READY STEADY GO: DESIGN OF A PROTECTIVE, STABILISING CAMERA GIMBAL

An exegesis presented in partial fulfilment of the requirements for the degree of

MASTER OF DESIGN
IN
INDUSTRIAL DESIGN

at Massey University, Wellington, New Zealand

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ABSTRACT

Image 1: Desborough, G. (2016). Testing prototype gimbal.

READY STEADY GO: DESIGN OF A PROTECTIVE, STABILISING CAMERA GIMBAL[1]

The rapid evolution of lightweight, high performance compact cameras in conjunction with electronic stabilisation has given photographers and filmmakers the ability to capture extremely high quality 'shake-free' footage. However most of the equipment currently available is cumbersome and offers poor protection for expensive cameras. This issue is especially problematic for subject matter like action sports such as BMX, skateboarding, and snow sports where the action is fast and the conditions can be extreme.

My design objective was to develop a protective, stabilising camera gimbal that was easy to use and extremely compact and lightweight. I also wanted to design for competitive cost in materials and manufacture to make my product available to a wide user base.

I used a spiral product development process involving multiple prototype iterations to develop aspects of the design, particularly the external roll axis which is a major feature. My final design incorporates innovation: in how the roll axis and drive was achieved; the mounting system which enables rapid set up and lens changes; a very high level of protection; and ease of use in a compact and lightweight unit.

The end result is a product which should appeal to leading edge amateur and semi-professional filmmakers in this area, and give them new options to expand their craft.

Keywords: industrial design, gimbal, stabilisation, action sports, lifestyle sports, low volume manufacturing.

[1] A gimbal is a stabiliser, usually in all three axes of rotation, that brings together electronics, sensors and motors to cancel motion and shake from the camera operator before it reaches the camera.

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Many thanks to my MDes Joint Supervisors; Lyn Garrett[2]and Helen Mitchell[3]. As a BDes(Hons) graduate in Photography, embarking on an Industrial Design Masterate was a huge challenge. Thank you for your faith in me as I tackled this challenge which involved both photography and industrial design elements. At the beginning of my Master's study I also completed a Fab Academy Diploma in Wellington, and am very grateful for the support and assistance of Wendy Neale[4] and Craig Hobern in completing that course. All of the 3D workshop staff, especially Ken Howe, have also been of great help to me.

I am fortunate to have had the input of my brother, Jimmy Desborough, a talented engineering student, for specific advice on electronic design and general troubleshooting. I am also indebted to Spyro Serepisos of Grizzly Pictures (grizzlypictures.co.nz) for user experience perspectives and the opportunity to be part of commercial projects using traditional camera gimbal equipment.

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1 INTRODUCTION

Image 2: Desborough, G. (2014). Blair 1, Whakapapa.

1.1 PERSONAL INFLUENCES

I have been an action sport enthusiast all my life as a BMX rider, skateboarder, moto-crosser and skier, and absolutely love the thrill and adrenaline rush involved with these sports. I have also worked as a Level 2 Ski Instructor in New Zealand and the USA. My passion for action sports has directly influenced my academic studies. I have a Bachelor of Design (Honours) in Photographic Design and my final year project studied how imagery from action sports, particularly BMX, skateboarding, and snow sports is used to define a person's identity.

As a photographer I have developed an extensive knowledge of equipment capabilities in many different types of environments: alpine, concrete bike parks full of obstacles, following skateboards from a moving vehicle, etc. In practical assignments I have used techniques like stop motion, follow cam filmmaking, and high frame rate/high shutter speed photography. For example, this image was taken in the air from alongside a skier completing a 12m jump (and has been purchased by Mt Ruapehu for use in its marketing campaigns):

Image 3: Desborough, G. (2014). Mt Ruapehu marketing.

First-hand interest in the physical and academic aspects of these sports has enabled me to push the boundaries and really understand what is needed and what could be designed to capture the thrills and spills on film. My area of research interest is the equipment used for image capture for action sports such as BMX, skateboarding and snow sports.

This Master's project is effectively a hybrid that applies my photographic experience and skills along with my industrial design knowledge. I want to push myself to design an innovative product that solves existing, known problems when filming action sports and has widespread benefits for sports photographers and filmmakers. The terms cinematographer and videographer are also used in this context. I have taken cinematographer to mean someone responsible for all artistic and technical decisions related to the image, for a film, and videographer to mean someone who shoots video, i.e. a camera operator. Current thinking is that there is no longer any distinction based on one shooting on film and the other digitally, as most cinematographers now use digital technology.

