the controller inputs.

```
Outputvalues[0] += (Logic_levels[0][0] * Logic_levels[1][0]  * Logic_levels [2][0] * Logic_levels [3][0]);
```

Instruction 3-6 Code required for a single rule

The manual coding of the rules was found to be impractical because of the quantity of the rules necessary and the code representation of the rules is not easy for a human to develop or problem solve. Commercial fuzzy logic aided design C code generators were investigated however none were found to be suitable. LabView and MatLab were able to produce C code for a developed fuzzy logic controller but the code produced was for a PC complier and would require extensive modification to be used in an embedded system. Neither option was capable of allowing membership functions that could be changed and were required to be stored in program memory that was not possible because of inadequate storage capacity. The option was then to develop an individual fuzzy logic code generator. The developed generator was to produce the C code in a format and layout that could be used on the microcontroller.

The generation of the rules was proving to be time consuming in C code and a more efficient method of generating the rule base would be the major requirement. The rule base generation software for MatLab and LabView used a mouse pointer to selecte individual variables and operations for each of the rules in the controller. The resulting controller shape is displayed as a graph while the rules are being produced. With the potential to have 625 rules, the individual selection would be more efficient than C code generation although it would require a time investment that would not be acceptable. A more efficient method of producing the rule base was considered to directly modify the shape of the graph.

- Allows more direct shaping of the control output.
- Reduction in the required time by modifing more than a rule at a time.

The difficulty with generating a graphical solution to the production of the rule base is how to represent the controllers with a high degree of freedom. A three dimensional surface plot is only capable of demonstrating two inputs and the output variable on each graph. The control development software was required to represent up to four possible input variables and an output. High dimensional forms are impossible to be demonstrated graphically to human vision without using separate objects or cross sections. A four dimensional representation(three inputs, one output) was considered that used colour as the controller output representation though this was ruled ineffectual in a three dimensional input space for the reason that only the colours around the extremes are visible.

The difficulty with three dimensional representation of objects is the experience required in generating the computer graphics and the displaying of a two dimensional point on a three-dimensional object. The simpler option is to use a graphical means of producing the rule base but operating in a two dimensional cross section and using colour as the output control identifier. The advantage of using this method is that the development of the software is made simpler without the need to generate three-dimensional objects. The difficulty with using three-dimensional objects is the experience required to generate the graphics and modification of the result in three dimensions displaying on two-dimensional images.

The investigation into the development of the rule generator was focused on the simplest method of developing the program. The four PC programming languages and development packages were available to be used for the application; Visual basic, C++, Java and C#. The program to be developed had the requirement to have relatively complex and important graphical user interface and at the same time complex data handling in the background. The programming languages mentioned have their own strengths and weakness. Visual basic allows easy development of the interface and simple coding process, however it is not capable of object-orientated process and would make the coding much like C and required long tedious coding to achieve the background processing. C++ and Java programming languages provide a very good means of object orientation although they suffer from complex interface design. C# development allows a simple construction of the interface with the ability of to facilitate object-orientated programming. The disadvantage of C# compared to the other object orientated capable programs is that the code can be slower because it operates from a higher level of abstraction.

The application to generate the rule base has three areas of use

1. Controller Setup.
2. Rule base generation.
3. Recording information.

The first task of the application is to build a record of the structure of the controller to be used. The user decides upon the layout of the required controller. The application then gathers this information to build a bare framework for the controller. To construct the controller, the user enters the following information that is used to build the necessary structure

- Input variables
    - Number of variables
    - Ranking of importance
    - Number of memberships
- Controller Output
    - Output memberships
    - Power of memberships

The construction process also requests information that is used to aid the development and readability of the coding and rule generation that is not required for the processing of the controller. The framework of the control is saved as a file once completed

Rule base generation

Generating the rule base is produced with a graphical interface that represents the fuzzy control space by a set of cross sectional views. The cross sectional views represent a variable in each axis and the output of the control is displayed by the colour of the variable space. To generate the rule space the user selects the desired output control and then selects the relevant input spaces by the use of the mouse pointer.

With input spaces greater than two degrees of freedom, the cross section is dependent upon the input space of the higher priority variables. This allows an easier overall generation of complex controllers by quickly defining the extreme areas of space by ignoring the minor variables. Such actions allowing the minor variables to be used for precise rules around the centre of the control without impeding the development of the coarse extremes.

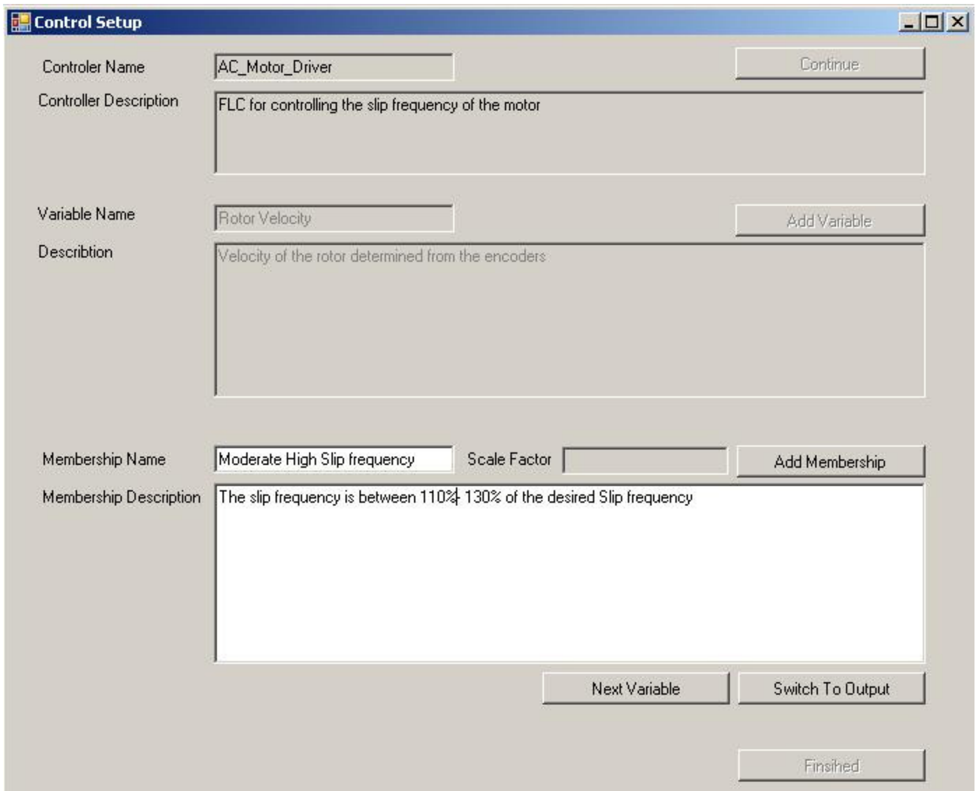

Figure 3-46 GUI of initialising a new controller using the FLC generator.

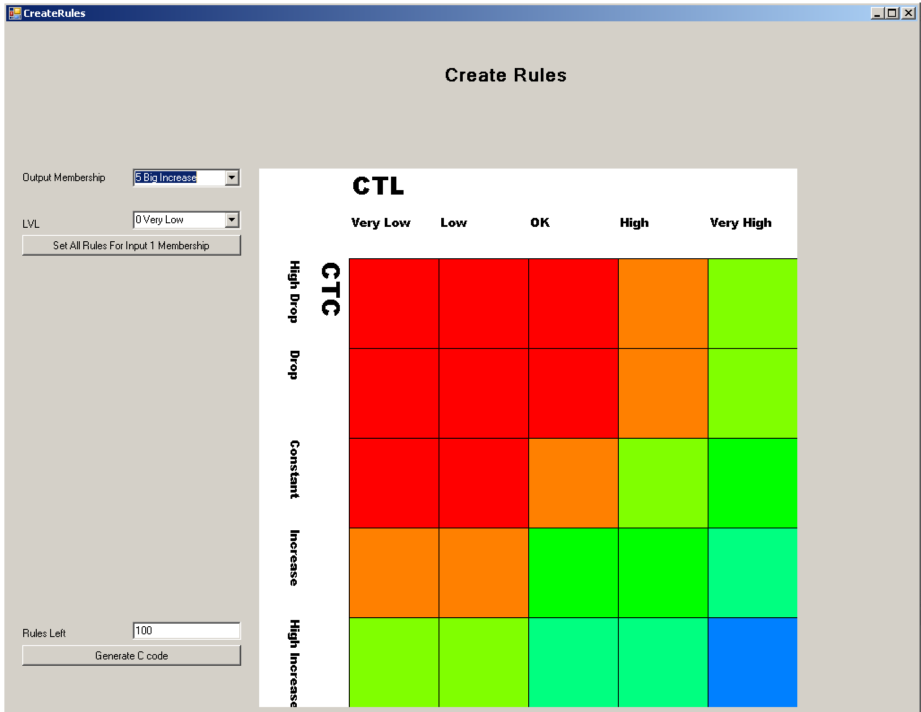

Figure 3-47 GUI of fuzzy logic control code generator.

Once the rule base has been fully determined the developer gives the command for the rule base to generate the C code for the microcontroller. The C and H file generated can then be added to the microcontroller.

Recording information

The allocation of the output control is stored in a database file that allows the control setup to be stored for later recalling and modification. The program then generates the C code files for the controller based on the input of the application.

3.4.2.4 Defuzzification

The output from the rule base is a representation of the desired control output as a fuzzy value. The FLC output is required to be a numerical value that covers both negative and positive control instructions. The defuzzifier is therefore required to convert the fuzzy control response to a numerical value. The output memberships are represented by singleton membership functions that are used to reduce the processing requirement of the controller. The singleton membership functions allow the output to be calculated with the same centre of gravity approach to produce a controller that responds to all inputs. The advantage the singleton method has over the centre of gravity (COG) and centre of sums (COS) methods is that it demands less processing requirements. The processing requirements are reduced by using simple linear equations rather than an integration or an area calculation. The drawback to the singleton method compared to the COG and COS is that the output control cannot be fine tuned by the shape of the memberships which can be useful in some cases to create bias or quicker responses.

To determine the numerical output from the controller, the defuzzifier has two events in sequence that reduce the dimensionality of the calculated result down to a single numerical value.

1. Individually calculate the numerical effect on the controller output from each output membership
2. Combine the numerical effects form the individual output membership to form the output of the controller

Each of the output memberships has a linear scaling factor used to produce the numerical value. The scaling factor is the desired controller output in the event of that membership being fully activated and all other memberships being inactive.

The FLC returns a single 16 bit control value that contains a 32768 (0x8000) offset to produce a range of 32767 in both negative and positive control response.

To avoid the need to convert between variable types, the output membership functions scaling uses an offset to the value of 32767 and the positive or negative control effect is from that set point. The scaling effect on the control output can be displayed by Figure 3-48 and is calculated by Equation 3-6 and Equation 3-7 which govern the outcome for positive and negative power membership outputs respectively.

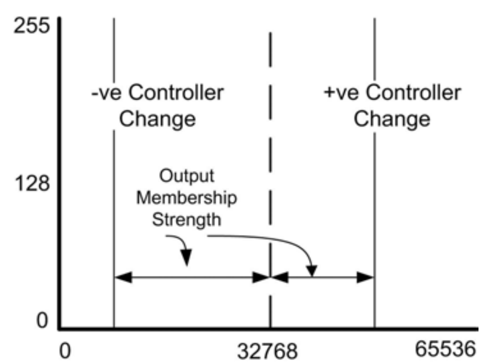

Figure 3-48 Offsets of membership powers.

$$O = 32768 + S \tag{3-6}$$

O- Control effec

S- Control adjustment strength

Equation 3-6 Positive change to control the equation

$$O = 32768 - S \qquad (3\text{-}7)$$

O- Control effect

S- Control adjustment strength

Equation 3-7 Negative change to control given by the equation.

The scaling factor is determined by the desired response of the controller if only that membership occurs.

Determining this value is made simpler and can be achieved using linear means through the removal of the need to normalise control responses. Normalisation of the control response is not required because of the configuration of the controller ensures the activation of all the output memberships is equal to one. Therefore, the scaling factor of an output membership is the desired response of the controller if only that membership is activated. If two or more memberships are activated then the output response is the mixing of the numerical values.

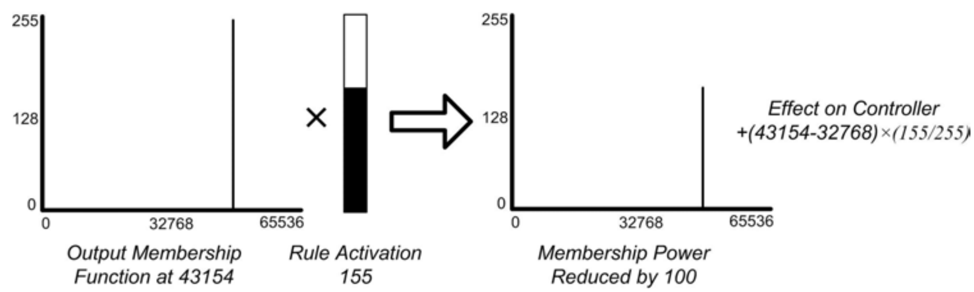

Figure 3-49 Numerical control value from an output membership is governed by the equation.

$$O = A \times S \qquad (3\text{-}8)$$

O- Numerical output from Output membership

A- Output membership activation

S- Output membership power

The overall control output is the combination of the output memberships summed together that form a simplistic centre of gravity response.

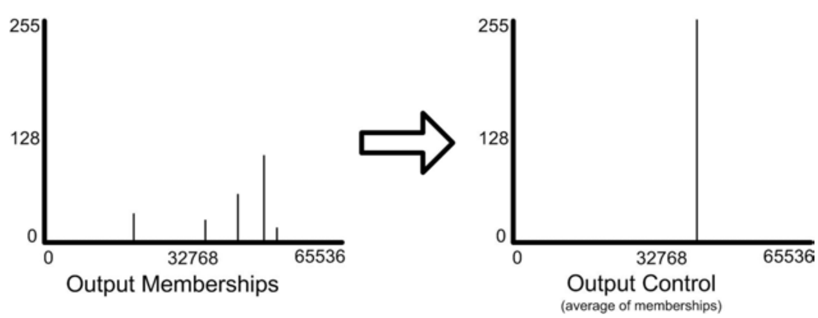

Figure 3-50 Calculating the FLC output from output memberships.

$$Co = \sum_{n=0}^{n=N-1} (A[n] \times S[n]) \qquad (3\text{-}9)$$

Co- FLC output

N- Number of output memberships

A- Membership activation

S- Membership scaling

3.4.3 Fuzzy Logic Control Demonstration

With no suitable hardware device, an applied test of the GICS and the FLC is not possible to be established. For a demonstration of the GICS and FLC, a test that inputs one or two analogue signals to a microcontroller that then outputs the processed value is used The test method utilised for the GICS and FLC is detailed in Appendix B.3 FLC and GICS Testing. Shown below is the oscilloscope trace of two results taken during the testing. Figure 3-51 demonstrates a SISO proportional control rule base with a single analogue single used as the input; the output of the control processing is shown in the trace. Figure 3-52 display the operation of MISO proportional plus proportional controller; two analogue signals are utilised as inputs and the output from the control is traced voltage. The two traces demonstrate the controller output from the input waveform traces. Figure 3-52 further shows the interaction between the two channels; this interaction is seen by the small oscillations during result during the resulting higher priority singles period. Further demonstrations of the GICS and the FLC are located within appendix C.2.

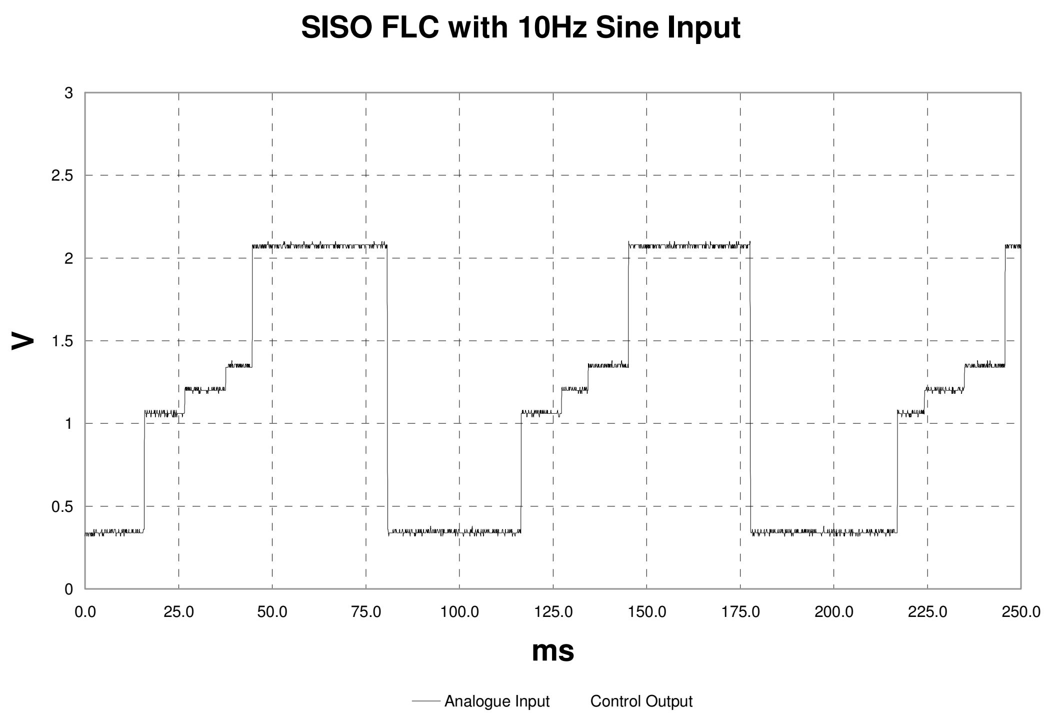

Figure 3-51 Fuzzy logic controller operating a single input single output proportional only control rule base.

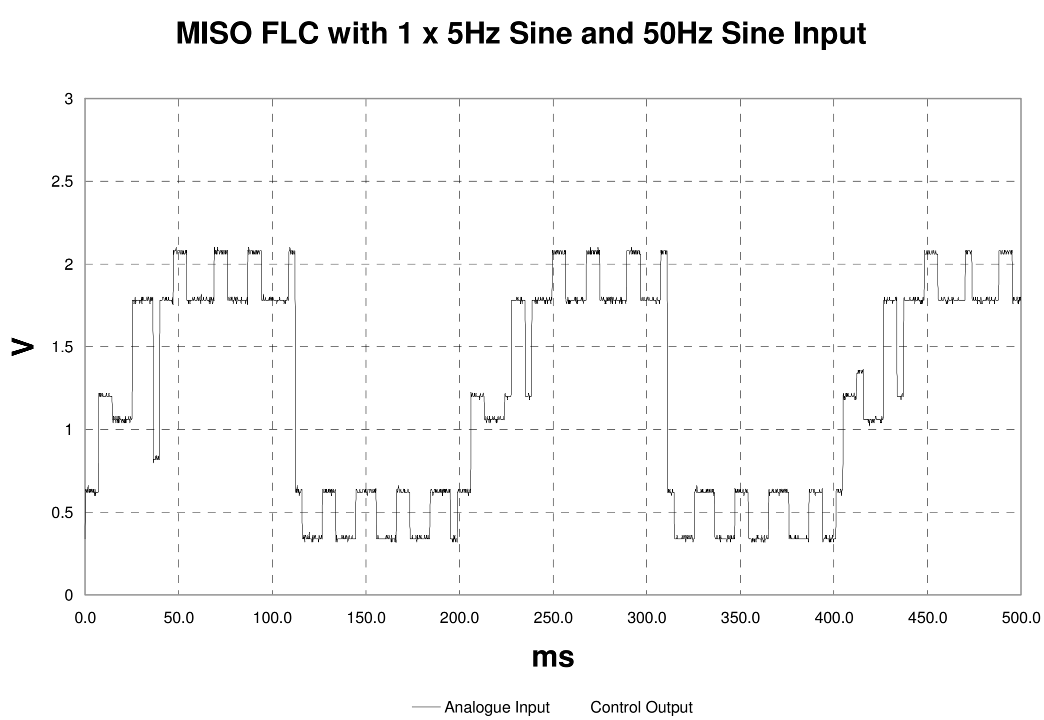

Figure 3-52 Fuzzy logic controller operating a multiple input single output proportional and proportional rule base.

CHAPTER 4 ELECTRIC PROPULSION DRIVE SYSTEM OUTLINE

This chapter provides an outline of the hardware design for an electric propulsion drive (EPD). The electric drive is designed as a distributed network of hardware modules. Each hardware module operates separately to the others and is controlled with commands received from a communication network. Each module is to contain a microcontroller control system. This control system is to employ the GICS researched from CHAPTER 3 The design of the EPD shall provide two proposed benefits for a later stage. Once manufactured, the EPD will provide a test bench to fully test and improve the GICS. The second benefit is physical realisation which will later allow investigation into the feasibly of a low cost generic propulsion drive.

The design investigation outlined in this and the next three chapters are a prototype for an electric propulsion drive. It is therefore likely that major changes will occur during development and lessons learnt will provide solutions to problems or improve the operational specifications.

The current high-end technology for batteries and PM AC motors is capable of delivering a performance that is suitable to replace ICE vehicles. The cost of the current high-end technology is prohibitive and does not allow a mass market. The technologies to be used in this prototype are an attempt to use the most effective option. The prototype will use a deep cycle lead acid battery arrangement and a 3 phase asynchronous induction AC motor. These are the same low cost technologies that were used by GM and Ford to produce their EVs for the California market[55]. The use of these technologies was allegedly trending to become economically viable in the near future at the time of stopping production. Engineers working on the projects for GM and Ford reportedly made the statements mentioned[41]. These technologies are chosen and used for the prototype design because they have been proved capable and the selection is an economical valid approach for this case. This selection will not produce a high performance system. The aim is to provide a low costing intermediate step until such time as the current high-end components become viable.

The proposed electric propulsion drive has five components to be developed individually and then integrated to form the overall system. The system consists of three low-level hardware modules that communicate with a controller based full microprocessor hardware. The microprocessor operates the overall control and provides a means of a user interface for the systems operator. Each hardware module receives a high-level command that governs its desired operation. The module's internal controller is then responsible for collecting the internal sensor values, running the control algorithm and then correcting the hardware operation. The topology of the proposed system is shown in Figure 4-1.

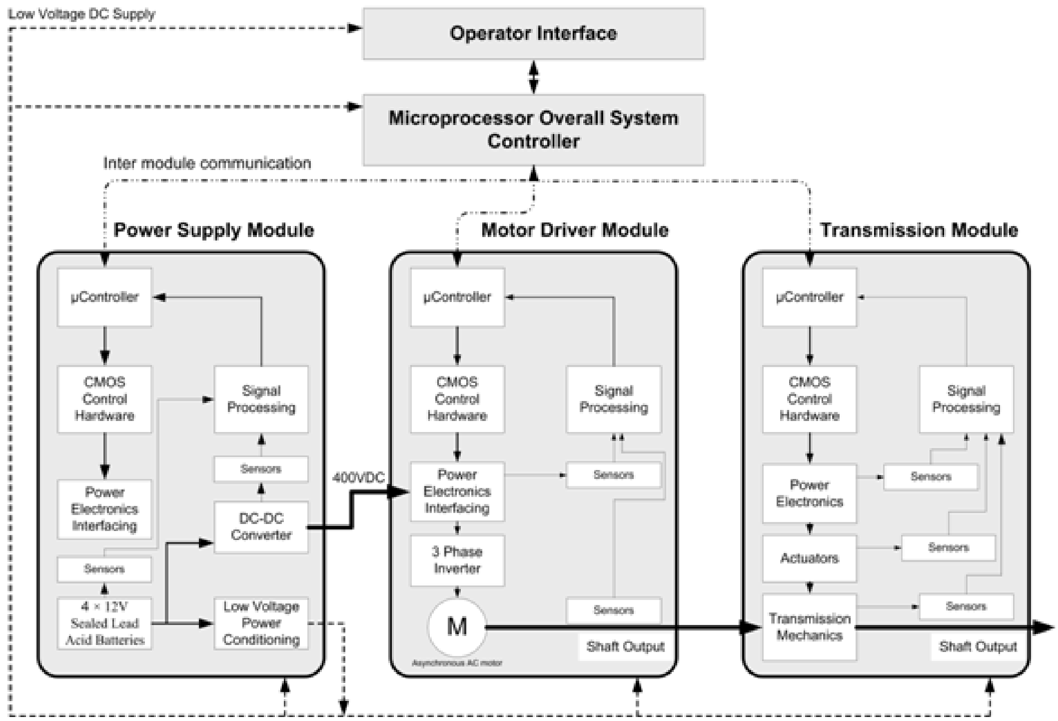

Figure 4-1 Proposed system overview of the EPD.

The first stage of development focuses on design of the hardware modules and uses simple PC software to manually send commands. The power supply, motor driver and transmission modules are connected to the system controller via a serial communication channel. The system controller transmits commands via the serial communication channel to the microcontrollers within each module. The controllers within each module internally send operational details of their relevant hardware back to system controller. The information sent is in the form of telemetry and fault alarms. The outlined purpose and the connections to form each of the hardware modules is listed bellow in Table 4-1.

Module	*Primary Objective*	*Module Input*	*Module Output*	*Secondary Inputs connections*	*Secondary Output connections*
Power Supply	*Convert low voltage supply from batteries to high voltage line*	*48V DC from Batteries*	*400 V DC to be used by the motor driver module*	*Serial Communication and hardware Interlock*	*Serial Communication, low voltage DC supplies and*

	for AC motor				*Power Supply Ready signal*
Motor Control Module	*Operate the induction motor from the received commands*	*400 V DC from the power supply*	*Mechanical power produced from the induction motor*	*Serial Communication, Interlock Signal, PS ready, and low voltage DC supply*	*Serial Communication*
Transmission	*Control the ratio of the transmission from the received commands.*	*Mechanical power from induction motor*	*Mechanical power from the transmission output shaft*	*Serial Communication, Interlock signal and low voltage DC supply*	*Serial Communication*

Table 4-1 Modules to be developed.

The equipment available for the research requires the prototype system to use prior purchased equipment. The equipment available is as follows.

- 180W 3 phase asynchronous induction motor
- 4 × 12V sealed lead acid batteries
- Silab 8051F020 mixed signal microcontrollers

Induction motor

An 180W 3-phase induction motor was selected for the prototype design. The particular induction motor was chosen solely because of economic reasons. The small induction motor was available within the school. The low power induction motor allows less expensive power electric components to used within the system.

The 180W motor, while underpowered for a production application should provide sufficient power to operate the EPD in a test bench simulation and for a go-kart test vehicle. (In 1886, Karl Benz, the inventor of the automobile produced a vehicle that weighed 265Kg and was powered by a 0.5Kw ICE. This vehicle successfully completed a round trip of 180 km through Southern Germany on dirt roads with three people on board)

Lead Acid Batteries

The arrangement of four 12V lead acid batteries is proposed for the prototype for multiple reasons. The voltage output from the arrangement totals 48V DC (52V peak charge). 48V DC is a compromise offering a lower current requirement and a safe voltage output.

Industry considers 42V safe in normal conditions and is likely to switch from 12 in the near future. Lead acid provides the best kWh per dollar and therefore reduces the system cost. Using sealed lead acid batteries reduces the risk of spilling the acid. Sealed lead acid batteries however are more dangerous while charging; this is because of the build up of gaseous pressure. The dangers with charging sealed lead acid batteries have been considered in this design and therefore will not employ regenerative charging.

Silab 8051F020

The Silab 8051F020 mixed signal microcontroller has been identified as the controller of choice to be used with the hardware modules. The microcontroller is a mid range controller that offers a reasonable level of performance for a relatively low cost. The 8051F020 has a large number of peripherals and is similar to other mid range microcontrollers. The Silab 8051 microcontroller is selected for two reasons. The first is that the School has a considerable number of Silab 8051 microcontrollers integrated with development boards. The second reason for the Silab microcontroller selection is in common usage, the availability of the development packages and the relevant technical support in the school. Such availability and capability removes the time requirement to get familiar with the microcontroller and the development devices.

To date the design of the hardware modules has been completed to a theoretical stage, however yet to be manufactured. The consideration and design of the each of the hardware modules is contained within its own chapter.

The details for each individual modules are as follows

- CHAPTER 5 Power Supply Module
- CHAPTER 6 Motor Driver Module
- CHAPTER 7 Transmission module

The chapters are specific to the application requirement, designed and focus on the specific needs. Common principles of operation occur between the different hardware modules. Instead of restating the same functionality, the later sections will refer to early chapters that explain the relevant information. The later sections will only introduce new material as required.

CHAPTER 5 POWER SUPPLY MODULE.

A power supply is required to convert the supply voltage from the battery arrangement to the voltage required by the electric motor. The asynchronous induction motor that is utilised is a small 180W unit which can be connected with a wye phase connection to operate at 400VAC. The max current given for the motor is 0.8A at 400V. The maximum power input to the motor is 320W. The power supply is designed to produce up to 500W; this value introduces a safety factor.

5.1 Power Supply Investigations

The power supply required is a DC to DC converter. There are a number of different types and differing configurations of converter. The relative high current and overall power output rules out a number of voltage increasing DC to DC converters as they are an unsuitable[47],[49]. The two most suitable converters for the task are the non-isolating and isolating boost converters.

5.1.1 Boost Converter

The boost converter can have two modes of operation, continuous and discontinuous. Only a continuous mode is valid for the application because of the high power requirements. The increase in voltage from the boost converter is attained by using an inductor and switching to induce a voltage higher than the supplied voltage.

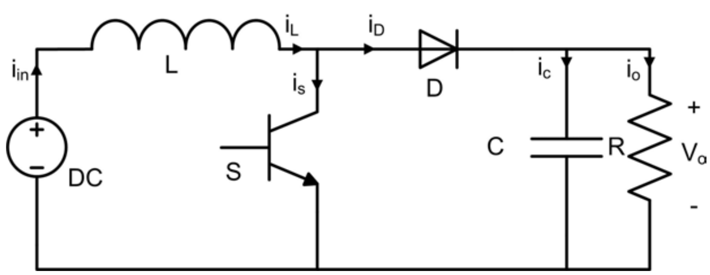

Figure 5-1 Non-isolated Boost Converter.

The boost converter has two state operations that are controlled by the switching device such as a MOSFET or IGBT.

5.1.1.1 Theory of Boost Converter

On State

During the conduction of the switching device the equivalent circuit shown as in Figure 5-2. The energy from the battery goes only through the inductor and is stored as a magnetic field. The power to the load is supplied from the energy stored in the capacitor.

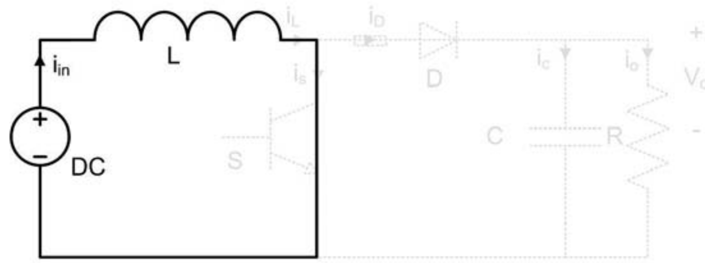

Figure 5-2 Equivalent circuit of non isolated boost converter during the on state.

Assuming the inductor has no DC impedance (ideal component), then the circuit during the conducting state is a battery and an inductor in series. The integral of the current over a discrete finite range is the representation of the conducting state current; it can be represented by Equation 5-1.

$$\Delta I_{Lon} = \int_0^{D\times T} \frac{V_i}{L} dt = \frac{V_i \times D \times T}{L} \tag{5-1}$$

V_i – *Input Voltage[V]*

I_{Lon} – *Inductor current during the on state[A]*

D – *Duty ratio*

T – *Period[s]*

t – *Time[s]*

L – *Inductance[H]*

Off State

During the non-conducting state, the switching device is open. Assuming ideal components the equivalent circuit during the non-conducting period as shown in Figure 5-3 is produced. During the off state, the power supplied from the input and the energy stored in the inductor is transferred to the load to produce a higher voltage than the input by itself.

Under the assumption of ideal components and an infinite sized capacitor, the equivalent circuit can be represented at any instant by Equation 5-2

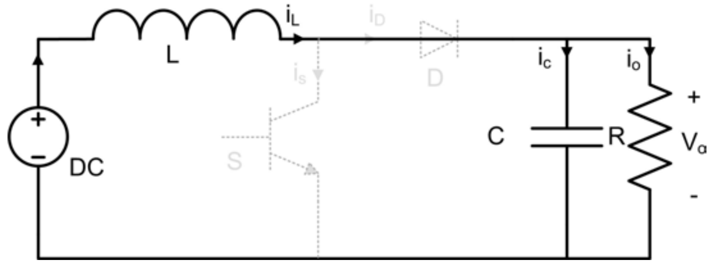

Figure 5-3 Equivalent circuit of non isolated boost converter during the off state.

$$V_i - V_o = L\frac{dI_{L_{off}}}{dt}$$

Vi – Input voltage[V]

Vo – Output voltage[V] (5-2)

t- Time[s]

L – Inductance[H]

I_{Loff}- Inductor current during the off state[A]

The integration of the differential equation applied to boost converter during the off state produces the Equation 5-3

$$\Delta I_{Loff} = \int_0^{(1-D)T} dI_L = \int_0^{(1-D)T} \frac{(V_i - V_o)}{L} dt = \frac{(V_i - V_o)(1-D)T}{L}$$

Vi – Input voltage[V]

Vo – Output voltage[V]

T- Period[s] (5-3)

t- Time[s]

L – Inductance[H]

I_{Loff}- Inductor current during the off state[A]

D – Duty ratio

To maintain a steady state of operation, the energy stored in the system must remain constant. Assuming ideal devices, the components in the circuit that store energy are the inductor and the capacitor. The circuit maintains a steady state when the current through the inductor and the voltage on the capacitor remains constant over a period of time. The instantaneous energy level can change but the overall cycle must produce no change in energy storage. Assuming the capacitor is large enough to cancel out any change in voltage, the circuit operation is governed by the inductor. A steady state is achieved when the charge to the inductor during the on state is matched by the charge leaving the inductor during the off state. The equation of the accumulated charge during the switching cycle is shown by

Equation 5-4 which is created by combining Equation 5-1 and Equation 5-3. For the SMPS to remain in a steady state, the accumulated charge over a cycle must equal to zero. Algebraic manipulation of Equation 5-4 combined with the requirement of no charge accumulation can be arranged to demonstrate the gain of the SMPS as shown in Equation 5-5

$$\Delta I_{Lon} + \Delta I_{Loff} = \frac{V_i \times D \times T}{L} + \frac{(V_i - V_o)(1-D)T}{L} = 0 \qquad (5\text{-}4)$$

Vi – Input voltage[V]

Vo – Output voltage[V]

D- Duty ratio

T- Period[s]

L – Inductance[H]

I_{Loff}- Inductor current during the off state[A]

I_{Lon}- Inductor current during the on state[A]

Equation 5-4 Charge flow for steady state operation.

$$\frac{V_o}{V_i} = \frac{1}{1-D} \qquad (5\text{-}5)$$

Vi – Input voltage[V]

Vo – Output voltage[V]

D- Duty ratio

Equation 5-5 Voltage gain for non-isolated boost converter.

5.1.2 Isolated Boost Converter

An isolated boost converter is a modified version of the simpler non-isolated converter that uses a high frequency transformer between the input and output of the power supply. The isolated boost converter can provide two benefits for high voltage and power applications. The voltage gain of the system can instead be produced by the winding ratio of the transformer; this avoids the issues related with the non-isolated design when providing high gains. The issues with the non isolated design will be demonstrated later in this chapter. Utilising a transformer in the design provides a means of isolating the output from the supply input; this increases the safety for high voltage systems. The transformers utilised in switch mode power supplies are high frequency transformers; these are much smaller than line transformers. High frequency transformers can be made to a smaller size as the high switching frequencies allow a smaller magnetic core[47].

5.1.2.1 Configurations

There are two configurations of an isolated boost converter that could provide the required power output.

Half bridge converter

The simpler option is the Half Bridge Converter (HBC) which requires only two switching devices. The main problem with the half bridge converter is that circuit requires a centre tap transformer. Half bridge converters should only be utilised in applications that require an output of 500W or less. The 500W limit allows the configuration to be utilised for the prototype system, it however will not allow an up scaling of the power supply at a later stage. The layout of the half bridge converter is seen in Figure 5-4 Half Bridge Converter.

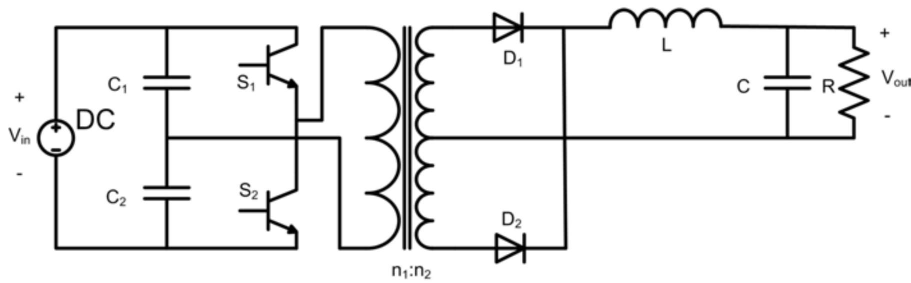

Figure 5-4 Half Bridge Converter.

Full bridge converter

The FBC combines a full bridge and full wave rectifier to produce a fully reversing range of current through the transformer's primary coil. Fully reversing the current through the primary coil better utilises the core material of the transformer by fully reversing the magnetic field. The Full Bridge Converter (FBC) necessitates a more complicated control process because of the two extra switches compared to the HBC. The FBC provides the advantage that the transformer to be used is a single ended design and the power supply can be scaled to produce power outputs governed by the switching devices. With current IGBT technology the power supply could produce over 2000 KW[49]. The FBC is displayed below in Figure 5-5

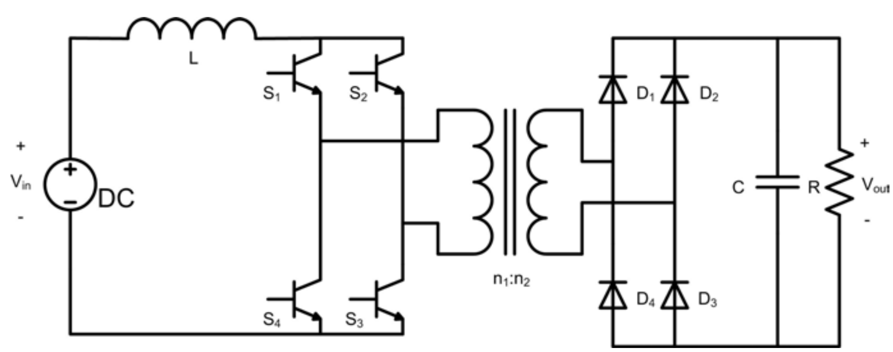

Figure 5-5 Full Bridge Converter.

5.1.3 Non Isolated vs. Isolated Boost Converter

The two variants of the boost converter offer either a low cost, simple or a complicated but better performing option. The non-isolated boost converter presents a simple low cost circuit; this is accomplished by the reduction in components as it does not include a bridge arrangement or a transformer. The disadvantage of the non-isolated boost converter is that the voltage gain results solely by the duty ratio of the switching device. A high gain from a non-isolated boost converter requires a duty ratio in a very nonlinear region. This produces problems for the control of the device[4]. The non linear gain produces two control problems when the circuit is providing a high gain. Operating at a high gain, only a small increase in DR is available for corrective action. The second problem is that at high gains, the resolution of control is very poor and makes high quality control difficult. The isolated boost converter does not suffer from the same problems. The gain of the isolated design is determined from the winding ratio of the transformer and the duty ratio of the switching. The transformer provides the advantage as it can produce the overall gain of the circuit without having to rely upon the switch duty ratio. This solves the problems inherent in the non-isolated design. The circuit is designed so that the transformer is responsible for the overall gain with the duty ratio set to 75%; the DR can then be used for precision control. The power supply in this application requires a gain of 8.3 to convert the 48 VDC to 400VDC as required by the motor. The graphs shown in Figure 5-6 and Figure 5-7 demonstrate the relationship between duty ratio and the gain of ideal non-isolated and isolated boost converters. The dotted line shows the required gain for the power supply, the location of the intersection gives the required steady state duty ratio. The graph representing the non-isolated converter shows the required duty cycle of 0.88 for the required gain of 8.3. The high duty ratio requirement therefore leaves little room for the controller to increase the power output if required. The graph shown in Figure 5-7 demonstrates the gain with respect to duty ratio of an isolated full bridge converter which is configured at steady state to produce a gain of 8.3 at 0.75 DR. The selection of the duty ratio at 0.75 places the steady state operation of the DR in the centre of the control range and allows a wider range of control. Figure 5-8 and Figure 5-9 demonstrate the operating point around the steady state duty ratio with the differing boost converter configurations. The rate in change of the gain compared to the change in duty ratio shown in Figure 5-8 demonstrates the additional problem with the non-isolated boost converter design. As displayed in the graph, the gain of the controller changes from 6.3 to 10 with a DR change of only 0.05. Figure 5-9 demonstrates the operating point for the isolated boost converter. The slope of the graph in

Figure 5-9 demonstrates the improvement in the rate of gain change with a gradient less than 50% of the non-isolated converter. Within the same DR change of 0.05, the gain changes from 7.7 to 9.1.

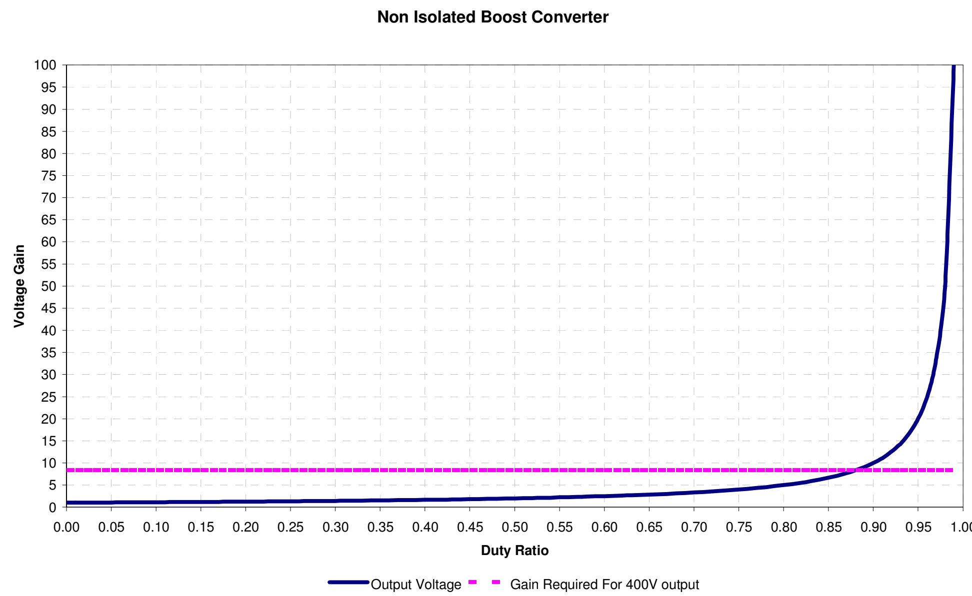

Figure 5-6 Relationship between duty ratio and gain of non isolated boost converter.

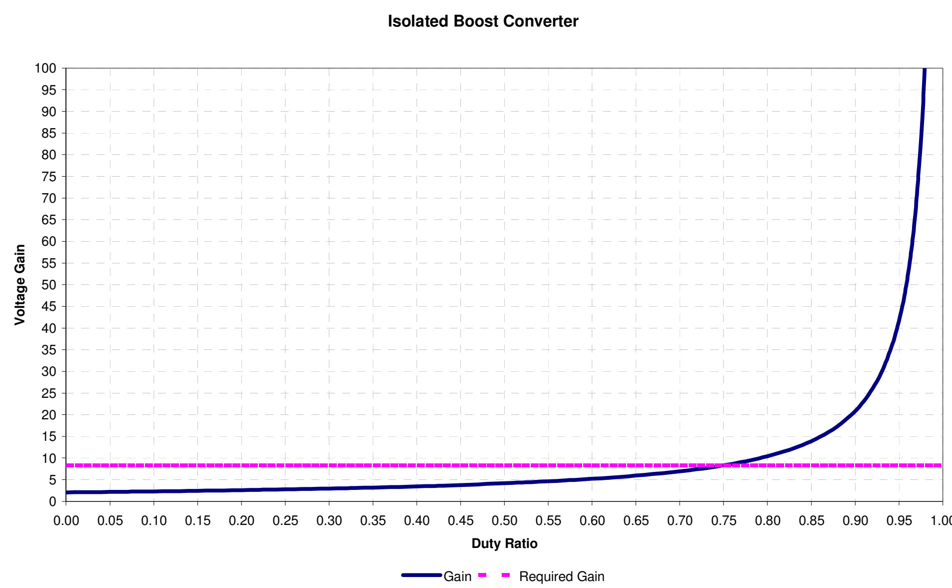

Figure 5-7 Relationship between duty ratio and gain of isolated boost converter.

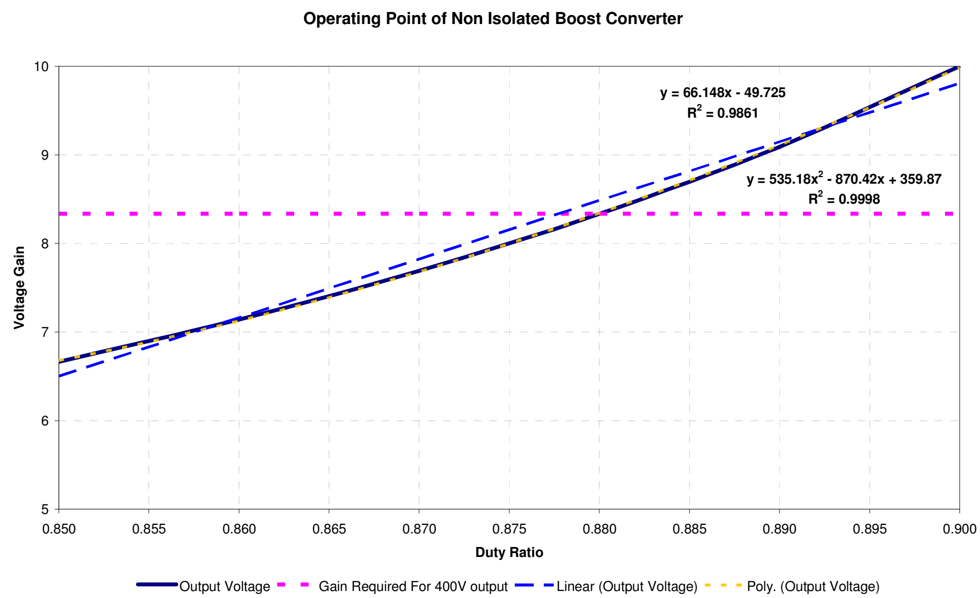

Figure 5-8 Relationship between duty ratio and gain of non isolated boost converter focused around steady state control point.

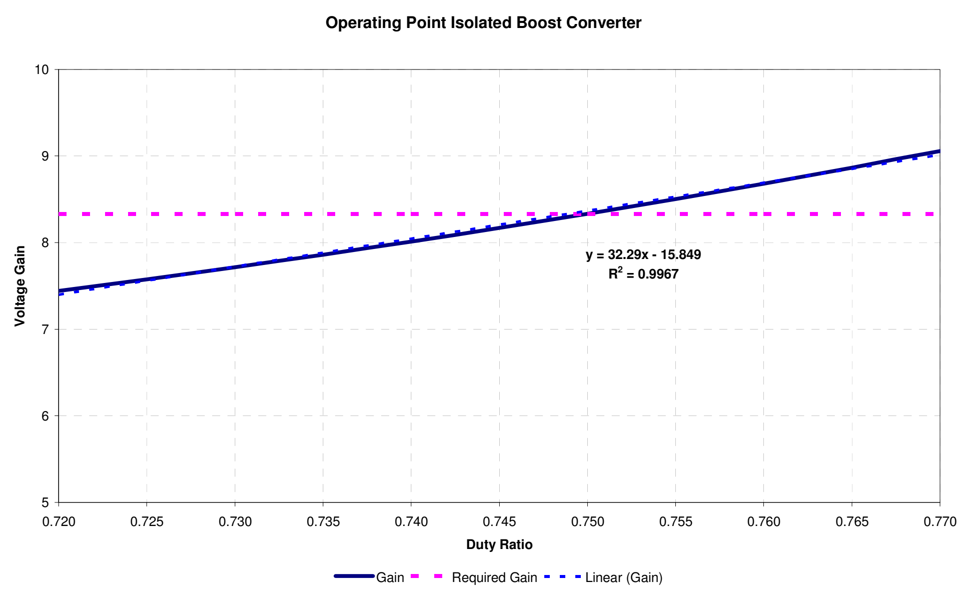

Figure 5-9 Relationship between duty ratio and gain of isolated boost converter focused around steady state control point.

The DC-DC converter is to use an isolated boost converter because of the difficulties of control with the non-isolated converter's characteristics. The isolated converter has the benefit that can be it can be up scaled later and is safer because of the isolated high voltage output. The high gain required from the power supply rules out the non-isolated converter, this is because of the low resolution and narrow range available of DR adjustment for corrective action. The effect of poor correction will be further amplified because of the increasingly non-linear gains around the set point of control.

5.2 Design Considerations

Factors to determine the design of the power supply.

- Voltage Levels.
- Peak Current.
- Quality of output supply.
- Safety of operation.
- Risk to humans.

5.2.1 States of operation

Once the converter type is chosen, an application design has to produce a power supply for practical application. The practical implementation has to include further factors in the design to insure a quality and safe power supply. The power supply requires at least two steady states and another two transient state modes; the supply has to maintain safe actions during all states of the operation. Each state has a different task and therefore different hazards that have to be identified in the initial stages of design. The state diagram of the operation of the SMPS is shown in Figure 5-10.

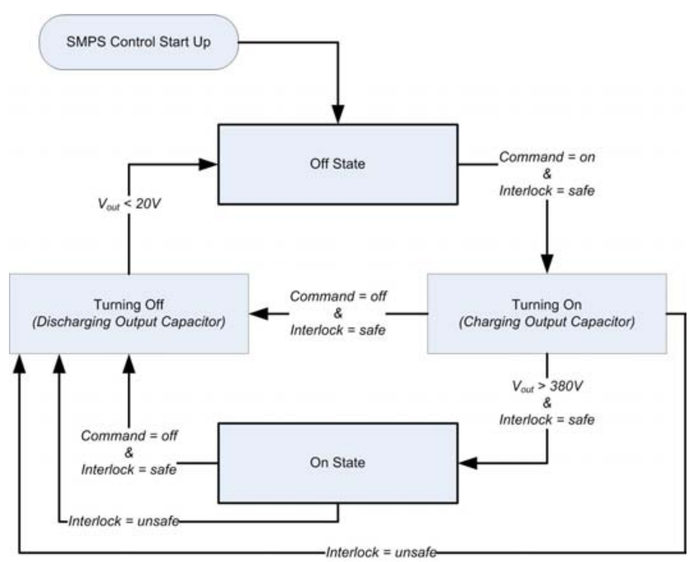

Figure 5-10 State diagram of power supply modes of operation.

5.2.1.1 State Control Objectives

- On State

    - Maintain the output voltage from the power supply depending upon a wide range of differing current drains.
- Turning On State
    - Charge the capacitor on the output as quickly as possible without damaging the components by a high current. The low output impedance will cause high current from the low charge state of the capacitor.
- Turning Off State
    - Switch the bridge output to a safe operation and drain the energy from the capacitor on the output; this is to remove the stored energy from the power supply.
- Off State
    - Monitor and correct to keep the power supply in a safe state of in operation.
- Interlock Sub-States
    - First State
        - Same as Turning off state.
    - Second State
        - Same as operation as off state except state is locked until the interlock is reset.

5.2.2 Hazard Identifications

This section will outline the hazards or events that may produce unwanted outputs and damage to the power supply or dependent systems. Four types of hazardous physical effects have been identified; these are voltage levels, current levels, temperatures and chemical contact. The controller for the power supply has to recognise the faults or if possible, predict future events and provide corrective action before serious issues arise. As the power supply produce a high voltage output, it has the capacity to cause serious or fatal injuries to people and severely damage system.

Voltages

The power supply produces a high voltage output of 400 VDC that requires a design that limits the risk to hardware and people. The high voltage output requires insulation on the board layout to minimise leakage currents. The 400V output requires isolation to the low voltage CMOS hardware as a means to avoid damage during a fault.

Current Limiting

High current draw is the most probable fault to occur and the catalyst of other faults arising. The current level of the primary side of the converter is subjected to high currents because of the low voltage input but high power requirements. The three devices subject to high current on the primary side are the battery, inductor and the switching bridge. The inductor can be chosen or manufactured to withstand high currents without to much difficulty or cost. The control system needs to measure the current through the primary side of the converter to detect high current, reduce the power output, and if necessary shut the system down if the fault appears to be caused by a short.

Real batteries have internal resistance and therefore at high current draw a large amount of energy is dissipated in the form of heat inside the battery. The battery can be damaged due to the heat and mechanical stress resulting from pressure build up. High flow of current into and from the battery can damage the molecular structure of the battery and reduce the available life cycles. High currents deposit the electrolytes (in lead acid) on the anode and cathode cell walls. The high current change results in a rapid change in mechanical deflection in cell walls; this cracks the electrodes at a molecular level.