The filmmakers I am designing for need equipment that is user friendly and robust. It has to be easy to use and able to be carried at all times in extreme environments. I have personal experience to draw on as well as many friends in this field, so I am familiar with the short-comings of existing equipment.

1.2 MARKET TRENDS

The product opportunity I am pursuing exists in a market that has been changing very rapidly in the past few years. An analysis of the major trends in the market is included in the Appendices, and in summary are occurring in three areas:

- Stabilising equipment has traditionally been designed for very heavy film cameras, with the go-to brand being Steadicam. In the last two years, small lightweight gimbals have come onto the market.

Image 4: Tustin, 2016. Body mounted Steadicam; a typical lightweight gimbal.

- Cameras have also evolved dramatically with cameras under 1kg now capable of excellent 4K video. Filmmaking is also changing: the hand-held follow shot that has been used by cinematographers is now possible for all filmmakers.

- There has been huge growth in 'lifestyle' sports (Wheaton, 2004) where technologically savvy people want to record in difficult and risky situations and distribute content through new media channels.

Image 5: Desborough, G. (2014). Zac, Whakapapa.

The world of photography and filmmaking is therefore changing. New low-cost technologies are expanding the quality and type of images it is possible to capture, and are effectively putting advanced tools in the hands of the masses. Naturally, having a good quality gimbal does not make you a cinematographer, but the technical constraints to producing high quality images of hard-to-film situations have been massively reduced.

I believe that filmmaking (and some aspects of cinematography) is entering a new era because of the convergence of camera and stabilisation technologies. Along with this there have been massive changes in the way that people relate to lifestyle sports and utilise technology in their lives, which includes the way they share and view digital content.

1.3 WHAT IS THE PRODUCT OPPORTUNITY?

The **product opportunity** is to develop a lightweight, compact, robust piece of equipment for camera stabilisation and protection – and for it to be cost competitive to maximise the size of the potential market.

To shoot good quality footage from a moving position requires a high quality camera, which in the past has meant a large and heavy camera, and generally some sort of stabilisation equipment. Traditional equipment like the Steadicam is extremely limiting and compact cameras were low quality. New handheld gimbals and cameras mean a user can glide through a scene, avoid obstacles, do high and low shots, and even hand off to another operator.

This inspired me because it gave the camera user enormous freedom of movement while still achieving high quality footage. I could see the implications for action sports where cameras were being taken into very difficult environments and situations. A prime example is a video of freestyle skier Nick Goepper (Red Bull, 2014) going over jumps with a filmmaker skiing alongside carrying a gimbal (a Movi M10). A rig weighing only about 5kg made it possible to capture this amazing footage.

I saw the opportunity to design a product that could exploit this potential along with protecting the camera in these high risk situations. From my own experience I also saw the opportunity to make set-up and balancing easier.

The **benefit proposition** is a piece of equipment that will enable users to capture high-quality moving or still images, while protecting their expensive equipment, and be easy to set up and adjust.

The **target market** for the product is prosumers, emerging filmmakers, professional videographer/filmmakers, and cinematographers, all of whom are likely to have a connection to action sports or a need to film hand-held in difficult or risky situations where there is the potential for equipment damage.

Key assumptions at the start of the project were that I could use off-the-shelf electronics with open source software, and the first part of my Masters programme would involve strengthening my industrial design skills.

1.4 SKILLS DEVELOPMENT

For years two to four of my undergraduate degree, all five of my elective papers were in industrial design. To increase my technical skills and advance my interest in product design, I completed a Fab Academy Diploma in digital design and fabrication at the beginning of 2015. The Diploma is Massachusetts Institute of Technology affiliated and run out of the Industrial Design workshop at Massey. The 16-week course was high pressure, but extremely useful. It helped me in the following areas:

- Electronics and Control Systems
- Digital manufacturing techniques such as laser cutting, CNC Machining and 3D printing
- 3D Computer Aided Design.

The final requirement of the Fab Academy course was to complete a project incorporating everything we had learned. I focused on an electronic baseplate which could in future be incorporated in my final design for this Master's project. The concept is that the camera mounting is electronically controlled to push it backwards and forwards on the x (roll) axis to rebalance the tilt and pan axis when quick lens changes were needed.

Image 6: FabLab electronic baseplate project.

I found the Fab Academy course to be an important stepping stone for understanding and using new technologies. I became particularly interested in digital fabrication, prototyping, and how computer controlled cutting can produce highly accurate cutting and engraving across a wide range of materials.