Temperature

Increases in device temperatures are caused by power dissipation though non ideal components. The power loss through a non ideal component is normally produced as heat energy. If the power dissipation through the device is greater than the device can disperse to the surrounding environment then the accumulated heat energy increases within the component and the temperature of the device increases.

Non ideal devices have a loss in efficiency (power dissipation) from a number of different possible causes. Switching semiconductor devices have small voltage drops that are generally harmless however, a loss occurs during the switching period of the semiconductor which has to be considered.

$$P = VI = I^2 R$$

P – *Power[W]*
V – *voltage[V]* (5-6)
I – *Current[A]*
R – *Impedance[Ω]*

From Equation 5-6 above the current through the device is the most destructive factor that causes resistance losses and is the major source of heat generation. Current can therefore be destructive into two ways, a high instantaneous destructive current level as mentioned above and a high prolonged current level that over time raises the internal temperature of device and/or a system. To maintain the safe operation of the system, the temperature of all critical components and the system has to be known. The most reliable and easiest to implement is to directly measure the temperature of the critical components.

Human Safety

The power supply is easily able to cause a fatality because of the high voltage produced, the stored energy and the ability to supply high currents if shorted. Battery explosions are less likely to result in fatalities but may produce severe injures. Injuries resulting from battery explosions may be caused by shrapnel, chemical burns or poisonous gas inhalation. Heat generated from the batteries may produce burns or burns resulting from the ignition of combustion materials around the batteries. As with batteries, excessive heat generated from other components in the power supply may produce burns directly or ignite other materials that may cause burns. Materials used in power electronic devices are known to produce extremely toxic fumes when ignited. The isolated converter does provides much improved safety compared to non isolated design; nevertheless if a person makes contact with the positive and negative outputs at the same time an electrocution will occur and fatality is almost guaranteed with a DC supply of 400 Volts. Further protection circuits could be produced to detect a short circuit; the usefulness of these circuits is limited. The current draw for any practical sized motor is many times greater than the fatal current to a person; relating this to a protection device means that the person is most likely to be dead before the power is cut. A person may be harmed from electrocution in two ways, ventricular fibrillation or severe burns. Ventricular fibrillation is generally caused by a small AC signal disrupting the heart and can cause instant death; DC supplies can cause the injury although the burning injury tends to have a greater effect. Severe burning is caused by the impedance across or through the human body, this causes burning along the current path. Burning generally occurs at the contact point (ie finger/hand) and internal organs. The power supply output is DC therefore the risk to humans is more likely to result from severe burning. The risk posed from the DC output is increased because of two further events that are likely to occur. The output is smoothed with a relatively large capacitor that will discharge rapidly if the output is shorted or it may remain charged once the power supply is turned off. A DC electric shock has a paralysing effect on the body's muscles though the disruption of the nervous system; this can cause a person to suffocate or "lock on" to the contact point.

Another way of increasing safety is to have an external interlock system. Interlocks are commonly used in process and automation plants that stop an entire system if a fault or an alarm is activated. The interlock works external to the controller and therefore stops the system even in the event of the controller failing. A simple safety measure is to have an indicator light on the case of the power supply to signal when the device is unsafe. Human hearing my be damaged form the sound emitted from switch mode power supplies. The damage to human hearing and irritating noise can be reduced by using switching frequencies above human audible range (20kHz).

5.2.2.1 Additional Start Up Hazards

During the initial start-up of the system the energy stored in the capacitor is zero and at 0V potential. The affect of this discharged state is the effectively low load impendence and therefore a potentially high current can be produced on the primary side of the power supply until the capacitor has been charged to operational levels. The primary control task during the start up state of the controller is to control the current to the capacitor.

5.2.2.2 Additional Shut Down Hazards

Simply turning off the power supply and stopping the electric motor does not leave the power supply in a safe state. To make the power supply safe once the operation has ceased, the energy is drained from the capacitor and inductor. The controller is required to manage the drain of energy from the capacitor on the output state of the power supply. The act of draining the capacitor is capable of producing high currents through the draining circuit due to low load resistance.

5.2.2.3 Off State

Delay in Temperatures

The heat dissipated from a component often lags the power consumption due to temperature coefficients and with this delay, runs the risk of an increase in temperature once the system has been turned off. The control system needs to continually monitor the system during the off state although possibly at a lower sampling rate to save power.

Fault Detection and Maintaining a Safe State

People will make the assumption that the device is safe to touch when it is turned off.
The controller is required to keep the device in a discharged state when turned off because of the capacity to store energy. It is vital to maintain a safe secondary side voltage as the hardware could potentially produce 400 VDC. The controller aims to maintain a safe secondary side voltage by keeping both sides of the transformer to 0V; this does not allow any current flow to the capacitor. The primary side of the power supply is supplied with a lower level of 48VDC. 48VDC is unlikely to be fatal although in certain conditions it has adequate voltage to cause fatal injuries. The risk of the potential fatally voltage from the battery supply cannot be entirely removed; an isolator switch or relay at the battery terminals however can reduce the length of live wires.

5.3 SMPS Control Design Investigation

Four possible methods for the control of the SMPS are considered. These topologies can be categorised into the following methods.

- Direct Microcontroller Control.
- Microcontroller combined with high speed fixed hardware.
- Microcontroller and with Complex Programmable Logic Devices (CPLD).
- Entirely CPLD based control.

5.3.1 Direct Microcontroller Control

The direct microcontroller approach relies entirely upon the operation of a microcontroller. This requires a minimum amount of interfacing hardware for the control of the power electronic devices. With the direct microcontroller method, the microcontroller is directly responsible for the operation of each switching element. The advantage of such a control design is that hardware count and complexity is kept to a minimum. The disadvantage of such a control system lies with the cost associated with the need for a more expensive high clock frequency microcontroller.

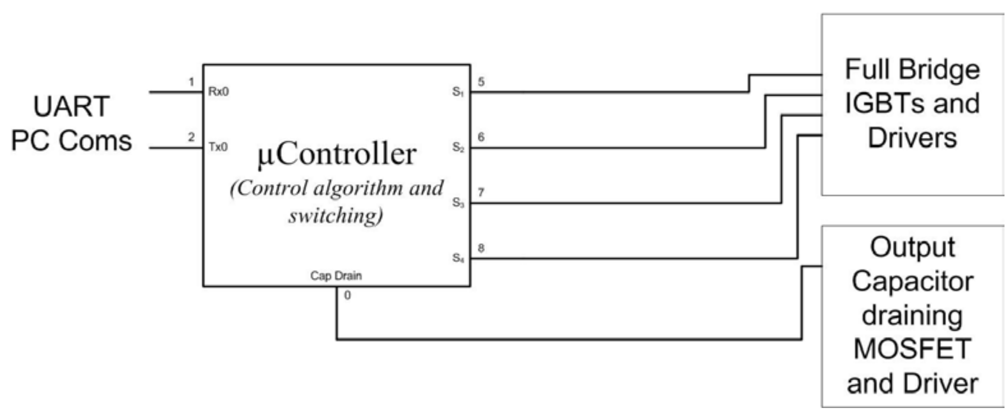

Figure 5-11 Microcontroller directly controlling the switching of the power electronics.

The reduction in hardware theoretically provides a number of advantages; reduction in components improves reliability, reduces cost from fewer components and a reduction in circuit board size and complexity. Practically, the only true advantage is the reduction in circuit board design and complexity which has implications for future manufacturing. The reduction in cost from fewer components is offset by the increase of a high performance microcontroller. The theoretical gain in reliability from fewer components is counteracted by the increased complexity of the control code, latency and stability dangers from the requirement of the high frequency interrupt routines.

5.3.2 Microcontroller and Hardware Combination

Mixing a microcontroller with a basic hardware design allows a reduction in the operating frequency of the microcontroller. Designing hardware to construct the basic logic calculations that operate at high frequency replaces the high frequency tasks assigned to the microcontroller. The same basic logic calculations can be completed reliably using either a cheaper slower microcontroller or allowing a more complex control algorithm. The control logic for the SMPS during safe operation is to change the duty ratio of the bridge switching. The switching sequence required for the full bridge is a relatively simple process and can be implemented without a complicated design. The controller's processing can be focused on the calculation of the required duty ratio removing the need for the controller to generate the time critical switching task. The control layout is shown in Figure 5-12

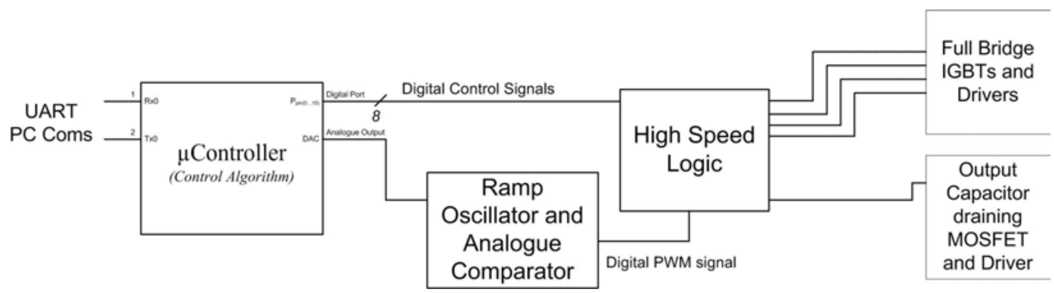

Figure 5-12 Microcontroller combined with fixed hardware to control the switching of the power electronics.

The control system works by the microcontroller reading the analogue values from the sensors, running the control algorithm in the microcontroller software and then output the desired duty ratio and on/off control to hardware. This reduces the outputs from the controller and allows more stable control.

5.3.3 Microcontroller and Firmware

Replacing the fixed hardware with a CPLD such as a FPGA, provides a wide range of benefits for the performance and a reduced component count compared to control methods explained above. FPGA is a technology that is between software driven sequential processors and fixed hardware. The processing capabilities of FPGA are much greater than a sequential processor although not quite to that of fixed hardware. Parallel processing technology is easier to design and modify their operation than fixed hardware but not as easy as sequential processor technology.

Using a FPGA would give the following advantages.

- An FPGA implementation of a high-speed circuitry reduces the components to two ICs.
- The algorithm that the FPGA employs is not fixed once designed, and can be reprogrammed.
- The controller is a more accurate and reliable system because it uses solely digital electronics.
- Depending on the level of complexity of the design, a FPGA design can be easier or more difficult than a fixed hardware approach.

The disadvantage of using a FPGA is the difficulty in development compared to software and the increase in unit cost compared to hardware. The initial "design capital" and cost for FPGA design requires high frequency interfacing circuits and a high cost per unit. A number of methods can develop FPGA firmware; the common methods are schematic descriptive and VHDL languages. For simple designs, schematic descriptive compilers allow the device to be programmed as simply as the design for fixed hardware. VHDL descriptive compliers allow a complex hardware layout to be designed more efficiently than using schematics.

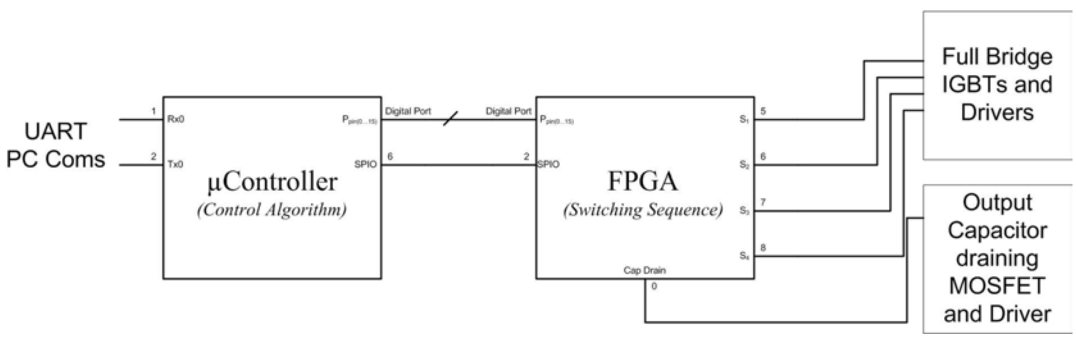

Figure 5-13 Microcontroller combined with FPGA to control the switching of the power electronics.

The controller layout presented in the Figure 5-13 reduces the chip count to a single chip on the gate control compared to fixed hardware design. The problem with using a FPGA is the requirement of specialist equipment for programming, high quality circuit boards and the difficulty in firmware development.

5.3.4 <u>Firmware Application</u>

Using firmware solely for the control circuit provides the highest performance of a practical control system. The disadvantage to using only a single FPGA is the high development resource required for the development of the firmware.

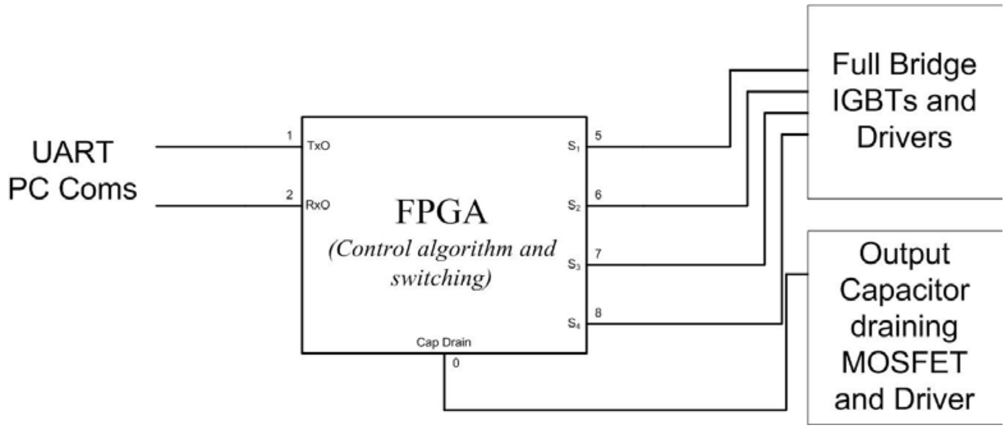

Figure 5-14 FPGA only to control the switching of the power electronics.

5.3.5 Control Development Investigations Findings

Using a FPGA for the control circuit was ruled out because of the availability of resources. A FPGA dependent design was decided to be the secondary plan if the other control design methods proved unworkable. The aim of comparing the models was to find the simplest method that would achieve the desired level of performance. The first model tested was the single microcontroller directly connecting to the interfacing hardware. This particular model of operation would be quick to develop and test. The model was tested with a Silabs 8051F020 mixed signal microcontroller.

5.3.5.1 Single Microcontroller Feasibility Investigation

To test the model the microcontroller was programmed to set the duty cycle of the switching sequence from commands received from the RS232 port, then produce the signal using internal interrupts operating from timers running at set frequency. The aim of the controller was to provide a 25 kHz operation of the switching cycle to avoid damaging human hearing. The microcontroller switching was required to produce a resolution of at least 50 steps. The timer would be required to operate 100 times per cycle to produce the resolution; this is to produce 50 steps of resolution for each polarity of bridge operation. To produce the required switching resolution the frequency would require an interrupt rate of approximately 2.5 MHz. The datasheets from the Silab 8051F020 provide information that interrupt routines require a minimum of 5 clock cycles to enter and 2 to exit. The controller clock frequency is approximately 22.18 MHz therefore if the control had the possibility of managing the required rate; the controller software would need to be as simple as possible. Instructions inside the software are required to be limited to single cycle instructions such as comparisons and setting internal memory registers. Instructions that are more complex would not permit any chance of meeting allowed periods. The flow chart of the operation is shown in Figure 5-15. The control program consists of only interrupt driven events once past the start-up code. The operation of the bridge is controlled from the interrupts; these use an internal timer that occurs at a rate of 2.5 MHz. The communication is handled by another interrupt; whenever a character is received, the value from the character is used to determine the duty ratio.

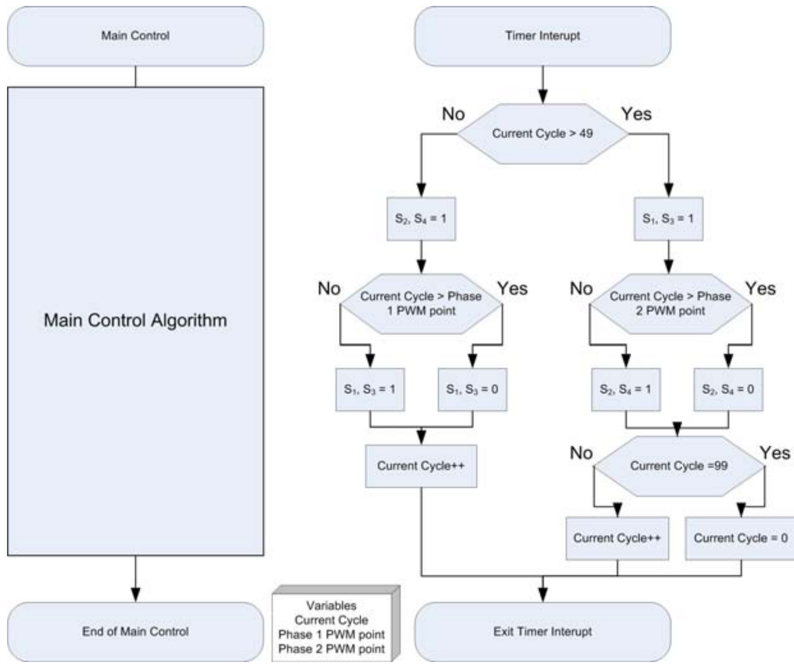

Figure 5-15 Flow chart of operation of single microcontroller the power electronics.

Attempting to gather quantifiable results from the test proved difficult with the unstable controller operation. The likely cause of the instability is that the time dependent operations do not have sufficient time to be completed and the next interrupt event is missed. The controller showed poor operation even without the control algorithm included in the software. While no quantifiable results were obtained about the capabilities of such a control system, it did demonstrate that the model was indeed impractical and other options were required to be explored.

5.3.5.2 Twin Microcontroller Feasibility Investigation

The problem identified with using a single microprocessor for the control was that frequency of interrupts to generate the switching sequence did not allow sufficient time for other algorithms to be completed and this produces instability. A solution to avoid the problem and still keeping a simple circuit layout is to use two processors in the design. One processor would operate the control of the system; the other processor used to generate the switching sequence.

The processor communication was accomplished using parallel communication from the microcontrollers' standard digital I/O ports. The microcontroller program calculates the required duty ratio for the bridge operation. The calculated 8-bit duty ratio then is produced on the digital ports. The switching microcontroller references this 8-bit value and uses it to generate the switching sequence.

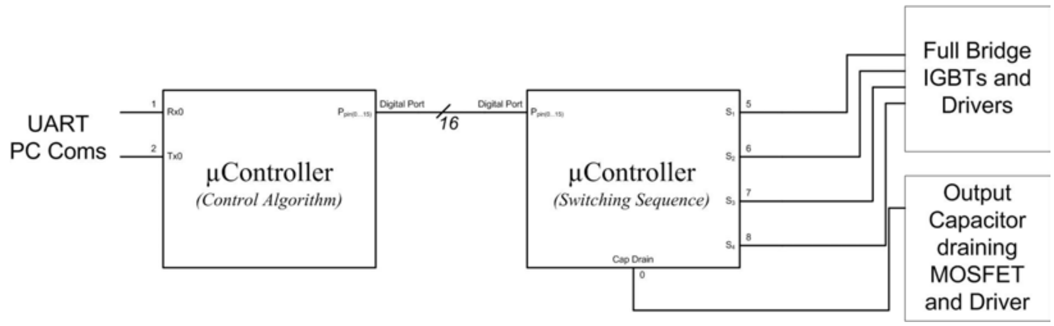

Figure 5-16 Adaptation of single microcontroller to switch the hardware by adding extra microcontroller dedicated to high speed switching.

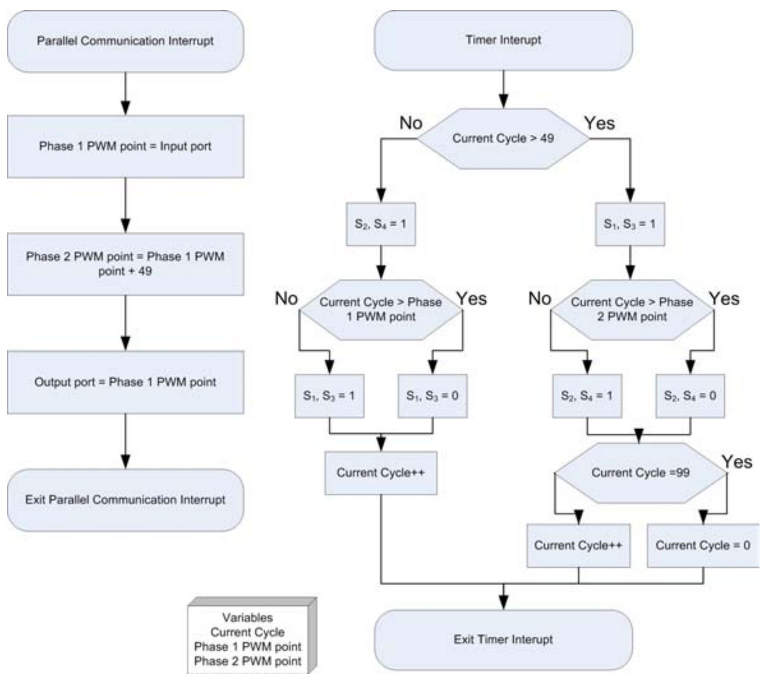

Figure 5-17 Flow chart of operation of using multiple microcontrollers the switching of the power electronics.

Testing the multiprocessor controller system with the oscilloscope showed the improvement in stability of the switching sequence and reliable control processing for the duty ratio. The improved stability of the output switching allows the oscilloscope to trigger the output voltage making it possible to gather some operation information to make the conclusions on this type of system.

Three problems with the control signals were discovered.

- Small fluctuations in the duty ratio and frequency
- Occasional error duty ratios appeared
- Control signals could not produce high duty ratios

5.3.5.2.1 Fluctuation of duty ratio

The errors in duty ratio can be produced by different events occurring. The two most likely reasons for the changing in the duty ratio can be attributed to either the timer interrupts not occurring at constant intervals or hazards occurring when reading the input port. Unreliable timer interrupt operation can be caused by a number of problems such as latency, missed interrupt flags and interrupt routine length. All of these problems can be related back to the overlaying fault that the microcontroller does not have sufficient operating frequency to carry out the required instructions in the available period. If the interrupts occur at a frequency higher than the microcontroller can operate the interrupt routine, then the rate of change of the output is limited on the rate the processing rather than the timer frequency. As only a single task is employed by the switching microcontroller, the faults causing latency and missed interrupt flags cannot occur without the interrupt being too long. A further possible source of error lies in hazards occurring during the reading of the port with the value of the duty ratio.

5.3.5.2.2 Duty Ratio Errors

Duty ratio errors were detected that changed the duty ratio for a cycle. The changes in the ratios were various around steady state and outside what one would expect for the varying interrupt periods. The likely source of the one off errors was the result from faults in reading the input port. This would explain the varying size of errors and the event only occurring for a single period. The two microcontrollers were connected by parallel port and without a common clock. It was therefore likely that occasionally the switch microcontroller was reading the port while the control microcontroller was changing the value.

5.3.5.2.3 Inability to produce High Duty Ratios

High duty ratios could not be produced because the period of the PWM signal was too short to allow a full transition between high-low-high. During a low duty ratio the transition period between high and low is not a major concern because the transition is only a small portion of the period. With an increased DR, the transition period remains the same and therefore becomes a greater portion of the off period.

5.3.5.2.4 Investigation for Solutions

Communication Hazards

Switching hazards were the most probable cause of the fault in communication error. The problem occurs because the two microcontrollers do not share a common clock. This is because the microcontrollers are located on prototype boards and a common clock would require a new board to be developed. Developing a new board in the initial stage of the research was ruled out, as this would require circuit boards to be made off campus and the cost would be prohibitive. If the resources were available to produce circuit boards then a CPLD would be the best option, therefore developing for the twin microcontroller option is not viable. The remaining options would be asynchronous transmission or a handshaking of data. Asynchronous transmission would require using the serial port and the relevant code to complete the communication. The processing overhead for the serial communication was considered too great and would have an adverse effect on the operation of the microcontroller. Serial communication was considered the back up plan if a less processor intensive method was not found. The preferred option was parallel communication, as this would reduce the processing requirements. The problem with asynchronous parallel communication is the reliability of the communication. The hazards that the parallel communication suffer from appeared to be the changing of each bit of communication while the other microprocessor is reading the port value. A possible solution to avoid the reading of the port is to use a separate signal to identify when the value is safe to read. The signal to be used can either invoke an external interrupt routine or a simple polling method. Both options have advantages and disadvantages. The external interrupt method provides a method that has no disruptive effect on the switching controller while no communication is in progress. The disadvantage with the interrupt method is that the controller is disrupted while communication takes place. The interrupt routine operates for a period and this interferes with the switching process. The simple polling method has the advantage that only a small effect occurs on the switching process when communication takes place; the disadvantage however, is that the switching process is lengthened.

Interrupt period

The problem with the first version of the multiprocessor system was associated with the microcontroller being unable to operate the interrupt routines at sufficient frequency to work reliably and produce a high quality output over a wide range of duty ratios. If the same microcontroller is to be kept then two options are available; either reduce the code complexity or reduce the frequency of the timer interrupt used for the switching. The code to generate the sequence should be as small as possible to retain the optimum function; changing the microcontroller model needs to be avoided if possible. The required modification to the operation of the system is to reduce the interrupt to a frequency that provides a reliable, high quality control. Slowing down the interrupt involves either reducing the operating frequency of the switching, reducing the resolution of the duty cycle or a combination of both. The frequency of the power supply was originally chosen to be 25 kHz. The value is dependent on being a safe frequency range for humans. Human hearing is generally between 20-20 kHz to avoid damage, the switching frequency has to be above this range. As the switching frequency needs to be kept at the same rate, the resolution of the duty ratio is required to be reduced to lessen the timer interrupts.

5.3.5.3 Microcontroller and High-speed Hardware Feasibility

The results provided by testing the direct microcontroller methods showed the frequency of operation required to operate the switching is impractical to be achieved by a sequential processor. Achieving the desired resolution and frequency requires the use of external hardware to provide the high-speed operations. As mentioned earlier in the chapter the development of FPGA control systems was to be delayed if possible. The design of hardware during the initial stages of investigation is focused on fixed circuit development.

5.3.5.3.1 Digital vs. Analogue

The microcontroller handles the calculations and then passes the calculated duty ratio and operational controls to the hardware, the hardware then operates the bridge at high frequencies. The microcontroller used is a mixed signal controller with ADC and DAC ports and therefore is capable of producing an analogue or a binary representation of a duty ratio. There are three conceivable methods to generate a high frequency PWM signal from a set duty ratio value (analogue, digital and a combination).

Analogue

The basic circuit model for a linear PWM generation consists of three main sub circuits, these being the input, oscillator and comparator circuit. The principle of the circuit works by comparing the input voltage against a liner increasing reference voltage. While the reference voltage is less than the input voltage the output of the circuit is high. Once the reference increases above the input voltage the output switches to low.

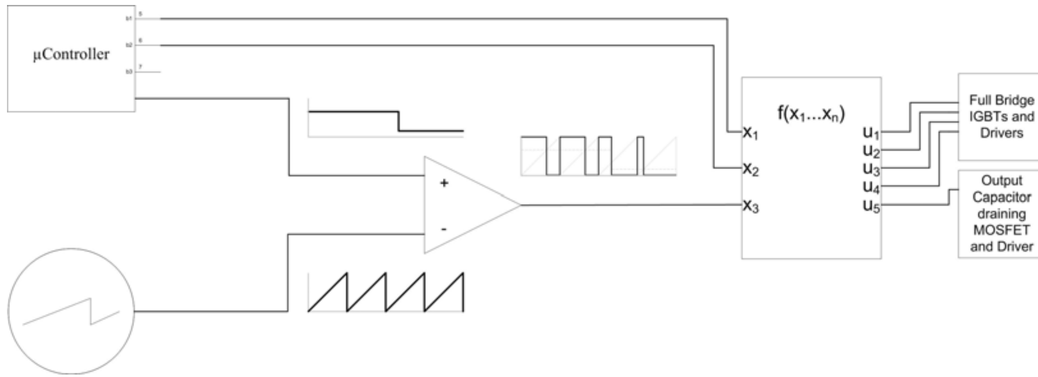

Figure 5-18 Diagram of analogue switching circuit.

There are a number of different options of the oscillator but some of the simpler designs use 555 timers or a Schmitt trigger oscillator. Both methods use a resistor and capacitor to produce the timing for the circuit. The disadvantage is that the capacitor voltage is used to generate a time period. The voltage across the capacitor is theoretically a linear ramp although practically the voltage across the capacitor is not strictly linear across the whole range of voltages.

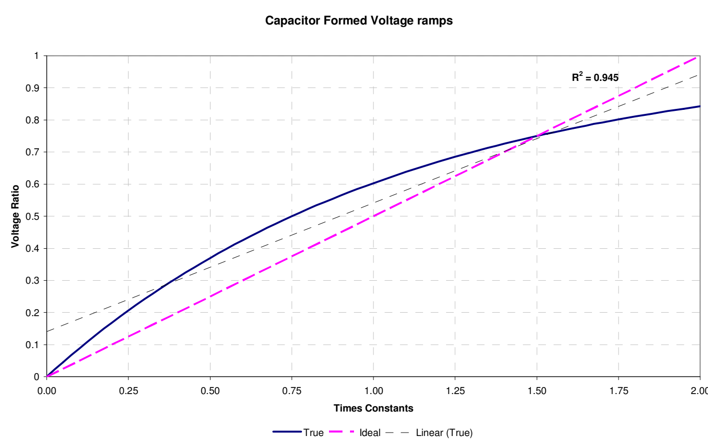

Figure 5-19 Non linearity of using analogue circuit.

The oscillator can be configured to operate in the near linear region of voltages across the capacitor to avoid the non linearity of the real component. Improving the linearity of the control creates has the disadvantage in that the circuit is susceptible to noise as the difference between high and low voltages is reduced. Noise can affect the analogue system by creating errors on either the input voltage or the oscillator produced ramp. Filters on the analogue inputs can reduce the errors although there is a section of track that will be the processed voltage and therefore unprotected against EMI, this interference can have an effect on the comparison. To protect against EMI, a comparison circuit with hysteresis is a way of reducing multiple triggering that occurs with noise on the input voltages.

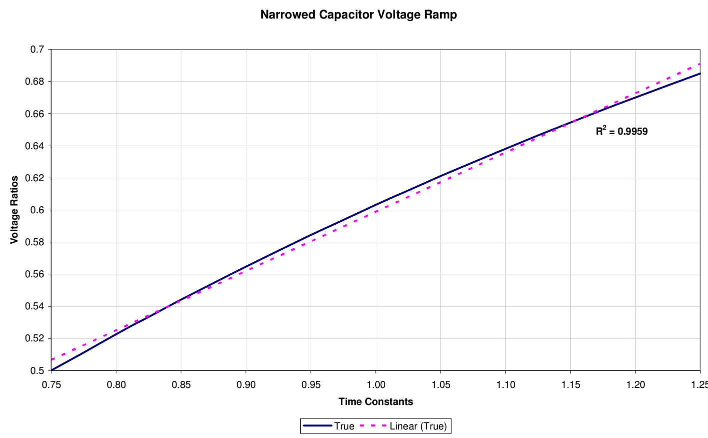

Figure 5-20 Increase in linearity using a narrower operation point.

The PWM signal is required to function with a 50- 50 operation of the bridge phase, to achieve this the leading edge of the PWM needs to be synchronised with the operation of the bridge. A 555 timer provides an output pulse on the switching of the device. This switch pulse can be used as a clock edge with a counter to provide an oscillating phase control.

Digital

The digital system uses only digital devices in the circuit to produce the PWM signal to the switching logic. The advantage that the digital system has over the analogue circuit as explained above is that because the system is digital it is less prone to EMI and the counter is a strictly linear output.

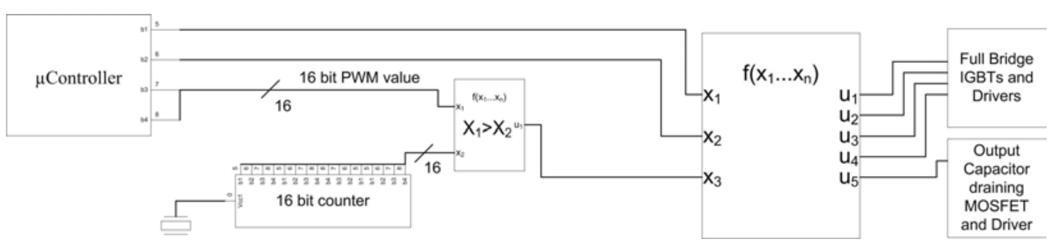

Figure 5-21 Diagram of digital switching circuit.

The circuit operation is based around the cycling though a counter to provide a digital representation of a linear ramp. The comparison result between the ramp value and the control signal is produced with a 16 bit digital comparator. The source of possible errors in the above circuit is the switching hazards from the output from the microcontroller. These errors can be removed by using a latch to the input of the circuit. This latch produces a one cycle delay but produces a stable switching at the converter.

The disadvantage of the digital circuit is the complexity of the circuit board, this mostly arises from the increase in tracks required on the PCB to carry parallel digital data. The digital option further requires more I/O pins, this does not cause a significant concern because the microcontroller has 64 digital I/O available.

Combination

Using a combination of the digital and analogue methods provides some gains in the quality of operation compared to the analogue concept without some of the drawbacks from the digital option. As with the full digital implementation, the ramp voltage is produced with an oscillator and counter, the difference is that the binary value is converted to an analogue value. The analogue value is compared with the analogue signal from the microcontroller and the circuit produces a PWM signal using an analogue comparator. The advantage compared to the analogue method is a linear voltage ramp for the comparison, with less effect from EMI due to reduced analogue circuitry. With respect to the digital system, the combination concept requires fewer pins to be dedicated from the microcontroller and a reduction in PCB complexity.

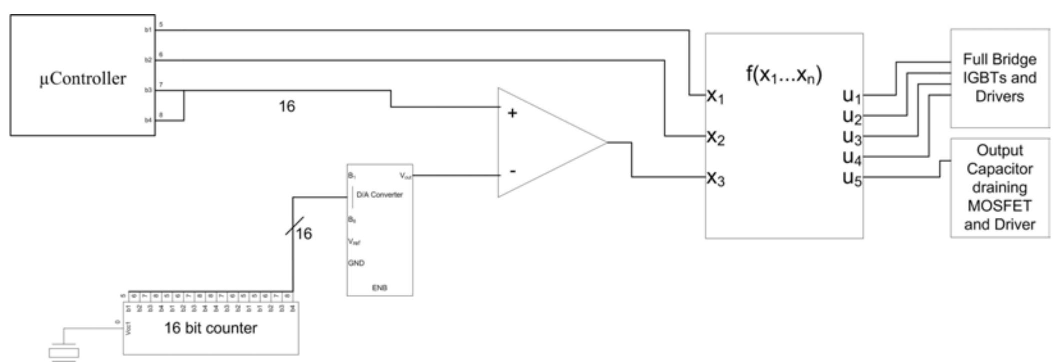

Figure 5-22 Diagram of using a combination of digital and analogue techniques in producing a switching circuit.

Conclusion

Method selected for the bridge switching was chosen to be the analogue approach; chosen for its simplified circuit board design. The boards required for the digital and combination methods would be too complicated and beyond available resources for the circuit board manufacturing. If the ability to produce complex boards was available then the option of a FPGA would be chosen over the discrete digital approach.

5.4 Control System Design

The control system for the power supply is to use the combination of a microcontroller and fixed hardware. The physical operation of the hardware is sampled by analogue sensors before passing through signal conditioning and finally the analogue input ports of the microcontroller. The steady state control output from the microcontroller uses a DAC output to control the duty ratio of a PWM generator. The layout of the developed embedded control system for the SMPS module is shown below in Figure 5-23.

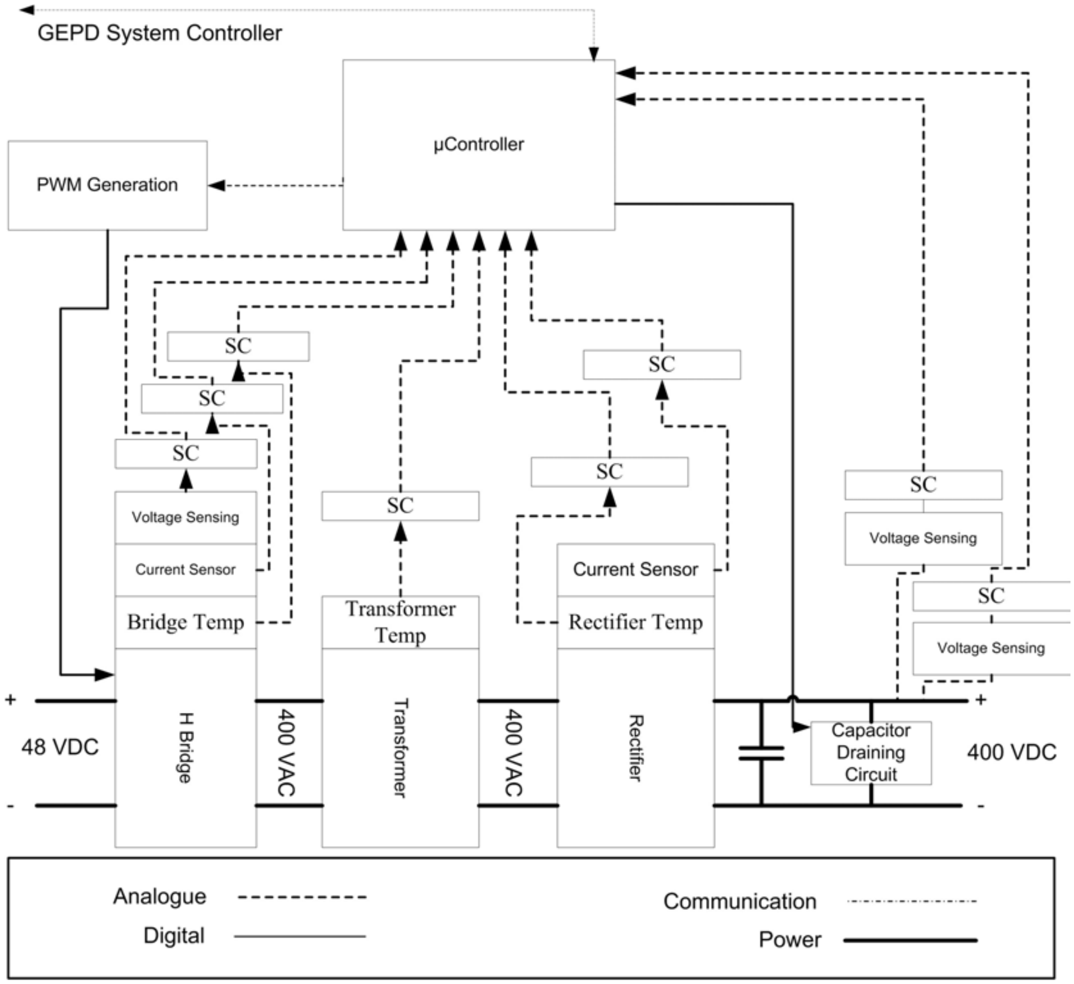

Figure 5-23 Embedded SMPS Control System.

5.4.1 Control Inputs

The microcontroller requires operation information about the power supply to provide a closed loop control system. The power supply has differing control states and each requires differing input variables. During the steady state operation of the power supply, the objective of the control is to maintain a constant voltage output of 400V and maintain a safe operation. The most direct variables to measure the output is the voltage with the change in voltage and current drain giving an indication of the future operation of the power supply.

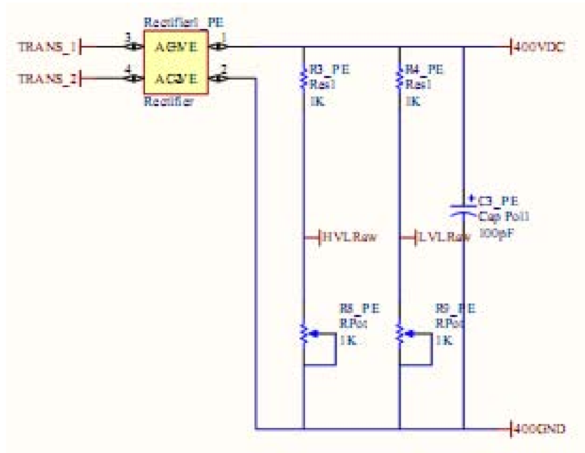

Figure 5-24 Example of collecting input variables showing the high and low-resolution voltage output prior to signal conditioning.

Initially at start up the capacitor will have no stored charge and this will produce a low load impedance on the secondary side of the power supply.

During the transient states the controller objective is to change between steady state modes of operation as quickly as possible, yet keep the system in a safe mode of operation. Initially at start up, the capacitor will have no stored charge and this will produce an inrush of current to the device and effectively produce a low load impedance on the secondary side of the power supply. The controller objective during this time is to operate at the maximum safe possible current through the power supply. The most direct variable to measure in the charging and discharging states is the instantaneous current level with the instantaneous and change in voltage giving the indication of future operation of the controller.

During the off state, the controller is required to keep the power supply turned off. The controller is programmed to hold the power supply in a discharged state, because faults may occur the controller continuously monitors the potential dangerous variables as insurance. The two variables required to ensure that the SMPS is in a safe condition is the output voltage and the battery current. The output voltage is the variable that is dangerous to humans and dependent devices, whereas the battery current is capable of showing if the power supply is damaging itself due to a short in the bridge.

5.4.1.1 Required Variables

State	V_{out}(Volts)	dV_{out}(ΔV/sample)	$I_{primary}$(Amps)
Steady State Operation	380-420	-40 - 40	0-10
Transient Start up	0-420	-420 - 420	0-10

Transient Shut Down	0-420	-420 - 420	0-10
Off State	0-420	-420 - 420	0-10

Table 5-1 Required Variables for SMPS.

The variables listed above show the three same variables are used for the control in all modes of operation. Each of the variables are processed depending upon the state requirements. The Transient and off modes of operation require a voltage measure across the entire range of possible range of voltages. During the on state, the operation of the power supply voltage is measured to a higher resolution around the steady state level. If the voltage changes from this high resolution range then the controller changes the mode of operation. If the digital representation of the voltage is focused only on the allowed range then the resolution can be increased and therefore should give more precise control.

To achieve the required control of the power supply over all modes of operation, the following analogue input variables are required be sampled at high rate.

- High Resolution V_{out}
- Full Range V_{out}
- Output Current

The change in both the high resolution and full range voltages is achieved by comparing the previous reading and not with a hardware signal.

5.4.1.2 Monitoring

Apart from variables gathered for normal safe control of the power supply, other variables are helpful for the microcontroller to monitor for faults and transmit as telemetry to a system controller. To guard against unsafe operation occurring further sensors are required to monitor the temperature of critical devices. As mentioned in section 5.2.2.3 instantaneous current and power readings do not provide a measure of the temperature of devices in the system; further temperature sensors are required to assure safe operation. Temperature critical devices for monitoring are identified as are the battery, H-bridge and rectifier.

The voltage level of the battery provides an estimate of the current charge state of the battery and is useful as it gives an estimate of the remaining power. In addition to the high speed collection of the control variables mentioned above the following variables of the system operation are collected at a reduced rate. The variables trigger software interrupts to shut down the system and are transmitted as telemetry.

- Battery Voltage

- Battery Current
- Battery Temperature
- H-Bridge Temperature
- Rectifier Temperature

5.4.1.3 Interlock Input

The external interlock signal to the system is fed to the microcontroller through an interrupt port. This provides the microcontroller with a signal that a fault has occurred and the SMPS needs to be turned off.

5.4.1.4 Hardware

The system variables are required to be converted to 0-2.5 V range to represent the signal before the analogue to digital conversion can take place inside the microcontroller.

Variable	*Variable Unit*	*Sensor Type*	*Method*	*Range*	*Sampling Frequency*
High Resolution V_{out}	*V*	*Voltage Divider*	*Offset, Scale*	*380-420 V*	*300Hz*
Full Range V_{out}	*V*	*Voltage Divider*	*Scale*	*0-420V*	*300Hz*
Output Current	*A*	*Hall Effect Sensor*	*Scale*	*0-1A*	*300Hz*
Battery Voltage	*V*	*Voltage Divider*	*Offset, Scale*	*44.8 – 54V*	*4Hz*
Battery Current	*A*	*Hall Effect Sensor*	*Scale*	*0-10 A*	*4Hz*
Battery Temperature	*℃*	*Thermistor Voltage Divider*	*Scale*	*0-80 ℃*	*4Hz*
Bridge Temperature	*℃*	*Thermistor Voltage Divider*	*Scale*	*0-80 ℃*	*4Hz*
Rectifier Temperature	*℃*	*Thermistor Voltage Divider*	*Scale*	*0-80 ℃*	*4Hz*

Table 5-2 Required inputs for the controller.

5.5 Microcontroller Details

The microcontroller selected for the application is the Silab 8051F020 and is integrated with the development board. This section will provide the details and the development that is required for the specific task of control of the power supply. The generic algorithms and operational details for the microcontroller are explained in CHAPTER 3 and will not be covered here.

The microcontroller's objective is to operate the power supply in the best performing and safe operation. The device receives operational orders about the required action of the power supply and carries out the task in normal operation.

5.5.1 Control Algorithm

The controller has three possible modes of control of the power supply. The task of the steady state is to maintain the voltage output at the set level. The control objective used for the transient states is assigned the control purpose of changing the voltage levels on the output as quickly and safely as possible. The controller topology used for all modes is a linguistic fuzzy logic MISO PD+P controller. The operation of the fuzzy control is contained within section 3.4 Fuzzy Logic Control.

The general summary of the operation of the control algorithm is listed (in sequence).

1. Process communication buffer and identify command changes.
2. Process analogue input values.
3. Decide upon the state of operation of the power supply based from changes in analogue values and commands with respect to the previous state of the controller.
4. Begin fuzzy logic control
    a. Fuzzification of the input values.
    b. Run the rule base.
    c. Defuzzification of the output fuzzy value.
5. Change the controller's output using the fuzzy control result.
6. Send telemetry if required

The inputs to the controller were originally planned to use Fuzzy PD (Proportional and derivate) representation for both the high resolution output voltage and the output current. The Fuzzy sets were to consist of 5 membership functions and would result in a fuzzy input space of 625 rules. The difference between the steady state and transient control was the desired control response. The focus of the steady state control is the control of the output voltage, therefore the voltage output has the highest effect on the control with the current used a fine tuning element. The focus of the transient control is the current through the power supply while the load impendence from the capacitor is low, therefore the controller's most powerful input variable is the current measurement with the voltage output being the fine tuning factor.

The variables available to the power supply controller were as follows.

- High resolution voltage output (380-420V)
- Change in high resolution voltage output with respect to time
- Low resolution voltage output (0-400V)
- Change in low resolution voltage output with respect to time
- Rectifier current
- Change in rectifier current with respect to time

The steady state control mapping was planned to use the high resolution voltage variable to give the best precision during operational modes and also use the rectifier current as secondary control variable. The transient controller was to use low resolution output voltage to give the entire range of possible voltages and use it with the rectifier current. The development of controller with 625 rules was found not to be feasible because either the microcontroller had insufficient program memory to store each rule individually or did not have the processing capacity to operate in a generic method. The fuzzy control space was modified to three fuzzy variables that reduced the number of rules to 125. This allowed the rulebase to be stored with the program memory and allow space for the remaining sections of the control. With 125 rules the controller was capable of running the rule base within 6ms when no interrupting requests occurring.

Steady State Fuzzy Control Variables

1. *High resolution output voltage*
2. *Change in high resolution output voltage*
3. *Current draw*

Transient State Control

1. *Current draw*
2. *Low resolution output voltage*
3. *Change in current draw with respect to time*

5.5.2 Mixed Signal Microcontroller Requirements

To interface the microcontroller with the hardware and communication channel, the following internal devices are required.

- Single 12 bit DAC output to control the switching frequency.
- Eight 12 bit ADC inputs.
- One external interrupt.
- Three digital outputs.
- Serial communication port.

5.5.2.1 DAC

An analogue output is required to control the duty ratio of the PWM signal. The voltage varies from 0- 2.5 VDC and is governed by the outcome of the control procedure. The control uses DAC0 within the microcontroller package and provides the signal to the oscillator circuit.

5.5.2.2 ADC

The microcontroller samples the analogue voltages that represent the power supply operation. The analogue values are used for control and monitoring purposes. Internal operations of the analogue inputs are carried out in the background at a set frequency initiated by timer overflows. The detailed operation of ADC inputs is covered in section 3.2 ADC Conversion.

5.5.2.3 Digital Inputs

An interlock is connected to an external interrupt port of the controller and triggers interrupt an routine once the interlock switches low. The interrupt routine immediately shuts down the system and activates a software latch that does not allow the power supply to be restarted until a specific instruction is given. Once the hardware has been confirmed to have been shut down the control transmits fault details to the overall controller that then continue transmitting telemetry.

5.5.2.4 Digital Outputs

The microcontroller outputs three general digital outputs. The first is the on/off control to the bridge that is connected with logic that selects either safe off operation or the switching sequence from the bridge oscillator. The second output pin is the interlock to the motor driver controller. The signal is high when the power supply is operating with the steady state and is used by the motor controller to identify when the controller power supply is ready. The third digital output is used to generate the PWM control signal to the IGBT drivers in the capacitor draining circuit.

5.5.2.5 Communication

The microcontroller responsible for the hardware control of the power supply communicates with an overall system controller. The communication channel is operated using the RS232 serial communication standard. RS232 serial communication was used for the application because it is a standard communication protocol for both microcontroller and computers. The operation of the serial communication is explained in section 3.3 Communication.

CHAPTER 6 MOTOR DRIVER MODULE

The motor driver developed is to maintain the smooth operation of the induction motor which was chosen for the research prototype. The module is to operate from commands received from the system controller and then achieve the desired action by the monitoring and controlling of the hardware. The electric propulsion drive is to replace conventional ICE powered vehicles. If users are to accept the change the EPD is required to operate in a similar manner to ICE powered vehicles. An operator of an ICE powered vehicle controls the power output from the motor by the use of a throttle device that increases or decreases the power. The change in the motor power has a primary effect in that the torque produced from the motor is changed and this torque change has a lead on effect in the change of rotational velocity. The throttle device is typically used as a speed adjustment depending upon the load however the operation is changing the instantaneous torque.

6.1 Investigation into possible control methodologies for induction motors

The material from the investigation into power electronics demonstrates the wide range of control philosophies available that could be used for the motor driver module. This section will demonstrate the exploration of the possible methods for operating the induction motor as required for the research.

6.1.1 Control methods

The control objective for any electric motor can fall between the parameters of either speed or torque control. Each objective of control has a wide range of methods that aim to improve the performance or cost. The investigation into control methods demonstrated some of the research direction and the outcomes.

6.1.1.1 Speed Control

The objective of speed control is to maintain a constant angular velocity of the rotor independent of torque applied to the rotor. This is common for industrial applications such a driving pumps or conveyor belts.

6.1.1.2 Torque Control

The objective of torque control is to provide constant torque output from the rotor independent of the angular velocity. The difficulty of torque control with induction motors is that the measure of torque produced is not a simple relationship and requires an estimation and then corrective control.

6.1.2 Control Approaches

6.1.2.1 Scalar

Scalar control is the traditional approach that involves basic processing requirements by monitoring the rotor angular velocity and then changing the stator frequency. The controller produces the frequency for the stator supply and keeps the volthertz ratio constant by the use of a PWM switching operation.

6.1.2.2 State Vector

State vector is a modern control approach that has became available with the increase in digital processing power. Individual phase voltages and or currents are individually sampled and combined with the angular position of the rotor in state vector control to model the magnetic flux densities. These new approaches have demonstrated an improvement in stability and transient response of the motor operation however they require complicated mathematical processing[56],[57], [58].

6.1.2.3 Control Options

State vector control methods are limited to FPGA(field programmable gate array) or DSP(digital signal processor) implementations with the need for flash converters to gather sensor values at a high sampling rate. Using FPGA or DSP devices was not favoured for the development of the electric drive system because of the investment in time and facilities availability. Investigation into state vector control shows that many experts focus entirely upon the research using direct torque control (DTC). The integration of DTC methods would require extensive research and development outside original scope of this research. At this stage a lesser performing controller can be considered adequate for this research objective.

6.1.3 Electric Drive Control Investigation

The decision was made to investigate options of torque control using traditional scalar techniques that would not require as much time invested to develop compared to producing a state vector method.