1.5 PRODUCT DEVELOPMENT PROCESS

In relation to my product opportunity, my skills development in digital design and fabrication encouraged me to pursue a spiral product development process as illustrated below, where I could use many iterations of laser cut or 3D printing parts to rapidly prototype and develop parts of my design, to speed up the process and reduce risk (Corbett, 2014; Rayna & Striukova, 2014; Ulrich & Eppinger, 2012, Unger & Eppinger, 2006).

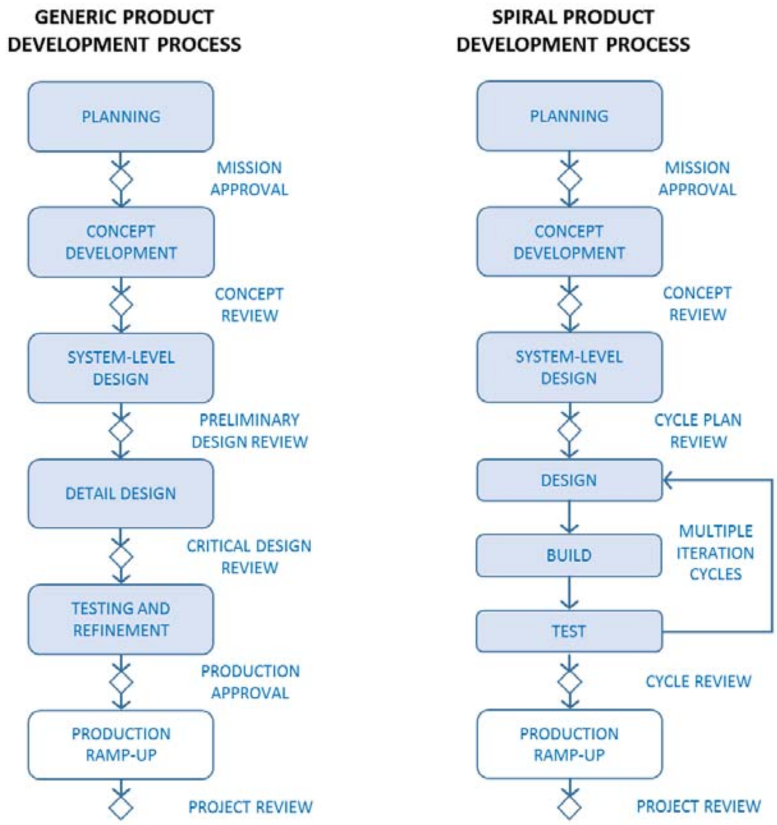


Figure 1: Generic and Spiral Development Processes. Adapted from Ulrich & Eppinger, 2012, p22.

Although 3D printing has some limitations, particularly in terms of speed, one of my project objectives was to explore a design process using 3D printing, laser cutting, and multiple prototype iterations for a complex design with several issues to resolve. Using this approach, I wanted to reduce risks and get further, faster by making and testing possible design directions.

This potential impact of digital design and rapid fabrication on the design process has been known for some time (e.g. Hopkinson, Hague, & Dickens, 2006), but the reality of 3D printing for design students has sometimes not lived up to the potential (Choi & Zhang, 2015). However, testing the impact of different design approaches (Camburn, Jensen, Crawford, Otto, & Wood, 2015) seems to show that multiple iterations can result in better outcomes.

As faster and more sophisticated printers come onto the market (Stratasys, 2014; Swartz, 2016), it appears that 3D printing especially is changing the nature of the design process (McClue, 2015), because it allows much faster development and testing of concepts than hand-made models, and the ability to translate directly to high accuracy manufacturing techniques like waterjet cutting and laser cutting.