6.1.3.1 Change in Angular Velocity

The initial option investigated refers to the first principles of mechanical power, torque and inertia. The mechanical power output from a shaft is a product of the shafts angular frequency and the applied torque. Rearranging this basic principle would mean that torque can be found depending upon the power output and the current angular frequency. If the induction motor was assumed to be 100% efficient or constant with respect to angular frequency then sampling the electrical power supplied to the motor and the shaft velocity would give the controller a value of the torque produced. This approach is difficult to implement as the efficiency of the induction motor depends upon a range of different variables, two of which are the angular velocity of the rotor and the stator supply frequency.

$$P = \omega \times \tau \tag{6-1}$$

P – Rotational mechanical power[W]
ω – Angular velocity of rotor[rads^{-1}]
τ – Torque from rotor[Nm]

As the torque could not be measured directly or be formed by a linear equation using the available sensors, the option of relating the angular acceleration of the rotor to torque was considered. The first principle equation for torque gives the relationship between τ_{net} and ω_{rotor} for first order systems with only an inertia load.

$$\tau_{net} = \alpha \times \iota + \tau_{load} \tag{6-2}$$

T_{net}- Net torque from rotor[Nm]
T_{load}- Torque from load[Nm]
a- Angular acceleration of rotor[rads-2]
l- Interia of rotor[kgmrads-1]

If the controller was to operate a system and the load was purely an inertia load then the calculation of the angular acceleration would give an accurate estimate of the torque. Applying the motor to a real world propulsion drive would produce an equation giving a high order load equation. Equation 6-2 would be unreliable in a practical application if any considerable correlation actually exists. Another problem with using the angular acceleration of the rotor as a means of determining the controller correction is the increase of power output required as the angular velocity increases. The problem is that the motor is unable to produce the same rate of acceleration at high angular velocities. Maintaining the same acceleration would require ever increasing torque outputs that is not realistic.

6.1.3.2 Slip Frequency Control

The second investigated option was to control the torque output from the motor based upon the slip frequency[59]. The measure of slip is given by Equation 6-3. A value of 0 indicates that the rotor is at synchronous speed with the stator frequency. A value of 1 represents the rotor is stalled.

$$s - \frac{n_s - n}{n_s} \qquad (6\text{-}3)$$

s- Slip Rate

n_s- Synchronous speeed[rads^{-1}]

n- Rotor speed[rads^{-1}]

To control the torque output from the motor the controller changes the slip rate between the breakdown torque value and the synchronous frequency. Adjusting the slip frequency allows the controller to provide torque control between the minimum and maximum available for any angular velocity.

6.1.3.3 Chosen Control Method

Mentioned at the start of this chapter is the requirement for the electric drive system to give the impression of operating in the same manner as the current technology of ICE powered vehicles. An operator who is familiar with an ICE powered vehicle is aware of the change in available torque at different velocities. The throttle position in an ICE powered vehicle effectively controls the minimum and maximum percentage of torque that is available for the current linear velocity. Comparing the angular acceleration and slip frequency control methodologies, only the slip angle control has the same response as current ICEs.

6.2 Motor Driver Module Design

The electric drive system uses a multilayer control approach to direct the hardware to the desired operation. The electric motor operation is controlled overall by a PC system level controller that decides upon the required operation of the motor and transmission modules with the objective of acting in the manner the operator requested. The system controller is to calculate the desired torque response of the motor from the "throttle position" and then communicate the desired response to the microcontroller embedded in the motor driver module. The microcontroller using the given torque command attempts to maintain the desired hardware operation by adjusting the slip rate using a predictive control algorithm. The microcontroller within the module has the primary tasks of controlling the motor as requested and keeping the module in a safe operation. Secondly, the controller provides telemetry about the operation of the module and provides warnings to the overall PC based system controller. Figure 6-1 displays the layout of the control system used for the motor driver module.

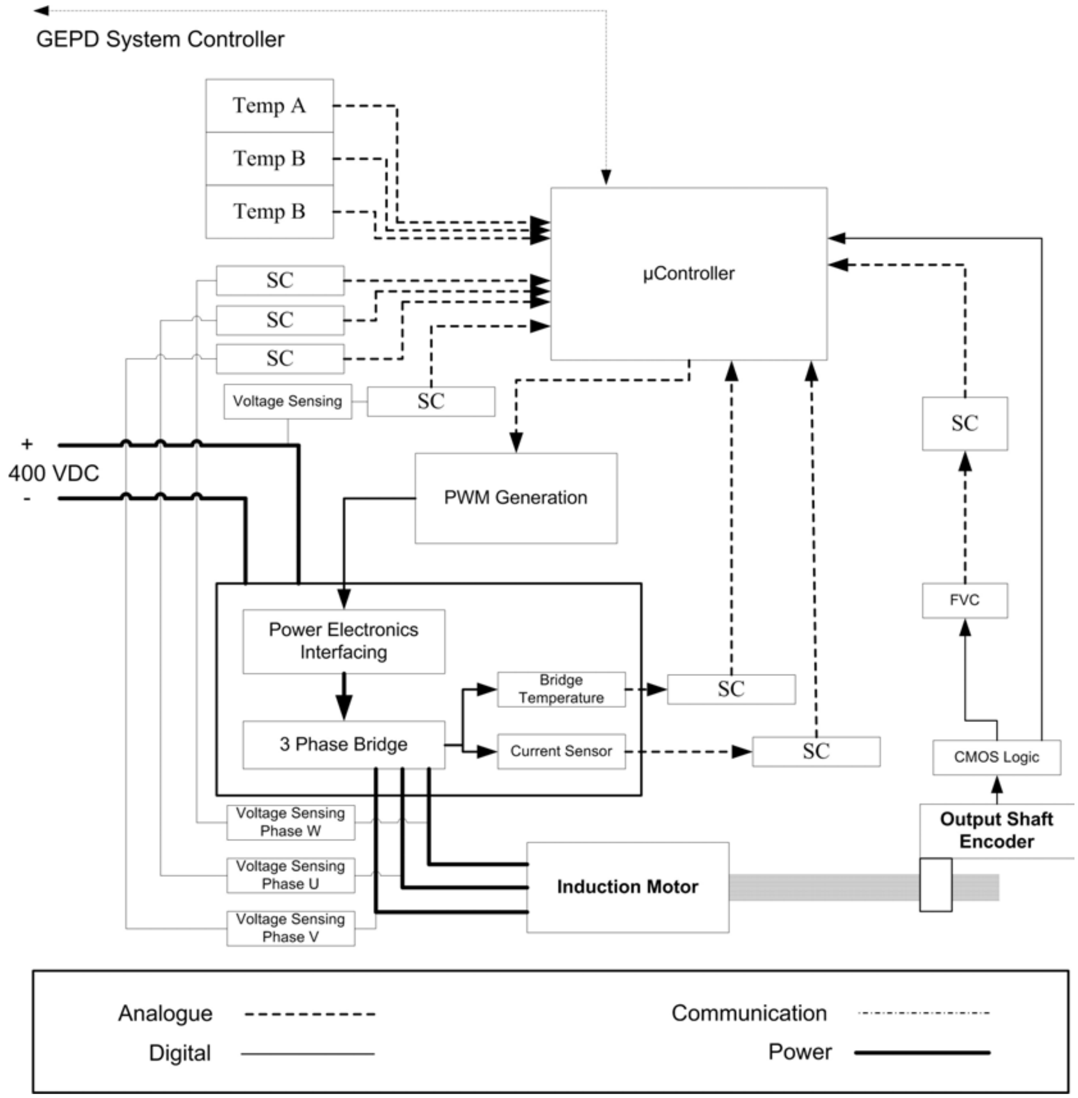

Figure 6-1 Embedded Motor Driver Control System.

The module is supplied with a 400VDC input from the power supply; the objective of the module is to control the operation of the three phase bridge to produce an appropriate 3 phase AC supply to the induction motor. The primary objective of the hardware control is to maintain the desired slip frequency of the motor. This is done by controlling the switching frequency of the bridge that feeds the motor. Using a scalar control technique requires that the volthertz ratio of the motor is kept constant to avoid the saturation of the winding cores. To maintain a constant volthertz ratio the RMS(root mean square) voltage of each phase is required to be in proportion to the frequency of the supply. The control of the individual IGBTs within the bridge is determined by the stator supplied frequency and the volthertz requirement. The investigation into the control of the power supply in section 5.3 identified that the Silab microcontroller requires external hardware circuits to achieve the desired frequencies. The switching of the inverter is more complex than that of power supply. The volthertz control of induction motors can fall into two common methods.

- Equal Pulse PWM
- Sine generated PWM

6.2.1 **Equal Pulse PWM**

Equal pulse PWM is the simpler method and is the most common in generic applications that require a PWM signal. The PWM technique was used for the switching of the power supply. Equal pulse PWM signal produces a constant duty ratio from the controller or oscillator circuit that controls the average voltage output. As the equal pulse PWM controls only the average voltage and not the instantaneous voltage a separate method of generating the switching of the bridge is required. The simplest approach of produce the three phase wave output is to use a six step inverter. The six step inverter has six switching states that control the generation of each phase at 120° of separation. The induction motor for the device is to be connected using a wye configuration of the phase windings. The diagram showing the switching sequence is shown in Figure 6-2.

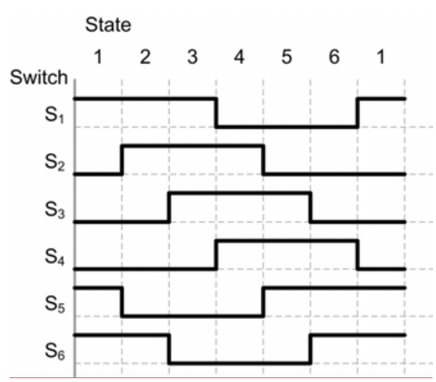

Figure 6-2 Switching pattern for a six step invert.

Using the wye configuration of the phase windings compared to delta gives the advantage of producing a voltage divider circuit through the motor and the resulting voltages through the phase windings closer matched a sine wave. The wye configuration produces a higher power factor.

The resulting phase voltages are shown in Figure 6-3

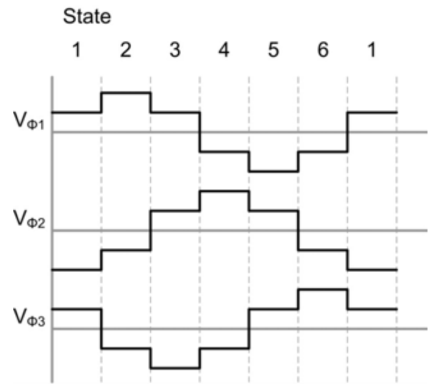

Figure 6-3 Phase voltages during the different states of the six step inverter.

Generating the switching sequence requires knowledge of the prior state and therefore necessitates the inclusion of memory in the circuit design.

6.2.1.1 Hardware Switching

Two possible fully discrete hardware options were considered that used a counter to store the current step from 0 to 5. The first option considered was to use discrete logic ICs and establish the necessary logic equation for each IGBT in the bridge using the counter as the input. This was quickly ruled out because of the complexity and the number of ICs that were likely to be required. The second option was to replace the discrete logic ICs with a SPLD(simple programmable logic device). This would allow the integration of further digital inputs that are required to produce the PWM, on/off control and interlock control within a single IC. The problem with either of the full hardware implementations was that the microcontroller was still required by some means to control the counter hardware. A simple method would be to provide the counter with a digital output from the microcontroller and use that input to cycle through each step. Generating the step changes on the microcontroller is not a processor intensive task as the maximum frequency of changing the output pin is 360Hz (60Hz × 6 steps).

6.2.1.2 Integrated Microcontroller and Hardware Switching

Given that the microcontroller would be required to interrupt for each step of the six step inverter, the counter hardware and an element of the logic equations could be replaced by a port output from the microcontroller without any detrimental effects. Using six output pins from the microcontroller would reduce the complexity of the hardware with no reduction in performance because the timing interrupt would operate at the same frequency. External hardware would still be required to generate a PWM signal, on/off control and interlock as these signals are to operate at high frequency for providing an external override in case of a controller fault.

Using the individual microcontroller pin outputs to control each of the IGBT would require only a simple logic equation to be produced in hardware.

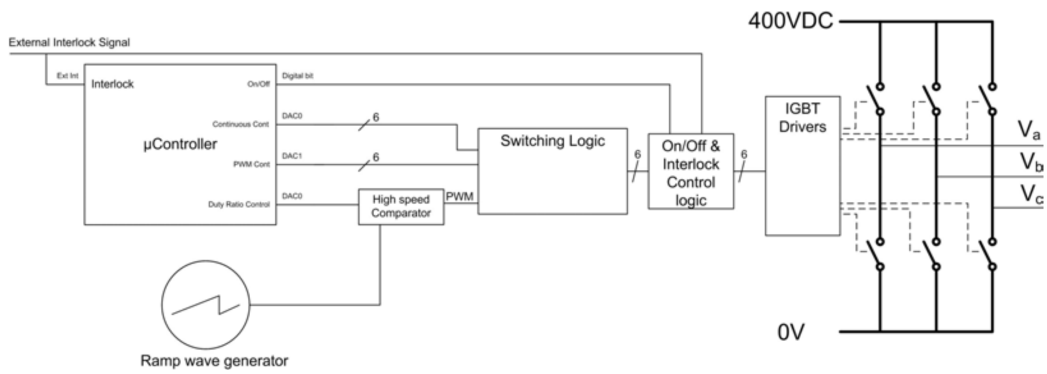

Figure 6-4 Layout of control hardware using discrete logic ICs.

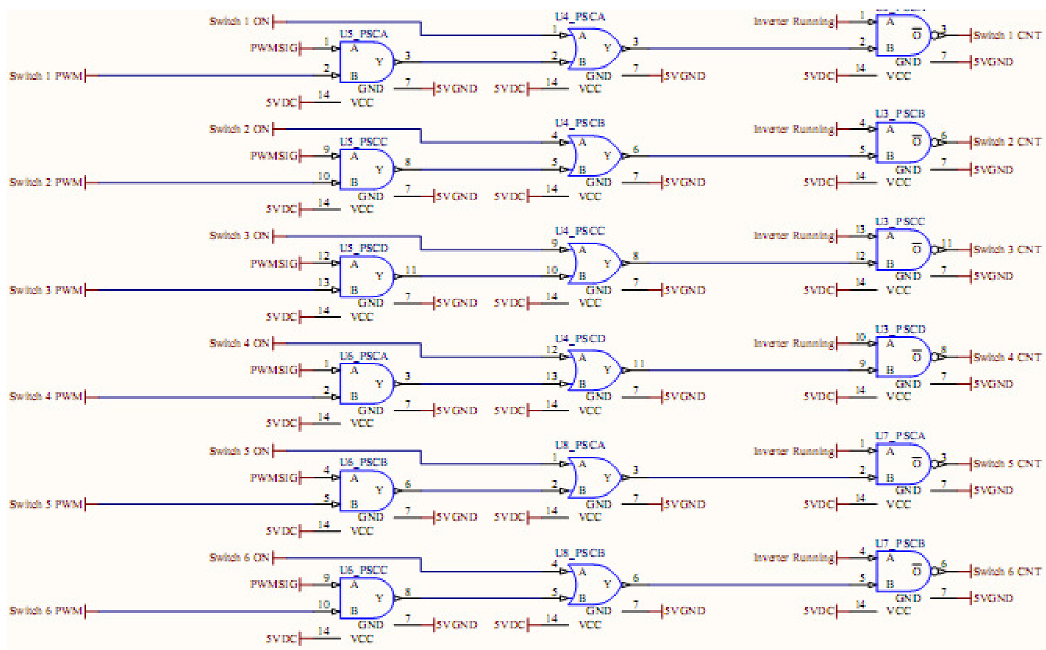

Figure 6-5 Logic arrangement to generate the switching logic block shown is Figure 6-4.

Using a SPLD instead of discrete ICs means the physical board design is made simpler by reducing the required number of ICs and data lines. The number of outputs from the microcontroller can be reduced from 7 to 4 digital pins.

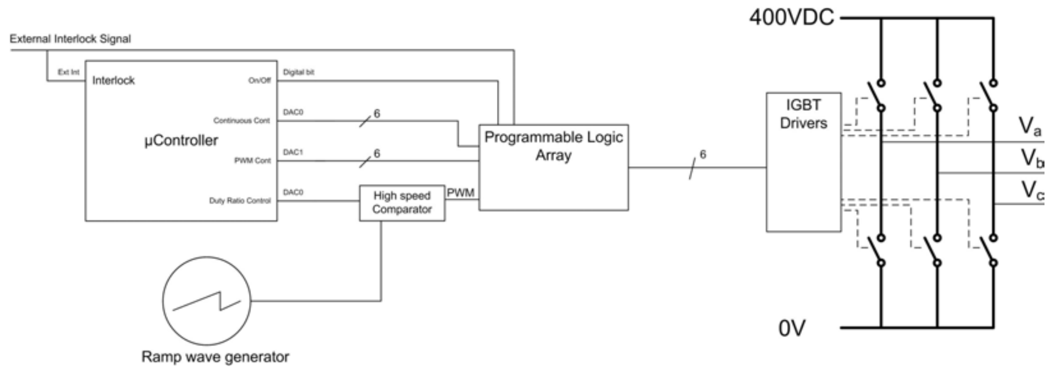

Figure 6-6 Layout of control hardware using simple programmable logic array.

6.2.2 <u>Sinusoidal Generated PWM</u>

Sinusoidal PWM signals change the duty ratio of the modulation throughout the period of the waveform. The manipulation of the duty ratio during the period allows the instantaneous voltage to closer match a sinusoidal waveform and therefore reduce harmonics that cause energy loses in the form of heat, audible noise and generating EMI. A simple method of producing sinusoidal modulation would use the DAC outputs from the microcontroller and using a timer to cycle through a mapping of a sinusoidal waveform. The waveforms can then be compared with a high frequency triangle waveform generator in hardware to create the sinusoidal PWM signal. The difficulty with using sinusoidal modulation compared to equal pulse is the requirement to generate three sinusoidal waves to be used in the switching.
Generating the sinusoid wave forms with the internal DAC has two problems.

- Reliable generation of three analogue sinusoidal waveforms.
- Negative effects from the interrupt request on the control algorithm.

6.2.2.1 Generating Three Individual Phases

To generate the switching for each phase the microcontroller is required to produce three waveforms with each 120 degrees out of phase. As the microcontroller is only capable of producing two analogue outputs at least one of the phase control voltages is required to be produced from external hardware. One option is for the hardware to generate the third phase by using the property that the three phases sum to zero. Another option is to generate all three phases separately and the frequencies all controlled by a single DAC. Figure 6-7 and Figure 6-8 show two layouts of possible hardware to generate three sinusoidal waveforms required.

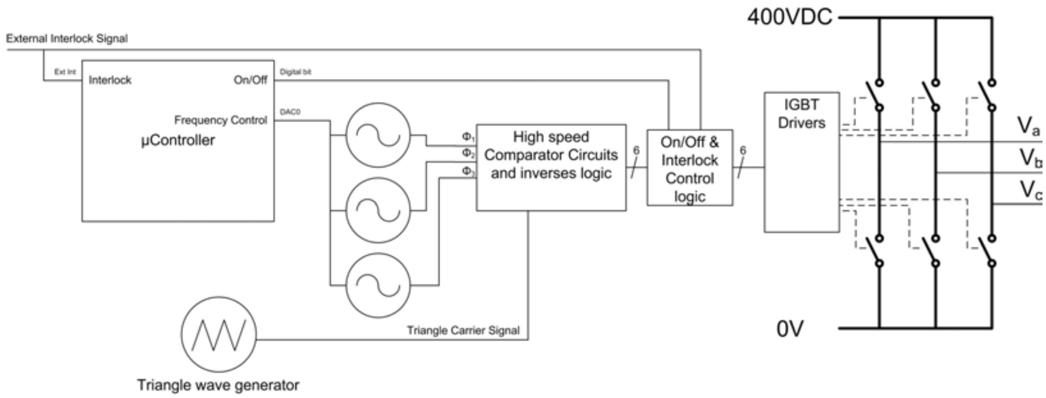

Figure 6-7 Layout of controller using external sine wave generators.

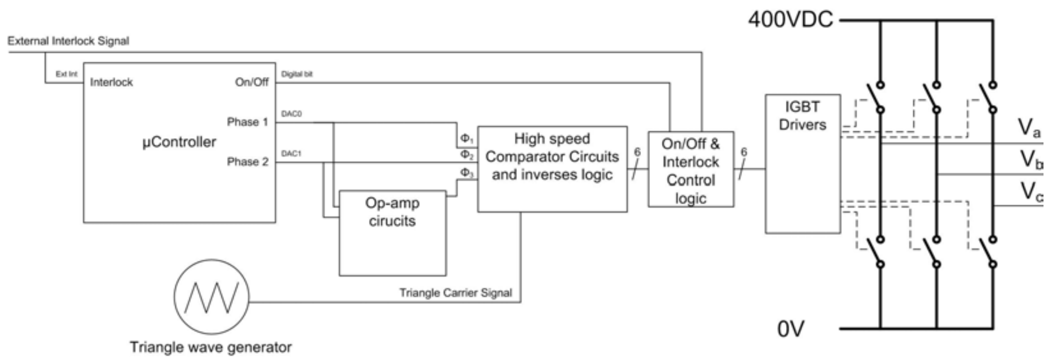

Figure 6-8 Layout of controller using the internal DAC to generate two of the required phase and a third produced by summing circuit.

6.2.2.2 Interrupt Frequency

The second problem with producing a sinusoid PWM signal is the regular occurrence of the timer interrupt routines used to form the sinusoidal output. The timer interrupt required to complete the task of changing the DAC outputs was estimated to be a calculation intensive procedure. The routine would need to work out the current angle of each phase and then scale and translate the mapped sinusoidal to keep the volthertz constant and minimise memory usage. The interrupt routine was considered to possibly involve 50 to 100 assembler level instructions. Before the controller was fully developed a safe interrupt request frequency was estimated as 1 kHz. Figure 6-9 and Figure 6-10 show the resolution and the resulting quantisation errors for the minimum and maximum stator frequencies of 10 and 60Hz.

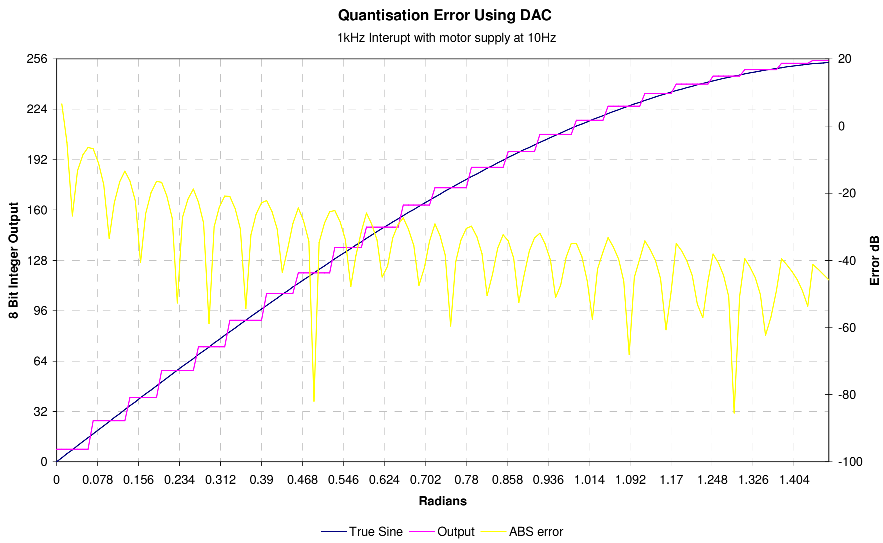

Figure 6-9 Theoretical resolution of the sinusoidal output from the DAC output and corresponding quantisation error when supplying a motor with a 10Hz modulation at fixed interrupt rate of 1 kHz.

Figure 6-10 Theoretical resolution of the sinusoidal output from the DAC output and corresponding quantisation errors when supplying a motor with 60Hz modulation at fixed interrupt rate of 1 kHz.

6.2.3 IGBT Hardware

The motor available for the research is a small 4 pole 400V 180W induction motor. The small power output of the motor allows the use of an IC that integrates a three-phase IGBT bridge with the power electric drivers and protection devices. The IC chosen is the IRAMS10UP60B produced from International Rectifier. The IRAMS is designed for low power AC motors and removes the need to develop any power electronic circuits. The device receives CMOS voltage level digital signals to control the hardware switching and provides different feedbacks and internal lockouts to protect the device. The device provides analogue voltage outputs representing the current draw and the temperature of the device in addition a digital signal provides indication of a fault. The schematic of the IRAM module for the PCB design can be seen in Figure 6-11.

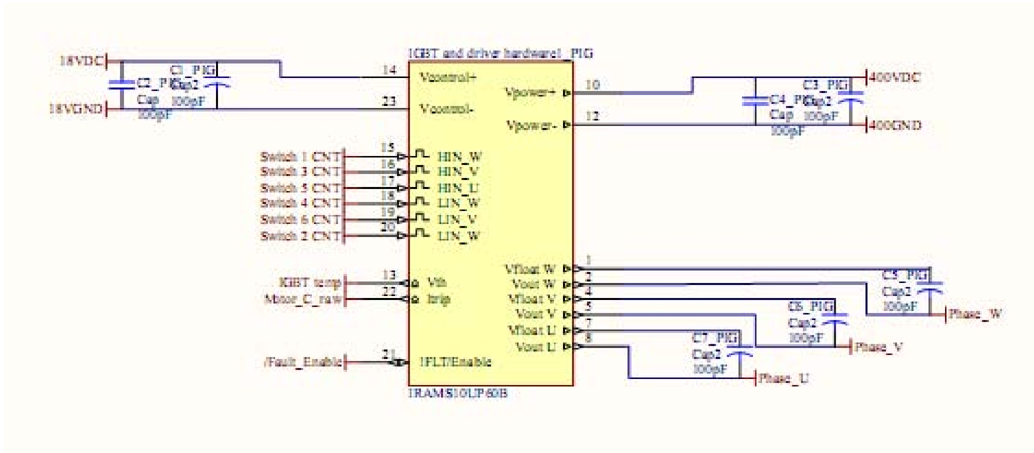

Figure 6-11 Physical configuration for three phase bridge operation.

6.2.4 Microcontroller Inputs

The microcontroller is required to collect operational information about the motor to produce a closed loop control system. Scalar control has been selected as the control method because of the limited processing capability of the available microcontrollers. The scalar control is to work primarily by controlling the slip rate that will govern the torque output. The two most direct variables to measure the slip rate are the angular velocity of the rotor and the frequency of the stator current. The controller is not required to sample the stator supply frequency because the value is already known from the previous control response. To provide a measure of the slip rate the controller is required to sample the frequency of the rotor. This value minus, the known stator frequency will produce the slip rate. For operation without disturbance, the only input required to the microcontroller is the sensor that specifies the angular velocity of the rotor. The slip rate can be determined by the consequential Equation 6-4, once the angular velocity value has been sampled.

$$s = \frac{\omega_s - \omega_r}{\omega_s} \qquad (6\text{-}4)$$

s- Slip rate

ω_s- Stator supply angular frequency[$rads^{-1}$]

ω_r- Rotor angular frequency[$rads^{-1}$]

The use of only instantaneous readings taken under varying load conditions makes control of the slip rate difficult; the result is the control will always lag behind the required response. Further control variables are to be used to form a predictive control method to improve control of the motor during varying loads. Using the change in slip rate with respect to time as extra control variable provides the controller with a means of estimating the slip rate in the future. The current draw from an induction motor does not give a direct indication of the torque the motor is producing; it does have a small correlation and can be used as a minor aid in the estimation of the future slip rate.

6.2.4.1 Required Control variables

State	Rotor velocity(rads^{-1})	ΔRotor velocity (rads^{-1} sample^{-1})	I_{total}(Amps)
Running Motor	-380 - +380	-720 - +720	0-6
Soft Start	-380 - +380	-720 - +720	0-6

Table 6-1 Control variables for the controller to generate slip frequency.

A directional input is required because the motor is capable of operating in both directions of rotation. The change in rotor angular velocity with respect to time could theoretically change from -760 to +760 within one sampling period. Practically sampling (at a rate of 300 Hz), the size of the external torque that would be required would be so large that the rotor would fail mechanically from torsion strain. The values given in the range of possible values for Δrads^{-2} are likely to be many times larger than needed as the inertia of the rotor alone would require an enormous amount of torque. The range of the possible currents is given from the datasheet of the IRAMS10UP60B.

6.2.4.2 Monitoring Inputs

To provide monitoring of the motor operation further information is gathered from the module and used for telemetry and fault detection.

The analogue inputs used for monitoring and fault detection are listed below

1. Line Voltage.
2. Phase W,V and U voltages.
3. Motor driver module temperature.
4. Motor temperatures 1, 2 and 3 placed though the motor.

Variable	*Variable Unit*	*Sensor Type*	*Input Conversion Method*	*Range*	*Sampling Frequency*
Rotor angular velocity	*Rads*$^{-1}$	*FVC*	*scale*	*380-420 V*	*300Hz*
Line current	*A*	*Driver module output*	*Scale*	*0-6A*	*300Hz*
Line voltage	*V*	*Voltage divider*	*scale*	*0-420V*	*4Hz*
Phase W voltage	*V*	*Hall effect sensor*	*Scale*	*0-420V*	*4Hz*
Phase V voltage	*V*	*Hall effect sensor*	*Scale*	*0-420V*	*4Hz*
Phase U voltage	*V*	*Hall effect sensor*	*Scale*	*0-420V*	*4Hz*
Driver module temperature	*°C*	*Driver module output*	*Scale*	*0-150 °C*	*4Hz*
Motor front temperature	*°C*	*Thermistor voltage divider*	*Scale*	*0-120 °C*	*4Hz*
Motor middle temperature	*°C*	*Thermistor voltage divider*	*Scale*	*0-120 °C*	*4Hz*
Motor rear temperature	*°C*	*Thermistor voltage divider*	*Scale*	*0-120 °C*	*4Hz*

Table 6-2 Required inputs the controller.

Individual phase voltages are sampled for a means of monitoring the condition of each phase rather than instantaneous voltages. Sampling at a frequency less than the operational frequency should produce signals that represents the RMS voltage. If a difference occurs between the phase voltages it should indicate that a phase has been damaged.

6.2.4.3 Rotor angular velocity

A measurement of the rotor angular velocity is required for the controller as identified above in section 6.2.3 . The angular velocity is sensed using an encoder that produces a tachometer pulse output to the signal conditioning circuits. The simplest method of processing a tachometer pulse is to supply the pulse to an external interrupt pin on the microcontroller. The microcontroller measures the time difference between the pulses thereby determining the angular velocity of the rotor. The problem with using the external interrupt approach is the disruption the interrupt routine has on the control algorithm. To avoid the disruption to the microcontroller an external frequency to voltage converter (FVC) was used to produce an analogue voltage which measures the period of the tachometer pulses. FVCs can be purchased as an IC that require only a simple RC circuit to produce the frequency to voltage ratio. The analogue value is then produced within the package and available from an output pin. Using the FVC provides the scalar value of the angular velocity of the rotor; the microcontroller requires a directional input to attain a vector representation of the angular velocity. The direction of rotation is determined using the phase between the channels using quadrature encoding. A straightforward logic operation can produce either 0 or 1 to express the direction of rotation to an input of the microcontroller. Combining the two channels from the encoder doubles the pulses to the FVC and therefore doubles the resolution used to generate the analogue value to the microcontroller.

6.3 Microcontroller Details

The microcontroller selected for control is the Silab 8051F020 and is integrated with the available development board. This section will provide the details and the development that is required for the specific task of the controlling the motor driver module. The general software operation for the microcontroller is explained in CHAPTER 3 and will not be covered here. The microcontroller receives commands that set the desired torque between zero and the maximum range for the current instantaneous velocity. The controller's physical objective is to maintain the slip rate of the motor to keep the torque at the desired point. The controller adjusts the slip rate by controlling the frequency of the stator supply which is determined by a multiple input single output PD + P fuzzy logic controller.

6.3.1 Control Algorithm

The controller has two possible modes of operation. The normal operational mode is applied when the rotor is turning at an angular velocity that allows the stator current to be operating at least 10 Hz and the relevant slip frequency to be less than the breakdown torque slip frequency. The soft start control mode of the motor operates the slip frequency in the pull up slip frequency range because the efficiency of operating the stator frequency at less than 10 Hz.

The general summary of the operation of the control algorithm is listed below.

1. Process communication buffer and identify any command changes.
2. Process analogue input values.
3. Calculate consequential variables from analogue inputs.
4. Decide upon the mode of operation based upon the command received and the rotor angular velocity.
5. Begin fuzzy logic control.
    a. Fuzzify the input values.

   b. Calculate the rule base.
   c. Defuzzify the output fuzzy value.
6. Change the frequency of the six step inverter to the current rotor angular velocity plus the control value from the fuzzy controller.
7. Send telemetry if required

The controller was developed to use equal pulse PWM control to maintain the volthertz ratio and a six-step inverter to produce the frequency of the stator supply. The physical arrangement of the controller was intended to integrate with the prototype hardware that was described in section 6.2 using discrete logic ICs.

6.3.2 Mixed Signal Microcontroller Requirements

To interface the microcontroller with the hardware the following internal devices are required.

- Single 12 bit DAC0 output to control PWM DR
- Six 12 bit ADC0 inputs
- Four 8 bit ADC1 inputs
- Two external interrupt
- Additional two digital inputs
- Seven digital outputs
- Serial communication port

6.3.2.1 DAC

An analogue output is required to control the duty ratio of the PWM signal. The voltage varies from 0- 2.5 VDC and is governed by the frequency of supply to the stator current. The control uses DAC0 within the microcontroller package and provides the signal to the oscillator circuit.

6.3.2.2 ADCs

The microcontroller samples the analogue voltages that represent the operation of the motor driver module. The analogue values are used for control and monitoring purposes. Internal operation of the analogue inputs is carried out in the background at a set frequency initiated by timer overflows. The detailed operation of ADC (0 and 1) inputs is covered in section 3.2

6.3.2.2.1 ADC0

ADC0 has a 12 bit resolution and is used as the ADC device for converting the control variables. ADC0 is further used to monitor the voltages of the line and phases as using the 8 bit ADC1 would have a resolution error greater than 1V per division over the 420V range. ADC0 is used to sample the following inputs.

- Rotor angular frequency.
- Line current.
- Line voltage.
- Phase W, U and V voltages.

6.3.2.2.2 ADC1

ADC1 is used to sample the analogue representation of the temperatures throughout the module. ADC0 has up to 8 possible channels to be sampled. Since the module requires more than eight channels therefore the ADC1 is required to be used. The temperatures are sampled using the lower resolution ADC1 because the accuracy of the reading is not vital and the quantisation error of 0.4°C is adequate.

6.3.2.3 Digital Inputs

The microcontroller uses four digital pins as inputs in total. Two of the pins are used to trigger external interrupt routines for fault shutdowns and the remaining two are used as general I/O pins.

6.3.2.3.1 Interrupt Pins

The interrupt pins are used for fault detection to immediately shut down the operation of motor supply module. One external interrupt (ext 6) is used to connect to the overall propulsion system's interlock circuit. The second external interrupt (ext 7) is used to connected to the fault pin from the bridge IC. The bride IC switches the fault low and turns off the bridge when the internals detect a fault. The fault initiates the interrupt routine because the controller needs turn off the bridge within 20ms or else the module resets and may cause further damage.

6.3.2.3.2 General Pins

A digital signal is supplied from the power supply module to determine when the PS output is within the correct range. The second digital input is supplied from the logic circuit that determines the direction of the rotor rotation.

6.3.2.4 Digital Outputs

The thirteen digital outputs are responsibly for three different operations. A single pin is used as an on/off control signal for the operation of the bridge. When the signal is high the bridge is allowed to operate from the switching sequence. If it is low, the bridge switching sequence is overridden and all phases are tied to 0V. The remaining twelve pins are used for the control of individual IGBTs within the bridge; each is dedicates two pins. One pin activates the IGBT for continuous conduction and the second activates the IGBT for PWM conduction.

6.3.2.5 Communication

The microcontroller responsible for the hardware control of the power supply communicates with an overall system controller. The communication channel is operated using the RS232 serial communication standard. RS232 serial communication is used for the application because it is a standard communication protocol for both the microcontroller and PCs. The operation of the serial communication is explained in section 3.3

CHAPTER 7 TRANSMISSION MODULE

The aim of the transmission is to adjust the rotation ratio between the electric motor and the final drive of the vehicle. The purpose of including a transmission into the propulsion system, is to achieve the minimum and maximum possible torque output or power for any given vehicle velocity. This allows the power drain from the motor to be controlled rather than be fixed depending upon the velocity. The fundamental equation for rotating mechanical power though a transmission results in the relation shown by Equation 7-1

$$\eta \times Pi = \eta \times \omega_i \times \tau_i = P_o = \omega_o \times \tau_o \tag{7-1}$$

P_i = Input shaft power[W]

P_o = Output shaft power[W]

ω_i- Input shaft angular velocity[rads-1]

ω_o- Output shaft angular velocity[rads-1]

τ_i- Input shaft torque[Nm]

τ_o- Input shaft torque[Nm]

n- Transmission efficiency

A gear driven transmission physically connects the input and output shafts by a fixed ratio that can not slip without a failure. The effect of the fixed ratio is that the efficiency of the transmission has no effect on the relationship between the input and output shafts. The relationship between the input and output rotational velocities can therefore be given by Equation 7-2

$$\omega_i = r \times \omega_o \tag{7-2}$$

ω_i- Input shaft angular velocity[rads-1]

ω_o- Output shaft angular velocity[rads-1]

r – Transmission ratio

As the angular velocity of the shaft is fixed, the torque output is reduced by the efficiency loss. Using Equation 7-1 and Equation 7-2 the equation for torque can be given by Equation 7-3.

$$\tau_o = \eta \frac{1}{r} \tau_i \tag{7-3}$$

τ_i- Input shaft torque[Nm]

τ_o- Input shaft torque[Nm]

n- Transmission efficiency

r- Transmission ratio

If a propulsion system was to operate with ideal componentry there would be no need for a transmission because the motor would be capable of producing the same efficiency for any angular velocity. This research is to investigate the addition of a transmission into the propulsion system because of two points of practical limitation of induction motors.

1. Real induction motors do not provide a efficiency of 100% and this efficiency depends upon angular velocity of the rotor
2. Keeping the volthertz ratio constant when using the scalar method of control produces the effect of fixed torque across the velocity range, not the fixed power output. This means that the possible power output from motor depends upon the velocity of the rotor.

The advantage of being able to change the ratio allows greater torque at low speeds or a reduction in power use at high speeds. High torque is achieved by increasing the motor velocity and therefore increasing the power output. The transmission then maintains the same instantaneous velocity to increase the torque to the final drive. Low power consumption is achieved at high speeds if the torque requirement is low which allows an increase in the transmission ratio. The increase in the ratio reduces the rotational velocity of the rotor decreasing the power consumption.

7.1 Mechanical Design Investigation and Options

From the investigation into the types of automotive transmissions available, two types were identified as being possibly suitable for the application. The two identified transmission were the automated manual variants and the continuously variable transmission type.

7.1.1 Automated manual transmissions

The automated sequential transmission is the arrangement of a traditional manual sequential transmission with an electromechanical system which selects the gear set to use. The common forms of automated sequential transmission are not entirely sequential because using controller operated actuators allows each gear set to be controlled independently. The basic layout of a sequential transmission is shown in Figure 7-1.

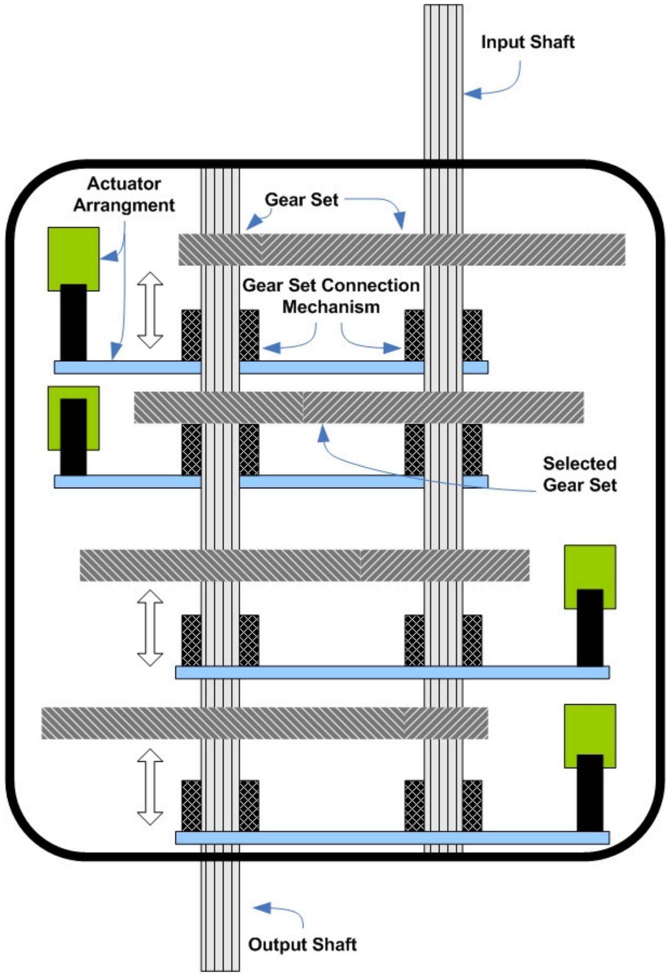

Figure 7-1 Layout of automated manual transmission.

The transmission consists of two parallel shafts with a variable number of gear sets. Each gear set has a different ratio and the selection of the particular gear set determines the ratio of the transmission. The research into transmissions outlines two methods of selecting gear sets. The two options are non synchronised and synchronised gear sets. Non synchronised gear sets can be ruled out because of the problems with the alignment of the gear teeth for the two gears to mesh without causing damage. The synchronised type is the most common in production automobiles because of their ease of use. The disadvantage of the synchronised type is the ability to withstand high torque. Mechanical failure from external torques is not considered to be a major design concern for this research so there is no disadvantage in the use of the simpler system.

The gear sets in synchronised transmission are fixed longitudinally to the shaft but not axially. This allows the individual gears on the shaft to rotate relative to the shaft and therefore allows the gear set to be constantly meshed.

7.1.1.1 Design Challenge

The AMT from a layout view simply consists of two shafts with a gear set arrangement. The most complicated and difficult feature of the transmission is the connection of the gear set to the shafts. To select the gear set a connector mechanism is moved to connect the rotating gear set to the shaft. Three locking mechanisms were considered as a result of the original investigation into automobile transmissions had been completed.

1. Dog clutch
2. Cone clutch
3. Zero shift/seamless shift technology

Dog Clutch

A dog clutch was the first type of locking mechanism used for synchronised transmissions. A dog clutch is a simple slider lock that is fixed axially to the shaft and is moved along the shaft longitudinally by some mechanical means. The slider has a meshing pattern that mirrors the pattern on the gear set allow the clutch is to interlock. A visual representation of the mechanism can be seen in Figure 7-2

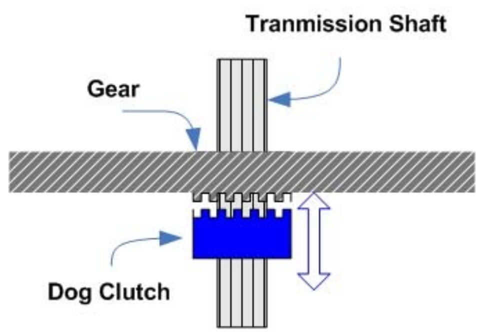

Figure 7-2 Simplified dog clutch.

The disadvantage of the dog clutch is the harsh engagement during the engaging or disengaging of the gear set. This harsh process is felt by the operator of the vehicle as a sudden change in speed. The harsh process produces high instantaneous torque strains on other mechanical parts of the gear train.

Cone Clutch

The cone clutch is the common method of fixing a gear set to the shaft in a "normal" manual transmission. The connection made between the gear set and the clutch is by two conical faces which engage under pressure and transfer torque using the friction generated by contact between the two surfaces. This removes the harsh engagement typical of the dog clutch, but reduces the transmissions torque capacity. The simplified operation of a cone clutch is show in Figure 7-3

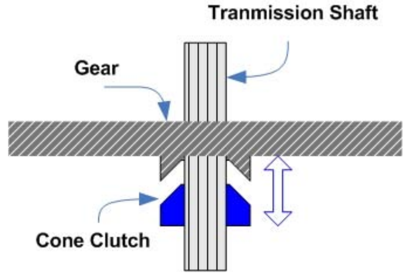

Figure 7-3 Simplified cone clutch.

Zero Shift / Seamless Shift Technology

Seamless shift technology is a recent advancement in transmissions which allows the period between gears and corresponding break in torque output to be minimised. This is made possible by mechatronic systems that control small solenoids (typically) that engage and disengage small ratcheting components that are around the clutch mechanism. These ratcheting components allow two gear sets to be connected softly to the shafts for a period to match the gear sets rotational velocities. This action allows instantaneous gear change without a period where the clutch is selecting neither gear set. The arrangement and operation of a seamless shift transmission is shown in Figure 7-4.

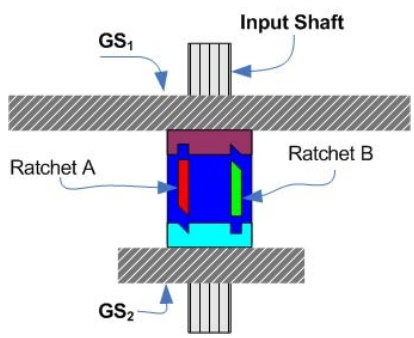

Figure 7-4 Seamless method of fixing gear sets to shafts .

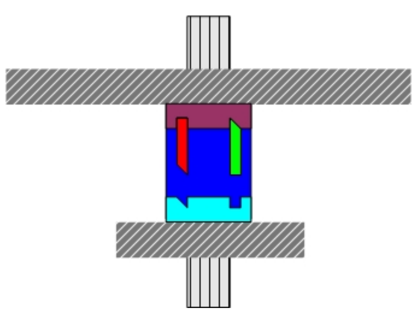

Figure 7-5 Seamless shift stage 1.

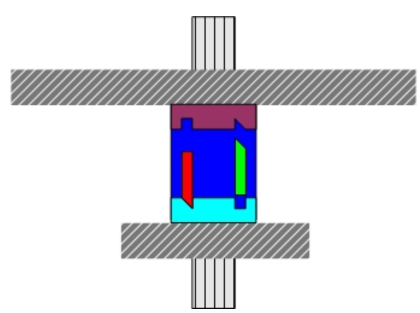

Figure 7-6 Seamless shift state 3.

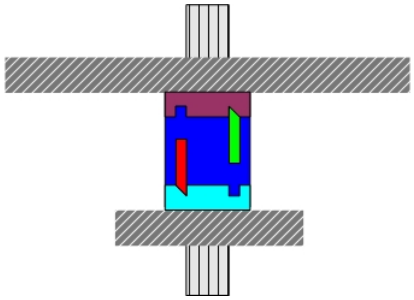

Figure 7-7 Seamless shift stage 2.

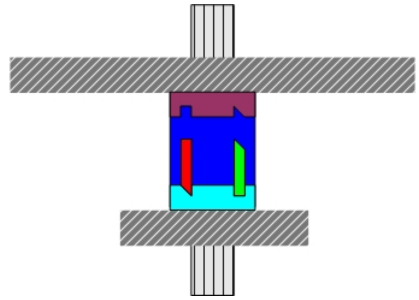

Figure 7-8 Seamless shift stage 4.

1. GS_1 is fixed to the shaft, GS_2 is free to rotate. Ratchet A and B are locked into GS_1
2. Ratchet B is still fixed to GS_1, Ratchet A moves to ratcheting position with GS_2.
    a. At this point GS_1 is fixed to the shaft
    b. GS_2 has torque applied and this brings GS_2 up to the same rotational velocity as GS_1. At this stage ratchet A is pushed back from connecting from GS_2 because of the angled face; this allows a torque to be applied to GS_2 to get to the correct speed but not lock the shaft. Avoiding locking two gears set is vital as this would cause irreparable damage of the transmission.
3. Ratchet A is moved to a ratcheting position slightly off GS_1, Ratchet B moves to lock with GS_2
    a. Fixed torque transfer is moved to GS_2.
    b. The shape of the ratchet means GS_1 ratchets during transition period.
4. Ratchet A is moved to fully connect with GS_2
    a. GS_2 is now connected to the shaft by ratchet A and B.

The difficulty with using seamless shift type transmissions is the complexity of the mechanical systems to be manufactured. The practical application demonstrated in motor sport has proven the unforgiving operation of the ratchets if the controller mis-times the operation and both shafts inadvertently become locked at once. Automobile manufacturers are slow to accept this technology because until now it is unproven in a production vehicle and the reliability problems that have arisen in motor sport applications.

7.1.1.2 AMT Conclusion

The best option for the prototype transmission is to fix gears sets axially with a simple dog clutch. The dog clutch has the benefits of being the simplest to operate, has a proven history of reliable design and provides for ease of manufacturing. The problem faced with the dog clutch method is the reliability issues from the harsh changes of torque and the impact felt by the user. As this is at the prototype stage, the reliability of the transmission is not a major concern. The harsh gear change experienced by the user could be a useful advantage during the early prototype stage because it makes the control problems more obvious and more difficult to solve in terms of control action. Applying the lessons learnt during the development of a dog clutch driven transmission should be able to be transferred to the cone clutch system at a later stage.

7.1.2 Continuously Variable Transmission

A continuously variable transmission is a type that theoretically allows an infinite set of ratios between a minimum and maximum value. The review initially carried out shows there are two common forms of CVTs that have been used on automobiles. The two practical options for possible use are variable diameter pulley (VDP) and the tordial systems. Both methods use friction as a means of power transmission and allow a continuous ratio change. Chapter 2.8 explains the operation of both types of transmission and the details will not be explained here.

7.1.2.1 Initial Consideration of CVT Methods

When evaluating the two possible CVT methods, VDP appears to provide a better solution in efficiency and reliability for mass production methods. In a basic prototype form both systems offer a poor efficiency with numbers given in the range of 80-90%. The conical system developed by Audi is shown to have an acceptable reliability and efficiency of approximately 94%. The efficiency of the Audi CVT is comparable with tradition valve operated automatic and manual transmissions that have approximately 90% and 96% respectively. The high efficiency shown by the Audi system has demonstrated that the VDP transmission is capable of an acceptable level of efficiency when designed correctly. The toroidal system in comparison has been a commercial failure because of the limitations of a low power throughput, low efficiency and poor reliably history.

7.1.2.2 Design Challenge

The VDP CVT system works by changing the effective diameter of the two belt operated vee pulleys. The effective diameter of the pulleys is modified by the longitudinal displacement between the two pulleys sections. As the pulleys are a vee belt design and the width of the belt is fixed, the belt is required to move up and down the radius to maintain contact.

The simplest approach from a theoretical point of view, is to move each pulley half individually therefore the four halves in total. The benefit of this system is that the longitudinal position of the belt remains constant and makes the system easier to visualise. The practical design and manufacturing application of the moving each pulley half individually increased the cost and complexity of the engineered design. The practical application of VDP CVT used by Audi and the majority of other prior attempts was to fix one half of each pulley pair and displace the moveable pulley half twice the distance. The advantage of this system is that the number of components is reduced by 50%. This reduction in component numbers provides benefits ranging from performance to economic constraints. The complexity of the system is reduced which therefore reduces the cost of the manufacturing by minimising the number of components and allowing simplification of the assembling process. The reliability of the system is increased because fewer components means a reduction in the sources of malfunctions. Fewer components reduce the likely hood of the system failing (product of all components reliably) and a simpler design means less compromises and a more robust manufacturing process.

Pulley Movement

Investigation into automobile versions of the VDP transmission demonstrates that production transmissions rely upon hydraulic systems to vary the displacement of the pulley section. This makes the system simple because of the reduction in components and controlled via variable flow and pressure. A hydraulic system was preferred to be avoided because use of such a power transfer medium would require another primary system to be developed and considered.

A possible simple method was discovered in some light vehicles that use a mass in the pulley to takes advantage of centripetal forces to move the displacement pulley depending upon the rotational velocity. A diagram illustration of how the system works is shown below in Figure 7-9.

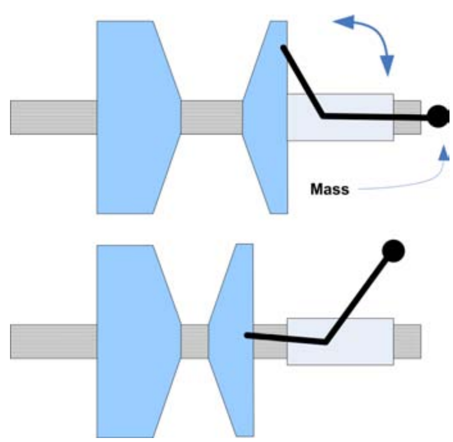

Figure 7-9 Centripetal force driven VDP CVT.

A similar method that used ball bearing races was found in competition go karts. No diagram is shown in this thesis, however the system works by having a bearing race path that forces the pulley to move depending upon the radial position of the ball bearings. The problem with the fully mechanical system is that the ratio depends solely upon the rotational velocity and a controller is not able to set a desired ratio.

Concepts for electromechanical actuated driven transmissions were investigated for possible practical solutions. The use of electromechanical devices such as solenoids and DC motors to produce mechanical force devices does not require any further primary systems and allows the controller to adjust the ratio unlike the mechanical systems investigated. The concepts investigated were judged on factors that had effect on the performance, cost and manufacturing requirements.

Double Shaft and Conical Power screws

The first option explored was the use of a power screw that fitted around the outside of the transmission shaft. The arrangement would produce the same effect as the hydraulic system by directly applying a longitudinal force to move the pulley half along the shaft. The arrangement of the power screw works by extending or retracting the inside collar of the device as the output side collar is rotated by some means of power. The envisioned conical system is displayed in Figure 7-10.

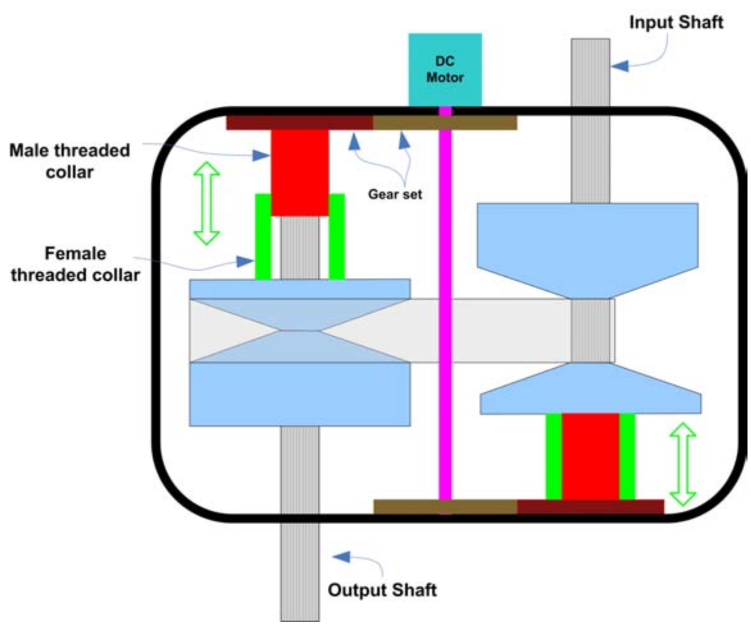

Figure 7-10 Pulley displacement by conical power screws.

The transmission is to work by having a power screw device on each transmission shaft that would adjust both pulley sets at the same time. The rotation power of the collar is to be produced by a single DC brush motor that connects to both outside collars by the means of a gear train. This concept was ruled unworkable for two reasons. Firstly it was considered unworkable because of the manufacturing difficulties to produce the power screw collars. The second problem is complexity of the drive train that would require a number of gears to attain the required displacement between the shafts and the relevant components that are needed for each gear.

Single Central Power Screw Solid Pulley Connection

Another option considered uses a single power screw between the two transmission shafts that connected the collar to the pulley halves. A DC brush motor connects to the power screw to provide a means of rotational power. The collar moves linearly along the power screw as the power screw rotates; the connection to the pulley halves moves the pulleys in and out. The diagram of the envisioned transmission is shown Figure 7-11.

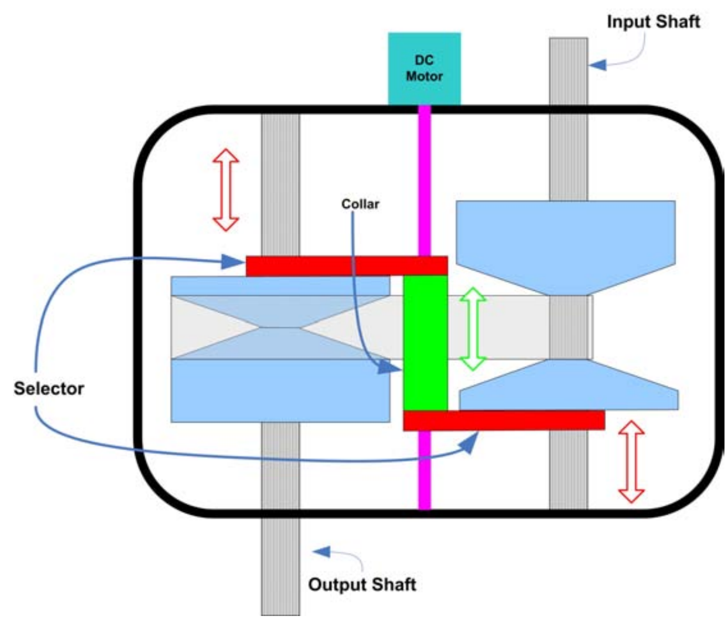

Figure 7-11 Pulley displacement by a single central power screw.

The concept in this form was ruled out because of the moments would act upon the collar as the force was applied to pulleys. Possible alternative configurations to reduce the moments acting upon the collar and selector were the use of linear bearings to provide guides on the outside of the pulley or the use of a pair of power screws on each side of the transmission.

Linear Bearing Support for a Single Power Screw

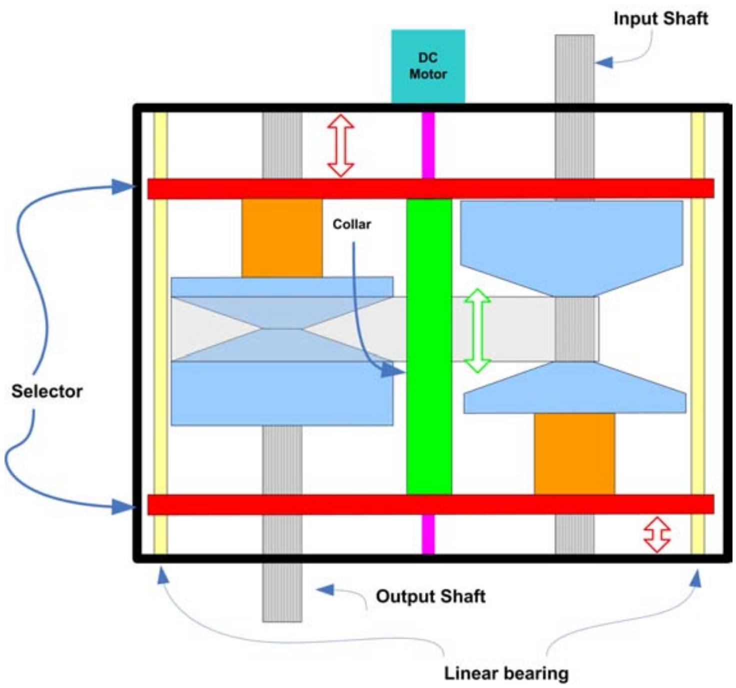

Figure 7-12 Pulley displacement with linear bearing support of a single power screw.

The possible configuration shown in Figure 7-12 using linear bearings was ruled out as the linear bearings shown would do little to reduce the moment on the collar and the bearings were likely to bind once the arms deflected due to load thereby deflecting the linear bearing track. Linear bearings were to be avoided because of the poor wear and reliabilty from contaminates on the friction surfaces.

Double Power Screws

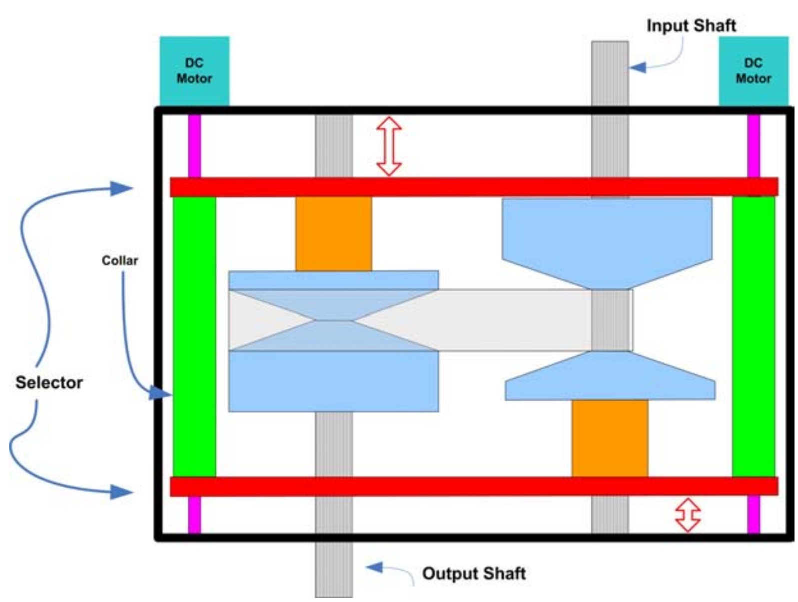

Figure 7-13 Pulley displacement with two power screws.

A complicated option was to add another power screw, collar and DC motor combination to the transmission. The configuration of power screws would be located either side of the pulleys. The power screws would act together to move the pulley in and out. Mechanically this arrangement would reduce the moments acting on the collar but would suffer from a large moment in the centre of the selector. The deflection of the selector would then deflect the power screw in a similar fashion to the linear bearing tracks. This deflection of the power screws could possibly be more destructive because of the hardened surfaces that would crack easier and stress concentrations from the geometry of the power screw. The complicated arrangement produces a high cost because of the increase in componentry and the added difficulty in manufacturing especially the tolerances required because of the parallel configuration of components.

Lever Operated Pulleys Activated by Power Screw

A simpler non linear method was considered that used a cantilever and motion ratio configuration to provide the linear motion for the movement of the pulley halves. The approach solves the mechanical problems faced by the linear motion methods mentioned above. The diagram of the cantilever configuration is shown in Figure 7-14.

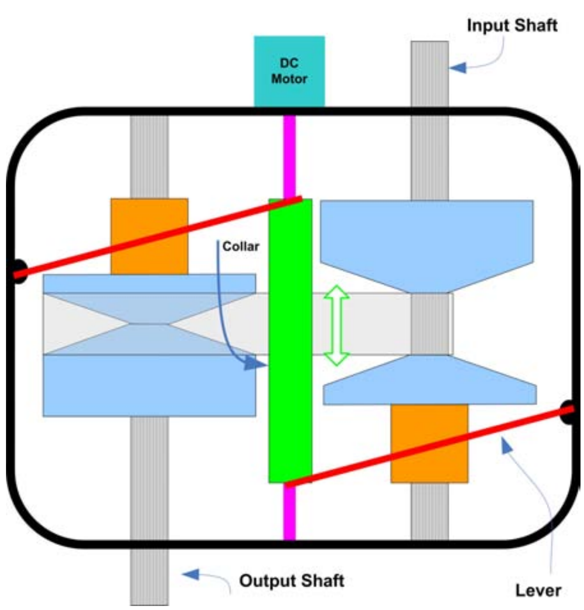

Figure 7-14 Pulley Displacement by cantilever.

The configuration still relies upon a central power screw and collar. However unlike the configurations explained above that have a fixed transverse connection to the rear of the pulley, the cantilever configuration uses a lever that rotates from a fixed hinge point on the case of the transmission. The lever is moved via the linear force applied from the power screw and provides a motion ratio gain to increase the forces available to move the pulleys along the shafts. This configuration provides a number of mechanical benefits compared to the other CVT concepts previously explored. The motion ratio gain by the lever requires less force (power remains constant) from the power screw to produce the same applied force to the pulleys. The lesser force applied via the power screw allows a weaker and cheaper design of the actuator system and casing. The use of a lever in the transmission removes the need for linear bearings which reduces the cost of component expenses, manufacturing tolerances and increases reliability.

7.1.3 Identified Solution

The CVT transmission was determined to be the preferred option when compared to the AMT. The CVT option was identified as a lower risk direction of development because of two reasons. A low performance prototype version of a CVT should be less complicated to manufacture than an AMT and the transmission should be more forgiving from a control point of view. The cantilever concept of the CVT transmission is the preferred option because of the ease of manufacturing.

7.1.3.1 Manufacturing

The assumption of a less complex manufacturing process involved with a CVT was made after investigating the feasibility of production of both types of transmission. A prototype version of a CVT could be produced without the need for any complex manufacturing process. No component in the system should require a tolerance that would increase the intricacy of the manufacturing to a difficult standard. In comparison even a simple prototype AMT was identified as being difficult to manufacture with the technolgy available and a larger risk of real world problems requiring a major redevelopment. The estimated tolerance that could be allowed for the manufacturing of the dog clutch and related components was considered to be a major hazard as this would require precision turning, milling and broaching that may not be able to be achieved under current research conditions.

7.1.3.2 Control

Controlling the CVT transmission is likely to produce less real world problems compared to AMT because moving the pulley halves should be forgiving as the belt and the pulleys are not rigidly connected and therefore cannot be any impact of the components. Controlling the AMT has two unforgiving properties. The gear set is a rigid connection that if jammed by a controller error would produce high load or torsion on at least one component. The operation of the AMT requires a transient state were the dog clutch will be in the process of engaging; during this time an impact will occur between components. If not controlled correctly the dog clutch may be unable to engage or possibly cause damage by an impact engaging force that is to large.

7.2 Control Task

The transmission works similar to that of the SMPS and Motor driver modules by receiving a command that sets the desired operation. The internal operation of the transmission module is to change the mechanical ratio between the input and output to the desired point. This is done by the control of a electromechanical structure that connects to the pulley halves. The manipulation of the transmission ratio requires the series of components to interact to provide the final result of moving the pulley halves.

The flow of interaction between the structure elements is listed below

1. The module's microcontroller runs a control algorithm and outputs the result via a PWM signal and control bit signals to a H bridge IC.
2. The bridge driver controls the H bridge.
3. The output of the H bridge is connected to DC brush motor.
4. DC motor is connected to the power screw located in the centre of the transmission.
5. The power screw moves the collar linearly, along the screw.
6. The levers are connected to either end of the collar and rotate around the hinge as the collar moves.
7. The rotation of the levers forces the linear movement of the pulley halves along the transmission shaft.
8. The linear movement from the pulley halves changes the ratio of the transmission by changing the radius the belt contacts with the pulley.

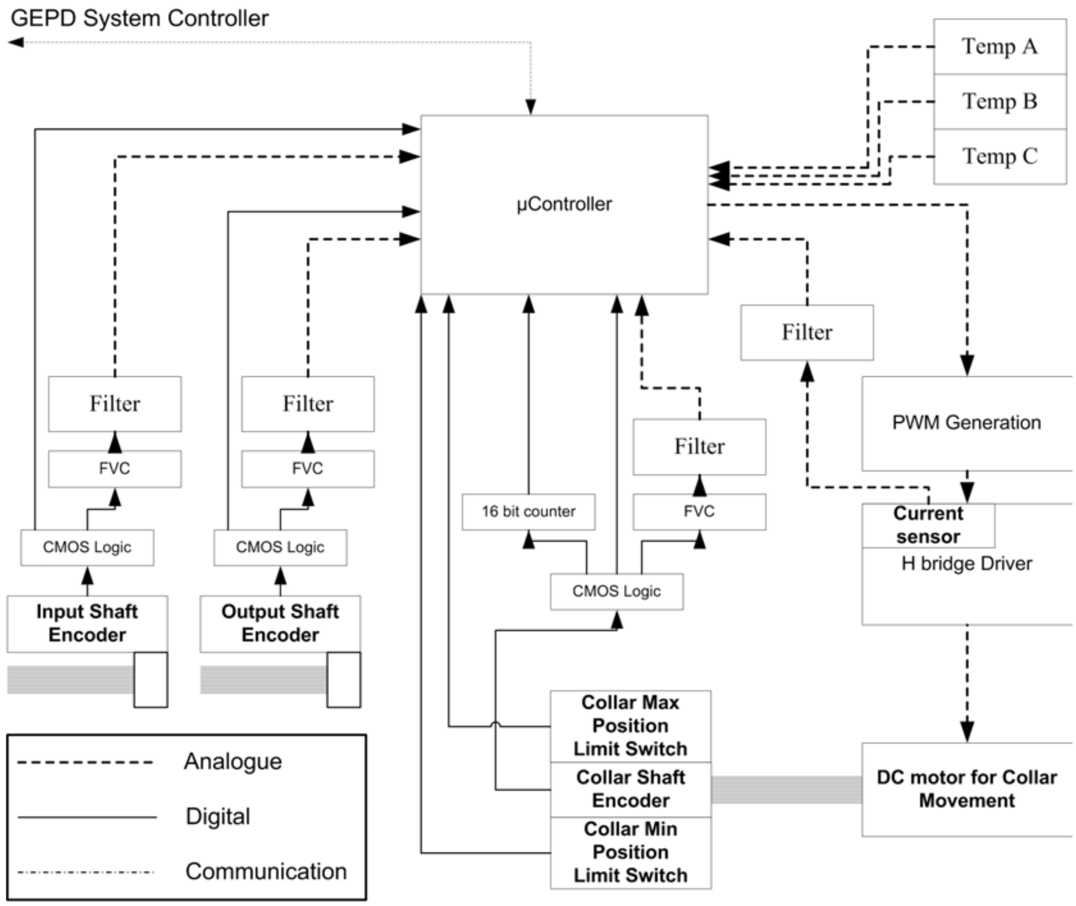

Figure 7-15 Embedded transmission control system.

The controller system is required to make a decision about the DR of the PWM signal to produce the most rapid and safe transition to the requested ratio set point. The most direct variable to control the transition between the current and desired ratio is the proportional value of the error. Including a derivate of the error with respect to time allows a rapid response without an overshoot. Using the proportional error and the derivate forms the basis of a simple linear MISO PD controller. A CVT transmission is not so straightforward to control because of two properties. The first complexity is the linear velocity of the pulley movement is governed by the linear velocity of the belt. The second complexity is the DR of the PWM is required to change with torque output from the AC motor.

7.2.1 <u>Governed Pulley Movement</u>

The rate at which the ratio of a CVT can be changed is governed by the linear velocity of the belt at the point of contact with the pulley. The effect of the governed value is the rate at which the pulley can be moved and that is determined by the angular velocity of the slowest shaft. The controller is therefore required to modify the rate of change of pulley displacement depending upon the angular rotation of either the input or output shaft.

7.2.2 Variable AC Torque Production

The force required to move the pulley is proportional to the torque applied to the transmission from the AC motor. The longitudinal force that acts on the pulleys is the result of the V shape of pulley. This vee shape produces the longitudinal force as the torque acting on the pulley is translated from the contacted angled grove. A torque measurement is useful to provide an estimate of the required DR of the PWM that ideally changes to match the torque change of the AC motor. The most direct method of receiving a value to determine the torque of the applied force during the ratio change is to measure the DC motor current.

7.2.3 Control Variables

Four control inputs were identified for the control of the transmission ratio; P_{error}, D_{error}, $P_{shaft\ velocity}$, P_{torque}. The controller was orginally planned to use four input variables to the fuzzy logic controller. This was found hard to implement because of the processing time constraints and available program storage. A MISO type controller was to be generated from the four control inputs. The literature on this type of controller tends to based around complicated mathematical models or fuzzy systems. The controller would employ a FLC because the mathematical models for this prototype system could not be considered reliable and the developed FLC was available from the SMPS and motor driver modules.

To use the FLC, one of the four identified control inputs was required to be removed from the control process. The proportion and derivative of the ratio error was considered vital to provide a rapid response to the set point change. The proportional value of the shaft velocity was required because of the mechanical properties of the shaft. The one reaming control input that is not a necessary was the torque output from the DC gear motor. The removal of the DC torque was manageable because the variable is used as a means of a performance increase and that the derivative of the positional error could be used to compensate. The DR ratio output from the controller is not an absolute value; rather it is relative to the prior DR output. The control requires the hardware to collect the following inputs.

Quadrature encoders

- Input shaft.
- Output shaft.
- Power screw.

The encoders for the input and output shafts are connected with hardware logic and a FVC to produce an analogue value of the speed and a digital bit representation of the rotation direction. The configuration is the same as used for the motor driver module and is explained in section 6.2.4.3. The encoder output for the power screw, in addition to rotation velocity output is used to return an absolute value of the position of the collar. The position of the collar is held within a counter and the value counts up or down depending upon the encoder's direction. The value from the counter is converted to an analogue value and supplied to the microcontroller. The microcontroller has the ability to reset the counter value to zero and this is achieved by an output signal to the counter hardware. Micro switches are located on each end of the power screw to enable homing of the collar. The analogue values are processed and manipulated within the microcontroller software. To form control, the identified are

- Ratio error
- ΔRatio error
- Minimum shaft velocity

Monitoring Inputs

To provide monitoring of the module, the microcontroller collects secondary information about the operation. The inputs are collected to aid in the protection of the DC motor and H bridge.

Telemetry Inputs

- Motor current
- H bridge temperature
- Motor temperature

7.3 Microcontroller Details

The microcontroller selected for control is the Silab 8051F020 and is integrated with the available development board. This section will provide the details and the development that is required for the specific task of controlling the transmission. The general functions for the microcontroller are explained in CHAPTER 3 and will not be covered here. The microcontroller receives commands that set the desired ratio. The physical objective of the controller is to control the ratio of the transmission by operating a DC motor with a PWM signal.

7.3.1 Control Algorithm

The general summary of the operation of the control algorithm is listed as below.

1. Process communication buffer and identify any command changes
2. Process analogue input values
3. Begin Fuzzy logic Control

   a. Fuzzify the input values.
   b. Calculate the rule base.
   c. Defuzzify the output fuzzy value.
4. Change the direction and PWM outputs if required
5. Send telemetry if required

7.3.2 Mixed Signal Microcontroller Requirements

To interface the microcontroller with the hardware and communication channel, the following internal devices are required.

- Single 12 bit DAC0 output to control PWM DR.
- Eight 12 bit ADC0 inputs.
- Two external interrupts.
- Additional 23 digital inputs.
- Four digital outputs.
- Serial communication port.

7.3.2.1 DAC

An analogue output is required to control the duty ratio of the PWM signal to the H bridge driver. The voltage varies from 0- 2.5 VDC.

7.3.2.2 ADCs

The microcontroller samples the analogue voltages that represent the operation of transmission module. The analogue values are used for control and monitoring purposes. Internal operation of the analogue inputs is carried out in the background at a set frequency initiated by timer overflows. The detailed operation of the ADC inputs is covered in section 3.2.

ADC0 is used to sample the following inputs:

- Input shaft angular velocity.
- Output shaft angular velocity.
- Power screw angular velocity.
- DC motor current.
- Solenoid current.
- H-Bridge temperature.
- Motor temperature.
- Solenoid temperature.

7.3.2.3 Digital Inputs

The microcontroller uses 25 digital pins as inputs in total. Two of the pins are used to trigger external interrupt routines for fault shutdowns and the remaining 23 are used as general I/O pins.

7.3.2.3.1 Interrupt Pins

The interrupt pins are used for fault detection and not used for immediately shutting down the controller. The interrupt pins are used to detect that the counter for the absolute position has over run (which should never happen depending upon the resolution) and whether the input and output shaft are rotating in opposite direction which therefore means a mechanical problem.

7.3.2.3.2 General Pins

The 23 digital inputs are responsible for three different operations. 16 pins are used as the input from the counter value; 3 give the direction that the shafts are rotating and 4 are limit switches for the movement of the power screw and the clutch linkage.

7.3.2.4 Digital Outputs

The control of the power screw DC motor requires a control signal for the direction of the motor and the on/off control. An output is required to reset the value for the position of the counter. The remaining output is the on/off control for a solenoid.

7.3.2.5 Communication

The microcontroller responsible for the hardware control of the power supply communicates with an overall system controller. The communication channel is operates using the RS232 serial communication standard. RS232 serial communication was used for the application because it is a standard communication protocol for both microcontroller and computers. The operation of the serial communication is explained in section 3.3.

CHAPTER 8 DISCUSSION AND CONCLUSION

8.1 Discussion

8.1.1 Generic Intelligent Control System

The microcontroller software developed does provide a good basis of future development with the current soft modules allowing the abstract controller to be developed very efficiently. This research was to reduce the development time for embedded microcontroller control systems; development time efficiencies have been realised. The reduction in programming time was gained by the development environments created and are reflected in the time savings in fuzzy logic processing. The FLC development environment allows a FLC to be rapidly developed for any control system using the Silab microcontroller. The development environment provides a means of graphically displaying and recalling any FLC controller developed, this has proved to be effective in reducing the time needed for tuning such controllers. Results from testing the ADC and communication modules have shown the software is operating as intended. The communication methodology developed has significantly improved the communication reliability and ease of integration into software.

The FLC and GICS demonstration operating as a complete unit although without suitable hardware to test the ability it was not possible to accurately quantify performance. The improvements in development efficiency provided by the generic intelligent control system reduced development time for the three original objectives. The most time consuming task now is developing software to form the controller's state machine. Further development of the GICS could focus on a soft module for state machines and with this in place, an application could be produced that links all the modules together internally to remove the need for a manual coding process.

8.1.1.1 State Machine Soft Module

The envisioned method for developing a state machine soft module would be a graphical user interface based PC application. A developer would use the PC application to produce a state machine or flow chart diagram similar to that achieved by using the Microsoft Office application Visio. The application would then create the soft module instance based on the diagram layout. The coding process for state machines has been found not to be a time consuming task but is complex to code and the structure is difficult to understand. The suggested application would produce code directly from a planning document, allow quicker changes and aid in the understanding for people other than the control system developer.

The perceived challenge with developing a state machine soft module is that the structure of the code would need to be extremely general and dynamic. The need for the extremely general and dynamic operation may make aim of the module a major challenge; any investigation into such a soft module should consider initially if it realistically likely to produce a successful module.

8.1.1.2 GICS Soft Module Link Application

If a state machine soft module application has been found to be possible and viable, the next logical development would be to provide an application that links the soft modules together in a higher level of abstraction. This linking application would almost entirely remove the need of manual coding for the microcontroller program. With the modules for communication, ADC operation, FLC produced and then the state machine as recommended, only the output component of the GICS is not produced by an automated means. The output components are the simplest to develop and tend not to need modification other than their parameters, this means that fixed code could be inserted into the linking application. The development of the linking application would provide the ultimate solution to the task of developing prototype control systems. With the completed linking application, a developer would no longer be forced to spend time manually writing code. To produce a control system a developer would be required to carry out only the following tasks

1. Identify control object.
2. Identify and set the configuration for the output from the microcontroller.
3. Identify the required inputs, then set the configuration.
4. Identify the communication requirements, set the configuration.
5. Decide upon the state machine of the controller.
6. Decide upon the numerical processing for controller task.
7. Run the link application to produce C code for the control system
8. Compile and download the developed program to the microcontroller.

Reducing the required tasks to those above allows the developer's time and skills to be directed more profitably; the resulting savings would be in time and project cost. Manually coding the control system would require the same steps regardless and further include the large amount of coding. Providing that the graphical user interface is well designed, the linking application with the soft modules embedded would allow a developer unfamiliar with the design to gain a greater ease of understanding.

8.1.2 Hardware

The hardware discussed through chapters 5, 6 and 7 outlines the considerations and design of the power supply, motor driver and transmission; although at this stage this hardware has not been manufactured. Without the hardware being manufactured, the designs are difficult to comment on their operation and performance. The designs outlined from these chapters had their individual sections of the hardware built on bread board to verify there operation as intended. The full designs were not produced as one unit and therefore results were unable to be gathered and quantified. For future work, a better idea would be to translate the operation of the fixed hardware into FPGA IC technology. The use of FPGA technology during this research was avoided because of concerns with the limited experience with the devices and the potentially inefficient use of time spent developing the firmware. Evaluation of time usage eventually designated to the planning and the numerous redesigns of the fixed hardware proved to be a considerable user of time resources. The time required to become proficient with FPGAs would have been compensated many times over by the large reduction in hardware development time. Late into the research the Silabs 8051F020 was discovered to have a programmable counter array (PCA) mode of operation capable of generate up to five separate PWM ratios. This PCA mode of operation is not mentioned in the two sources of literature that were predominantly used and therefore not found until too late. The PCA would have been able to generate a variable DR signal of 16 bit resolution without the requirement to be heavily operated within the software during steady state operation. The PCA operating in the PWM generation mode would have provided an ideal solution to the problem of high speed IC to IC communication encountered in section 5.3.1 Direct Microcontroller Control; it would further provide a useful performing option to communicating with a FPGA.

The PCA generated PWM could operate using a simple software handler and could modify the operation of PCA from a single instruction when a change in the DR is required. The reduction in processing requirements would have made it possible for a low processor cost PWM generation; and be implemented within the microcontroller package. The five available low processing cost PWM outputs could have been used as an efficient variable communication method to an FPGA and required a low gate count on the device. The earlier identification of the 8051F020 ability to produce low processing cost PWM signals at minimum would have removed the need for external oscillators to generate the high frequency PWM signals that are used in all three hardware control modules.

8.1.2.1 Hardware Development using FPGA

The next development stage is to develop the hardware with soft firmware modules for use with FPGAs. The microcontroller to FPGA control variable passing could be achieved with the available DR signals that can be produced from the PCA. The use of DR representation over currently used analogue signals would provide a range of benefits.

- PCA 16 bit resolution
    - DAC used provides 12 bit
- Exact linear output.
- Improved transient response by removing the port time constants.
- Improvement in noise rejection
    - Important advantage because of EMI from power electronic switching.
- Simpler circuit designs by involving only digital components.

The integration of FPGAs would provide better performing hardware for each of the modules even using the same control method; furthermore, FPGAs could improve the performance of the control algorithm within each module by accomplishing calculation intensive tasks within the FPGA package. The recommended changes and the potential gains for the individual modules are explained below.

8.1.2.1.1 Switch Mode Power Supply

The operation of the SMPS would require only simple VHDL code other than perhaps the interfacing code. The potential benefits of using a FPGA package with DR control inputs are as follows.

- 16 bit resolution
- Linear
- A single hardware control IC
- High frequency

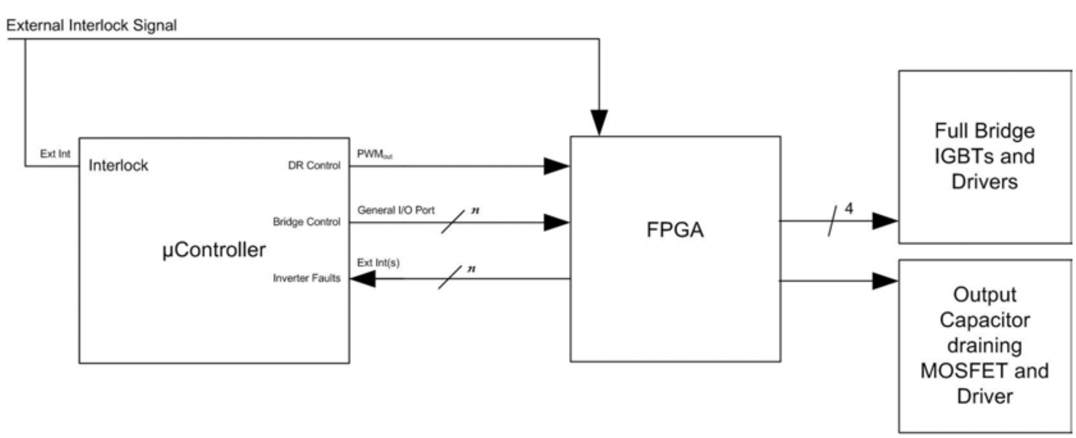

Figure 8-1 Recommend SMPS control arrangement.

The FPGA would provide a linear DR control and the switching frequency would be limited only by the power electronics semiconductor devices. The 16-bit resolution and linearity that the FPGA could provide has a major advantage over the analogue voltage saw tooth method that is used for the research. The non-linear output voltage gains of the isolated boost converter can be seen in Figure 5-7; therefore a 16 bit resolution and a correct linear signal would provide an increase in the accuracy of the control.

Using an FPGA would allow the integration of soft switching by quasi-resonance techniques for the power supply that is not feasible to manufactured fixed hardware. A FPGA would allow the generalization of the design to produce a high frequency switching circuit with the complexity required. According to Batarseh[47] soft switching offers a wide range of benefits over conventional hard switch PWM power supplies. With conventional hard switched SMPS, the switching process takes place at a high current or voltage. This high power switching results in a power loss during the switching and imposes high stresses on the semiconductor devices. Soft switching techniques switch the semiconductor devices during a period of either zero volts or current. The switching during the period of low power reduces the stress on the semiconductor devices and reduces the power loss from the switching. The reduction in power loss during the switching allows the switching frequency to be many times higher than that of hard switched components. Batarseh[47] gives the upper limit of hard switching of devices at 100 kHz and soft switching with current (2002) technology capable of 1-2 MHz. The available higher switching frequency provides the benefits of the reduction in the physical size of the passive components and reduces the EMI from reducing harmonics caused by the switching.

8.1.2.1.2 Inverter Operation

The use of the internal PCA of the Silab microcontroller to generate a 12-20 KHz PWM signal and the replacement of the fixed hardware with a SPLD would accomplish the same task as the developed hardware design with the advantages of a linear DR selection; increased resolution of the DR and reducing the required chip count to a single SPLD IC.

Integrating a FPGA would allow improved methods of scalar control of the inverter and could and be achieved with minimal effort. VHDL coding would allow sinusoidal modulation of the three phase bridge that was found not to be practical with a hardware design. The use of FPGAs designed for DSP applications would allow the integration of a state vector direct torque control algorithm. The application of the DTC method would make the microcontroller redundant because the only task remaining for the microcontroller is the communication that can be achieved with FPGA hardware. Appling DTC by FPGA is of questionable worth during early stages of prototyping as the induction motor will be replaced by a synchronous motor and the high resources required to develop the DTC method on FPGA will be discarded at a later stage. The use of state vector control for the application could be excessive for the reason that the objective is to control the torque perceived to the operator rather than a numerical torque output. The motor load can also be considered a high inertia load therefore the fast transient responses provided by a state vector DTC is not required although this method may increase the efficiency of the system.

8.1.2.1.3 Fuzzy Logic Controller

The fuzzy logic control algorithm requires approximately 90% of the controller's processing capability. Reducing the control algorithm period would produce an improved system by responding to errors sooner therefore minimising the disturbance. FPGAs have the advantage over microcontrollers with the ability to parallel process. The FLC would benefit significantly by applying the control within the parallel processor because most of the process can be achieved in this manner. With the microcontroller FLC algorithm, the procedure is to fuzzify the numerical input variables and calculate the rule activations, this is completed one calculation at a time. The FLC controller uses linear input membership functions with a singleton output defuzzifier that does not require any complicated calculation for each individual operation.

The original intension for the FLC was to produce a controller with four inputs variable,each with five membership functions. This would have required the control algorithm to calculate the activation of 20 possible input memberships and then the 625 rules to form a complete rule base. With the exception of the synchronisation between parallel paths, the FPGA controller could theoretically calculate all the membership functions in one stage, then the 625 rules in one stage; therefore calculate the rule base activation 625 times faster. Practically a FPGA is unlikely to have the required number of gates to produce the entire rule base in a single parallel process; however the rules could be processed in groups that would still reduce the overall number of cycles to calculate the controller response. The passing of the input variables and the FLC outcome could be accomplished using the capabilities of the programmable counter array. The five input or output PWM DR peripherals available would allow 4 to be dedicated to the transmission of the input values form the microcontroller and the remaining peripheral could be used as a input from the FLC output. A proposed general layout of new controller system realising the fuzzy logic controller and switching hardware is shown in Figure 8-2

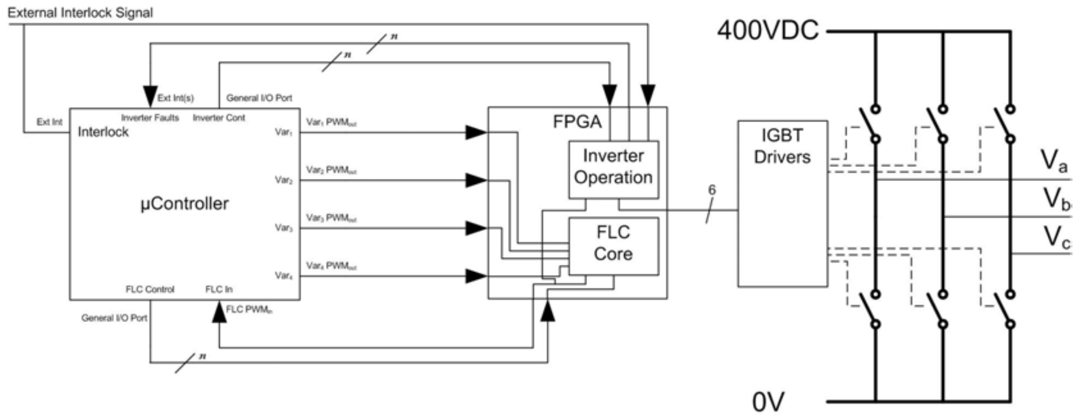

Figure 8-2 Proposed FPGA FLC implementation applied to motor control module.

8.1.3 Mechanics

The use of transmission should be investigated at a later stage to make comparisons between direct drive and the possible gain in using an adjustable ratio. The original concept for the prototype involved a transmission because of the use of asynchronous AC induction motor; the use of the transmission would allow a constant power output and not be governed by the volthertz constant.

The use of a continuously variable transmission needs to be re-evaluated, one reason for why the CVT option was chosen is for the ease of manufacturing during a prototype stage. This would allow a comparison to be made between the benefits of ratio adjustment against the loss in efficiency due to the transmission. The effectiveness of a prototype CVT transmission to determine between fixed and variable ratio is problematic because of the differences in operation between a simple prototype and the requirements of a commercial design. A prototype CVT using rubber belts and non metallic smooth faced adjustable pulleys is expected to have different characteristics to steel belt/chains and complex pulleys used in production transmissions found in late model Audis and Toyota Prius. The comparisons between a prototype and production automated sequential transmissions is likely to offer a stronger correlation between the stages of development and therefore offer a better comparison for real world difference. The option of using a CVT during development needs to be questioned because realistically the production cost of such a ratio adjustment does not offer the best trade off between performance and cost and for that reason a production transmission is likely to be of another type.

8.2 Conclusion

This research project has had a good outcome in the development of a generic intelligent control system which can be applied for future electric propulsion drives. All soft programming module components of the GICS have been shown to work in some capacity during development time. The layout of a multi agent collaborative system places importance on the reliability and quality of the communication channel used. The development of buffered communication methodology for microcontrollers and resulting increased reliability shown in Table 3-2 has provided a platform for future trails to have a reliable communication channel available with minimal effort using the soft programming techniques that were developed. The communication module presents a very effective method for transferring data between the modules and the external devices. The generic fuzzy logic control module built an excellent platform that allows a FLC to be rapidly developed for any control system using Silab microcontrollers. With the software components, the FLC is no longer required to be manually coded and only requires a small time investment in the planning and shaping of the fuzzy logic controller output. The output from the GICS research has been admitted and presented at two international conferences, one in New Zealand, the second Italy.

The hardware modules for the prototype electric drive have been designed and are ready to be manufactured. Once being manufactured they will provide a platform for future development of the GICS and the improvement of the hardware design. The hardware modules controllers all utilise the developed GICS and together form the MACS. The MACS and the GICS will allow the ease of integration of updated hardware in the future. The design process for the hardware has explored some methods of achieving the desired action and has provided a direction for future development.

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APPENDIX A BATTERY TECHNOLOGY

A.1 Batteries Technologies

Batteries are electrochemical device that stores energy chemically and converts that energy to electrical form. This section will not explain the operation of batteries as that is chemical science and not required for the understanding of this research. The information following will be an overview of the type, the benefits and disadvantages to the technologies that have been used or envisioned to be used as traction batteries.

A traction battery is the term given to high power, high storage batteries used for high power devices such as electric vehicles. The development of traction batteries is a major technical issue that needs to be overcome for the reality of electric vehicles. The difficulty to produce a traction battery is that it must be strong across all variables of a battery without compromising one area.

The areas that a traction battery must have high specification are as follows

- High storage per volume and weight
- High power output
- Quick Charge
- Safe operation
- Environmentally Safe
- Long replacement life
  - Lifetime in years
  - Lifetime in charge cycles
- Low cost

Section A.2 will be an outline of the three main types of chemical battery that have been developed since the invention of rechargeable batteries. Section A.3 will be an overview of recent batteries that are a promising solution for traction vehicles.

A.2 Current Battery Technologies and History

A.2.1 Lead Acid

The first rechargeable batteries were invented in 1859 by French physicist Gaston Planté. These first batteries are now known as lead acid. The batteries use lead and lead oxide as electrode and an acid as the electrolyte between the electrodes. Lead acid batteries are still a very common battery because the batteries can supply a very high power output and are a low cost option. Lead acid batteries however have a low energy storage per mass or volume. The environmental effects are severe as the lead and acid needs to be disposed of properly or it will leach into the environment and being a heavy metal continues to build up and poisons the area. Lead also builds up in the body and is strong neurotoxin (lead oxide is even worse) and can also lead to brain damage and blood disorders. Because of these dangers to humans its use is heavy restricted in most first world countries. Shallow Cycle (commonly known as automotive) lead acid batteries have a low cost to storage ratio and high power output. The disadvantages are the size and weight to storage ratio and the low drain cycle. To maintain a long life time shallow cycle batteries can only be discharged to 80% of the max charge. The low discharge cycle is because of the thin cell walls inside the battery. As the energy storage changes the cell walls distort, a larger discharge causes more distortion and the batteries will break down as the molecular structure of the battery cracks. Shallow cycle batteries are commonly used in ICE vehicles as a short powerful power supply to operate the starter motor that starts ICE. A shallow cycle battery is sufficient for this use as the power drain is only for a short period before being recharged by the vehicles alternator and lead acid battery provides a high power output for a low cost.

Deep cycle lead acid batteries are similar to shallow cycle batteries but have the advantage having discharge cycles down to 20% without derogations of the battery. To achieve the deep cycle the internal structure of the battery is thicker cell walls to withstand the variation in energy storage. The thicker battery cells increase the internal resistance and therefore reduce the power output of the battery. Deep cycle batteries are also more expensive than tradition shallow cycle lead acid batteries.

A.2.2 <u>Nickel batteries</u>

The first Nickel Cadmium batteries were developed in 1899 by Waldemar Jungner and also some work on Nickel lead batteries. Jungner abandoned his work on nickel iron batteries due to charging problems. These problems were solved by Thomas Edison and the work was patented in 1901. Nickel iron batteries were used in the first electric vehicles built in the early 20^{th} century. Thomas Edison developed the batteries for this use as he thought the electric vehicle was going to be the choice for transportation. Jungner work with nickel cadmium batteries was used in battery production after World War 2 that he and Germans had developed the technology for use in V1 and V2 rockets. Nickel Cadmium batteries provided a low cost battery that outperformed lead acid and earlier Nickel iron batteries. The Nickel Cadmium batteries had a long life and could withstand a high charge rate. The downside to the Nickel cadmium batteries was the very strong memory effect and latter concerns were the very harmful environmental effect from the cadmium.

In the 1970 Philips researchers discovered the association between nickel and alloys to produce a high energy cell. The batteries became commercial product in the late 1980s. NiMH batteries provided a major leap forward in battery technology and are commonly used for hybrid vehicles. NiMH provided a battery with a higher storage density compared to NiCad batteries, enable a high power output, no memory effect and environmentally safer. NiMH batteries still suffer from high cost of manufacturing although lower than new lithium ion batteries.

A.2.3 Lithium Ion

Lithium (non ion) batteries were first proposed in 1961 and research from bell laboratories led to the development of lithium ion batteries to solve the chemical issues with lithium. Sony released the first commercial lithium battery in 1991 and is now used in a number of mobile products such as laptops and cell phones. Lithium ion batteries offer a much higher level of storage of energy for mass and size as well as a high power output. Lithium ion batteries do have some technical issues that need to be solved before the integration into a wider range of equipment.

The first technology of lithium ion batteries called simply lithium ion (now known as lithium ion cobalt oxide). Offered very high performances as mentioned above and are quite common in devices where weight is a factor. The disadvantage to lithium ion batteries is the short life time of the battery before the performance degrades to low levels. Lithium ion batteries are also dangerous compared to Lead Acid, NiCad, NiMH batteries and there have been a number of failures world wide where batteries have became hot and exploded or caused fires. Lithium battery cells often include electronics in an attempt to keep the batteries in a safe operation and improve the life time. From the first Lithium ion batteries further development has lead to a number variation that attempt to circumvent the problems faced.

Lithium ion polymer(Li-poly) was developed to withstand to physical impacts and reduce manufacturing cost. A Li-poly battery uses a solid conducting polymer between the electrodes, instead of a liquid electrolyte and porous separator. This has two main advantages, first the battery is safer as polymer electrolytes are less reactive than liquid and then the battery can be made very narrow.

A.3 Promising Possible Traction Batteries

A.3.1 Lithium iron phosphate

Lithium iron phosphate ($LiFePO_4$) has been developed to be a safer version of the conventional lithium battery. The battery was first developed at the University of Texas were it has shown to be potentially a low cost and safe battery[60]. The battery is lower cost than tradition cobalt as the iron used is cheaper and easier to handle. The battery does have lower energy densities than cobalt battery and originally had internal resistance issues. The internal resistance issues were solved by researchers at MIT[61] and now outperform cobalt lithium batteries in high power devices. The battery envisioned to be the choice for high power devices such as electric vehicles and hybrids because of the low cost and the increased safety that is major concern for vehicles.

The uptake to the new battery is slow as commercial companies are resistant to investing in a technology that has lower performance compared to cobalt lithium ion batteries. The battery is also currently difficult to manufacture to a high quality standard in mass production. Companies that have developed the technology have produced batteries that have given a performance greater than any commercial high power battery and solve life time issues with cobalt batteries. In May 2007 Lithium Technology Corp announced that they are able to produce commercial batteries of the type and performance figures given are a notable increase over current commercial batteries[62]. Lithium Technology states that their batteries have usable life time (80% of original condition) of 3000 cycles which would give a plug-in hybrid vehicle batteries a lifetime distance of 240 000 km (stated as 150 000 miles) before replacement was required. The batteries would allow plug in vehicles to have a range of 100 km per charge. If these figures given are correct then the battery technology has reached a reached a level that is acceptable to consumers in both energy storage and lifetime. The batteries are reportedly expensive to manufacture at present time (not mentioned in Lithium Technology Corp press releases) though the cost should decrease significantly as manufacturing development and large scale production is initiated by larger corporations. The batteries have been included into production of electric bicycles and used in the computers for "One laptop per child project". Unverified statements mention that lithium ion phosphate is the direction Toyota is researching for their plug in hybrids.

A.3.2 Nano Titanate

Nano Titanate is a recently developed battery that promises to solve all the performance issues of lithium batteries. Altairnano started research into the development of lithium ion batteries in 2000 with the aim of investigating electrode materials to improve several factors of performance. During February 2005 a breakthrough was found in the use of a nano titanate structure[63]. The advance produced big improvements in reducing charge time, increasing the power output and life cycle. The battery devolvement replaces the graphite anode with nano-size lithium titantate oxide. The replacement provided two key benefits. The first is that the graphite cathode is removed which is the highly reactive part of the battery. The graphite cathode in connection lithium ion batteries causes what is commonly is called thermal breakaway the results of these events are the batteries igniting or exploding.

The second improvement is that the structure of the nano titanate is a three dimensional structure with holes of equivalent size to a lithium ion. The structure of graphite is a flat planer surface that requires the structure to distort in shape to accommodate lithium ions. The advantage of the three dimensional shape provides the benefit that the cathode structure has no distortion over the charge cycle and that lithium ions are able to move around easier. Altairnano calls this property "zero strain". This zero strain property has two benefits. Firstly batteries of all types suffer from reduced conductivity over time as the deformation "cracks" the molecular structure of the battery; "zero strain" removes this deformation and therefore greatly improves the lifetime of the battery. The second benefit to zero strain is that ion can move easier around the battery as the deformation of the cathode is not required. Removing the need for the cathode to deform allows an extremely high rate of charging and draining compared to all other battery technologies. A traditional Lithium ion battery has the tendency to ignite under high drains due the internal resistance and properties of graphite. If a conventional lithium ion battery is charged too fast the graphite does not deform quick enough and lithium metal (non ion) is deposited on the outside of the graphite and reduces the capacity of the battery.

A combination of the removal of graphite and the ability of the lithium ion to move easier allow a wider range of operating temperatures. Altairnano states the safe temperature range of the battery from -40^{O} C to 260^{O} C; this can be compared to the lithium ion battery range of operation from 0^{O} C to 130^{O} C.

Performance figures from Altairnano information sheets give some impressive figures on the lifetime and charge rates of the battery. Lab testing of the battery has shown to maintain 85% charge capacity after 9000 cycles[64]. 9000 Charge cycle put into the application of electric vehicles would allow once charge per day for almost 25 years[63]. The time required to charge batteries is stated as under 10 minutes and lab test have shown the ability to charge to 80% in under a minute. Altairnano has since been placed into receivership and the original source is no longer accessible because Altairnano's web site is no longer hosted. The references cited in this section are from news reports that stated the figures, not all figures given were able to be relocated.

APPENDIX B SOFTWARE TEST METHODS

B.1 Analogue to Digital Conversion Communication Testing

The ADC software module is tested to verify the quality of the conversion and the effect on the controller operation. The quality of the conversion is measured in two processes. The first checks the conversion value, the second checks the effect of cross channel interference.

The effect on the controller operation is measured by timing the interruption caused by the conversion process.

B.1.1 Setup

The same equipment and general layout is used for all testing procedures in the ADC software module. A waveform generator supplies the microcontroller with a changing analogue input. The microcontroller operates a modified version of the power supply control program. This modified version produces test points that can be recorded on an oscilloscope. The oscilloscope transfers the voltage traces to the PC and these waveforms are then used as the test result.

Hardware

- Desktop Computer with a RS232 serial port.
- Silab 8051F020 development board with an integrated RS232 serial port and level shifter.
- Oscilloscope.

Software

- Oscilloscope communication software.
- Modified instance of the power supply control program.

B.1.2 Conversion Quality Testing

Method

To test the accuracy of the ADC operation, the microcontroller is connected to the waveform generator output. The program operating within the microcontroller then recreates the converted signal using the processed ADC value and internal DAC provides an output. The oscilloscope trace demonstrates a comparison between the true voltage and the reproduced value. This comparison validities the accuracy of the conversion process.

Conversion Accuracy

The initial test procedure determines if the ADC software module is controlling and processing the results correctly.

An analogue value is connected to the input of the microcontroller. The microcontroller then outputs the determined voltage on the DAC. The correlation between the true and reproduced value then an gives indication of the conversion.

Channel Interference

The channel interference test is used to simulate the operation of the ADC software module in an applied application. Two analogue signals are connected to the microcontroller. The microcontroller samples these voltages and then reproduces the second on the DAC output. Using the findings from the conversion accuracy test, the extent of cross channel interference can be determined.

B.1.3 Control Interruption Effect

Method

The developed ADC software module has to measure the analogue value correctly and avoid considerable processing time requirements. To measure the processing time requirements, a modified ADC software module is tested. The modification outputs test points inside the software which demonstrates when the ADC software is using processor time. Upon entering the ADC module software, a test pin (PIN 3.6) is switched to digital high. The digital test pin is switched low when leaving the ADC software. The test pin is traced with an oscilloscope and the widths of the high pulses demonstrate the time requirement. The measured time period does not include the interrupt call and return. Gupta states in his book that the interrupt calls require 5 clock cycles to enter an interrupt routine and two clock cycles to return. The period can be estimated to increased by a further 0.31us when using the Silab 8051F020 microcontroller (7 clock cycles at a frequency of 22.184 MHz, this corresponds to a period of 0.045us).

B.2 Serial Communication Testing

The communication software component developed is tested to determine the performance of three factors; latency, reliably and the necessary processor involvement.

B.2.1 Software Latency

The latency of the communication channel can be described as the delay between sending and receiving a command. The ideal solution to testing the latency for a systems approach is to measure the period between Device A initiates the send command and Device B acts on the command.

Gathering an accurate latency result in this manner would be difficult and unreliable in the developed system. Too measure the full delay would require specialised PC equipment to allow common triggering for timing, secondly the PC operating system introduces differing delays between application requests and physical port operation. These two predicted difficulties are related to the PC communication operation and not the developed microcontroller communication. To form a comparison between the original and developed method of communication, only the software latency of the microcontroller needs to be compared.

To measure the relative latency between the different communication methodologies the period between physically receiving the command and acting on the command is measured. This period is then used as a relative comparison.

Setup

The photograph depicting the testing arrangement is shown below. The hardware and software required is listed directly below.

Hardware

- Desktop Computer with a RS232 serial port
- Silab 8051F020 development board with an integrated RS232 serial port and level shifter.
- Oscilloscope.

Software

- C# developed serial communication application.
- A modified instance of the power supply control program.

B.2.2 Method

The latency of the software is measured by the toggling of a digital output from the microcontroller package. The microcontroller software used is a modified version of the power supply controller that will explained in short within section 5.5. Modification of the power supply software is to provide an output that is measured by the oscilloscope to represent the latency period. Using the power supply program provides a processing load to the microcontroller. Involving a processing load to the microcontroller is essential as the developed communication methodology processes the buffers within the main control loop. The in-loop processing is a different method to the original method that processes within the communication interrupt. The extra delay for the new approach is required to be included to produce an accurate comparison.

The software used for testing is a modified version of the program for the power supply module. The modification adds a test point by changing the status of a digital pin (Pin 3.6) depending on the status of the communication. Upon receiving the final character in a

command (denoted by "\n"), the microcontroller outputs a high on the measured pin. Once the command has been processed and identified, the controller outputs a low on the pin.
The oscilloscope traces the port status continuously and latency of the software is given by the high pulse. The period of the pulse is used to determine the latency of the software.

Parameters

Baud rate: 115200Kb/s

Frequency of instructions from PC: 10Hz

B.2.3 Reliability

The developed GICS is to be applied to future battery electric vehicles in a modular approach. This modular approach forms a distributed control system and therefore the reliably of the communication is important for correct operation. The importance of reliable communication is further heightened because the control systems in BEVS will be responsible for devices that are potentially dangerous to human life.

Testing a microcontroller can be a time consuming task as the limited user interface restricts online fault detection and measuring. A communication test method was devised to negate measuring the pine outputs from the microcontroller. The test method uses a round trip from a PC to a microcontroller and then back to the PC. The PC runs an automated testing application that determines if the communication is correct.

This method was used to increase the efficiency of testing and to produce a simulated communication environment. The test has the disadvantage of not distinguishing between a communication fault caused by reception or transmission.

B.2.4 Setup

To test the reliability of the developed communication and make a comparison with the original method, a microcontroller was connected to a desktop computer and test software operated.

Hardware

- Desktop Computer with a RS232 serial port
- Silab 8051F020 development board with an integrated RS232 serial port and level shifter.

Software

- C# developed serial communication application
- Specialised microcontroller application

B.2.5 Method

Two programs were developed specifically to test the communication method. One application operates on a PC and the other application is operated from within the microcontroller.

The test is conducted by sending a command from the PC on a round trip to the microcontroller and this sends a response back to the PC. The test uses two lists of possible commands. The first list consists of possible commands that the PC may send to the microcontroller. The microcontroller identifies the commands received and sends back the corresponding command from the second list. The application operating on the PC operates automatically and initiates each test cycle. The application records the result of each test cycle and provides the operator with an error count.

The procedure is as follows

1. The PC application pseudo randomly chooses a command from the first list and transmits this to the microcontroller.
2. The microcontroller receives and processes the command. If the command is recognised then the corresponding return command is transmitted to the PC. If the command is not recognised then microcontroller returns a error command.
3. The PC receives the command sent from the microcontroller and then compares this command against the known correct answer.
4. A correct command received at the PC is counted as correct and a command that is incorrect is counted as an error.

B.2.6 Processing Requirement

The original transmission methodology used was noticed to be causing undesired control actions. An objective of the new communication method was to reduce the effect that communicated transmissions were having on the microcontroller main control algorithm. The software was modified to include test points to allow the testing of the communication methodologies. These test points would change the status of an output pin (PIN 3.6) to low while control action was not taking place.

Setup

To test the transmission from the microcontroller the device is connected to a PC and an oscilloscope is connected to the test pin. The oscilloscope continuously traces the pin output. The connection to the PC provides only a visual check to the tester that the communication is operating correctly and is not used in the collection of results. The hardware setup is exactly the same as for the latency test the only difference is the software operating on the PC and the microcontroller.

Hardware

- PC with a RS232 serial port.
- Silab 8051F020 development board with an integrated RS232 serial port and level shifter.
- Oscilloscope.

Software

- C# developed serial communication application.
- A modified instance of the power supply control program.

Method

The microcontroller for this test is programmed with a modified version of the power supply control program. The modification of the power supply program is the introduction of test points around the transmission of telemetry. These test points demonstrate when the controller is actively controlling the process and when transmitting. The test output pin is high when the microcontroller is operating the control section of the code. The pin is low when the microcontroller is transmitting telemetry to the PC. The oscilloscope is connected to the output pin and is used to measure and display the microcontroller's operation.

B.3 FLC and GICS Testing

At this time there are no hardware designs that have been manufactured for the electric propulsion drive. Full testing of the FLC and the GICS is not possible without the hardware being available. It is possible to demonstrate the operation of the FLC and GICS by using signal generators and tracing the output.

The outputs from the GICS are either a digital state operation or a numerical value.

B.3.1 Boolean Control

Demonstrating the operation of boolean outputs without working hardware is not irrelevant at this time. This is irrelevant because the operation depends entirely on the serial communication module. This module has already been tested and the results would demonstrate the same occurrence.

B.3.2 Numerical Control

Numerical values are outputted in three possible ways, these are digital out, analogue out and PWM(Pulse Width Modulation). Any of these methods could be employed as the control output from within the convert to outputs software block shown in Figure 3-3. The simplest method to demonstrate the numerical processing is achieved by using the DAC (analogue output) to reproduce the numerical value. The output from the DAC can be traced with an oscilloscope to demonstrate the numerical processing results.

B.3.3 <u>Setup</u>

A simple instance of the developed GICS was generated to demonstrate the operation of the GICS and the FLC software module. The control instance is given the parameter to read one or two analogue input ports. These analogue inputs are then processed and the numerical value is outputted on the DAC. This demonstrates the operation of the ADC and FLC software modules as a working GICS controller. No advanced capabilities available from using the serial communication can be demonstrated without the development of suitable hardware.

Hardware

- PC with a RS232 serial port
- Silab 8051F020 development board with an integrated RS232 serial port and level shifter.
- Waveform generator.
- Oscilloscope.

Software

- C# developed serial communication application.
- A demonstration implementation of GICS.

B.3.4 <u>Method</u>

The demonstration of the FLC and GICS is done with four different software configurations. The first three configurations demonstrate the operation of the FLC module using increasingly complicated rule bases. The last software configuration demonstrates the on/off control of the numerical processing which is achieved using the serial communication capability.

B.3.5 <u>FLC Demonstrations</u>

The fuzzy logic controller is demonstrated using three different configurations of the rule-base.

The configurations of the FLC rule bases are as follows.

- SISO P controller (Single Input Single Output with Proportional control).
- MISO P + P controller (Multiple Input Single Output with two variables providing proportional gain control).

- MISO PD + P controller (Multiple Input Single Output. Control is determined by one variable providing a proportional and derivative gain, the second providing a proportional gain only).

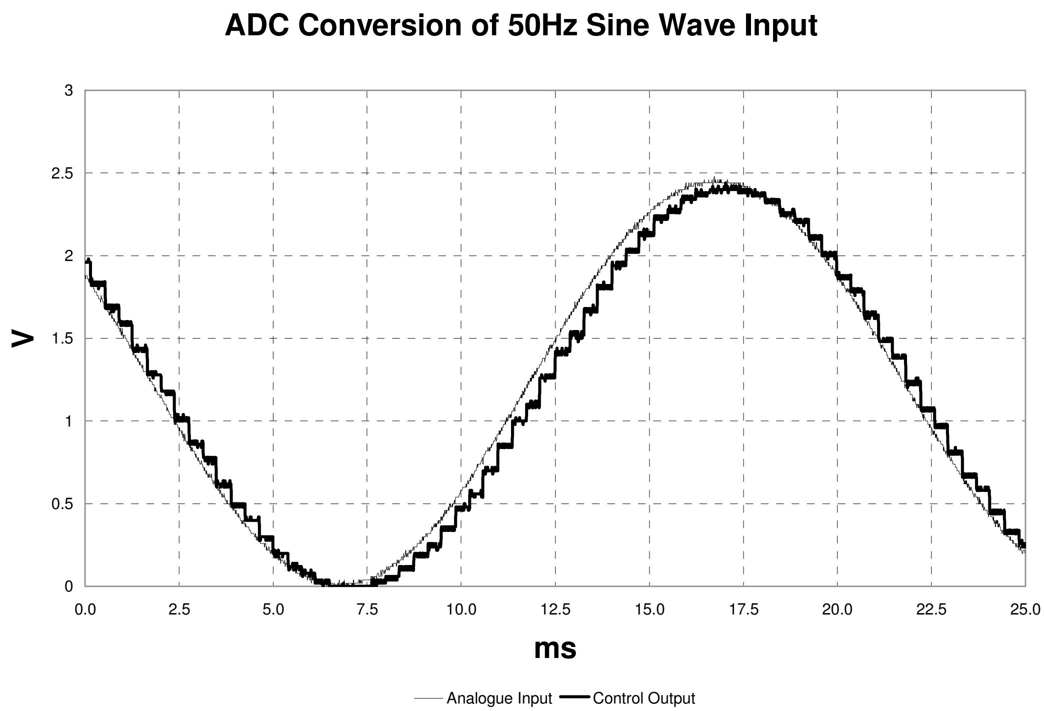
The microcontroller is programmed with the same program for each test, with the exception of the rule base. The SISO controller is demonstrated using a single input whereas the MISO is demonstrated using two inputs. The output from the microcontroller DAC demonstrates to the user the action of the control system.

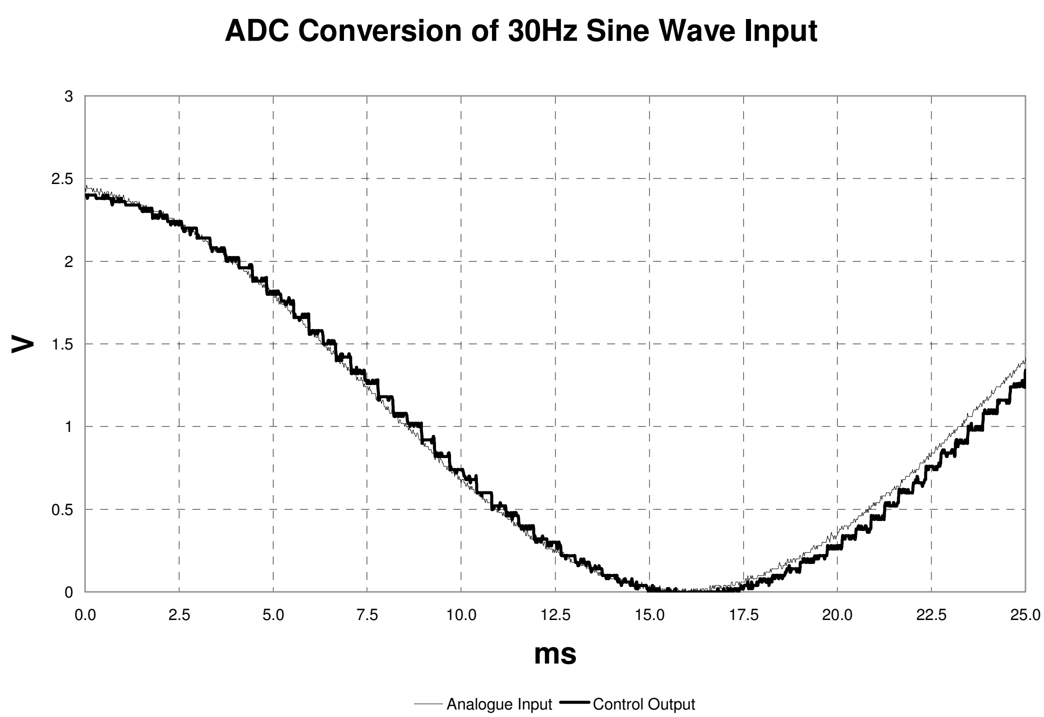
B.3.6 Serial Control Demonstration

The microcontroller is programmed with a simple state machine to demonstrate the control available from the serial communication capability. The command to the microcontroller is either to stop or start. Demonstrating the operation is achieved by outputting the numerical control value from the DAC. The microcontroller outputs a DAC value of 0 when the command to stop has been given. The microcontroller operates the SISO P rule base used to demonstrate the FLC when the start command is received.

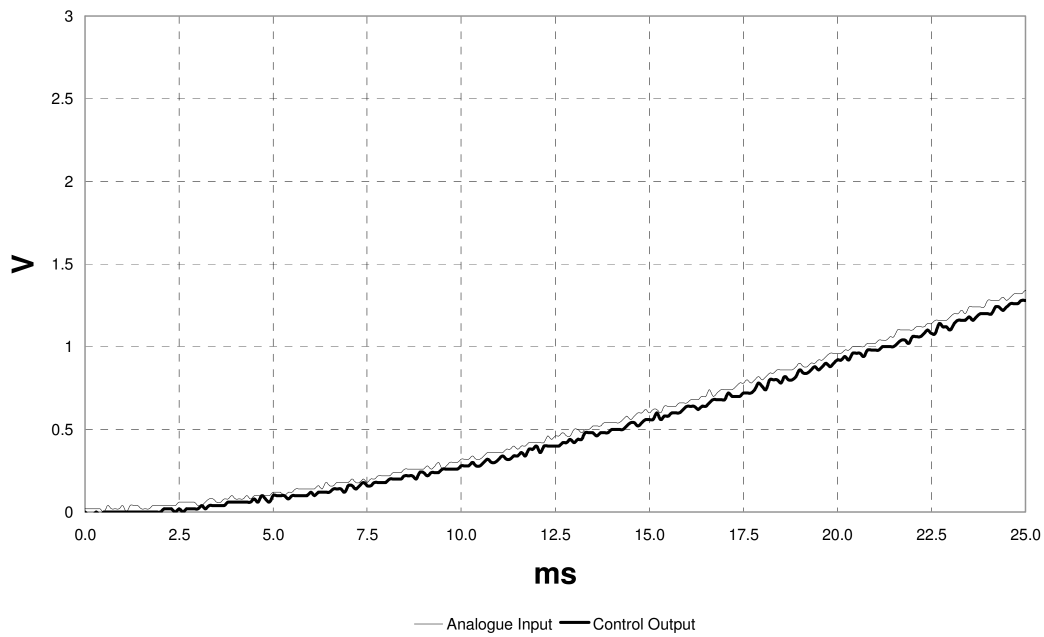
APPENDIX C SOFT MODULE TEST RESULTS

C.1 ADC Soft Module Oscilloscope Traces

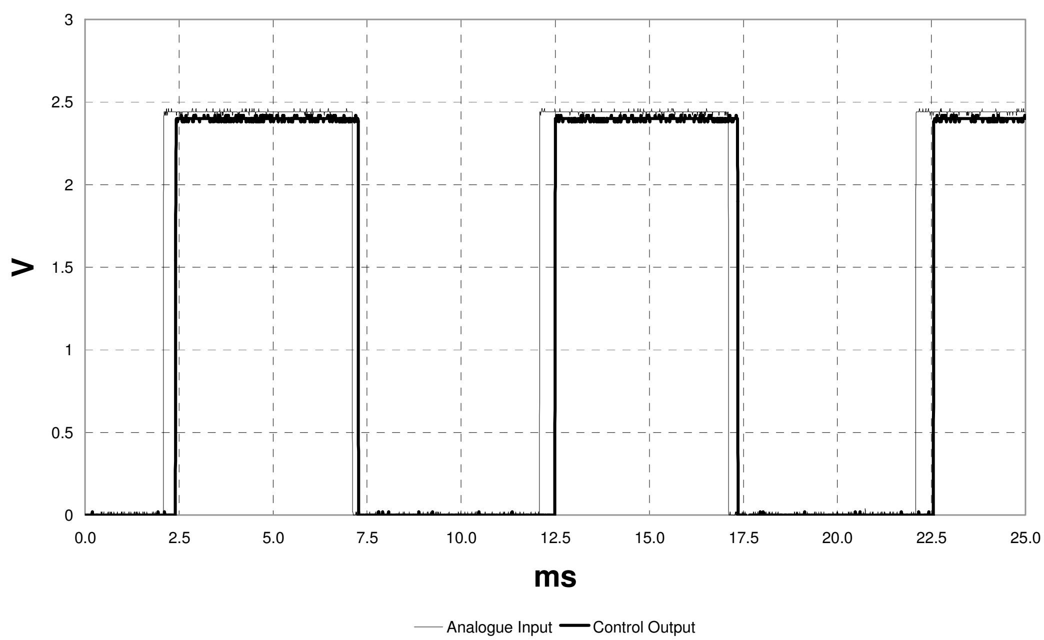




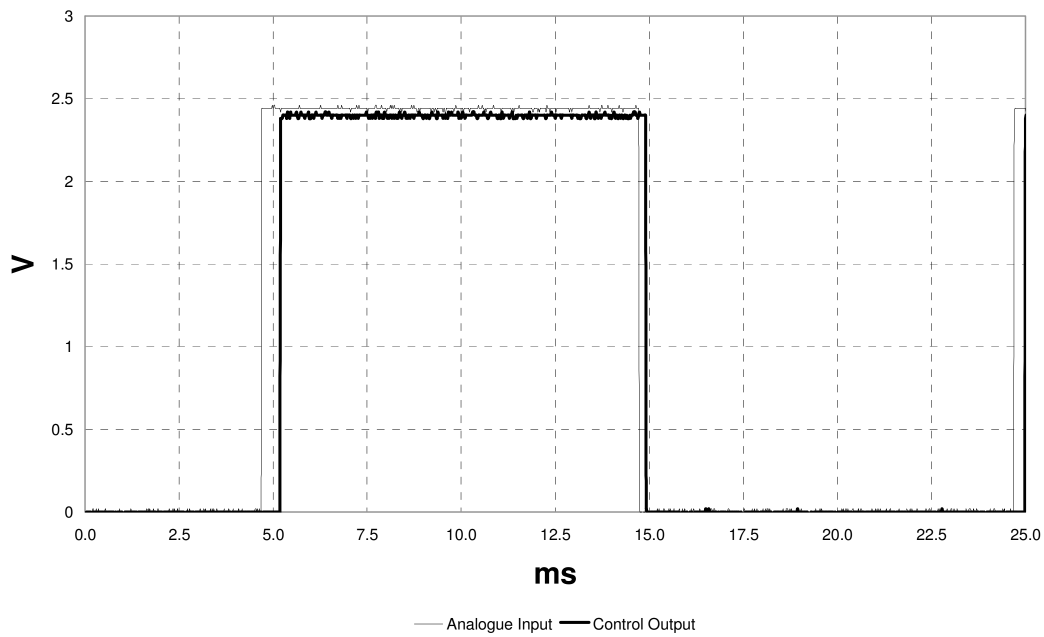
ADC Conversion of 10Hz Sine Wave Input



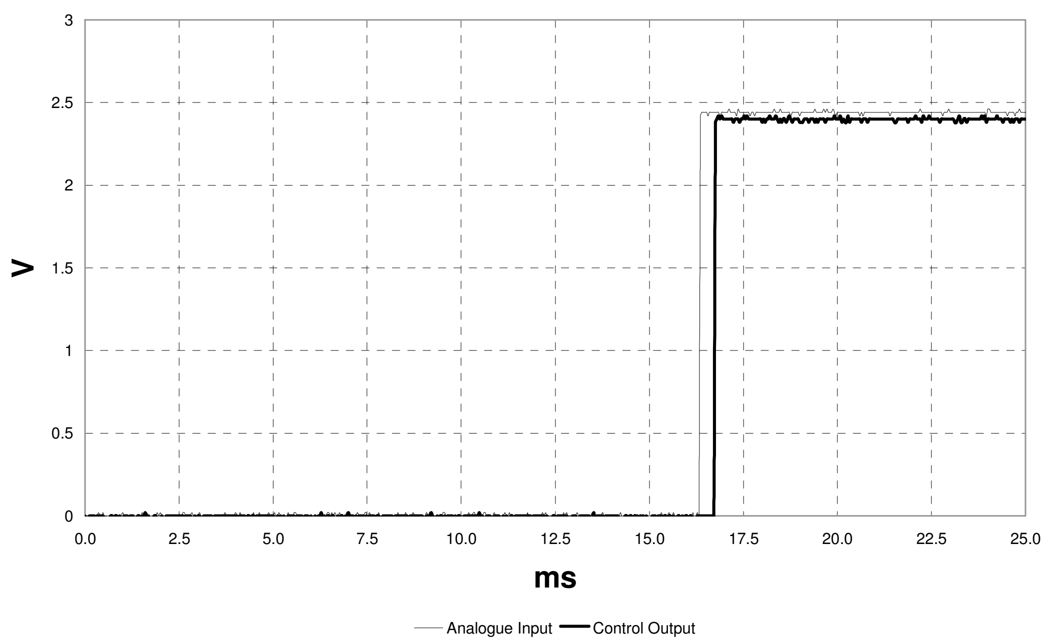
ADC Conversion of 100Hz Square Wave Input



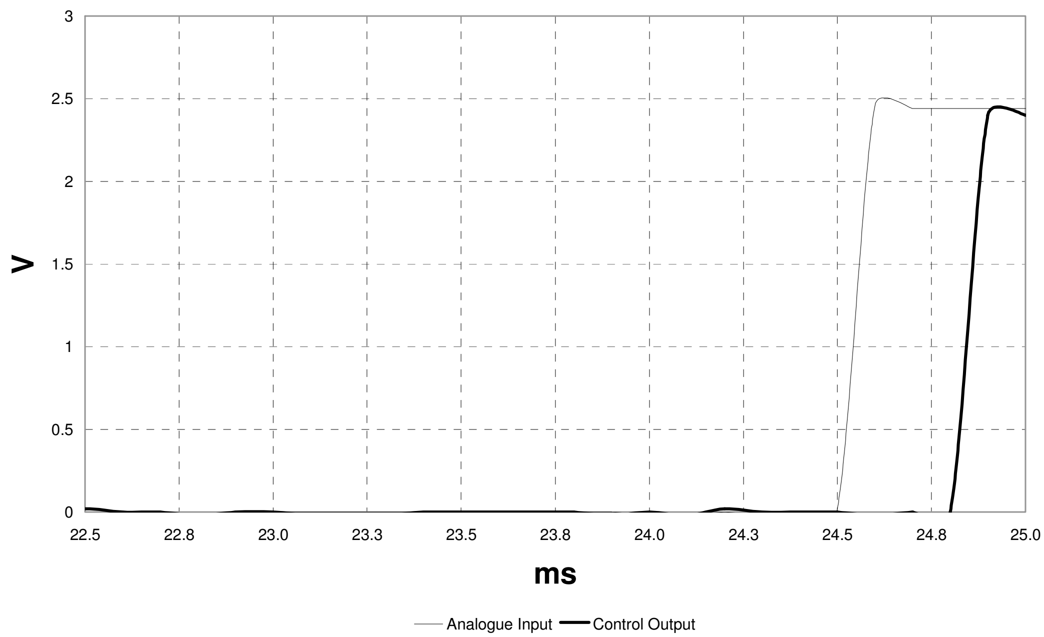
ADC Conversion of 50Hz Square Wave Input



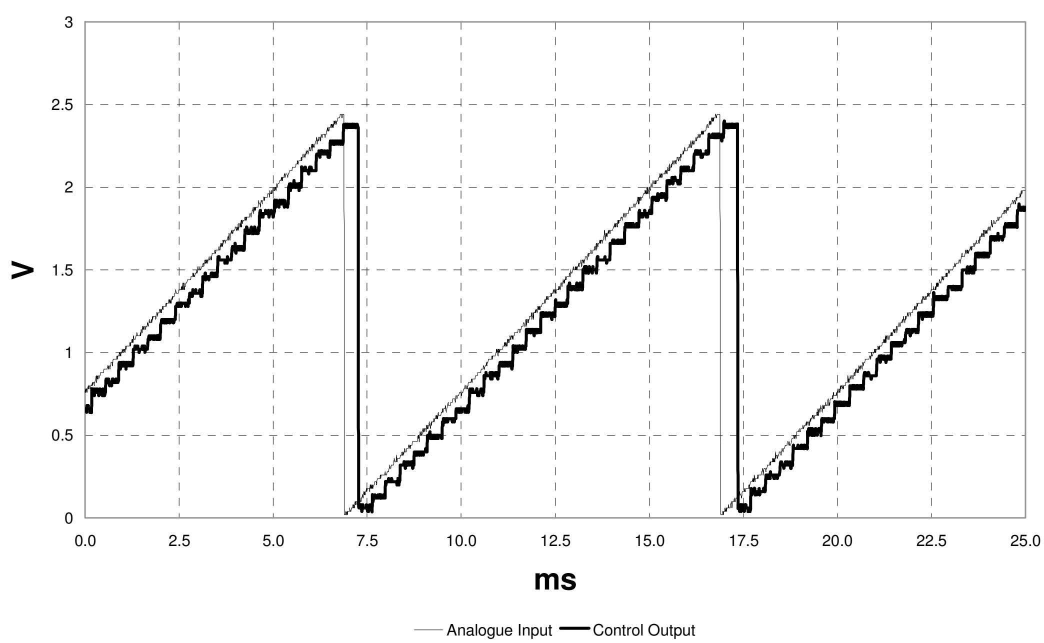
ADC Conversion of 30Hz Square Wave Input



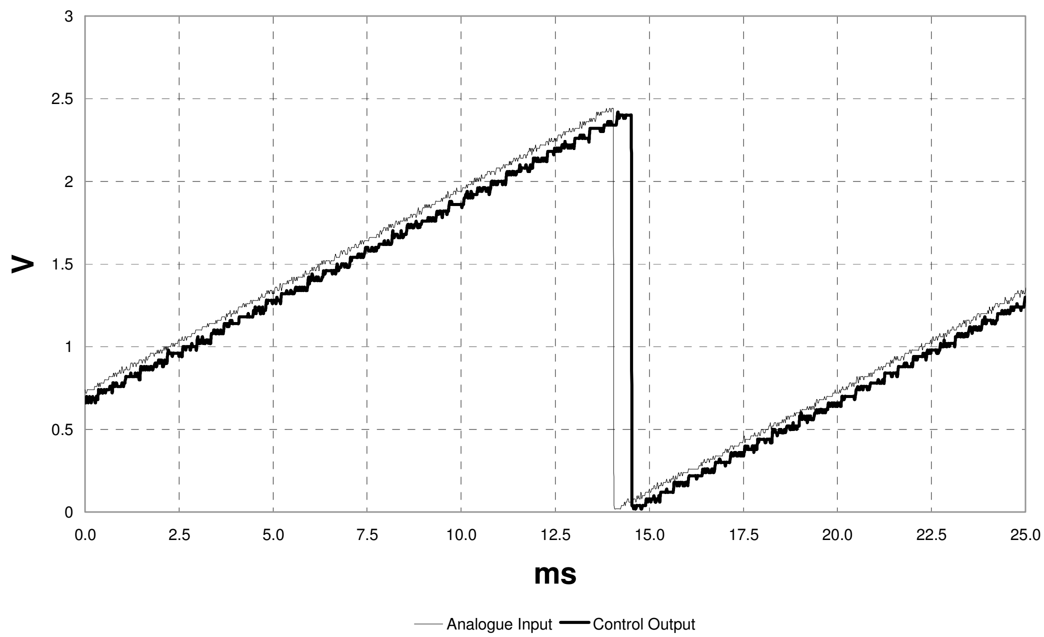
ADC Conversion of 10Hz Square Wave Input



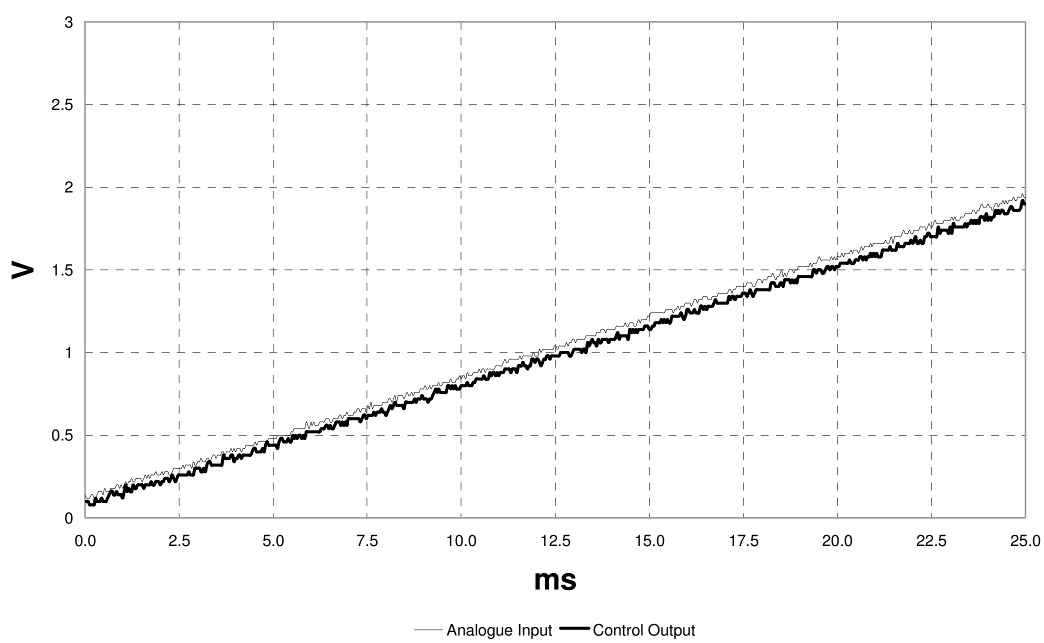
ADC Conversion of 100Hz Ramp Wave Input

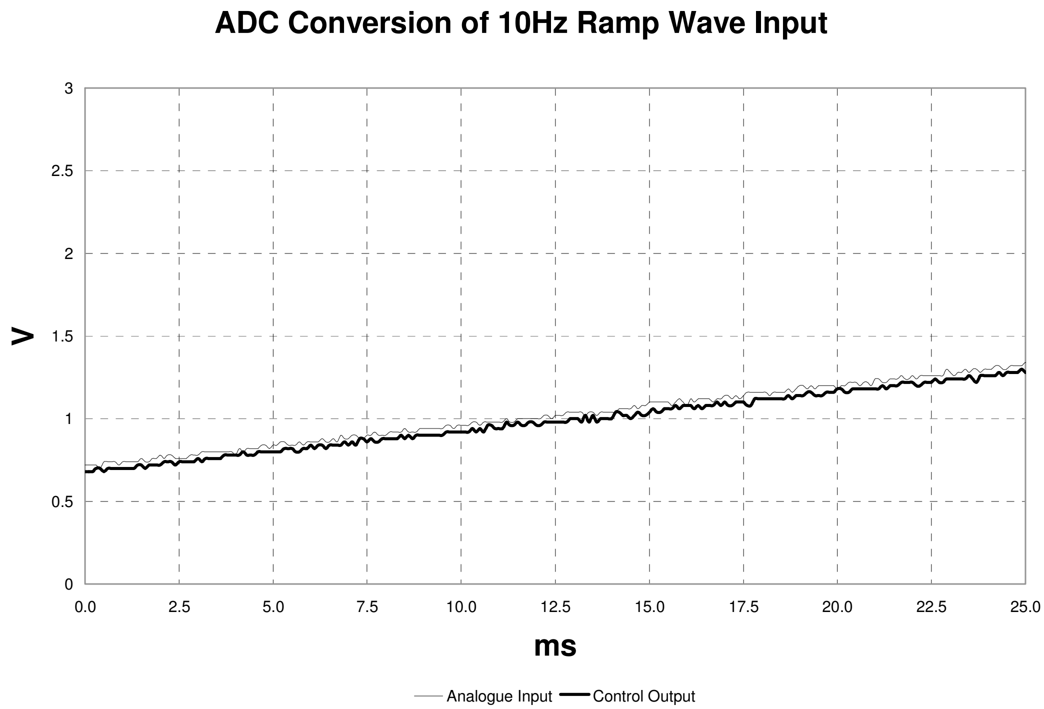


ADC Conversion of 50Hz Ramp Wave Input

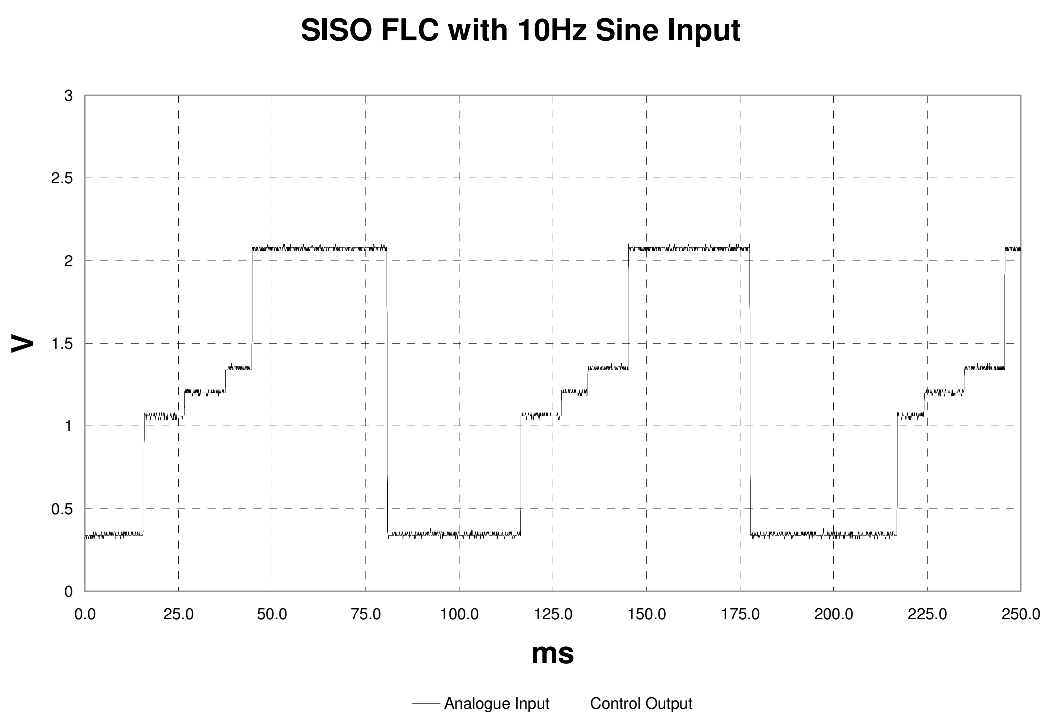


ADC Conversion of 30Hz Ramp Wave Input

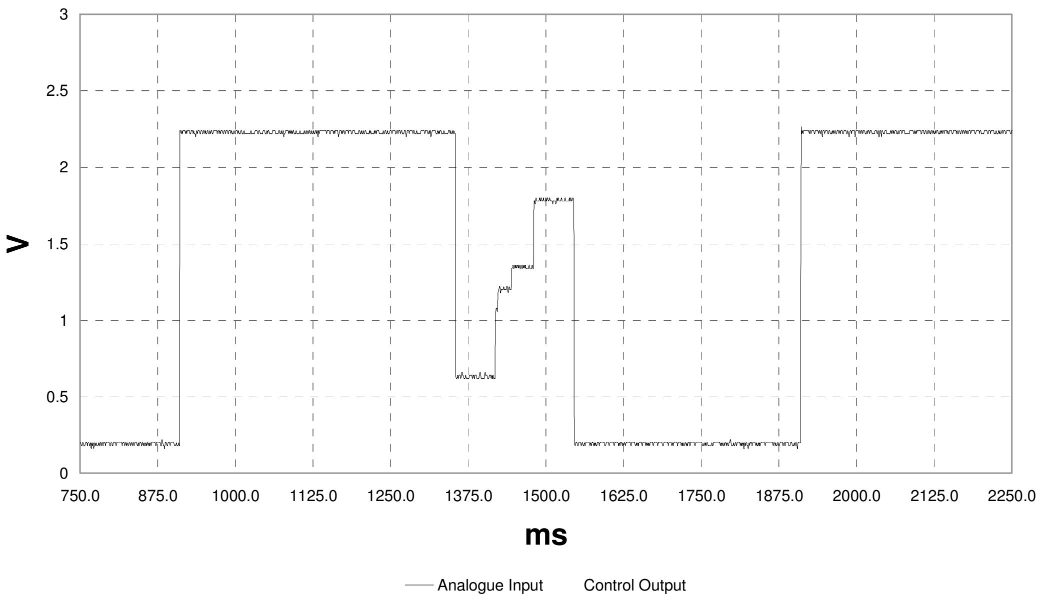




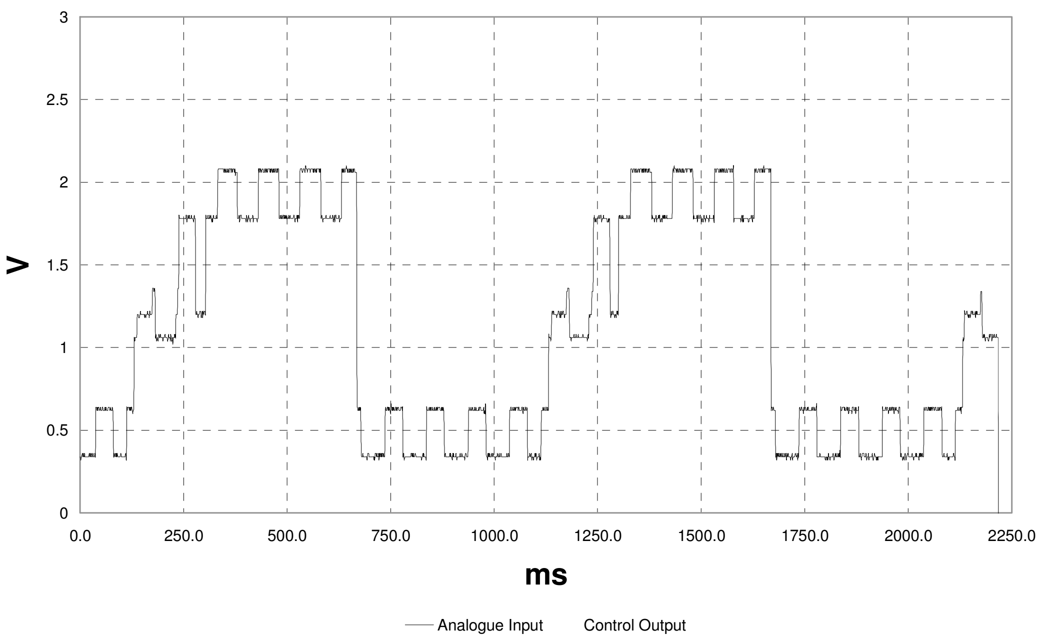
C.2 Fuzzy Logic Controller Oscilloscope Traces

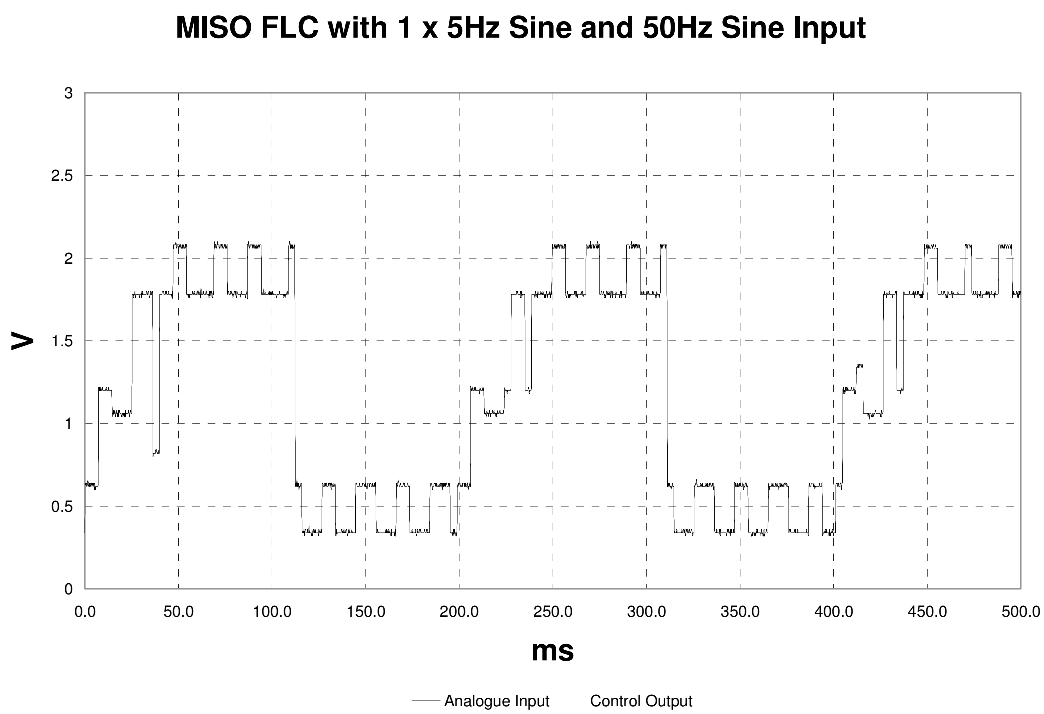


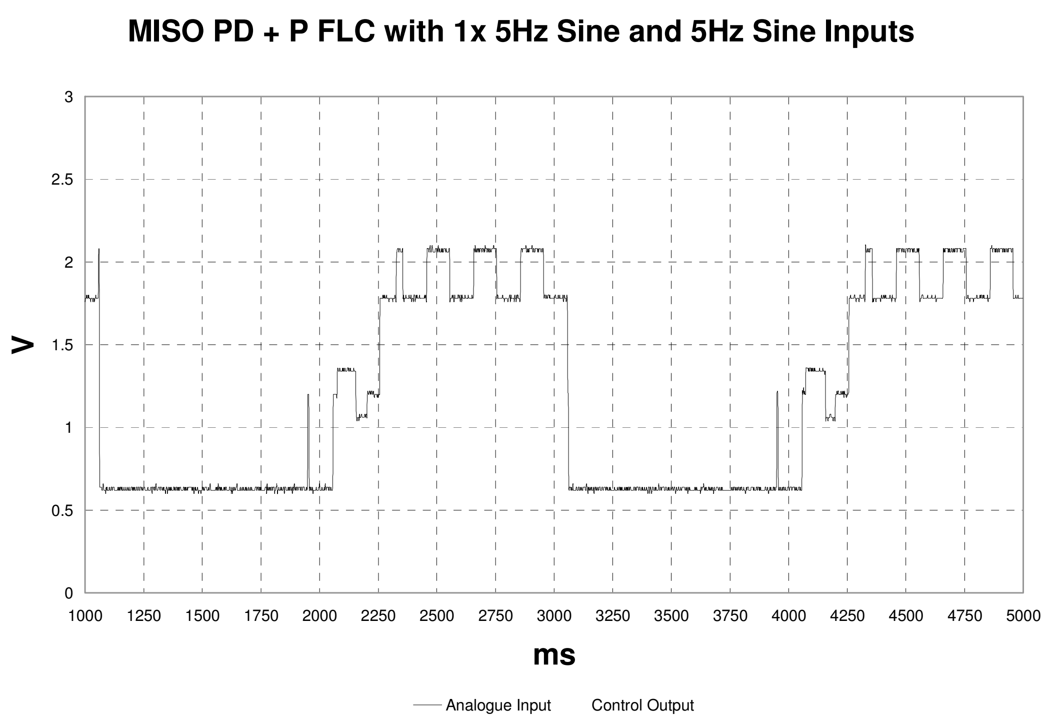
MISO FLC with 2 x 1Hz Sine Inputs (180 degrees phase difference)



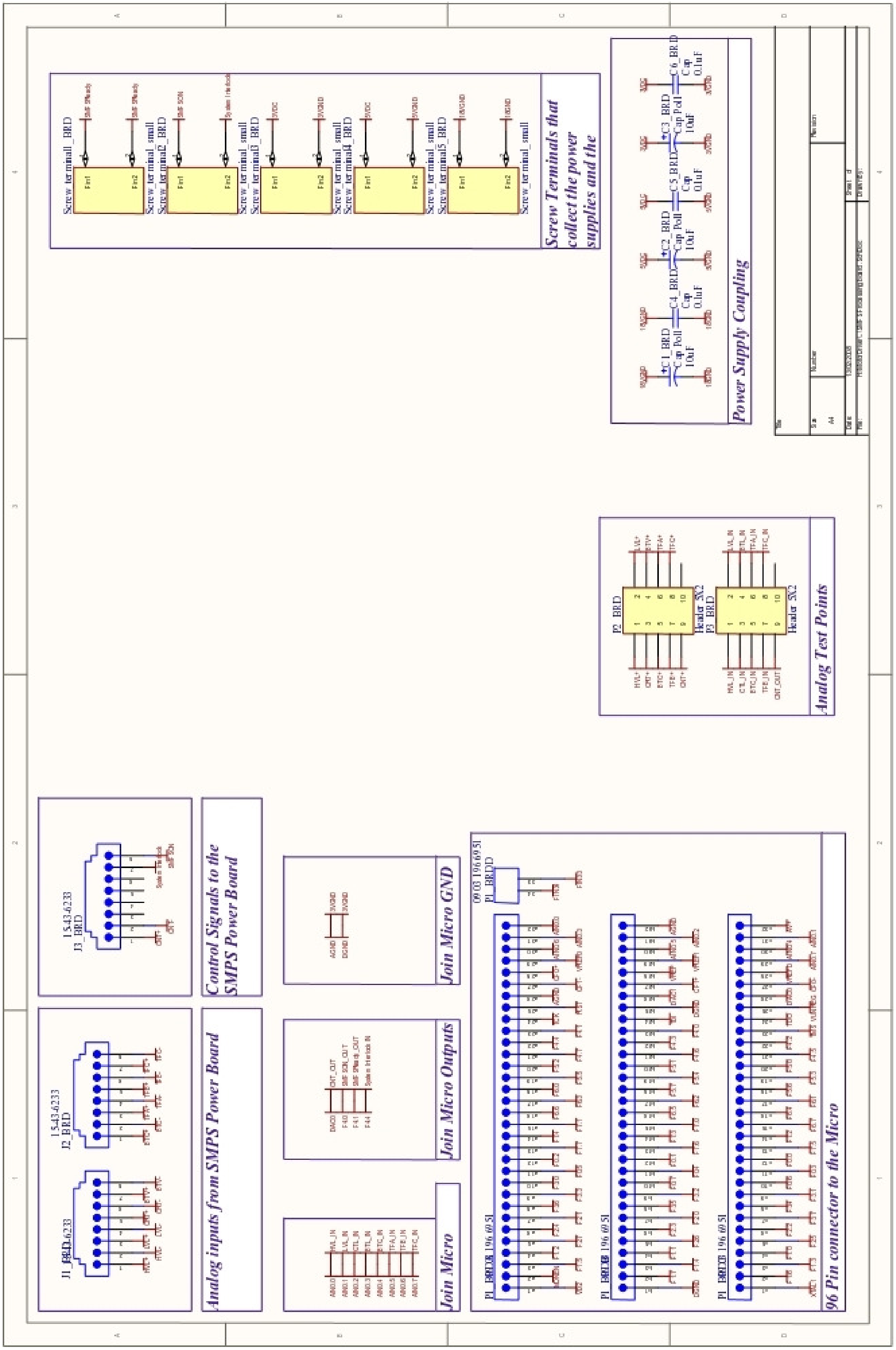
MISO FLC with 1 x 1Hz Sine and 1x 10hz Sine Inputs

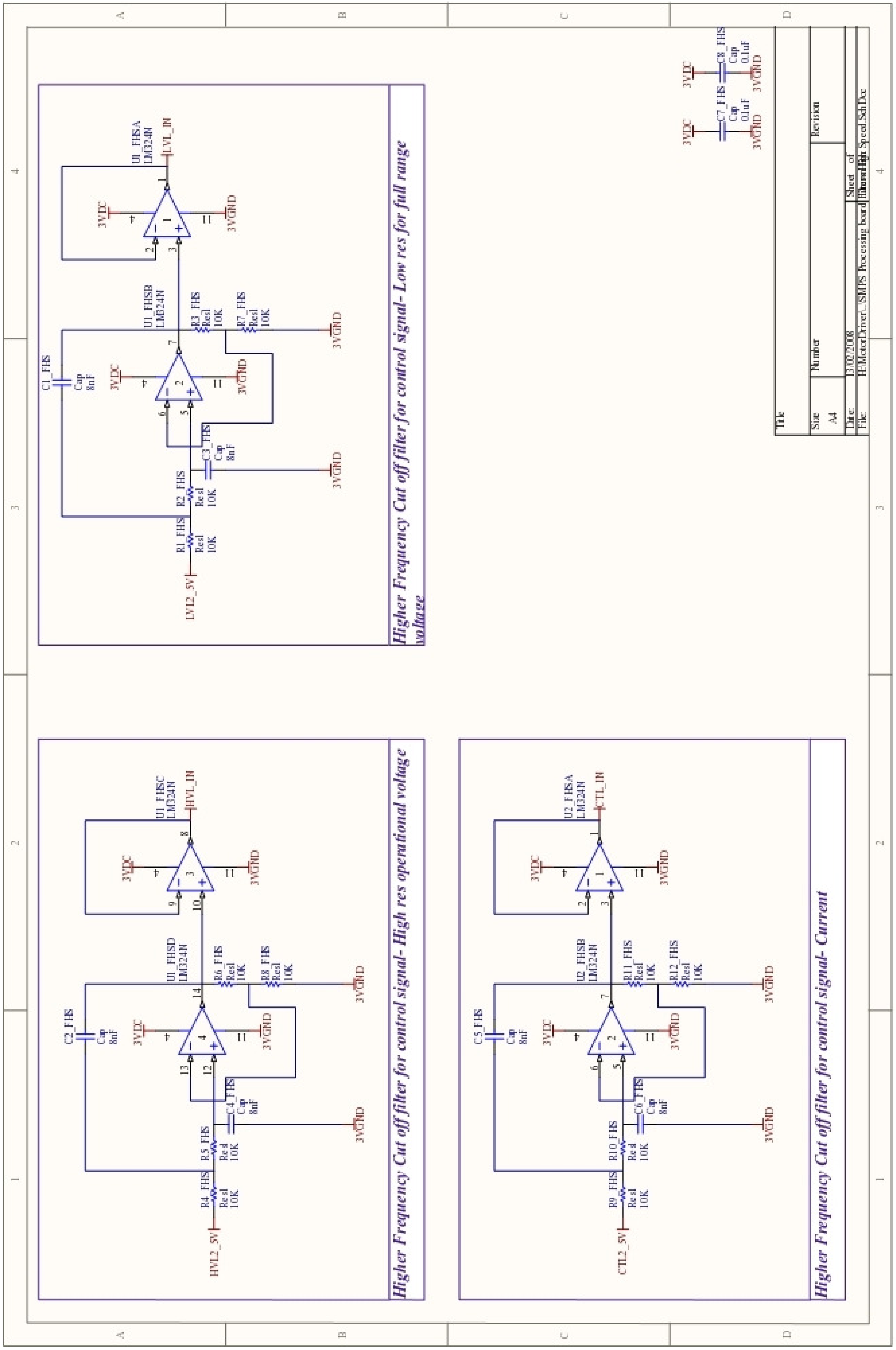


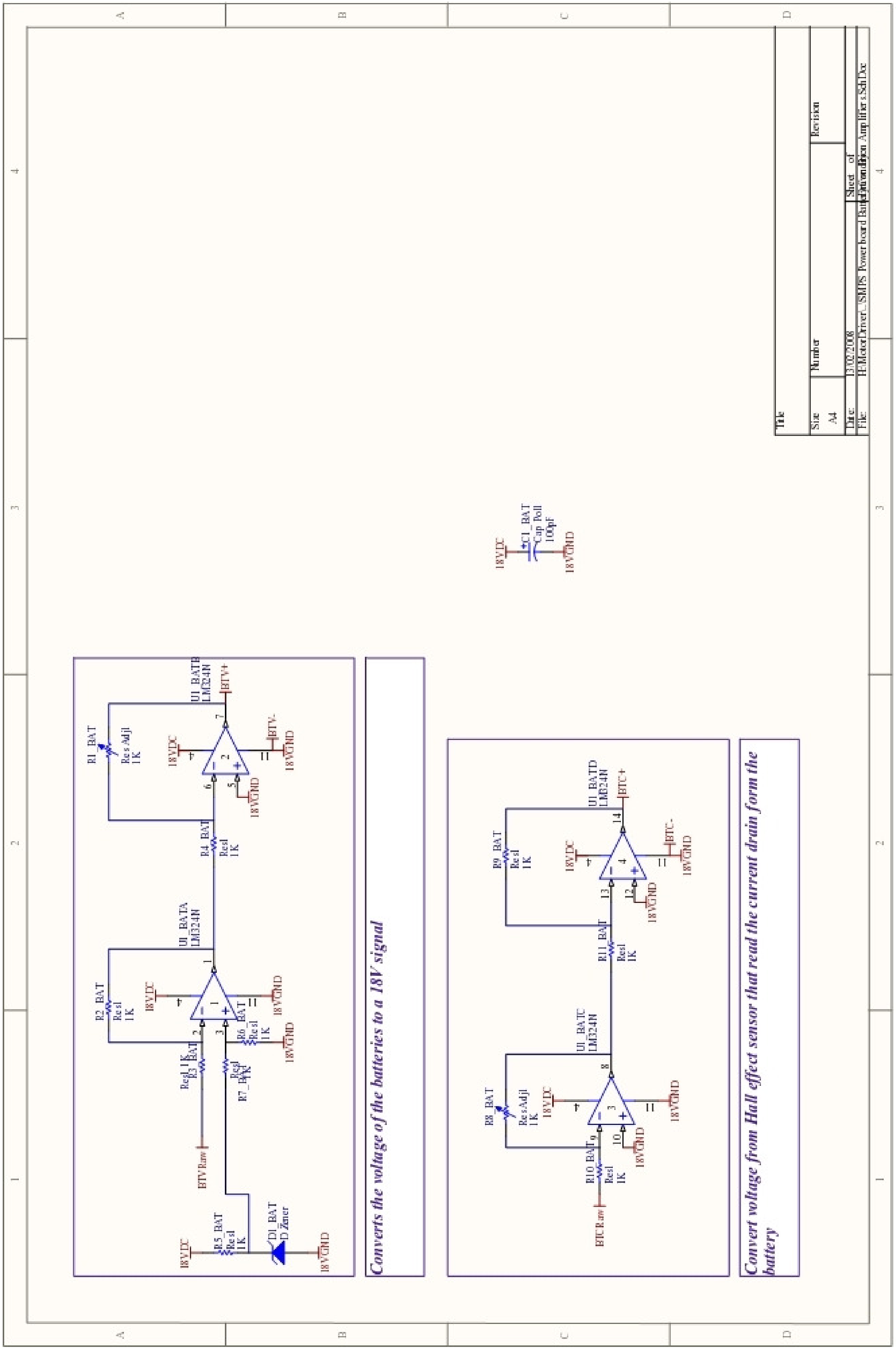

MISO FLC with 1 x 5Hz Sine and 50Hz Sine Input
3
2.5
2
1.5
1
0.5
0
V
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
ms
Analogue Input
Control Output

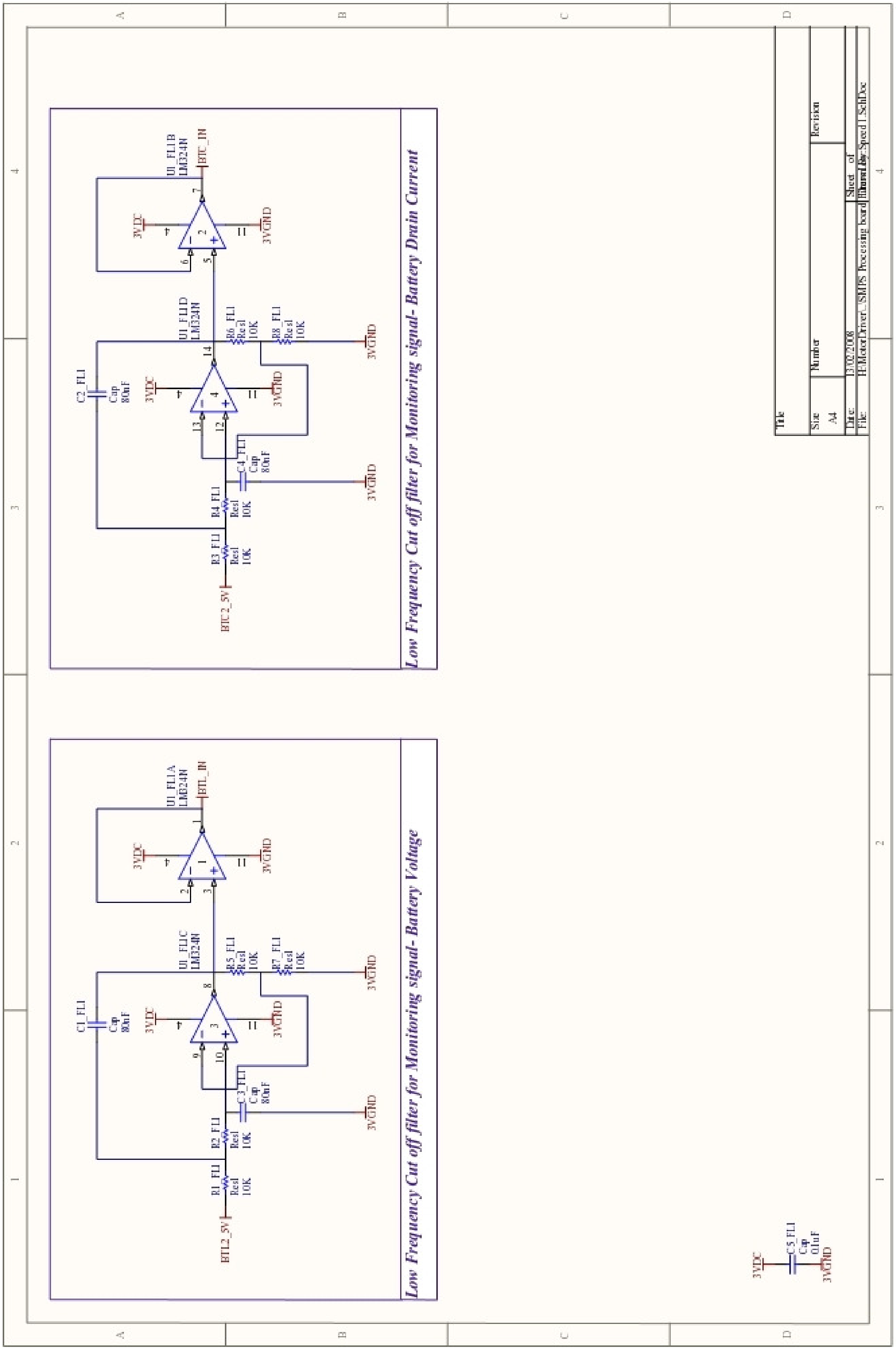

MISO PD + P FLC with 1x 5Hz Sine and 5Hz Sine Inputs
3
2.5
2
1.5
1
0.5
0
V
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3500
3750
4000
4250
4500
4750
5000
ms
Analogue Input
Control Output

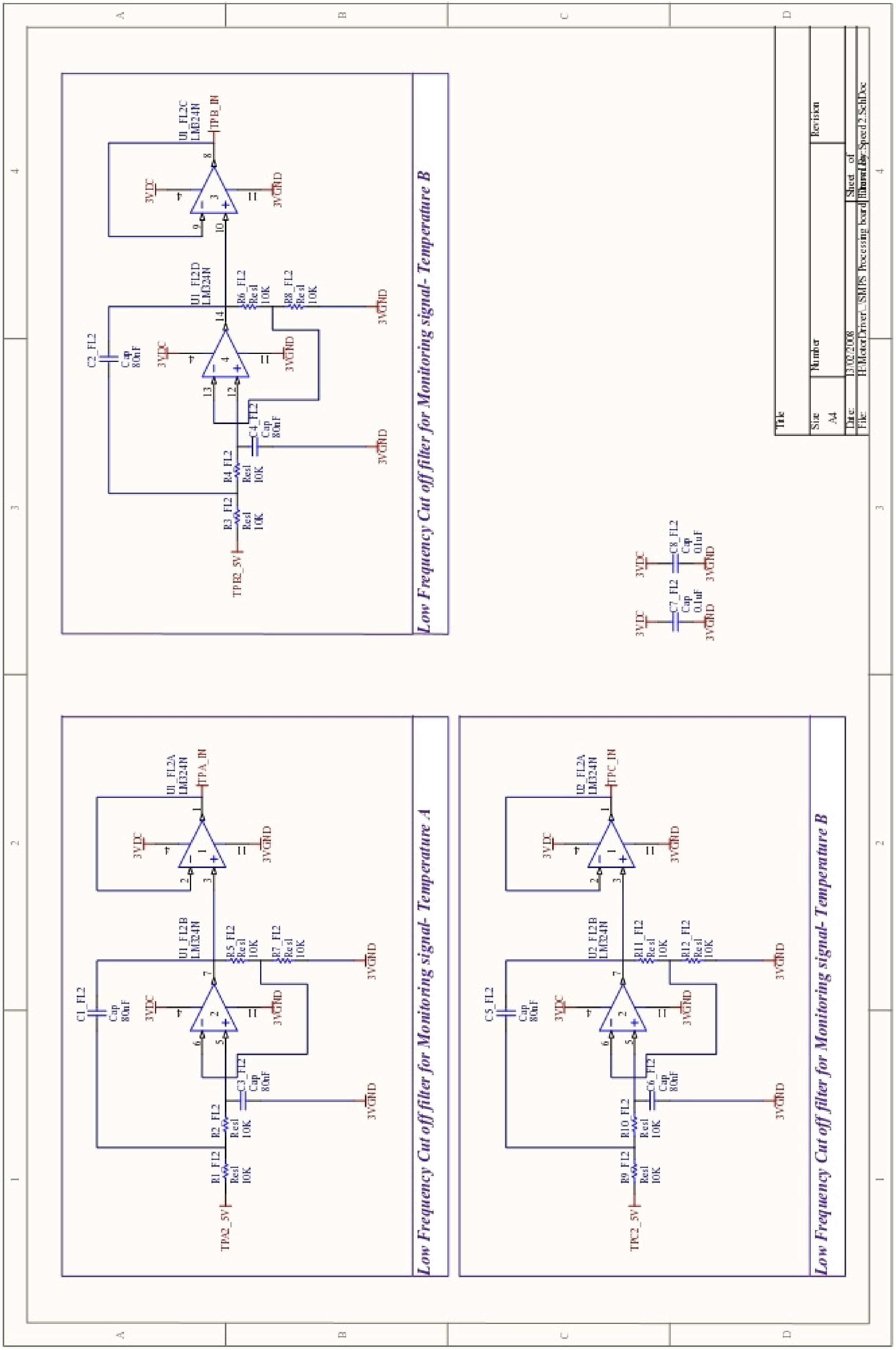
APPENDIX D POWER SUPPLY MODULE HARDWARE DESIGN

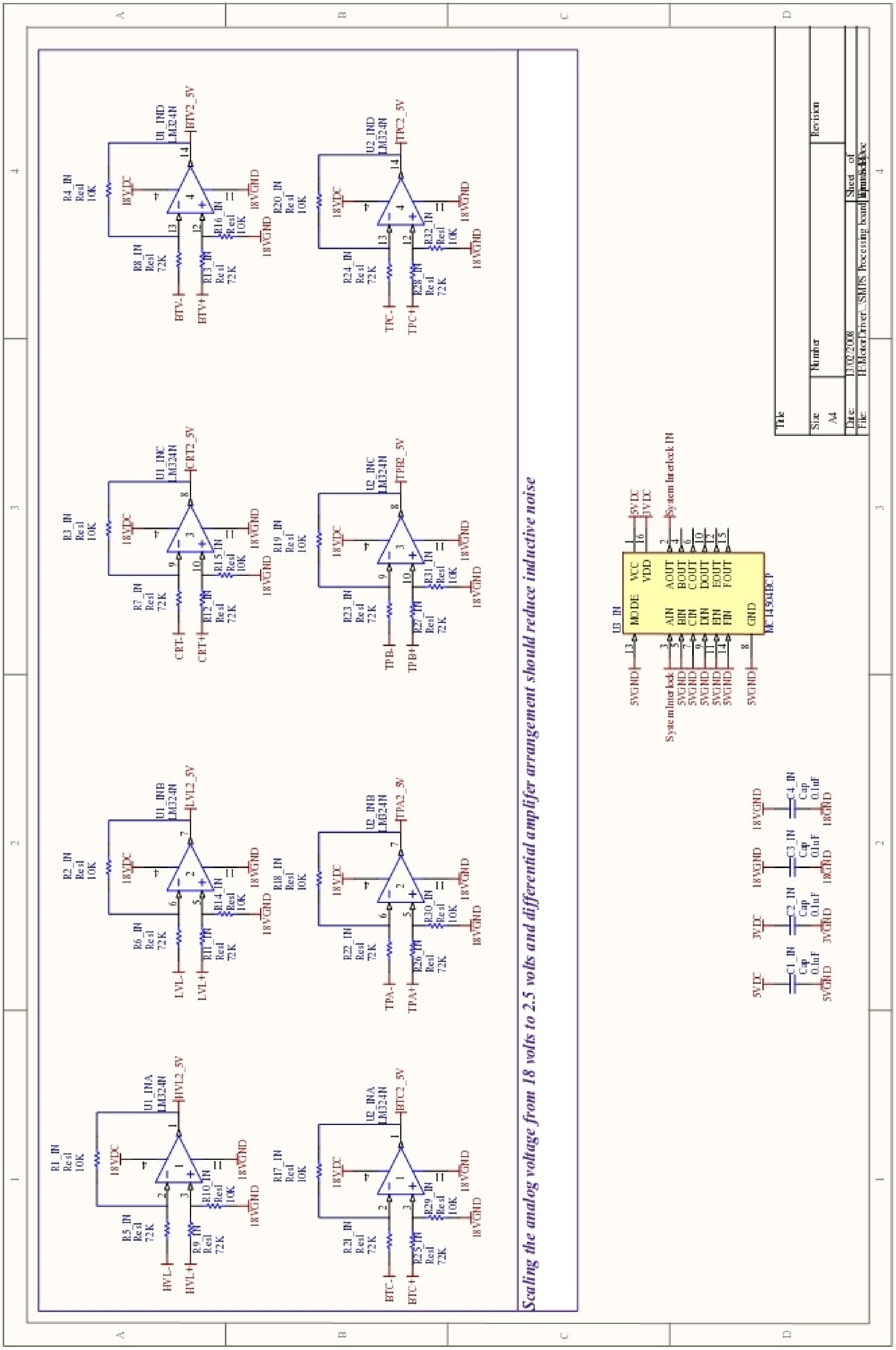

Screw Terminals that collect the power supplies and the
Power Supply Coupling
Analog Test Points
Analog inputs from SMPS Power Board
Control Signals to the SMPS Power Board
Join Micro
Join Micro Outputs
Join Micro GND
96 Pin connector to the Micro

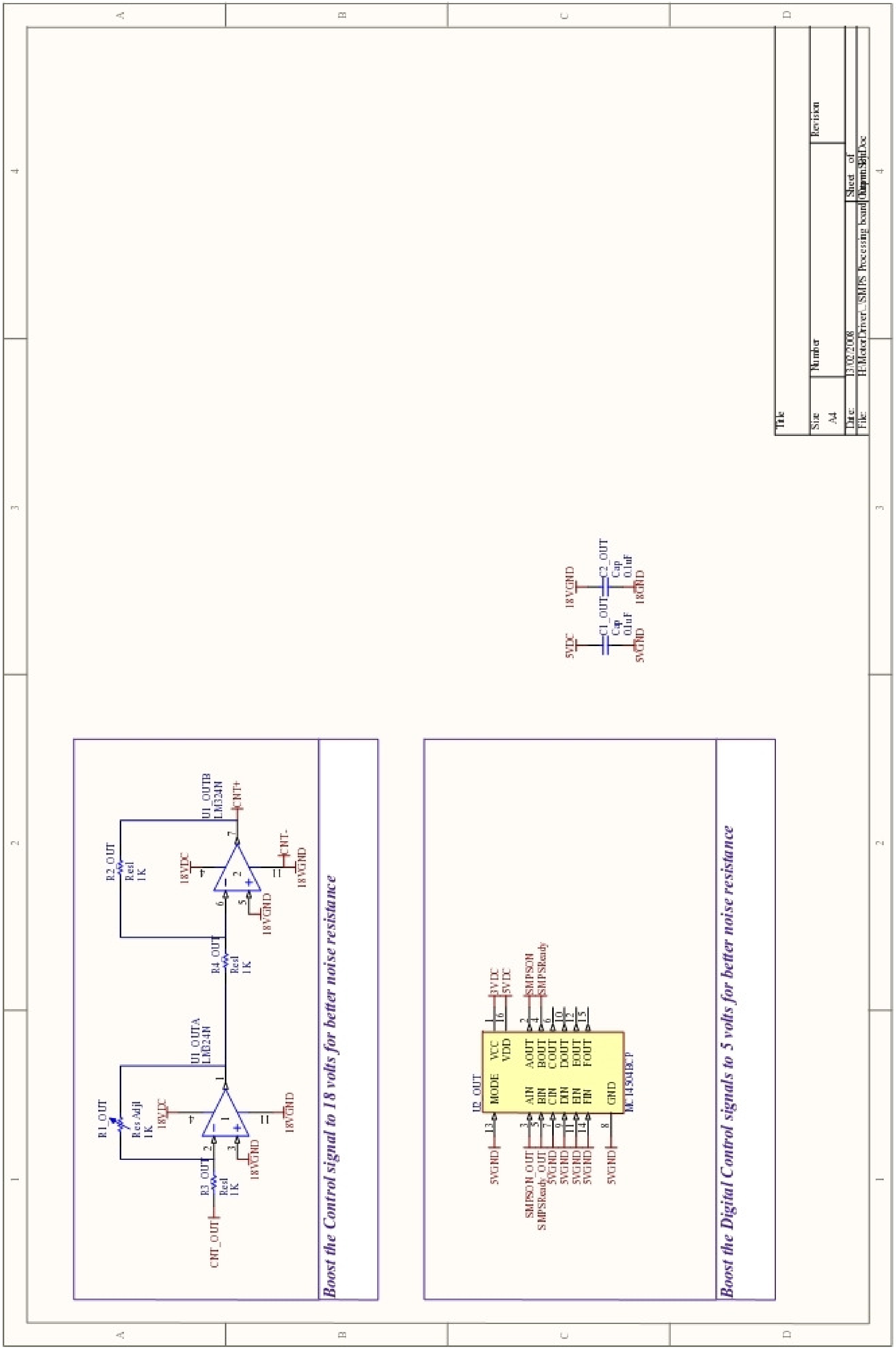

Higher Frequency Cut off filter for control signal- Low res for full range voltage
Higher Frequency Cut off filter for control signal- High res operational voltage
Higher Frequency Cut off filter for control signal- Current

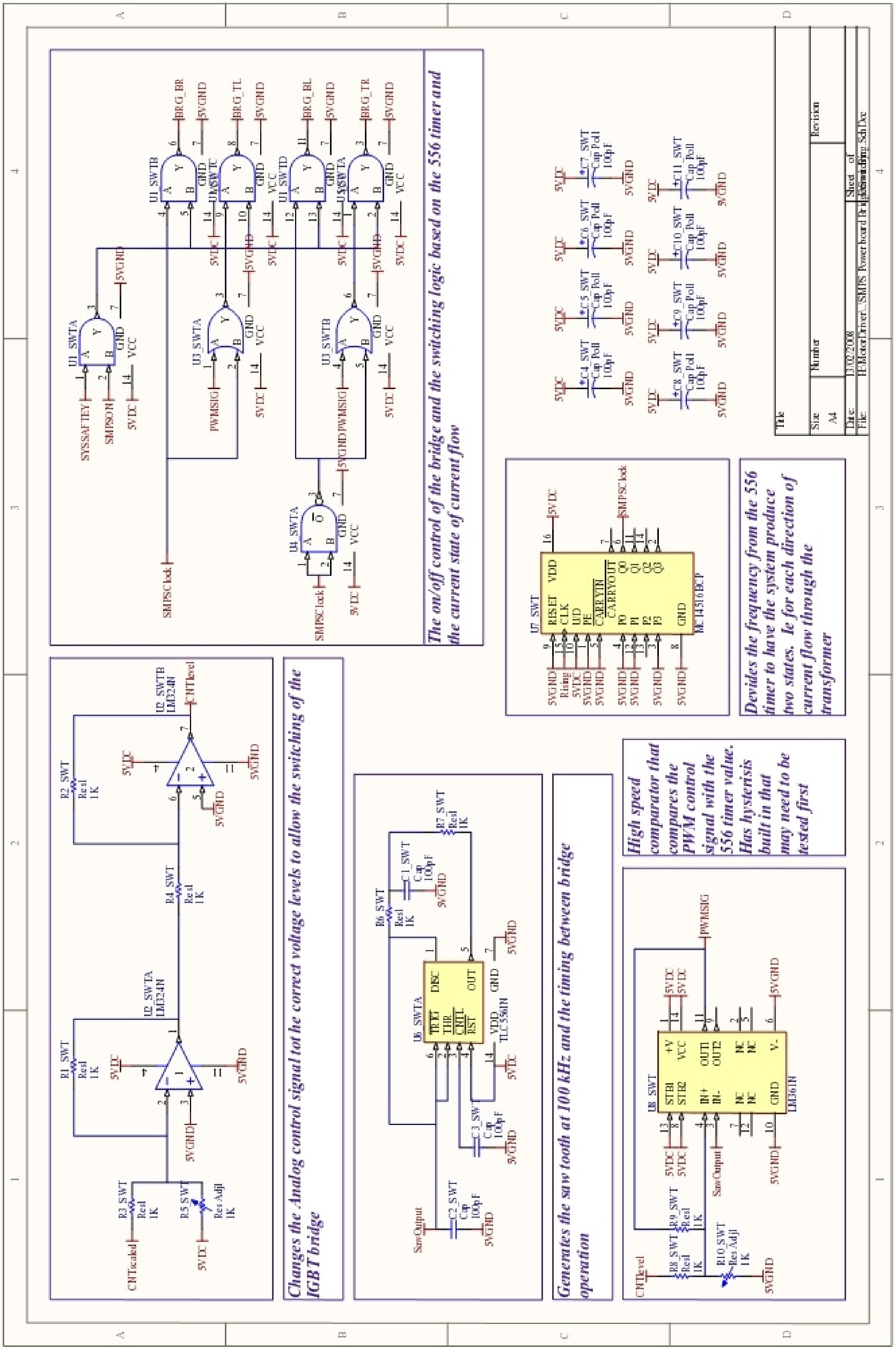

Converts the voltage of the batteries to a 18V signal
Convert voltage from Hall effect sensor that read the current drain form the battery

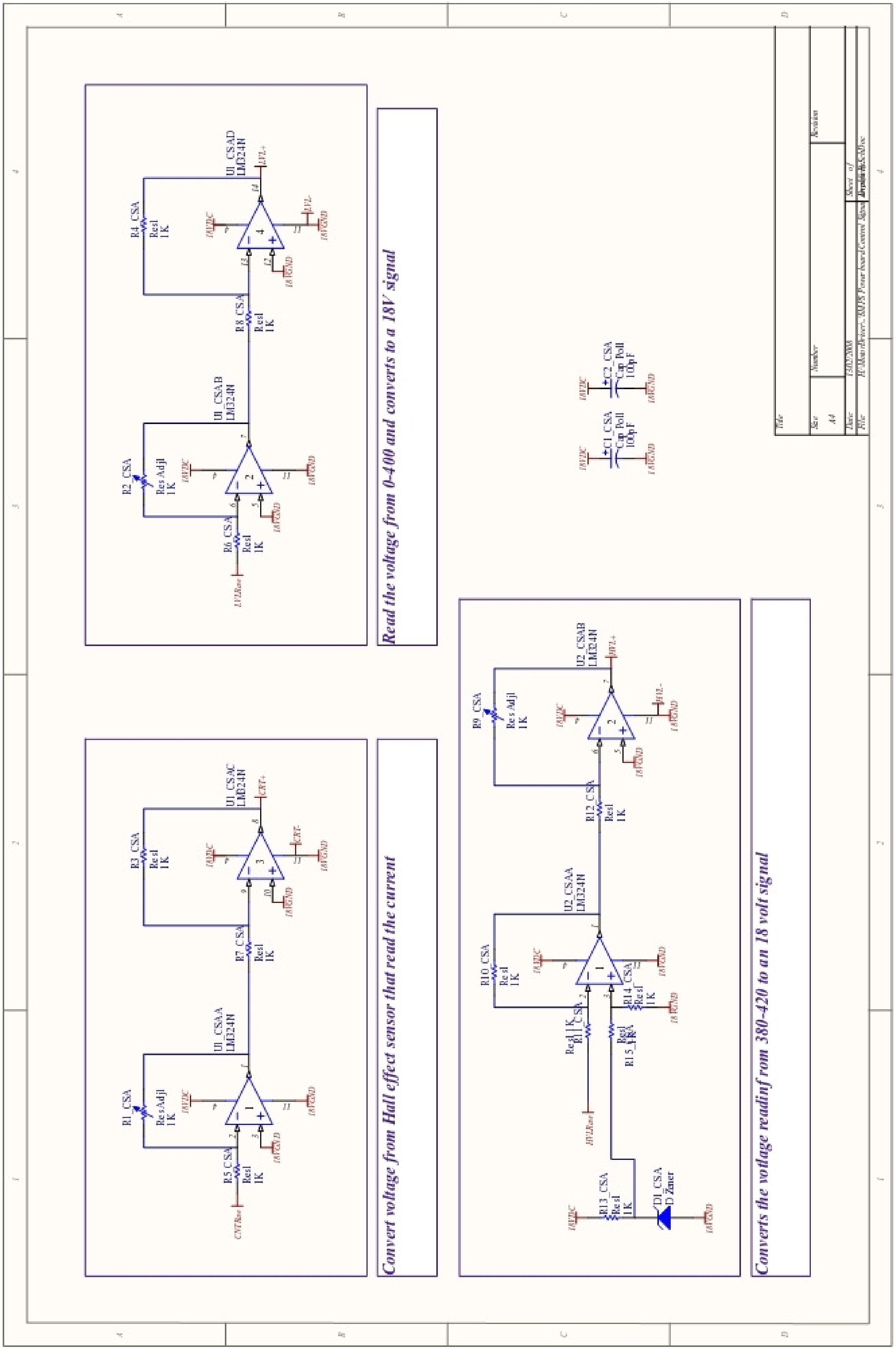

Low Frequency Cut off filter for Monitoring signal- Battery Drain Current
Low Frequency Cut off filter for Monitoring signal- Battery Voltage
U1_FL1B
LM324N
BTC_IN
U1_FL1D
LM324N
C2_FL1
Cap
80nF
R6_FL1
Res1
10K
R8_FL1
Res1
10K
C4_FL1
Cap
80nF
R4_FL1
Res1
10K
R3_FL1
Res1
10K
BTC2_5V
U1_FL1A
LM324N
BTL_IN
U1_FL1C
LM324N
C1_FL1
Cap
80nF
R5_FL1
Res1
10K
R7_FL1
Res1
10K
C3_FL1
Cap
80nF
R2_FL1
Res1
10K
R1_FL1
Res1
10K
BTL2_5V
3VDC
3VGND
C5_FL1
Cap
0.1uF
Title
Size
A4
Number
Revision
Date:
13/02/2008
File:
Sheet of


Low Frequency Cut off filter for Monitoring signal- Temperature B
Low Frequency Cut off filter for Monitoring signal- Temperature A
Low Frequency Cut off filter for Monitoring signal- Temperature B

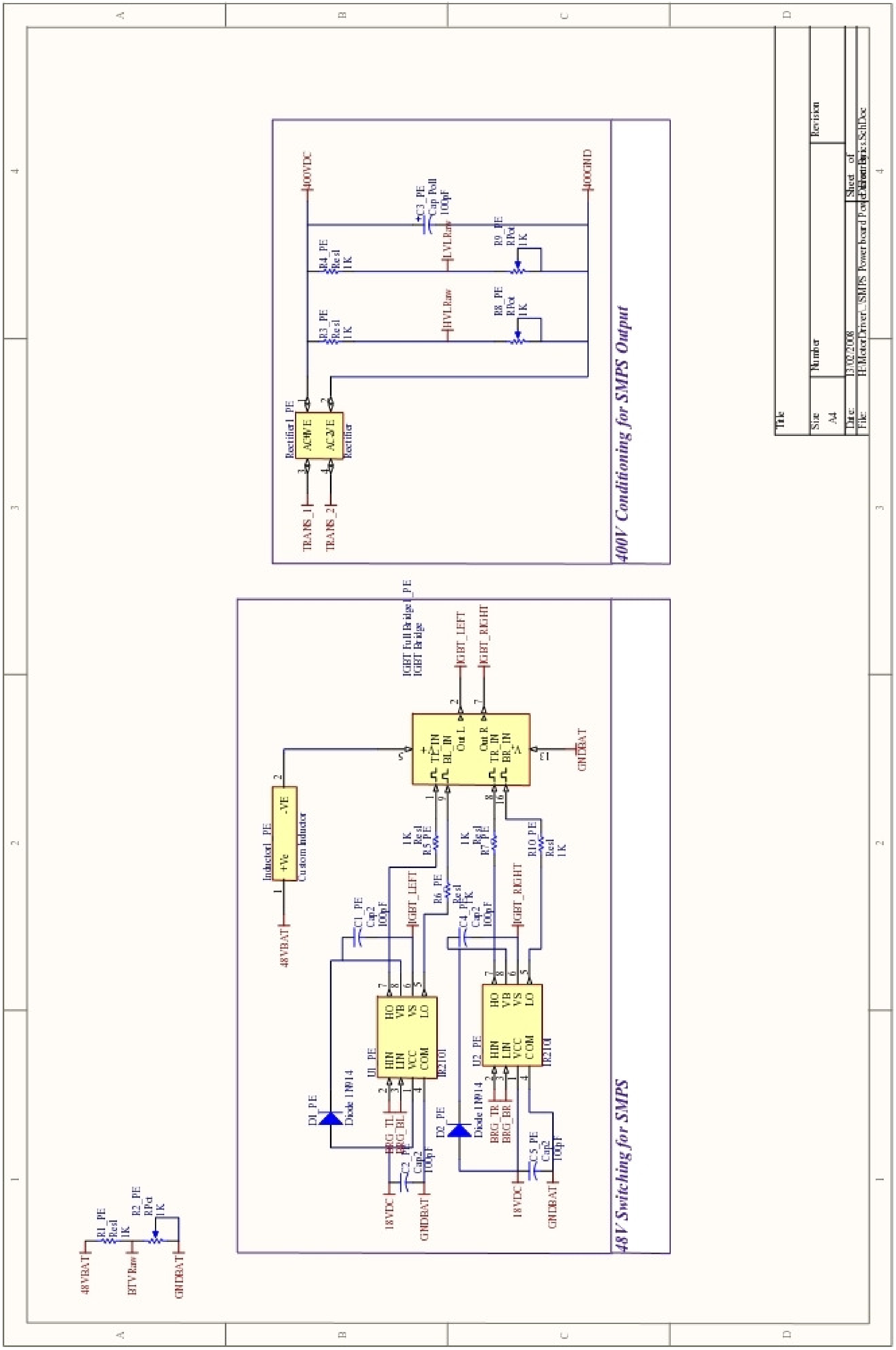

Scaling the analog voltage from 18 volts to 2.5 volts and differential amplifer arrangement should reduce inductive noise
MC14504BCP
LM324N

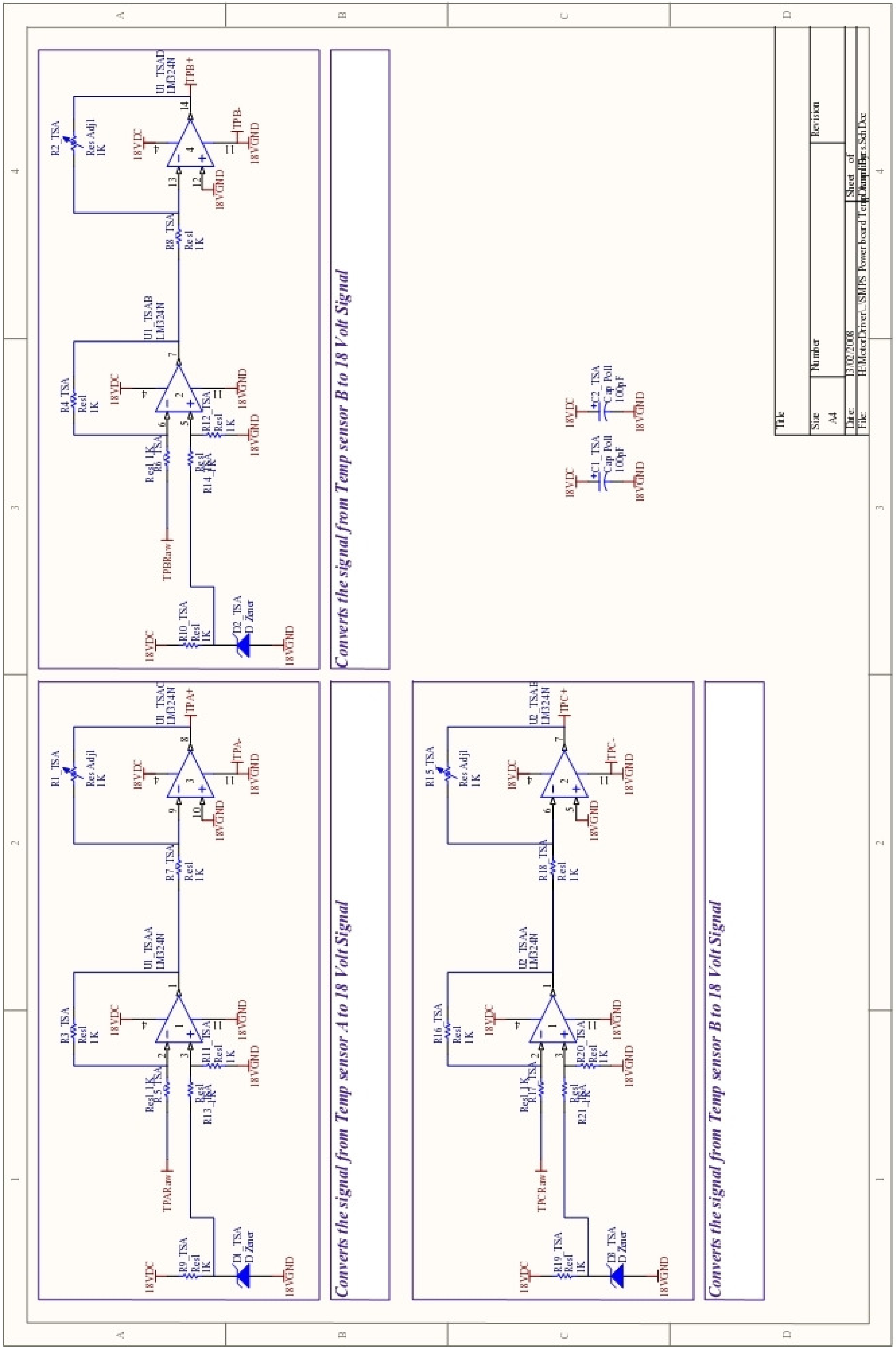

Boost the Control signal to 18 volts for better noise resistance
Boost the Digital Control signals to 5 volts for better noise resistance

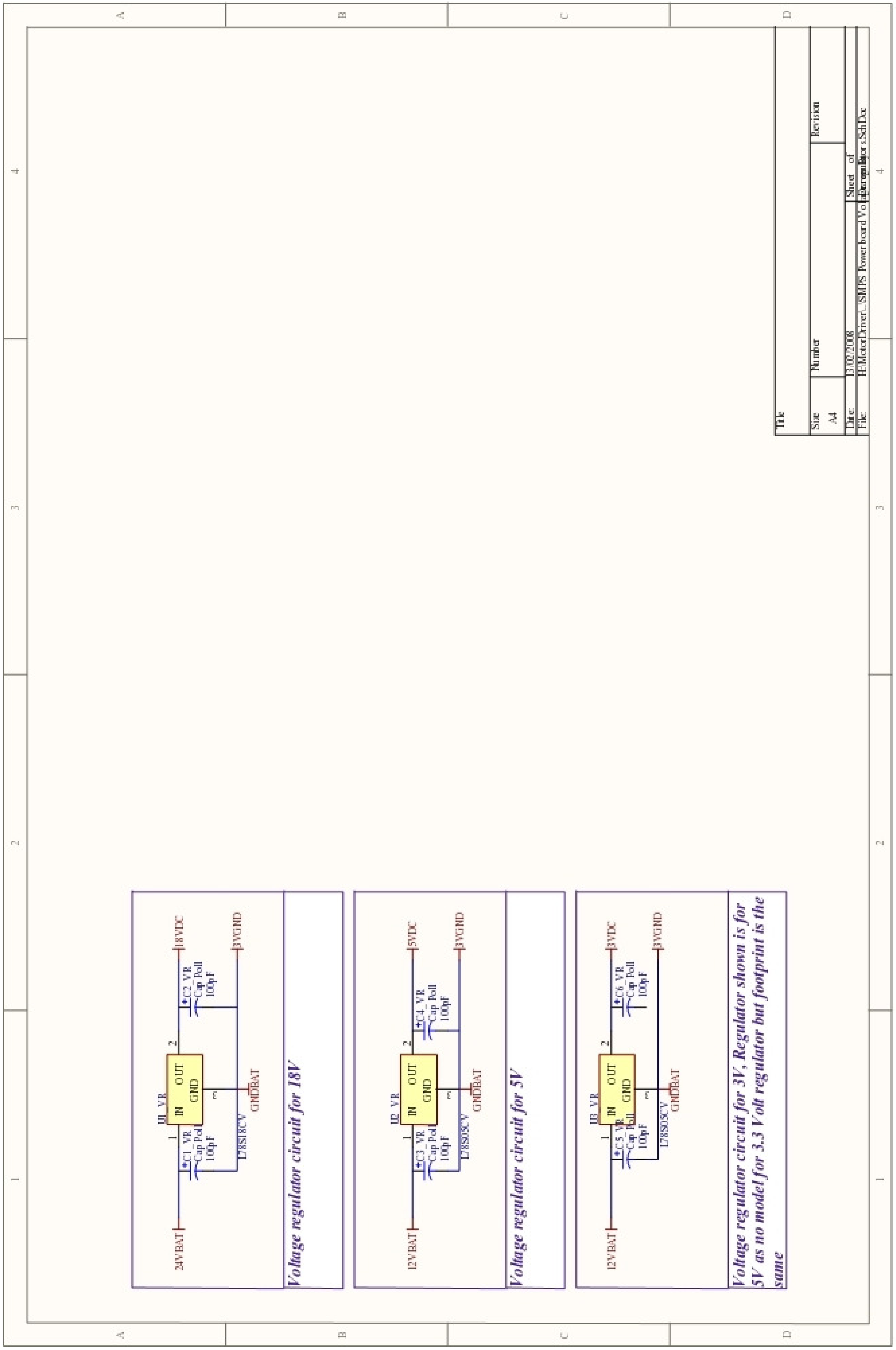

The on/off control of the bridge and the switching logic based on the 556 timer and the current state of current flow
Changes the Analog control signal tot he correct voltage levels to allow the switching of the IGBT bridge
Generates the saw tooth at 100 kHz and the timing between bridge operation
High speed comparator that compares the PWM control signal with the 556 timer value. Has hysterisis built in that may need to be tested first
Devides the frequency from the 556 timer to have the system produce two states. Ie for each direction of current flow through the transformer

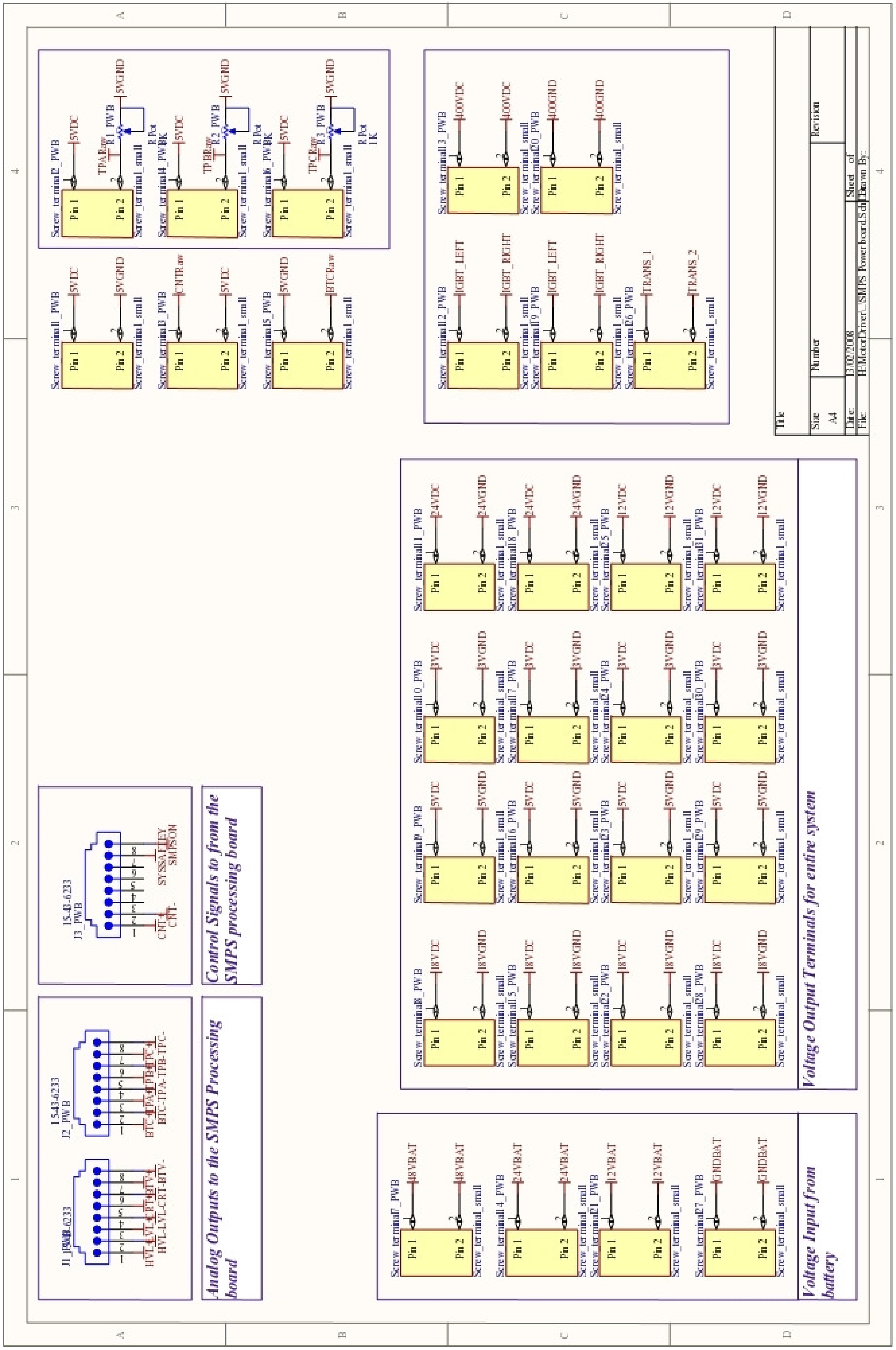


Read the voltage from 0-400 and converts to a 18V signal
Convert voltage from Hall effect sensor that read the current
Converts the votlage readinf rom 380~420 to an 18 volt signal

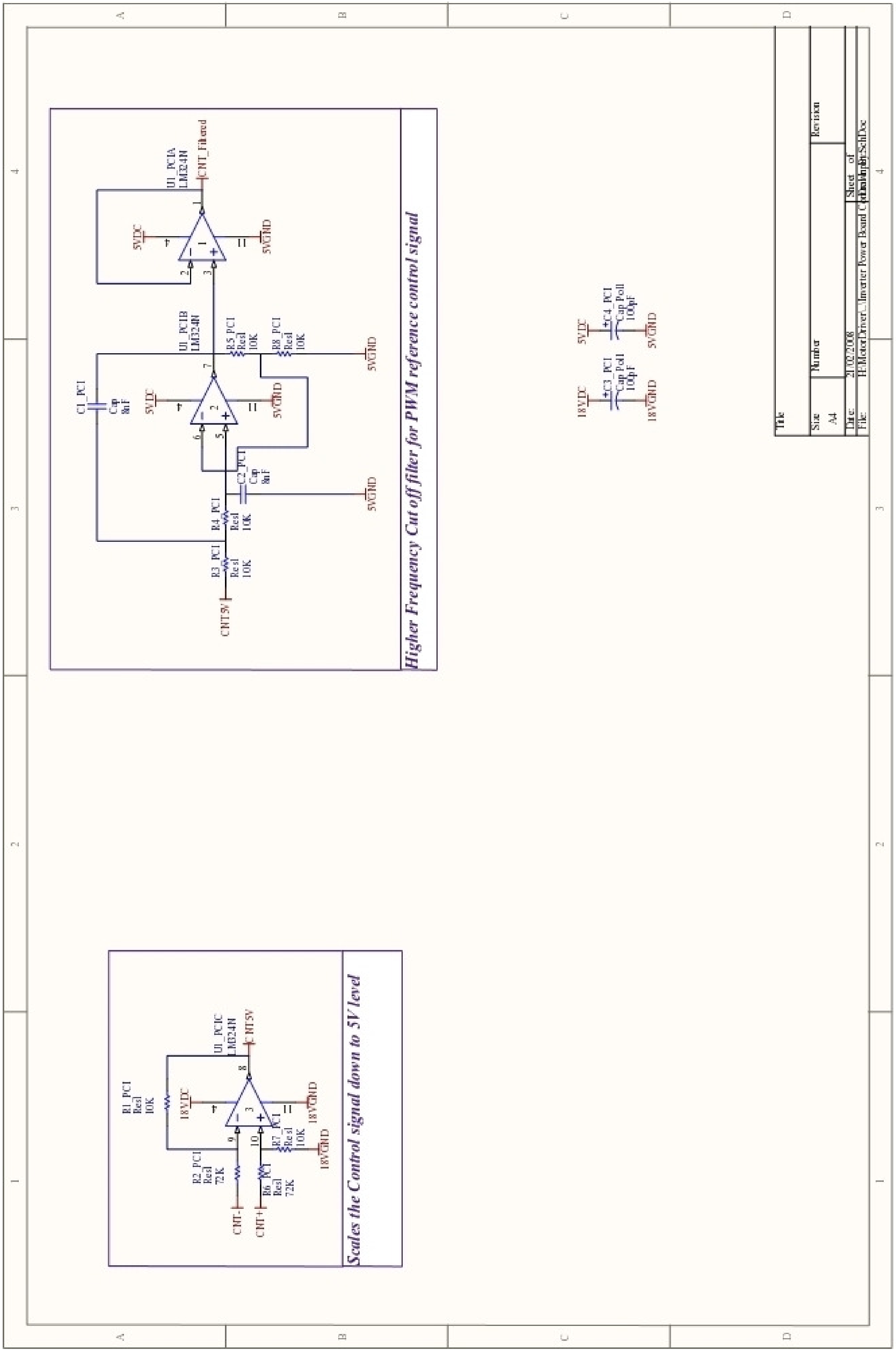

400V Conditioning for SMPS Output
48 V Switching for SMPS
Rectifier1_PE
TRANS_1
TRANS_2
400VDC
400GND
C3_PE
R3_PE
R4_PE
R8_PE
R9_PE
HVL Raw
LVL Raw
IGBT Full Bridge1_PE
IGBT_LEFT
IGBT_RIGHT
GNDBAT
Inductor1_PE
Custom Inductor
48VBAT
U1_PE
U2_PE
IR2101
D1_PE
D2_PE
Diode 1N914
C1_PE
C2_PE
C4_PE
C5_PE
R5_PE
R6_PE
R7_PE
R10_PE
18VDC
BRG_TL
BRG_BL
BRG_TR
BRG_BR
R1_PE
R2_PE
BTV Raw
Title
Size
A4
Number
Revision
13/02/2008
Sheet of

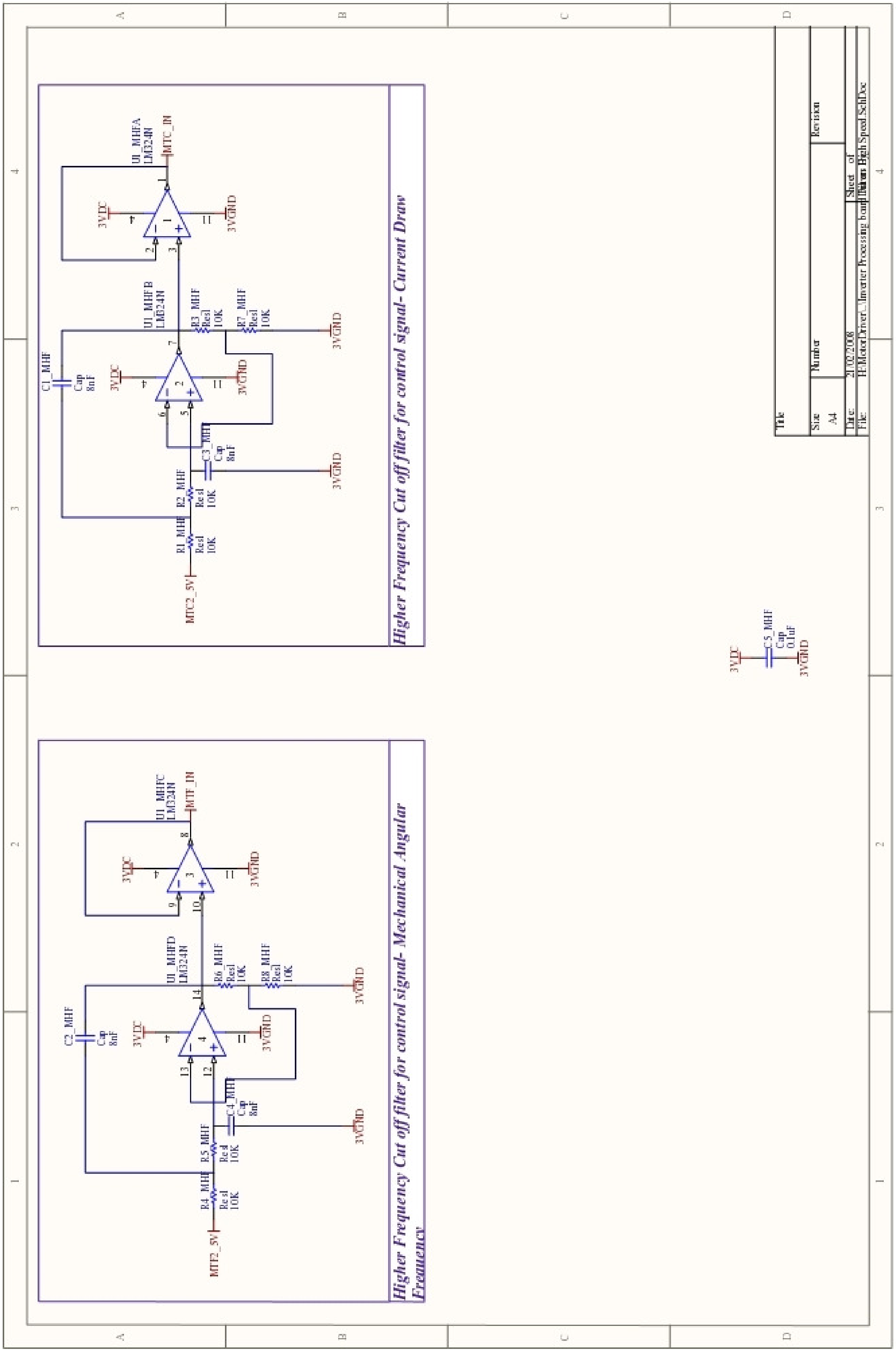

Converts the signal from Temp sensor A to 18 Volt Signal
Converts the signal from Temp sensor B to 18 Volt Signal
Converts the signal from Temp sensor B to 18 Volt Signal
TPARaw
TPBRaw
TPCRaw
TPA+
TPA-
TPB+
TPB-
TPC+
TPC-
LM324N
18VDC
18VGND

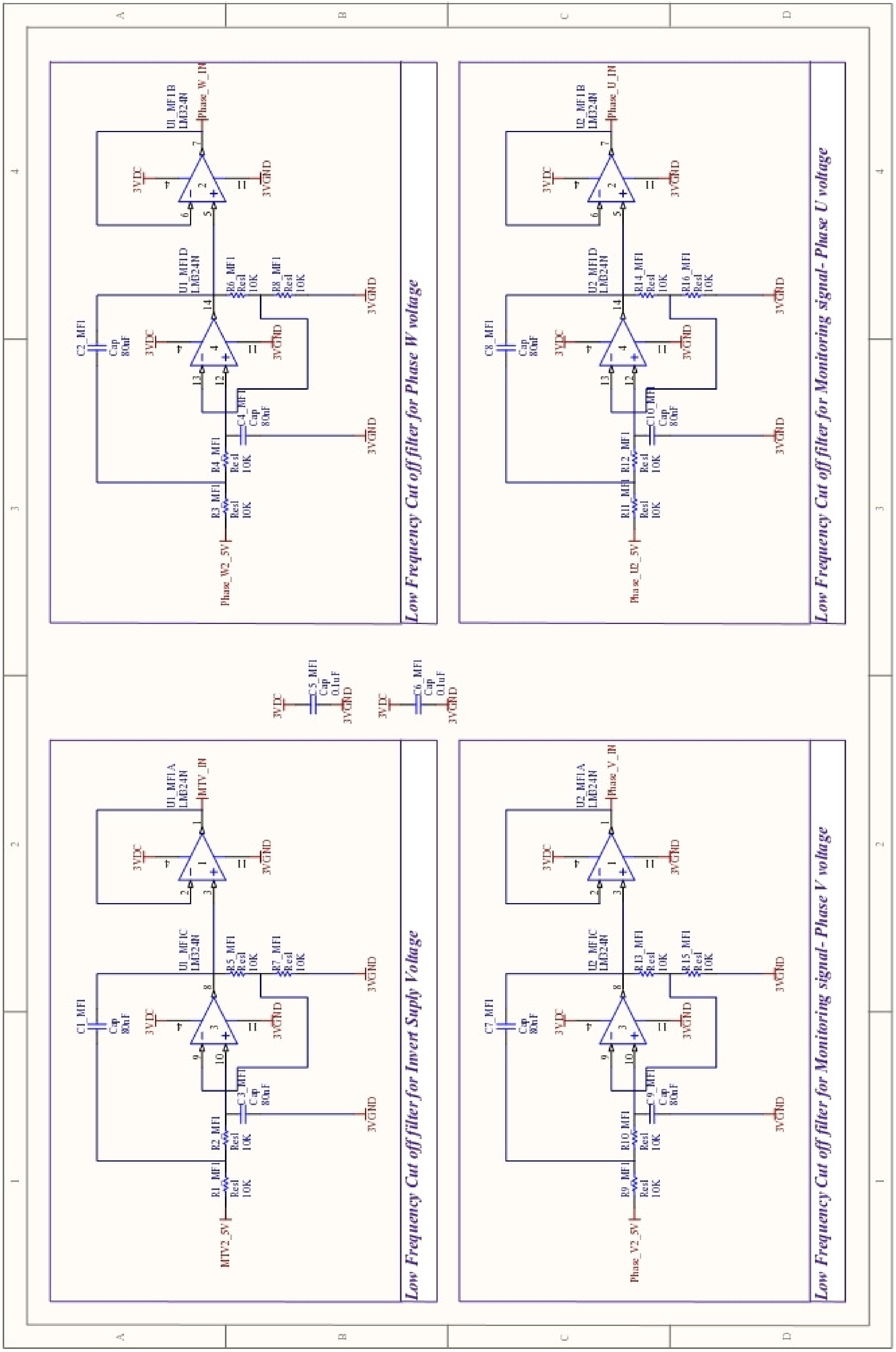

Voltage regulator circuit for 18V
Voltage regulator circuit for 5V
Voltage regulator circuit for 3V, Regulator shown is for 5V as no model for 3.3 Volt regulator but footprint is the same
24VBAT
18VDC
3VGND
GNDBAT
12VBAT
5VDC
3VDC
IN
OUT
GND
Title
Size
A4
Number
Revision
Date:
File:
Sheet of

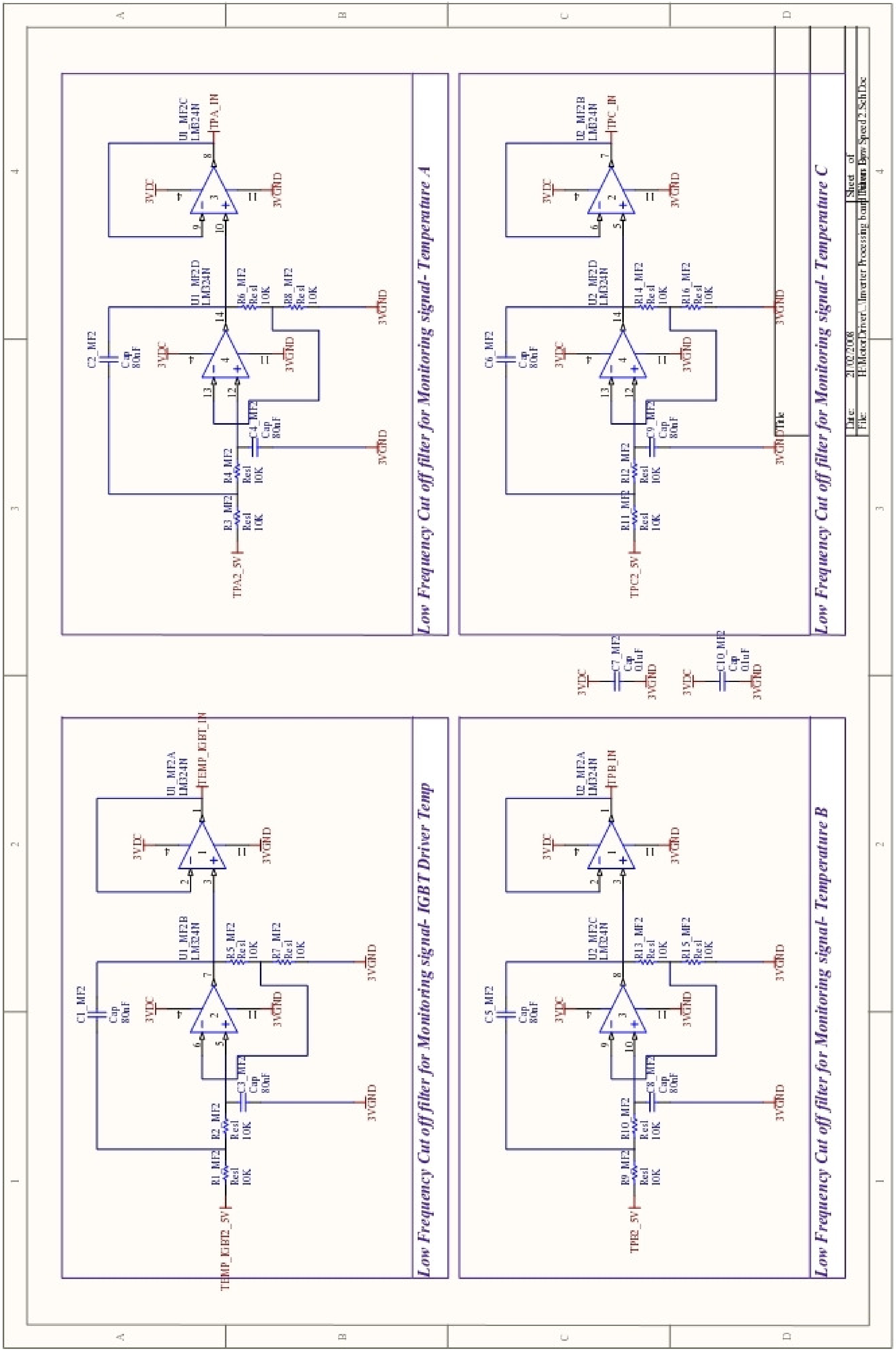

Voltage Input from battery
Voltage Output Terminals for entire system
Analog Outputs to the SMPS Processing board
Control Signals to from the SMPS processing board

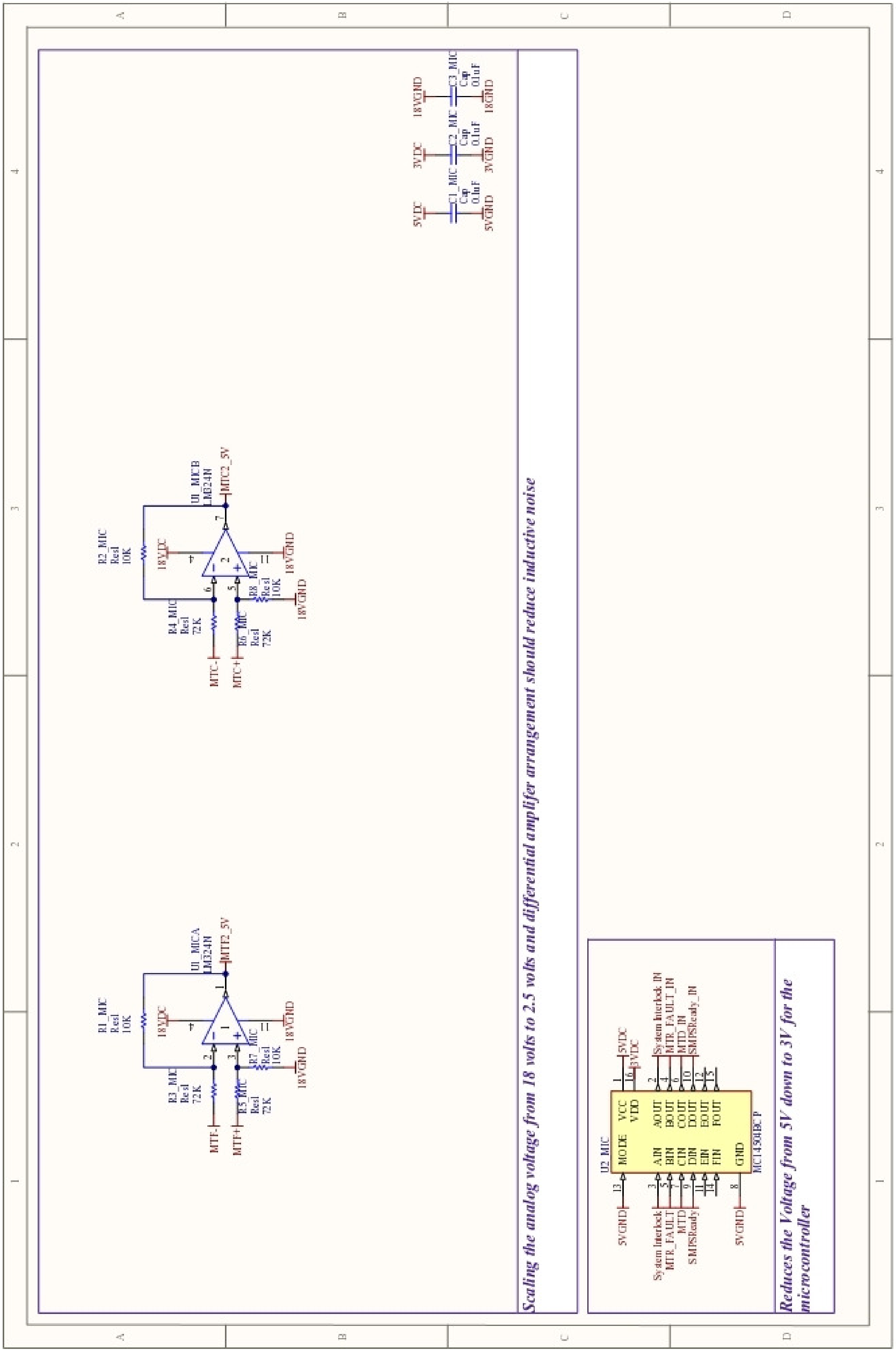
APPENDIX E MOTOR DRIVE MODULE HARDWARE DESIGN

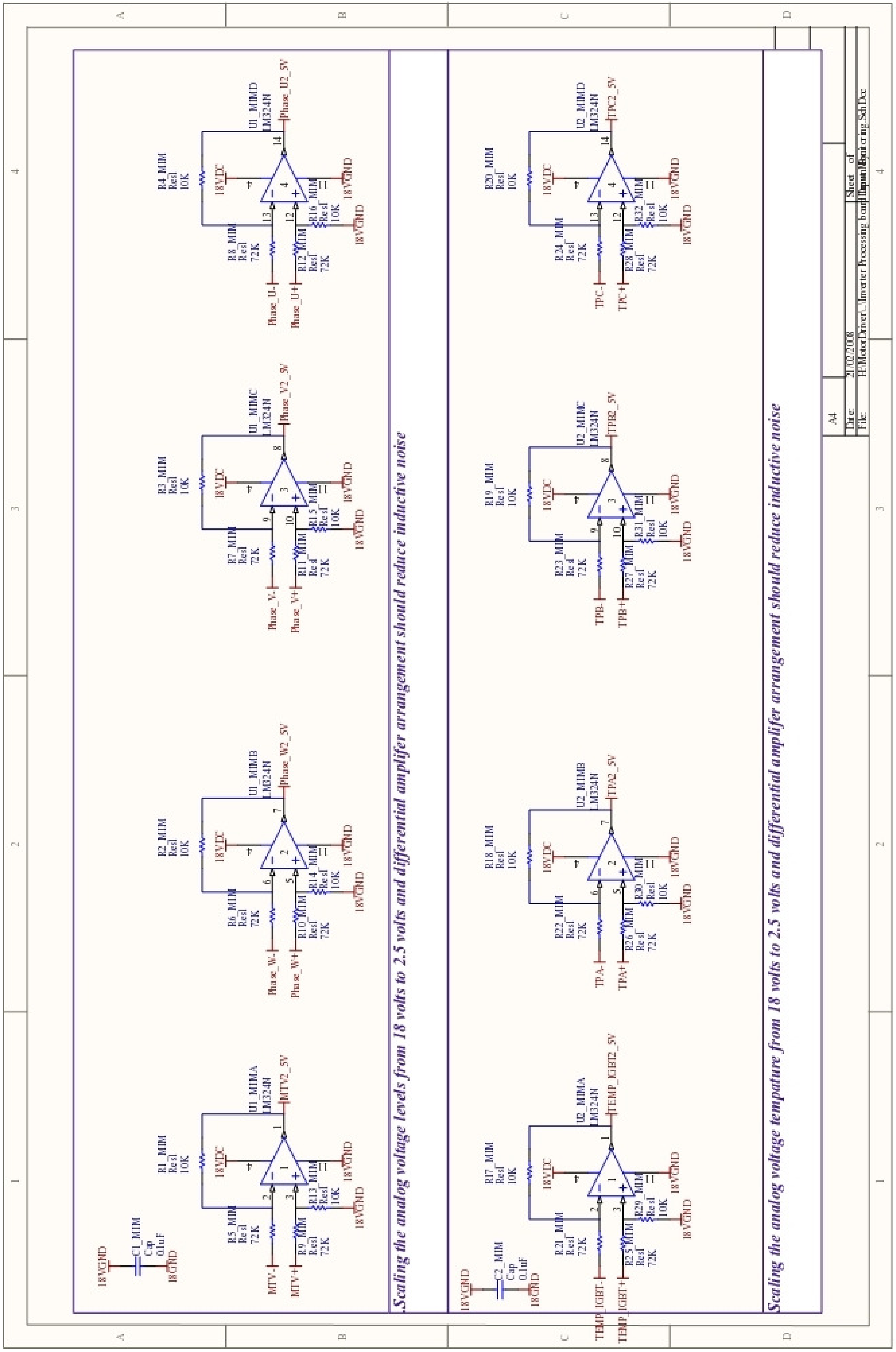

Higher Frequency Cut off filter for PWM reference control signal
U1_PC1A
LM324N
CNT_Filtered
U1_PC1B
LM324N
C1_PC1
C2_PC1
R3_PC1
R4_PC1
R5_PC1
R8_PC1
CNT5V
5VDC
5VGND
C3_PC1
C4_PC1
18VDC
18VGND
Scales the Control signal down to 5V level
U1_PC1C
LM324N
R1_PC1
R2_PC1
R6_PC1
R7_PC1
CNT-
CNT+

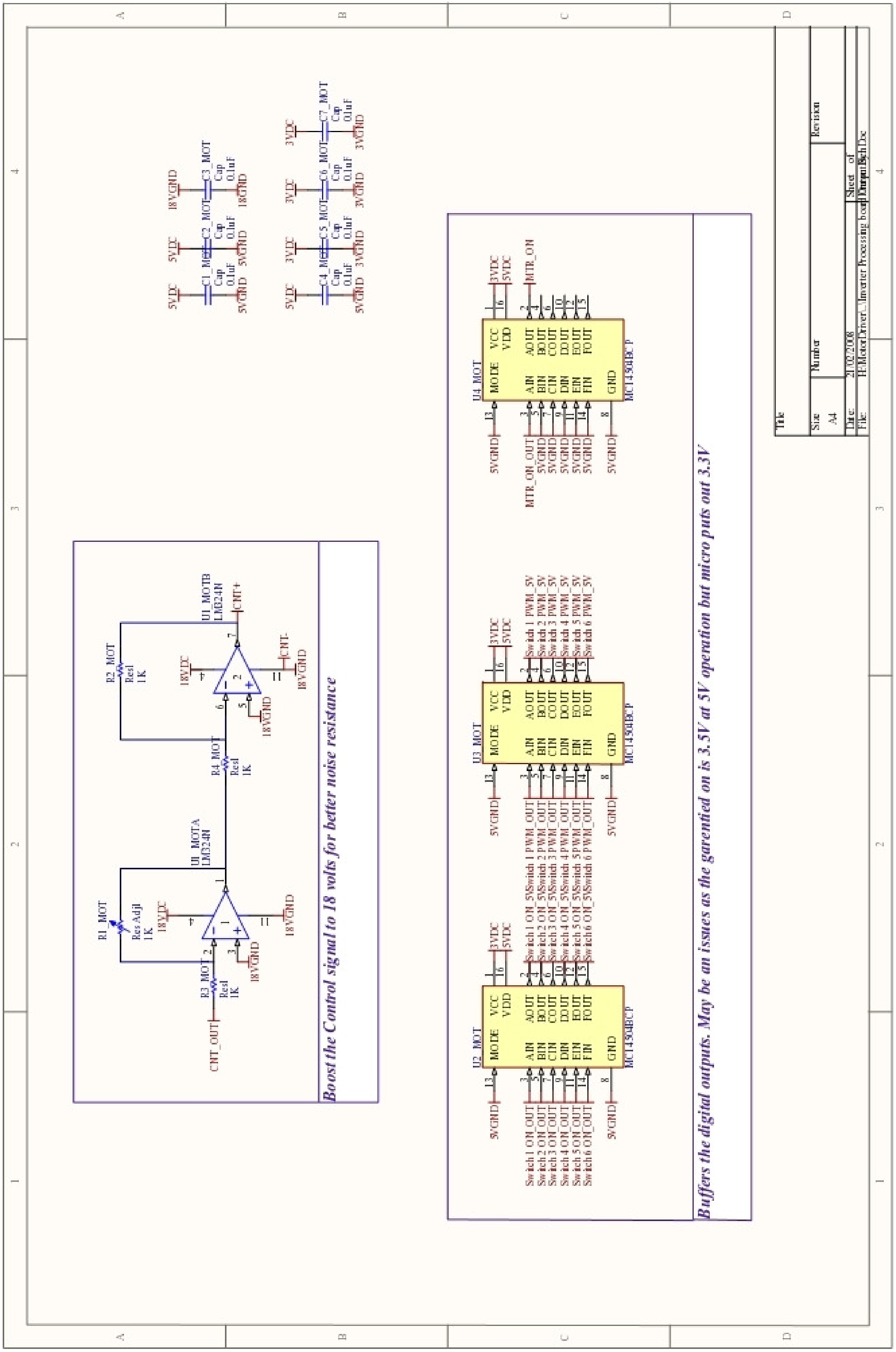

Higher Frequency Cut off filter for control signal- Current Draw
Higher Frequency Cut off filter for control signal- Mechanical Angular Frequency
U1_MHFA
LM324N
MTC_IN
U1_MHFB
U1_MHFC
U1_MHFD
MTF_IN
MTC2_5V
MTF2_5V
3VDC
3VGND
C5_MHF
Cap
0.1uf

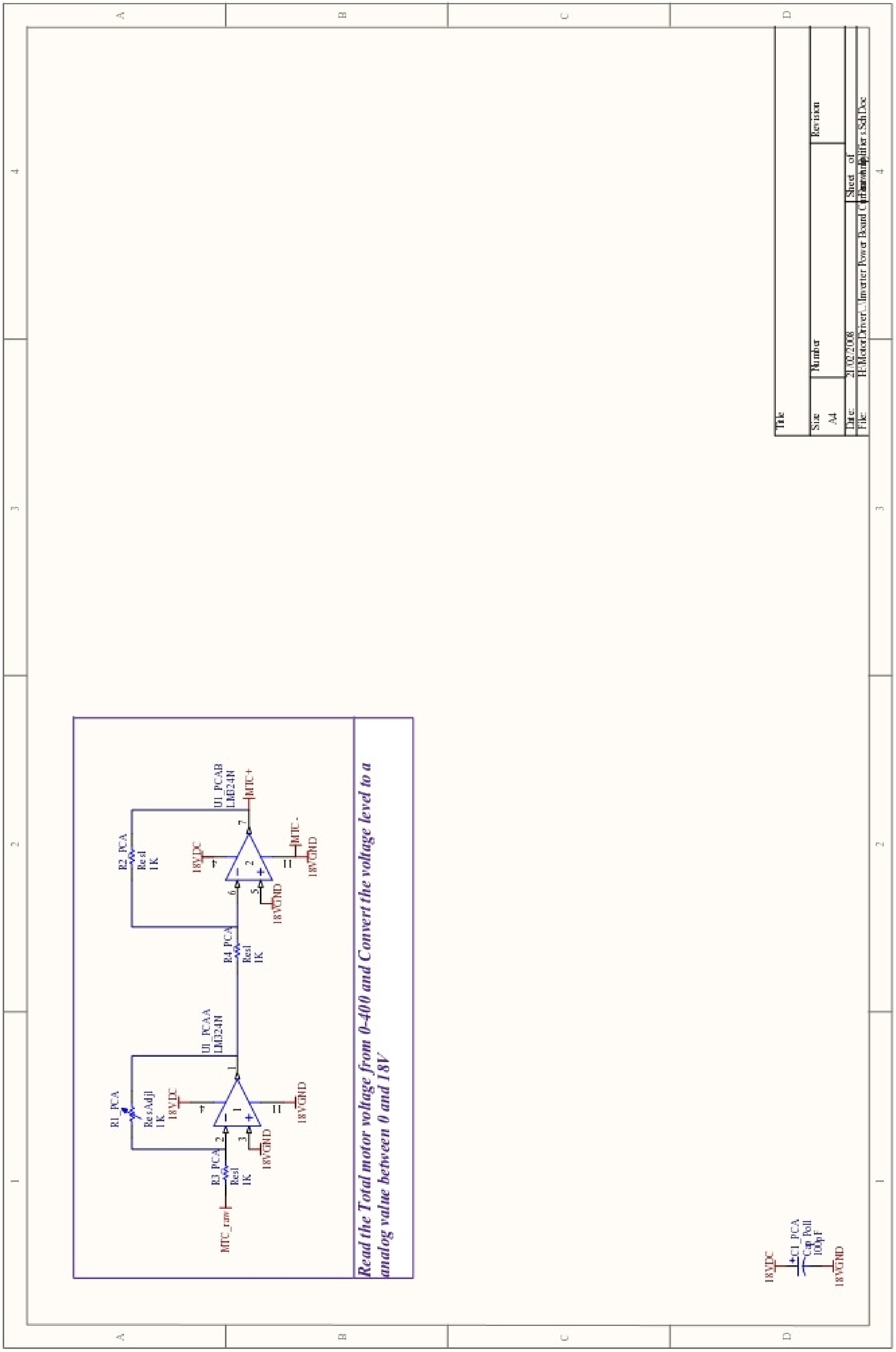

Low Frequency Cut off filter for Phase W voltage
Low Frequency Cut off filter for Monitoring signal- Phase U voltage
Low Frequency Cut off filter for Invert Suply Voltage
Low Frequency Cut off filter for Monitoring signal- Phase V voltage


Low Frequency Cut off filter for Monitoring signal- Temperature A
Low Frequency Cut off filter for Monitoring signal- Temperature C
Low Frequency Cut off filter for Monitoring signal- IGBT Driver Temp
Low Frequency Cut off filter for Monitoring signal- Temperature B


Scaling the analog voltage from 18 volts to 2.5 volts and differential amplifer arrangement should reduce inductive noise
Reduces the Voltage from 5V down to 3V for the microcontroller
U1_MICA
LM324N
U1_MICB
LM324N
R1_MIC
Res1
10K
R2_MIC
Res1
10K
R3_MIC
Res1
72K
R4_MIC
Res1
72K
R5_MIC
Res1
72K
R6_MIC
Res1
72K
R7_MIC
Res1
10K
R8_MIC
Res1
10K
MTF-
MTF+
MTC-
MTC+
MTF2_5V
MTC2_5V
18VDC
18VGND
C1_MIC
C2_MIC
C3_MIC
Cap
0.1uF
5VDC
3VDC
5VGND
3VGND
18GND
U2_MIC
MC14504BCP
MODE
VCC
VDD
AIN
BIN
CIN
DIN
EIN
FIN
AOUT
BOUT
COUT
DOUT
EOUT
FOUT
GND
System Interlock
MTR_FAULT
MTD
SMPSReady
System Interlock_IN
MTR_FAULT_IN
MTD_IN
SMPSReady_IN


Scaling the analog voltage levels from 18 volts to 2.5 volts and differential amplifer arrangement should reduce inductive noise
Scaling the analog voltage tempature from 18 volts to 2.5 volts and differential amplifer arrangement should reduce inductive noise


Boost the Control signal to 18 volts for better noise resistance
Buffers the digital outputs. May be an issues as the garentied on is 3.5V at 5V operation but micro puts out 3.3V


Read the Total motor voltage from 0-400 and Convert the voltage level to a analog value between 0 and 18V
R1_PCA
ResAdj1
1K
R2_PCA
Res1
1K
R3_PCA
Res1
1K
R4_PCA
Res1
1K
U1_PCAA
LM324N
U1_PCAB
LM324N
MTC_raw
MTC+
MTC-
18VDC
18VGND
C1_PCA
Cap Pol1
100pF
Title
Size
A4
Number
Revision
Date:
21/02/2008
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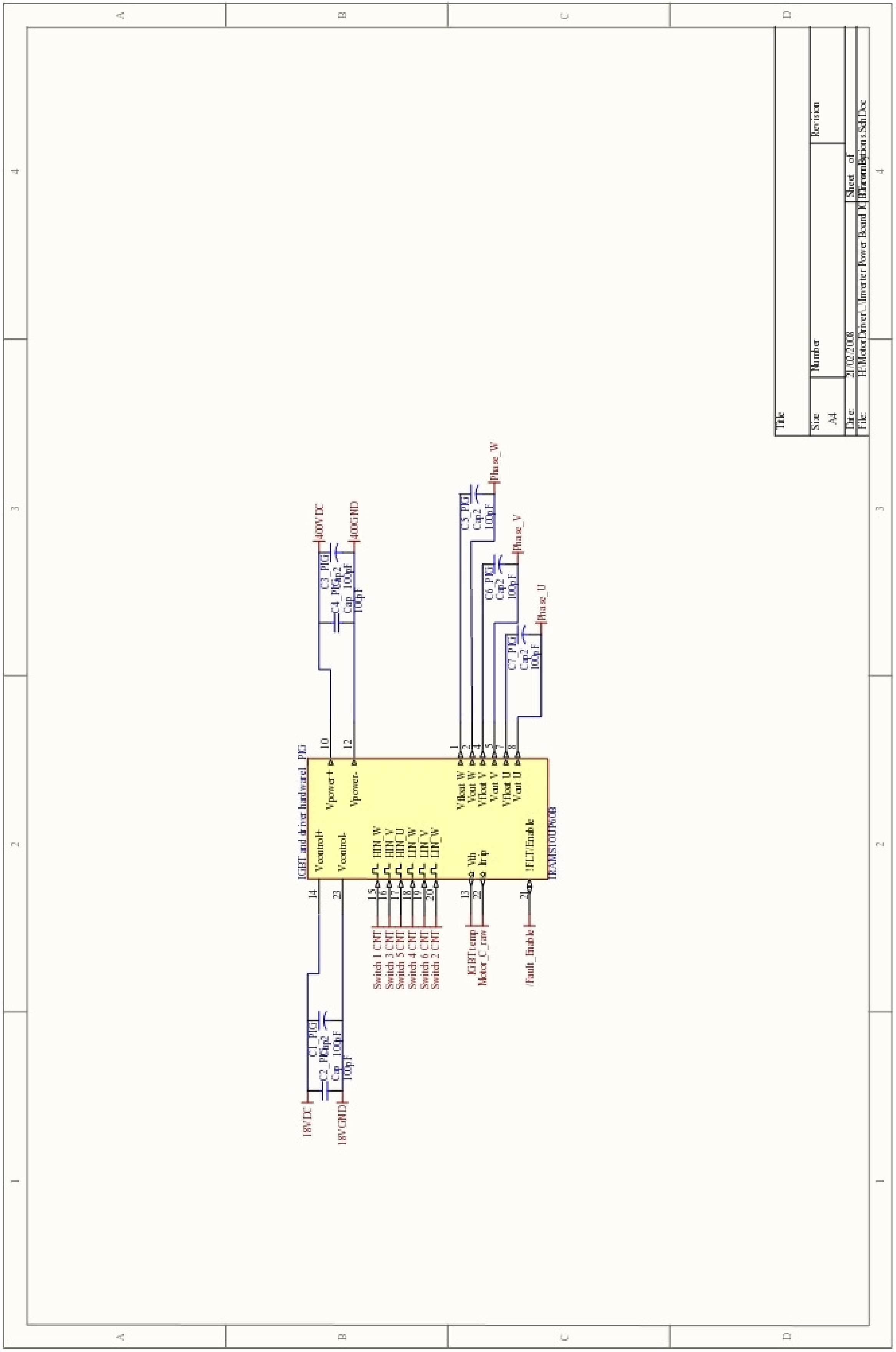
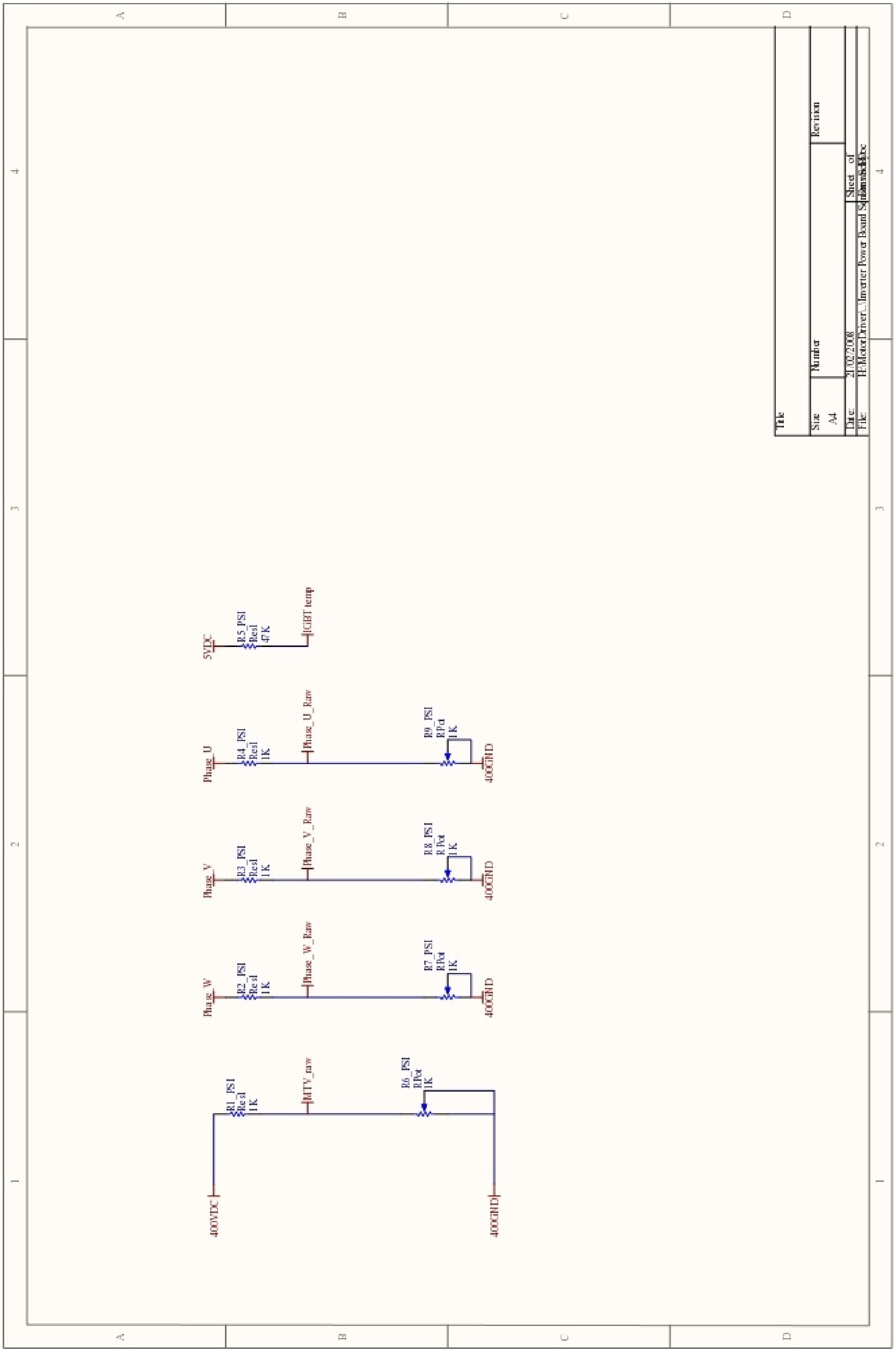
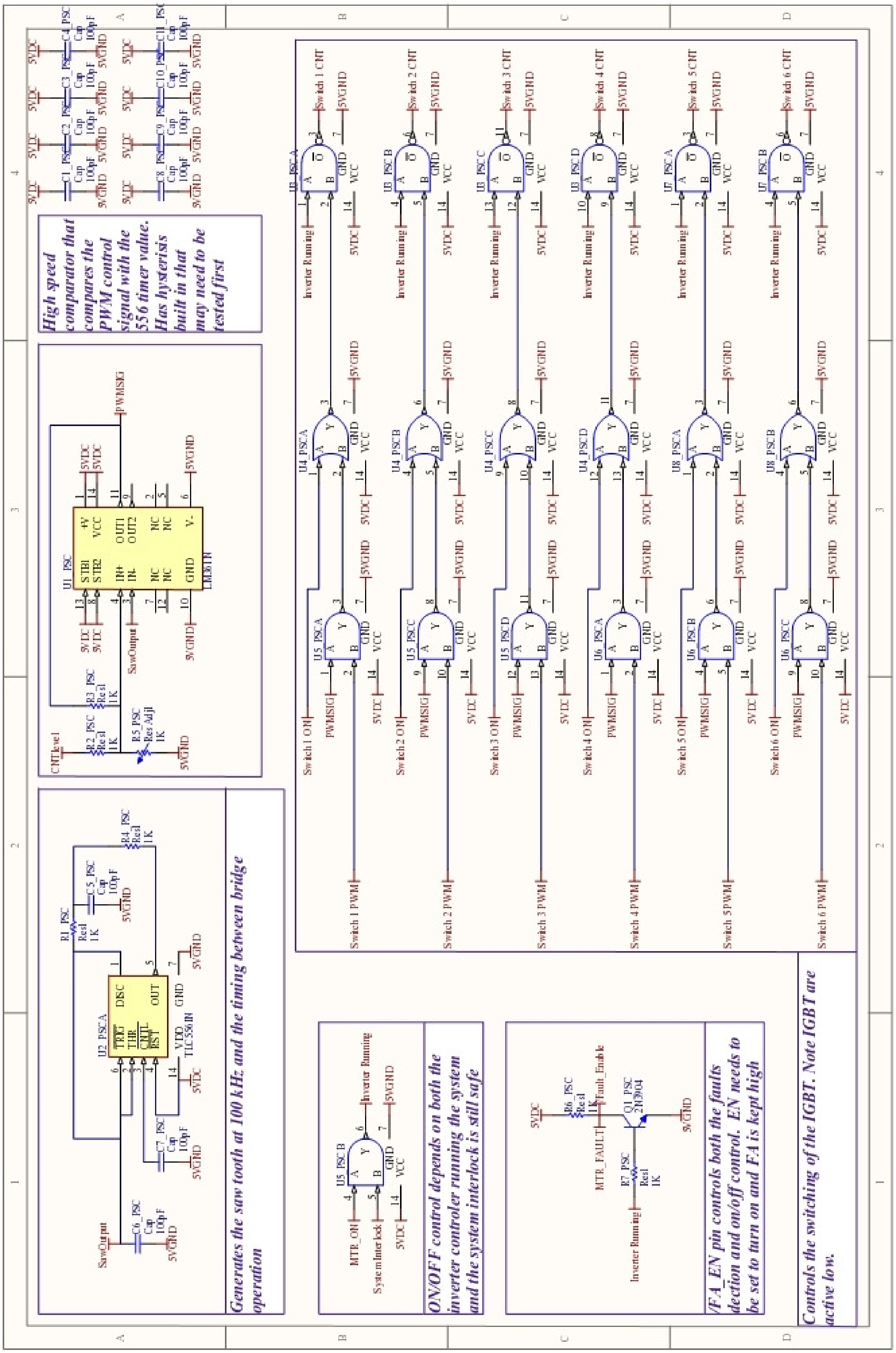
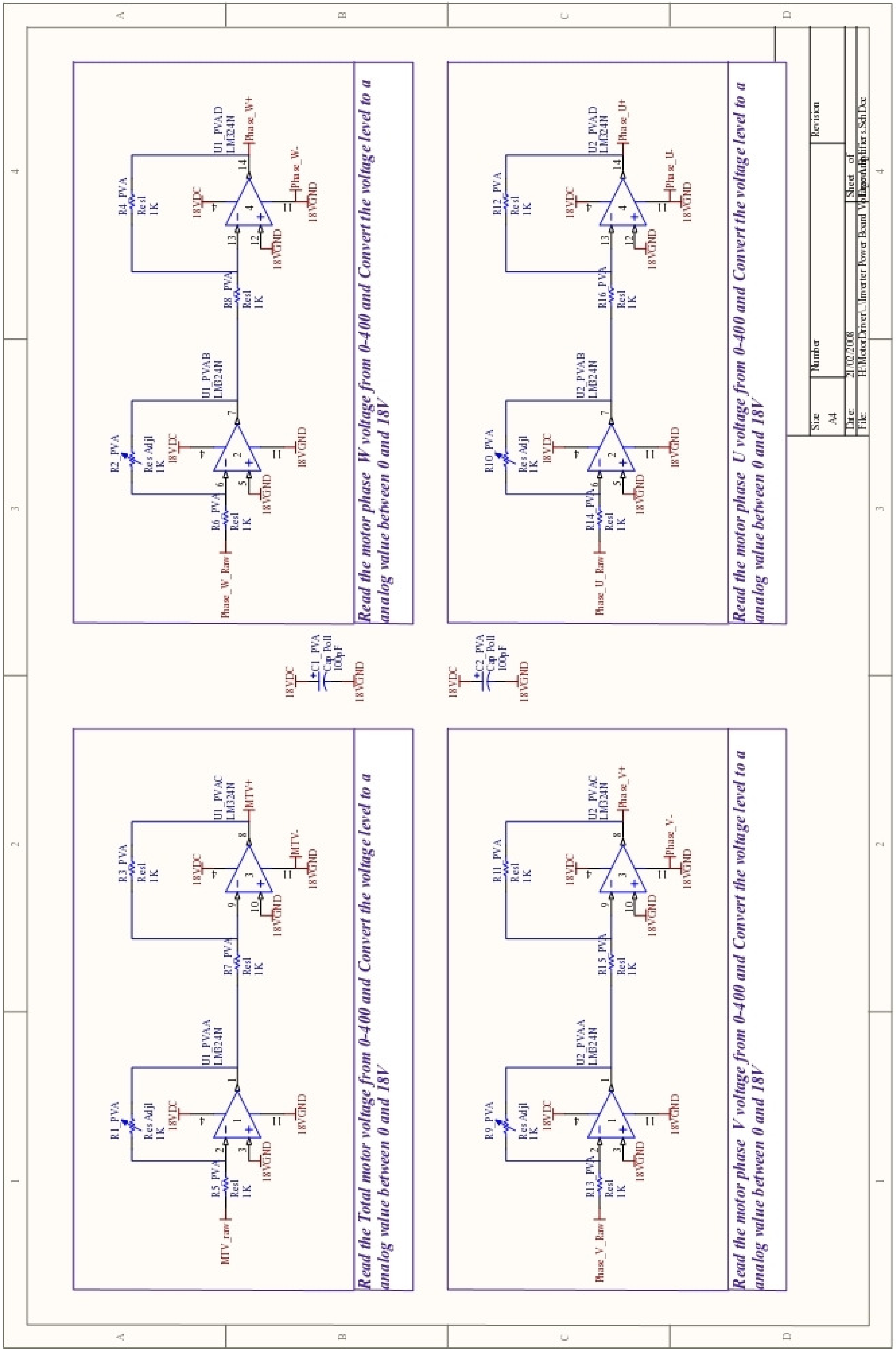
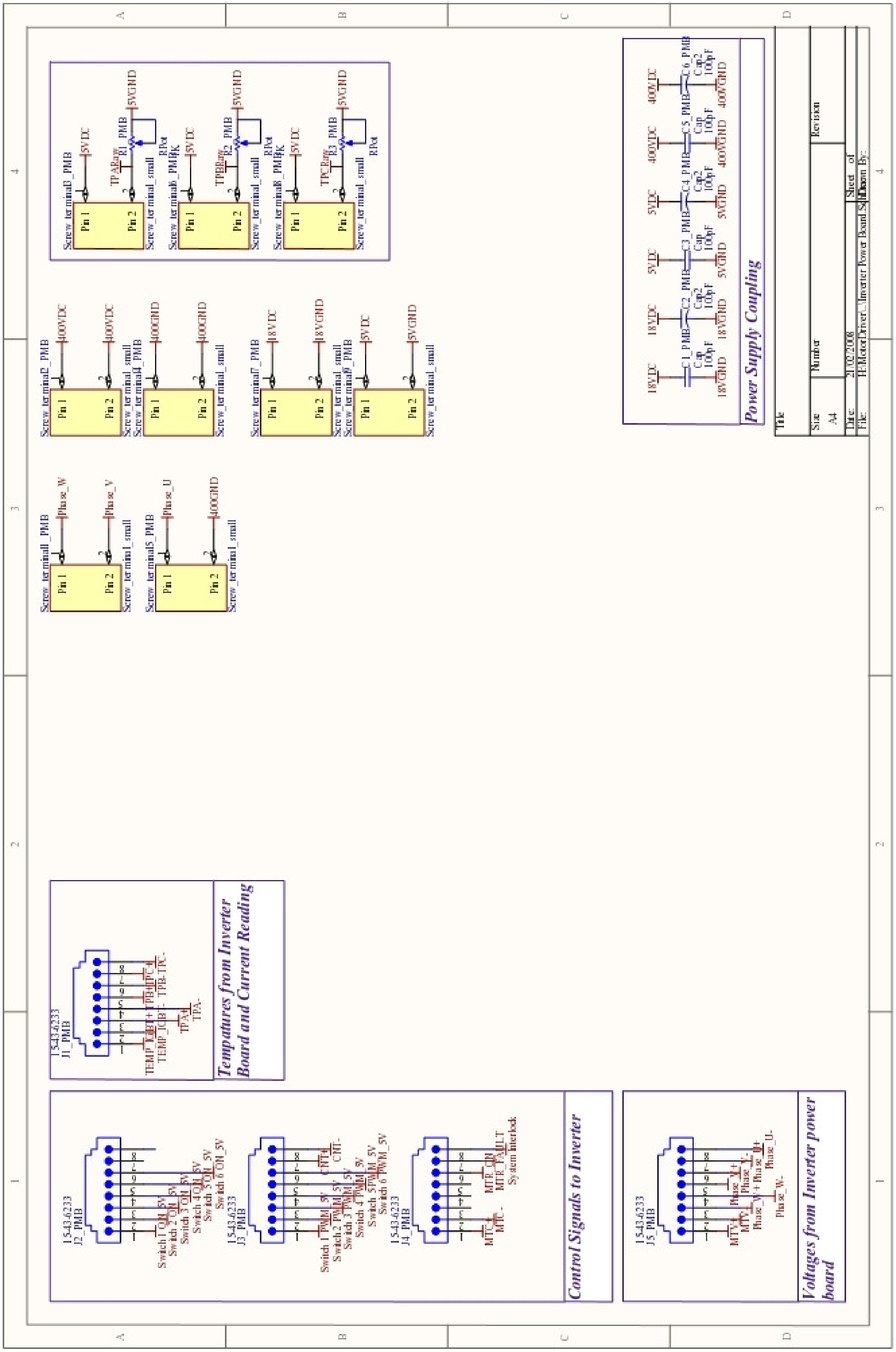
File:

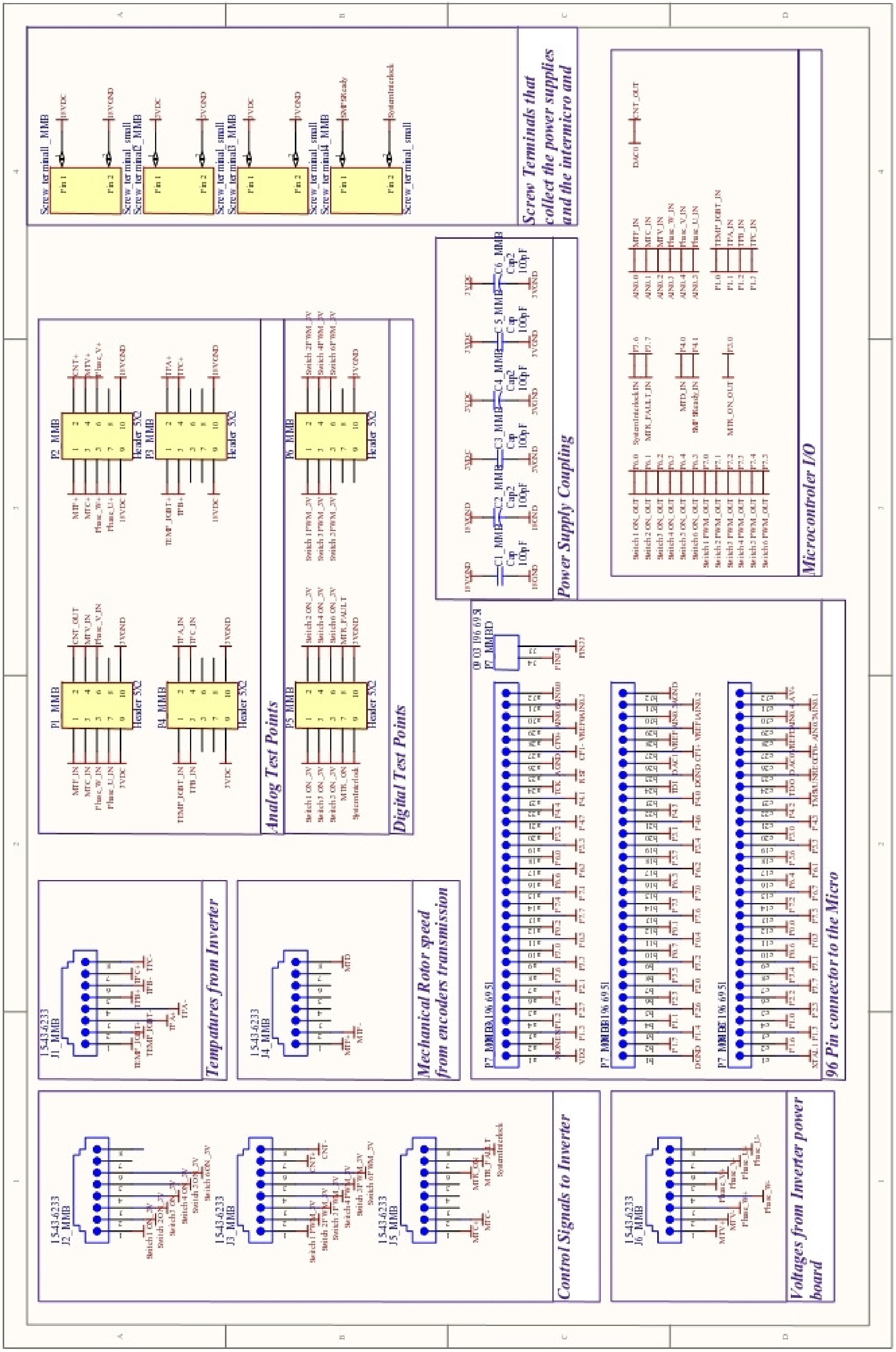

IGBT and driver hardware1_PIG
IRAMS10UP60B
Vcontrol+
Vcontrol-
Vpower+
Vpower-
HIN_W
HIN_V
HIN_U
LIN_W
LIN_V
LIN_W
Vth
Itrip
!FLT/Enable
VBout W
Vout W
VBout V
Vout V
VBout U
Vout U
400VDC
400GND
18VDC
18VGND
Phase_W
Phase_V
Phase_U
Switch 1 CNT
Switch 3 CNT
Switch 5 CNT
Switch 4 CNT
Switch 6 CNT
Switch 2 CNT
IGBT temp
Motor_C_raw
/Fault_Enable
Title
Size
A4
Number
Revision
Date:
21/02/2008
File:
Sheet of


400VDC
400GND
R1_PS1
Res1
1K
MTV_raw
R6_PS1
RPot
1K
Phase_W
R2_PS1
Res1
1K
Phase_W_Raw
R7_PS1
RPot
1K
400GND
Phase_V
R3_PS1
Res1
1K
Phase_V_Raw
R8_PS1
RPot
1K
400GND
Phase_U
R4_PS1
Res1
1K
Phase_U_Raw
R9_PS1
RPot
1K
400GND
5VDC
R5_PS1
Res1
47K
IGBT temp
Title
Size
A4
Number
Revision
Date:
21/02/2008
Sheet of
File:

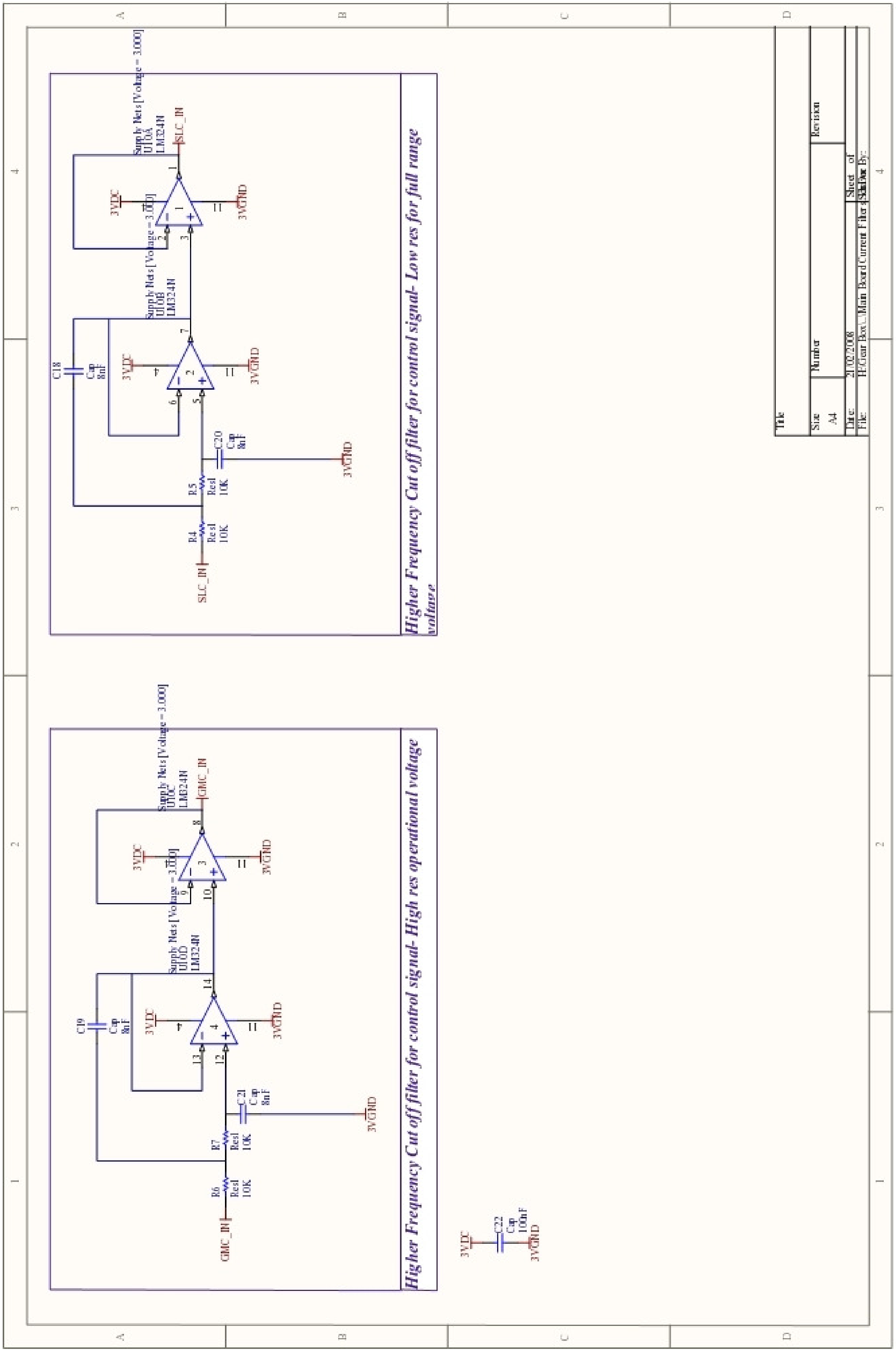

High speed comparator that compares the PWM control signal with the 556 timer value. Has hysterisis built in that may need to be tested first
Generates the saw tooth at 100 kHz and the timing between bridge operation
ON/OFF control depends on both the inverter controler running the system and the system interlock is still safe
/FA_EN pin controls both the faults dection and on/off control. EN needs to be set to turn on and FA is kept high
Controls the switching of the IGBT. Note IGBT are active low.

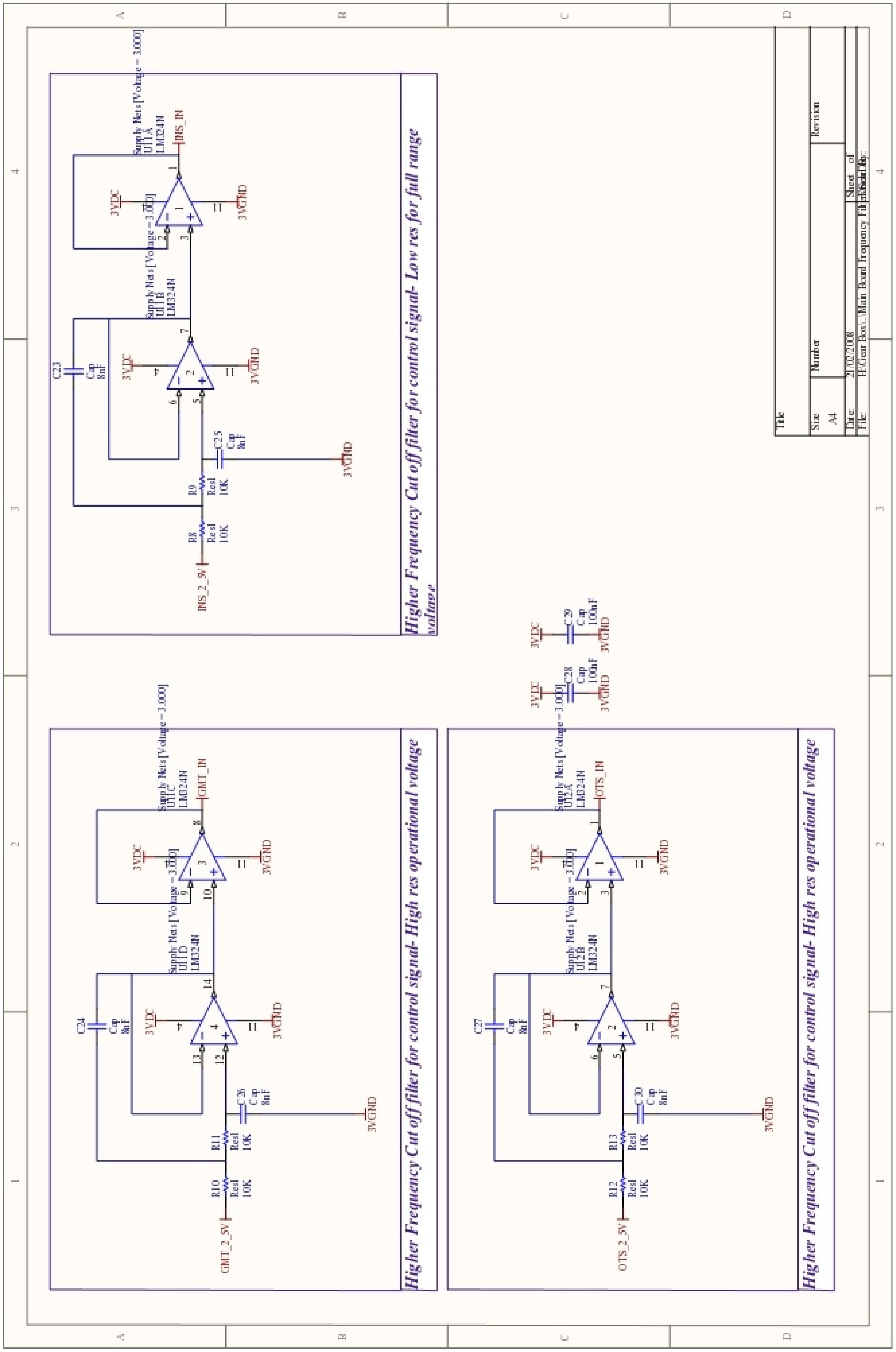

Read the motor phase W voltage from 0-400 and Convert the voltage level to a analog value between 0 and 18V
Read the motor phase U voltage from 0-400 and Convert the voltage level to a analog value between 0 and 18V
Read the Total motor voltage from 0-400 and Convert the voltage level to a analog value between 0 and 18V
Read the motor phase V voltage from 0-400 and Convert the voltage level to a analog value between 0 and 18V
U1_PVAD LM324N
U1_PVAB LM324N
U2_PVAD LM324N
U2_PVAB LM324N
U1_PVAC LM324N
U1_PVAA LM324N
U2_PVAC LM324N
U2_PVAA LM324N
C1_PVA Cap Poll 100pF
C2_PVA Cap Poll 100pF
Phase_W_Raw
Phase_U_Raw
MTV_raw
Phase_V_Raw
Phase_W+
Phase_W-
Phase_U+
Phase_U-
MTV+
MTV-
Phase_V+
Phase_V-
18VDC
18VGND
Size A4
Date: 21/02/2008
Number
Revision

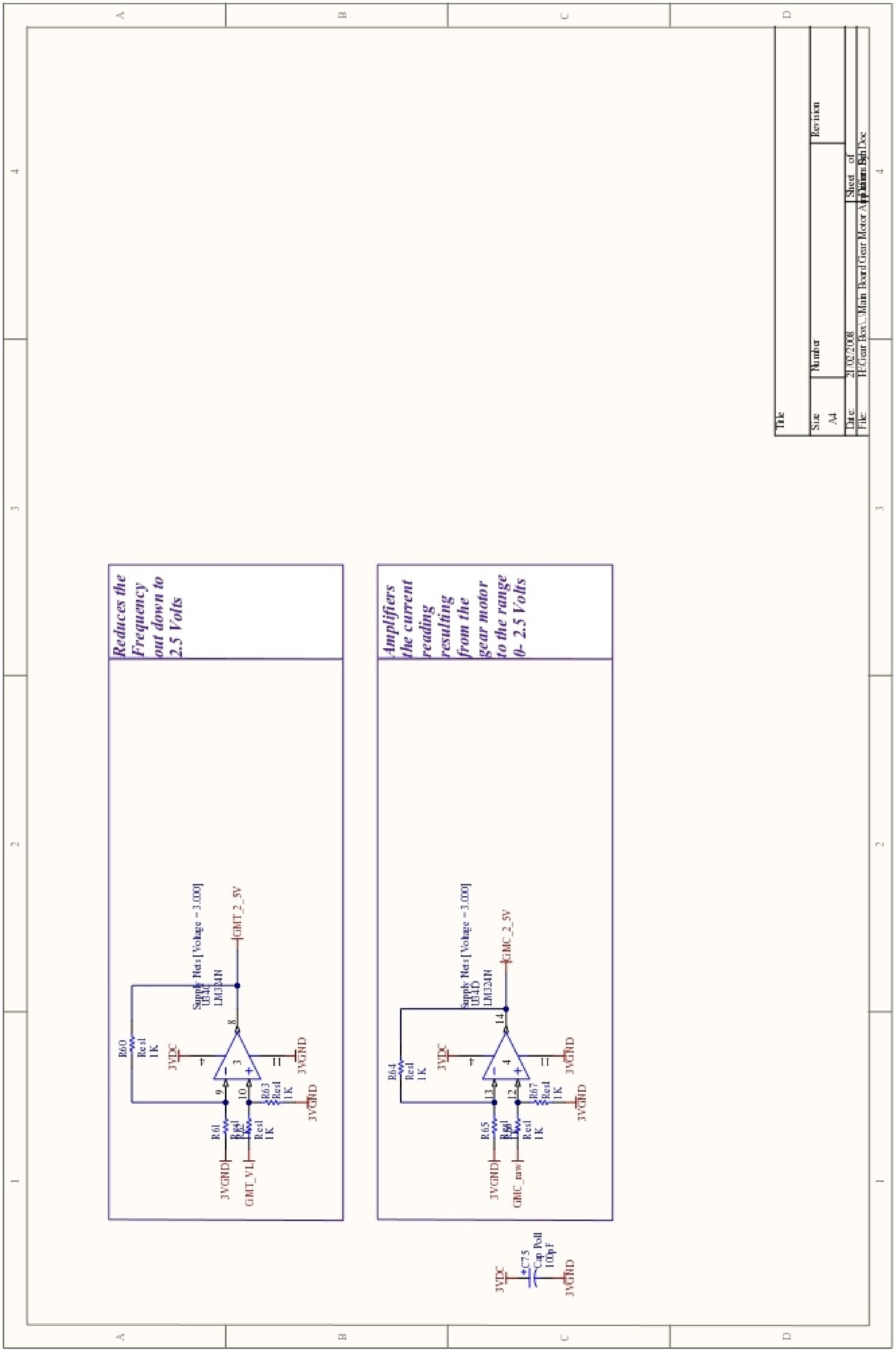

Power Supply Coupling
Tempatures from Inverter Board and Current Reading
Control Signals to Inverter
Voltages from Inverter power board

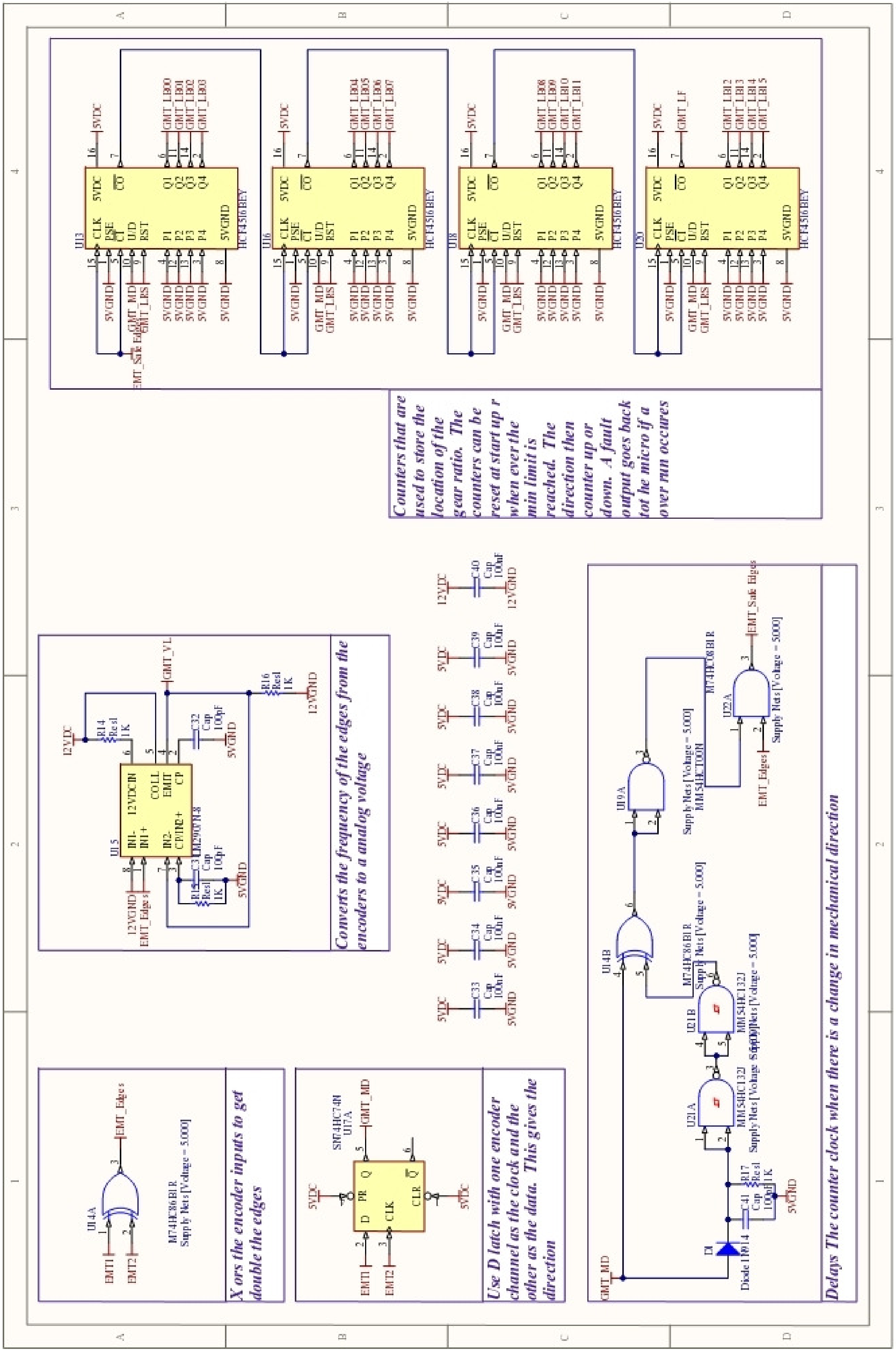

Screw Terminals that collect the power supplies and the intermicro and
Power Supply Coupling
Microcontroler I/O
Analog Test Points
Digital Test Points
Tempatures from Inverter
Mechanical Rotor speed from encoders transmission
96 Pin connector to the Micro
Control Signals to Inverter
Voltages from Inverter power board

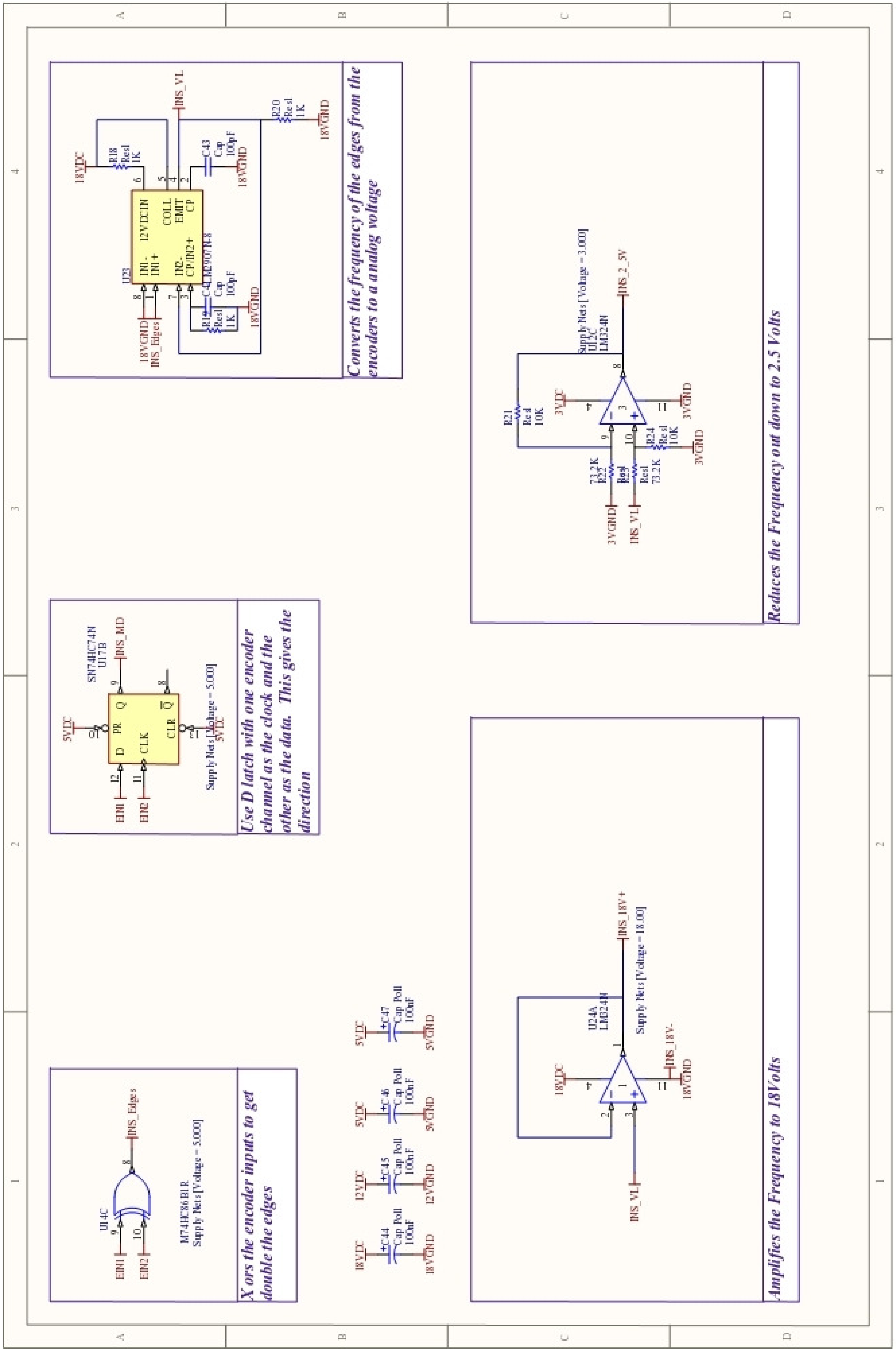
APPENDIX F TRANSMISSION MODULE HARDWARE DESIGN

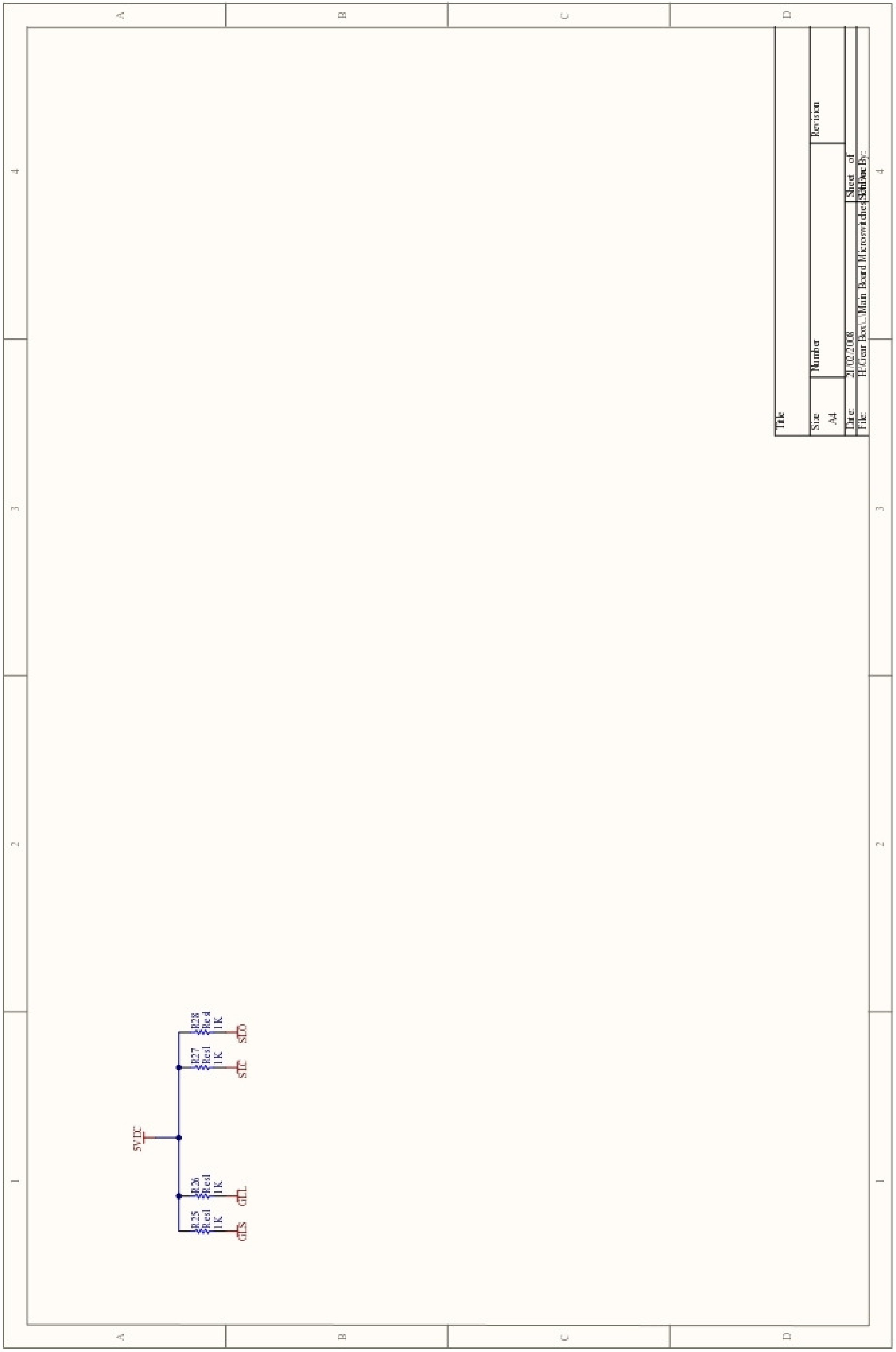

Higher Frequency Cut off filter for control signal- Low res for full range voltage
Higher Frequency Cut off filter for control signal- High res operational voltage
Supply Nets [Voltage = 3.000]
LM324N
SLC_IN
GMC_IN
3VDC
3VGND
C18
C19
C20
C21
C22
Cap
8nF
100nF
R4
R5
R6
R7
Res1
10K
Title
Size
A4
Number
Revision
Date:
21/02/2008
File:
Sheet of
Drawn By:

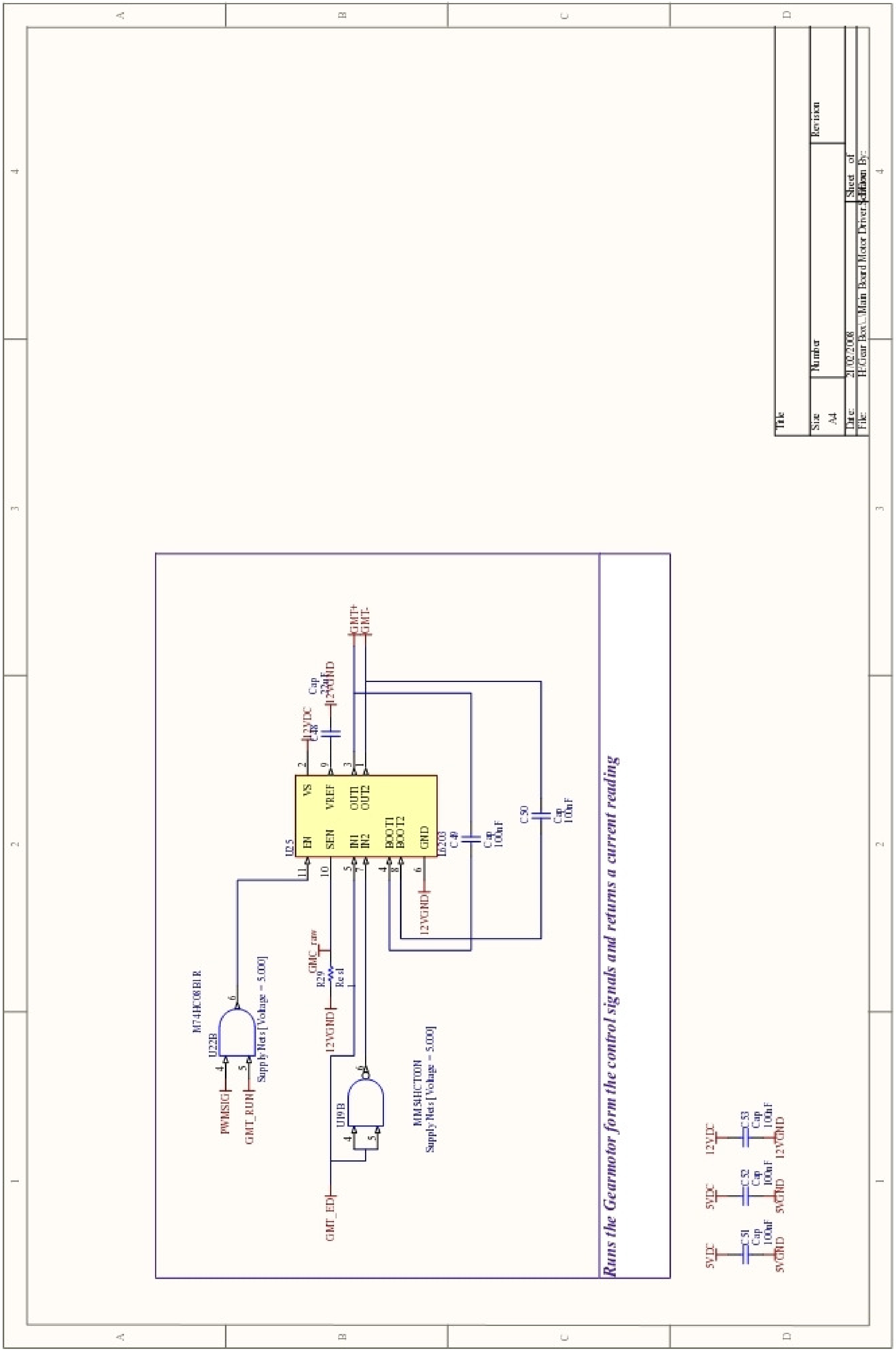

Higher Frequency Cut off filter for control signal- Low res for full range voltage
Higher Frequency Cut off filter for control signal- High res operational voltage
Higher Frequency Cut off filter for control signal- High res operational voltage
INS_IN
INS_2_5V
GMT_IN
GMT_2_5V
OTS_IN
OTS_2_5V
LM324N
3VDC
3VGND
Title
Size
A4
Number
Revision
Date:
21/02/2008

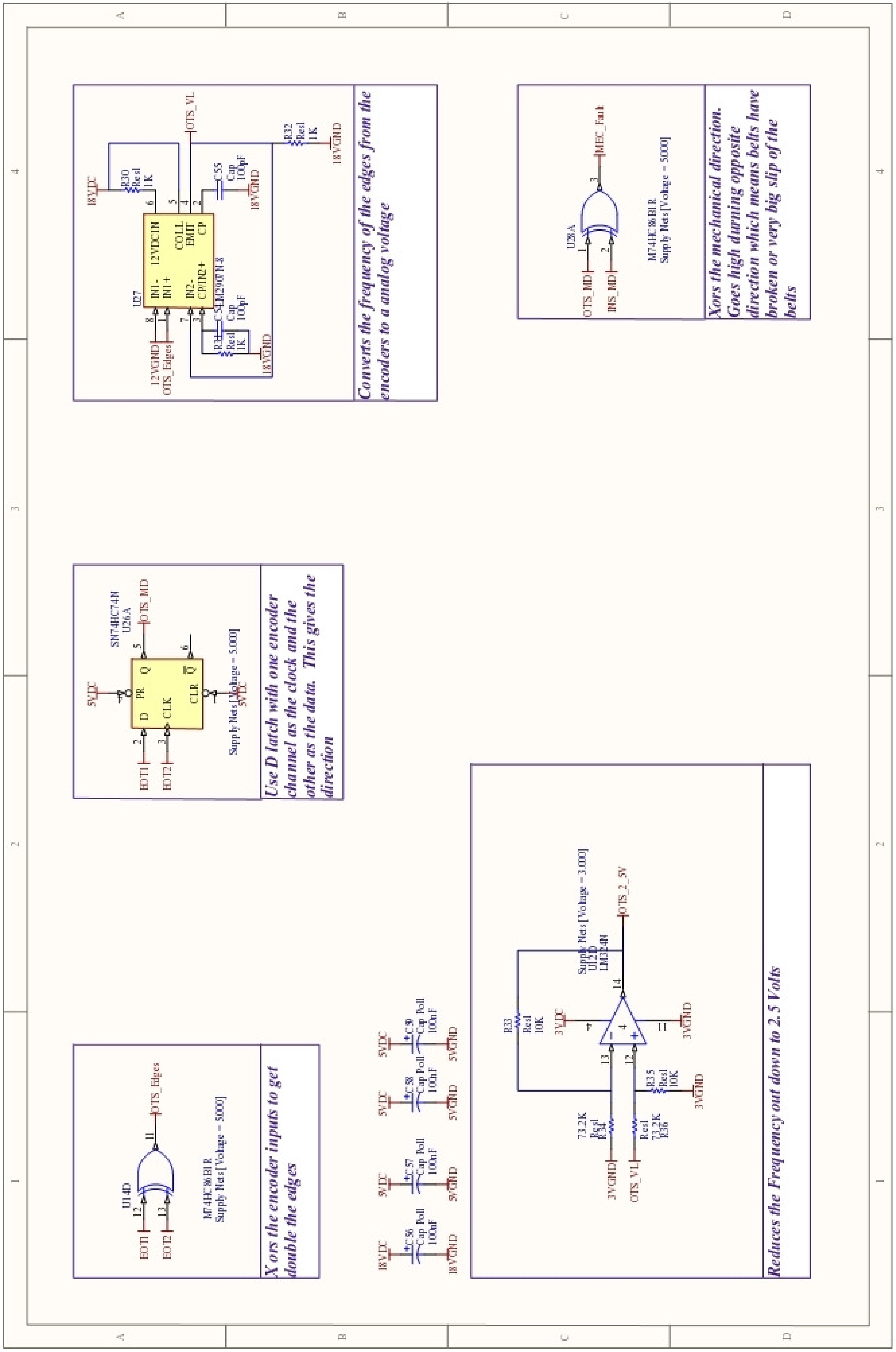

Reduces the Frequency out down to 2.5 Volts
Amplifiers the current reading resulting from the gear motor to the range 0- 2.5 Volts
Supply Nets [Voltage = 3.000]
LM324N
GMT_2_5V
GMC_2_5V
GMT_VL
GMC_raw
3VDC
3VGND
Title
Size
A4
Number
Revision
Date:
File:
Sheet of

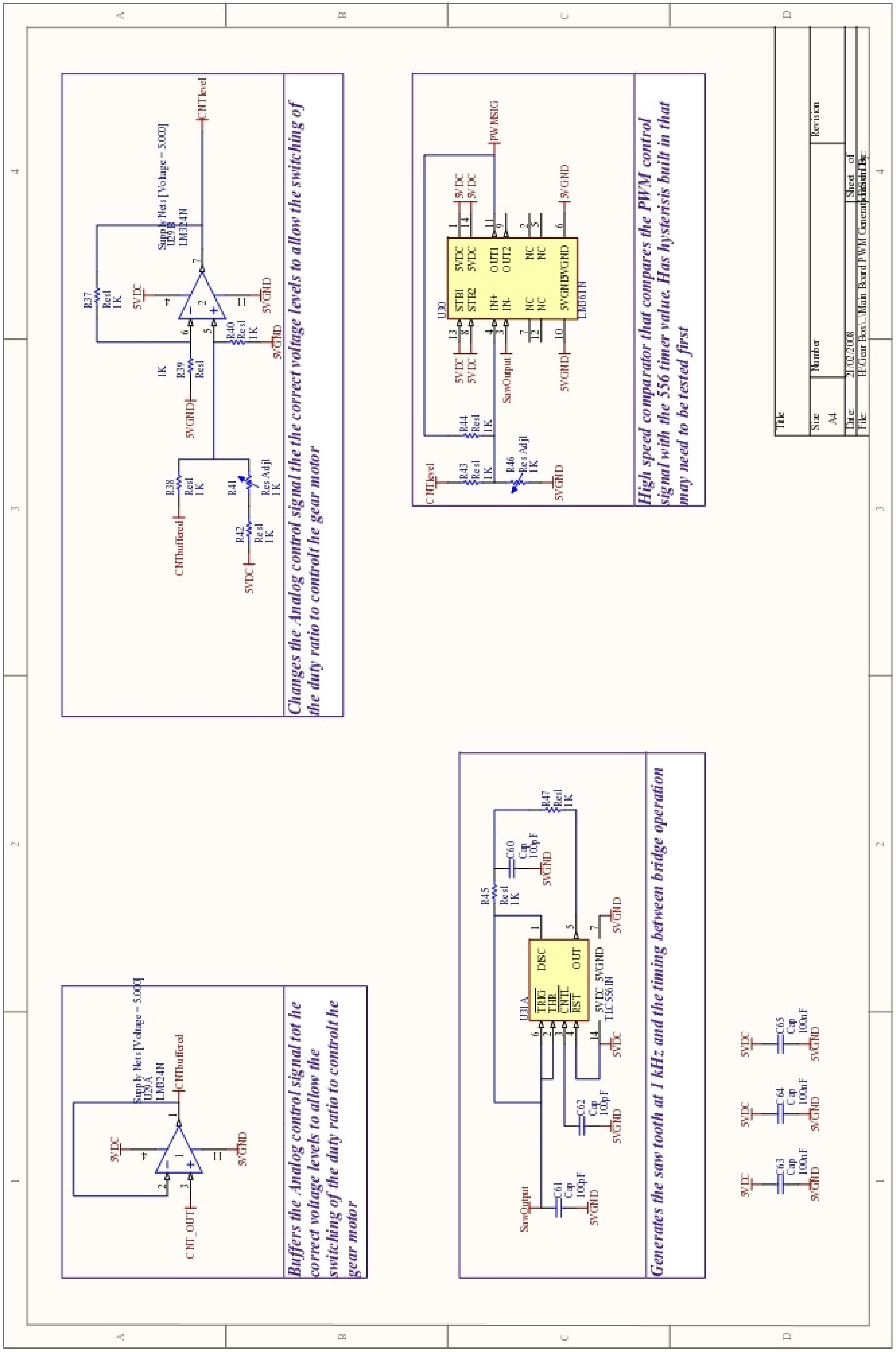

Counters that are used to store the location of the gear ratio. The counters can be reset at start up r when ever the min limit is reached. The direction then counter up or down. A fault output goes back tot he micro if a over run occures
Converts the frequency of the edges from the encoders to a analog voltage
X ors the encoder inputs to get double the edges
Use D latch with one encoder channel as the clock and the other as the data. This gives the direction
Delays The counter clock when there is a change in mechanical direction

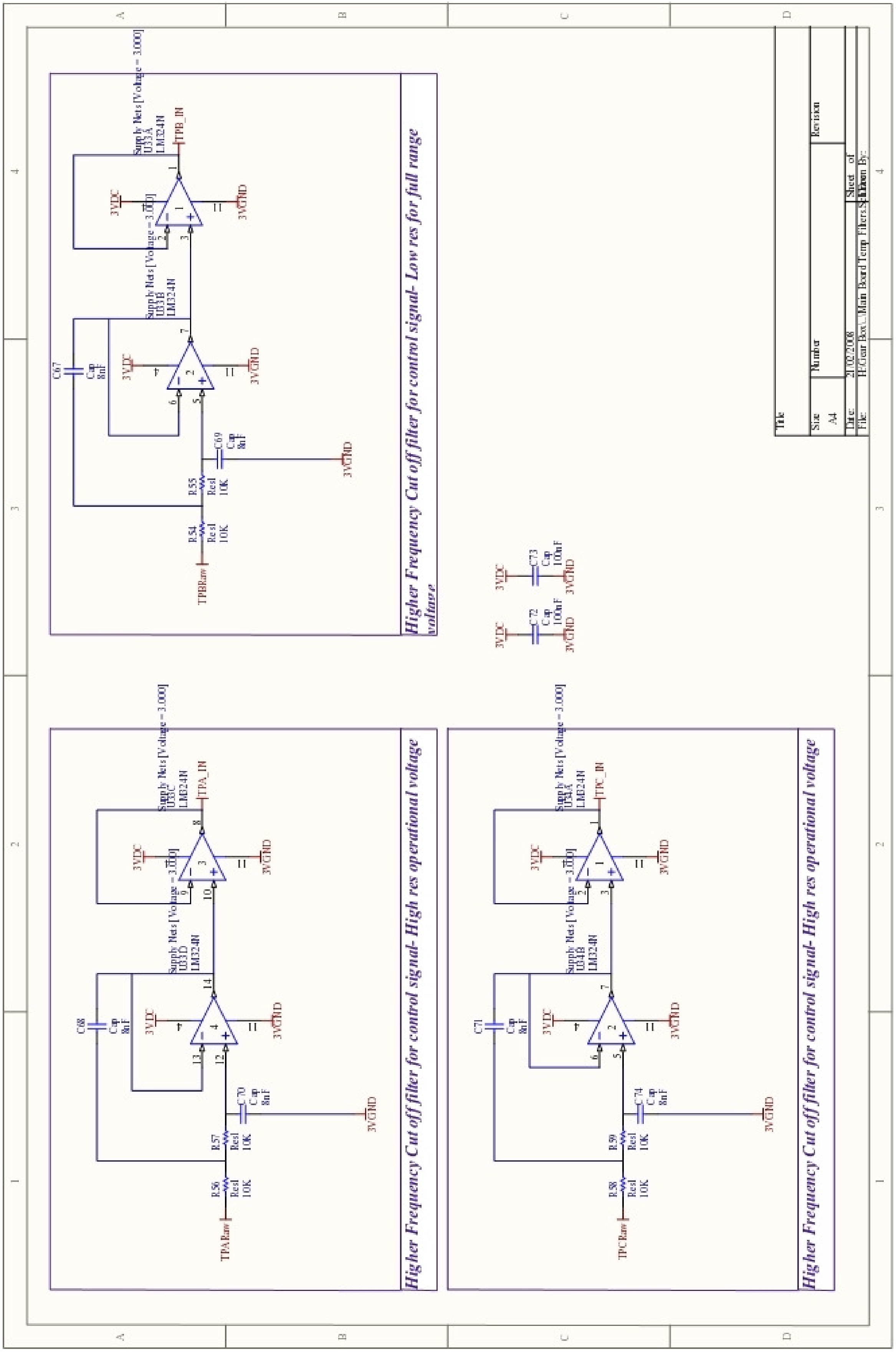

Converts the frequency of the edges from the encoders to a analog voltage
Use D latch with one encoder channel as the clock and the other as the data. This gives the direction
X ors the encoder inputs to get double the edges
Reduces the Frequency out down to 2.5 Volts
Amplifies the Frequency to 18Volts
U23
LM2907N-8
U17B
SN74HC74N
U14C
U12C
LM324N
U24A
LM324N
INS_VL
INS_MD
INS_Edges
INS_2_5V
INS_18V+
INS_18V-
EIN1
EIN2
18VDC
12VDC
5VDC
3VDC
18VGND
12VGND
5VGND
3VGND

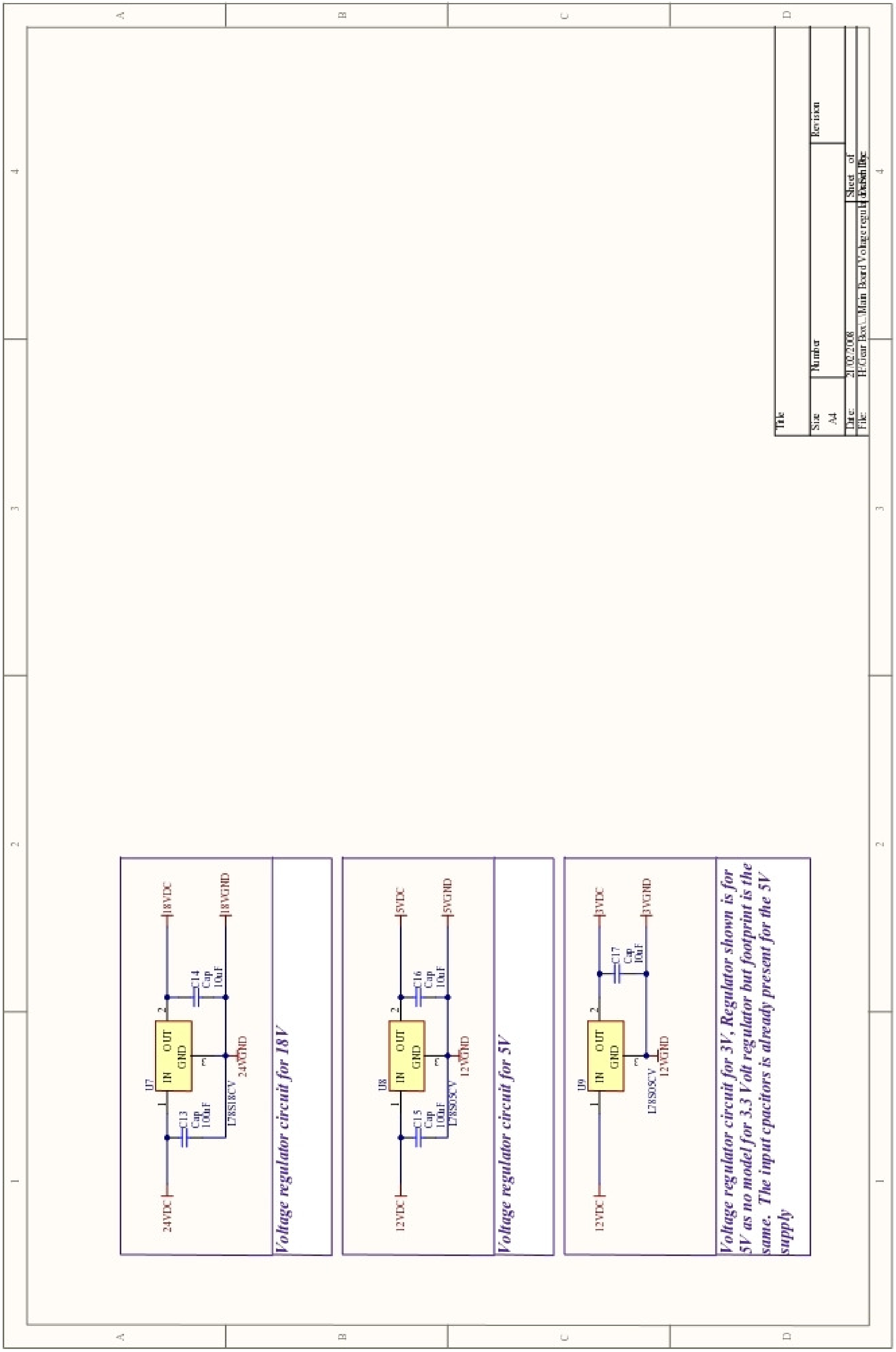

5VDC
R25
Res1
1K
R26
Res1
1K
R27
Res1
1K
R28
Res1
1K
GLS
GLL
STL
STD
Title
Size
A4
Number
Revision
Date: 21/02/2008
Sheet of
File: H:\Gear Box\...\Main Board Microswitches.SchDoc
Drawn By:

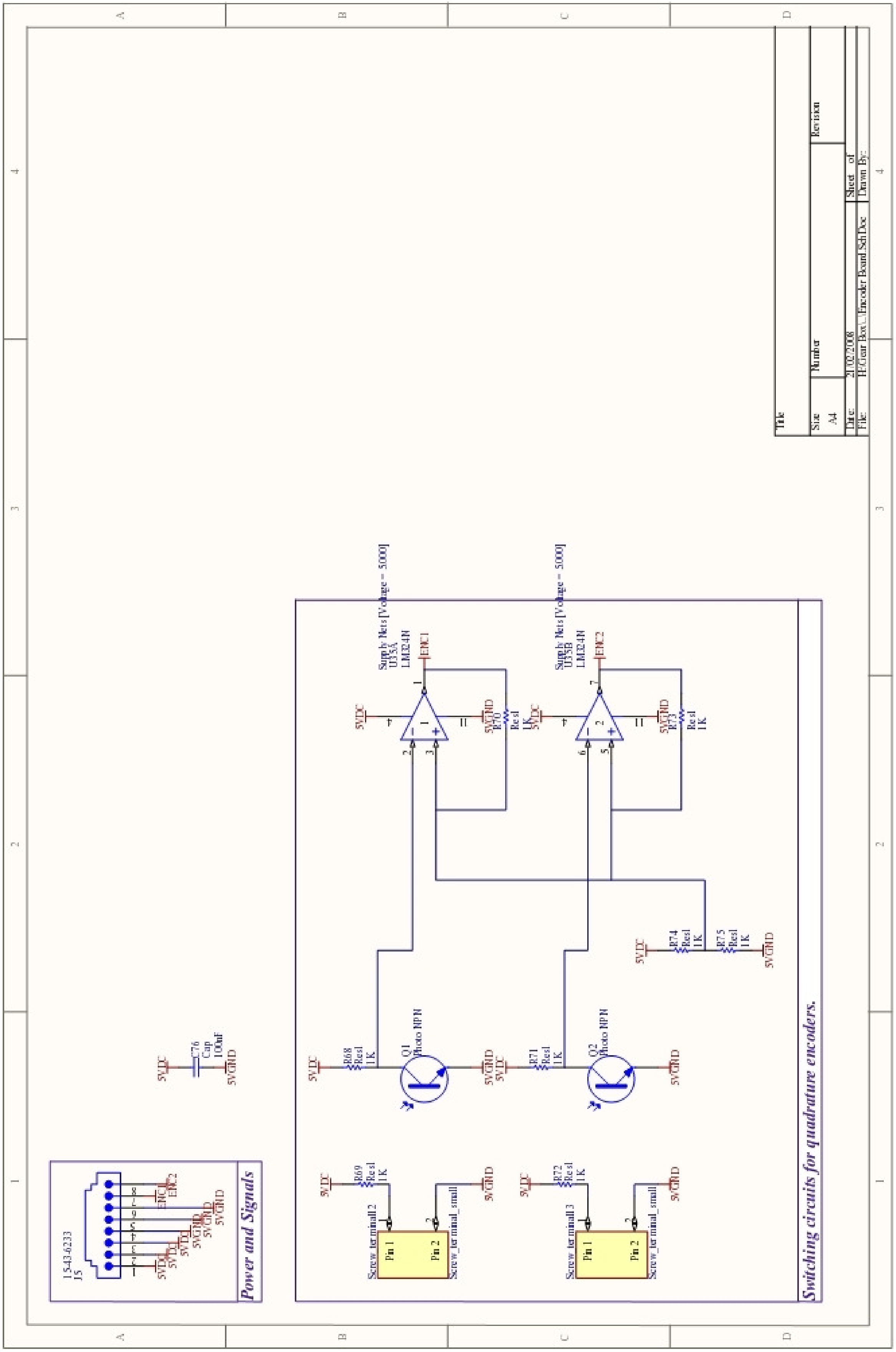

Runs the Gearmotor form the control signals and returns a current reading
U25
EN
SEN
IN1
IN2
BOOT1
BOOT2
GND
VS
VREF
OUT1
OUT2
L6203
GMT+
GMT-
12VDC
12VGND
PWMSIG
GMT_RUN
GMT_ED
GMC_raw
M74HC08B1R
U22B
MM54HCT00N
U19B
Supply Nets [Voltage = 5.000]
5VDC
5VGND
Title
Size
A4
Number
Revision
Date:
21/02/2008
Sheet of
File:
Drawn By:

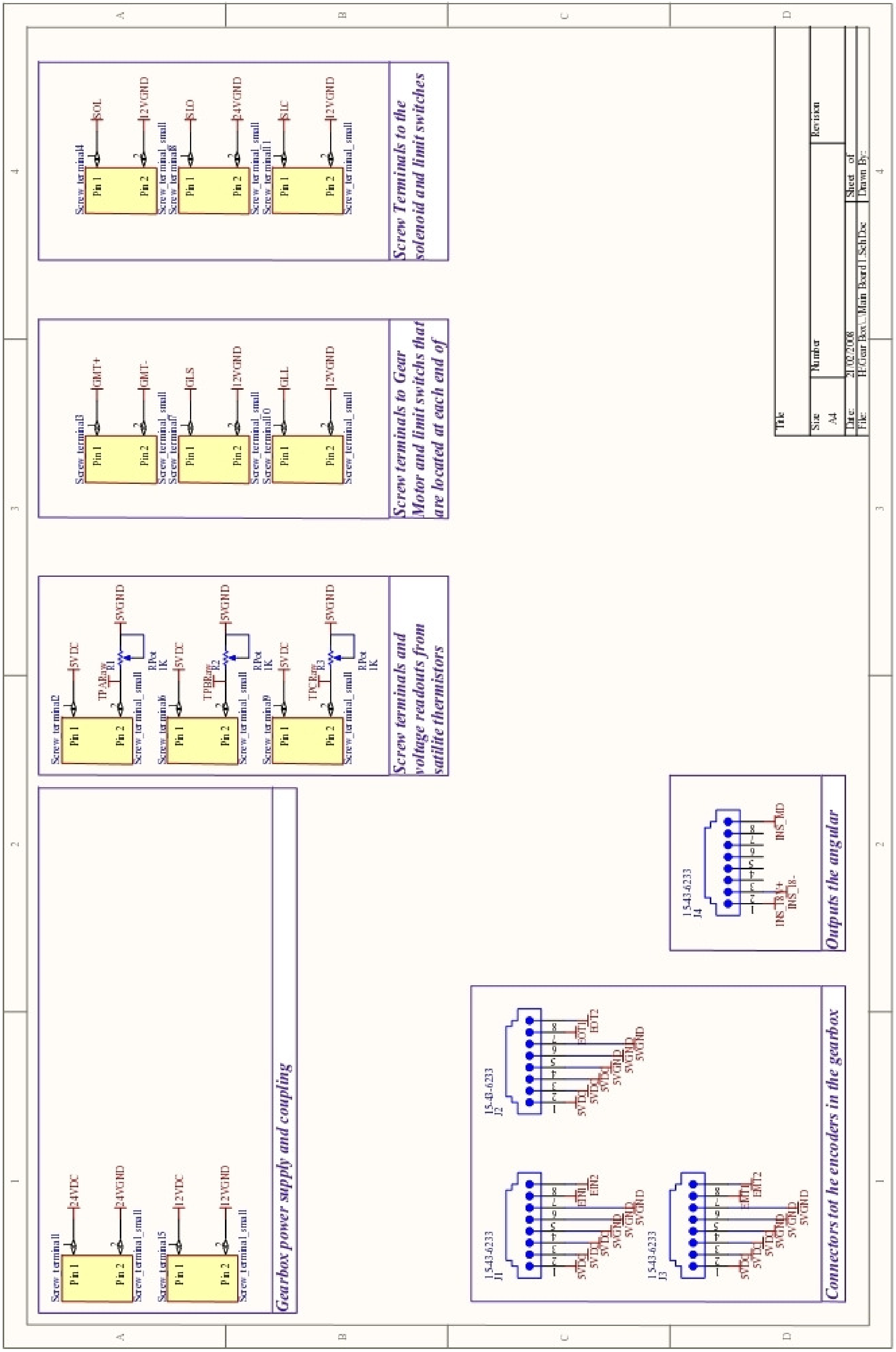

Converts the frequency of the edges from the encoders to a analog voltage
Xors the mechanical direction. Goes high durning opposite direction which means belts have broken or very big slip of the belts
Use D latch with one encoder channel as the clock and the other as the data. This gives the direction
X ors the encoder inputs to get double the edges
Reduces the Frequency out down to 2.5 Volts
U27
LM2907N-8
U28A
U26A
SN74HC74N
U14D
U12D
LM324N
OTS_VL
OTS_Edges
OTS_MD
INS_MD
MEC_Fault
OTS_2_5V
EOT1
EOT2

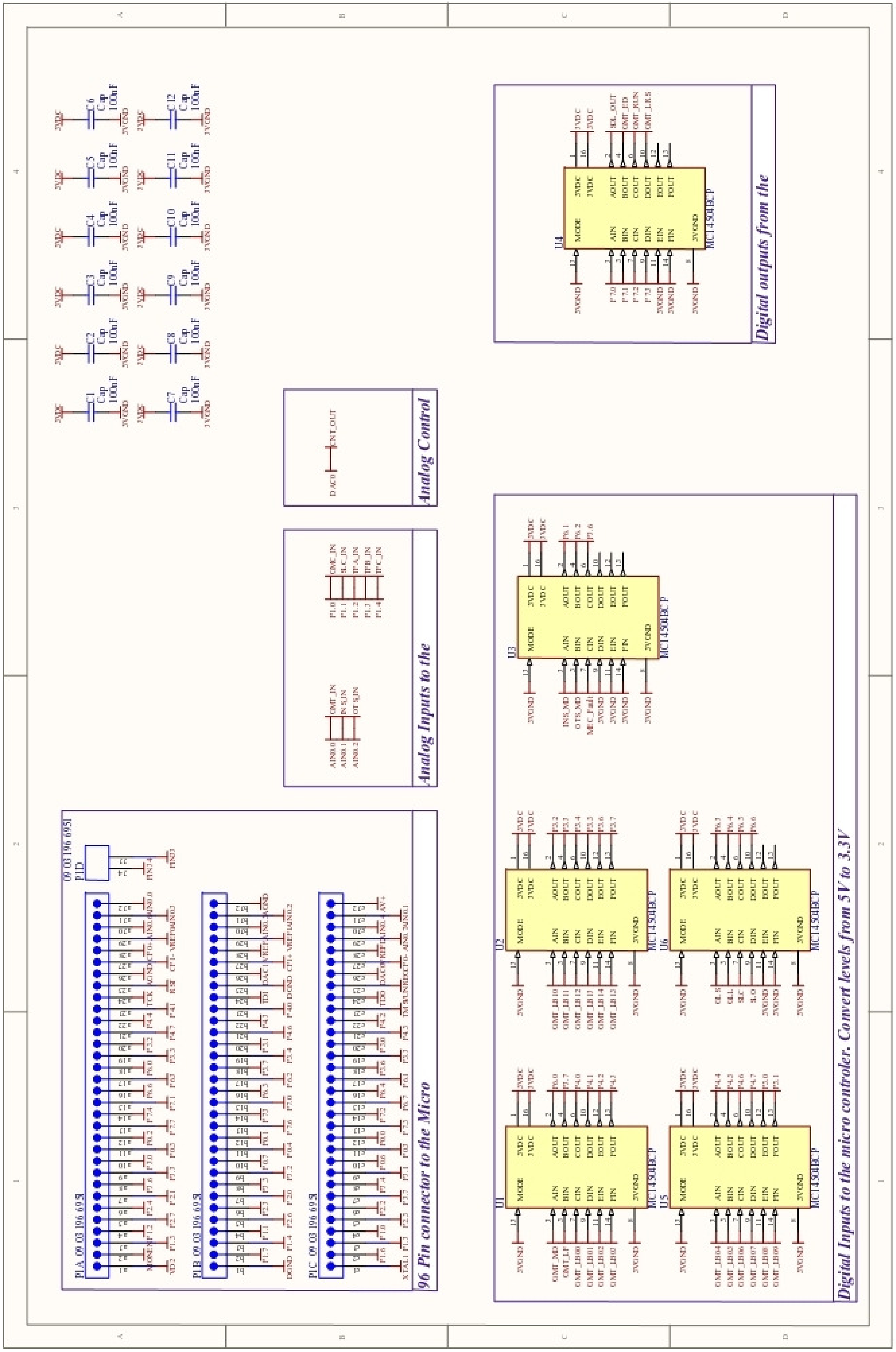

Changes the Analog control signal the the correct voltage levels to allow the switching of the duty ratio to controlt he gear motor
High speed comparator that compares the PWM control signal with the 556 timer value. Has hysterisis built in that may need to be tested first
Buffers the Analog control signal tot he correct voltage levels to allow the switching of the duty ratio to controlt he gear motor
Generates the saw tooth at 1 kHz and the timing between bridge operation


Higher Frequency Cut off filter for control signal- Low res for full range voltage
Higher Frequency Cut off filter for control signal- High res operational voltage
Higher Frequency Cut off filter for control signal- High res operational voltage
TPBRaw
TPB_IN
TPARaw
TPA_IN
TPCRaw
TPC_IN
LM324N
3VDC
3VGND
Title
Size
A4
Number
Revision
Date:
21/02/2008
File:


24VDC
18VDC
18VGND
24VGND
U7
L78S18CV
C13 Cap 100uF
C14 Cap 10uF
Voltage regulator circuit for 18V
12VDC
5VDC
5VGND
12VGND
U8
L78S05CV
C15 Cap 100uF
C16 Cap 10uF
Voltage regulator circuit for 5V
12VDC
3VDC
3VGND
12VGND
U9
L78S05CV
C17 Cap 10uF
Voltage regulator circuit for 3V, Regulator shown is for 5V as no model for 3.3 Volt regulator but footprint is the same. The input cpacitors is already present for the 5V supply
Title
Size A4
Number
Revision
Date: 21/02/2008
Sheet of
File:


Power and Signals
Switching circuits for quadrature encoders.


Screw Terminals to the solenoid and limit switches
Screw terminals to Gear Motor and limit switchs that are located at each end of
Screw terminals and voltage readouts from satilite thermistors
Gearbox power supply and coupling
Outputs the angular
Connectors tot he encoders in the gearbox


96 Pin connector to the Micro
Analog Inputs to the
Analog Control
Digital outputs from the
Digital Inputs to the micro controler. Convert levels from 5V to 3.3V