1.6 SCHEDULE

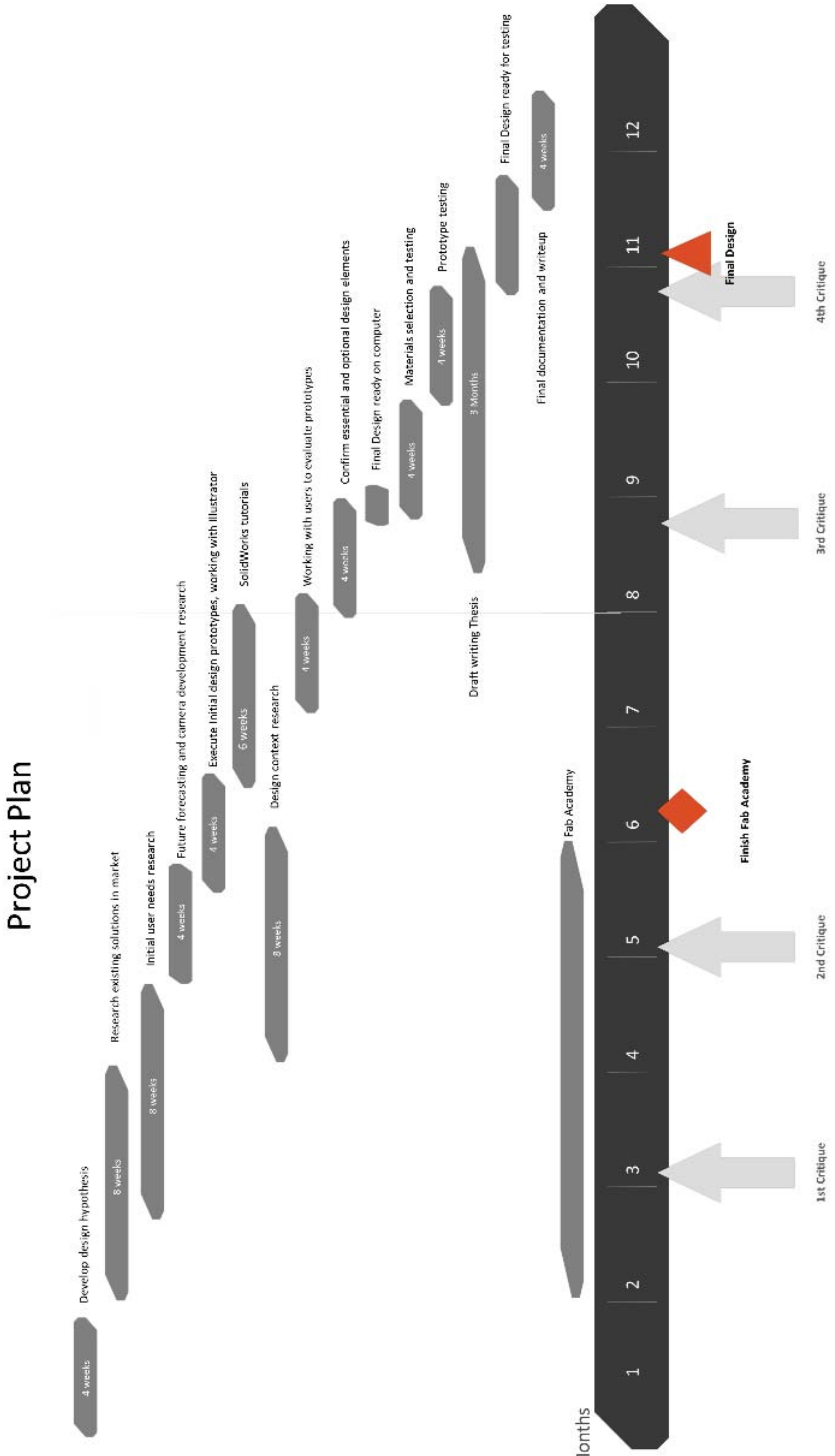


Figure 2: Project plan.

2 CUSTOMER NEEDS RESEARCH

Image 7: Desborough, G. (2014). Taz, Whakapapa.

2.1 TARGET MARKET

The target market for the product is consumers who are either involved in action sports in some way - as a part-time filmmaker, participant, coach, or parent – or need to film in a difficult or risky environment. I have further divided that into:

- prosumers[5];
- emerging filmmakers;
- professional videographer/filmmakers; and
- cinematographers.

For all of these groups, they:

- are passionate about their filmmaking and/or photography and want to capture high quality images;
- are probably in the 20 to 50 years age bracket, and have high disposable income;
- appreciate the value of high performing technology and are prepared to spend on it; it is possible they are somewhat obsessed with technology; and
- because of the reach of the internet I consider my market to be international especially USA, Europe, Japan, Australia, and New Zealand.

I have developed some personas of the types of people that would be using the product and the types of environments they would be using them in. These are included in the Appendices.

[5] 'Prosumer' is a term used from a business perspective, for high-end electronic devices (such as digital cameras), meaning a price point between 'professional' and 'consumer' devices.

2.2 USER NEEDS RESEARCH

The market for hand-held gimbals is still relatively young, which created some challenges in terms of connecting with user groups. I was also conscious of the commercial sensitivity of discussing or disclosing future concepts with users, especially in an online environment. So I used the following approach:

- Prosumers – internet research: discussion groups, industry experts, equipment reviews, etc.
- Emerging filmmakers – personal knowledge as I have extensive first-hand experience in this area including using a range of equipment in many challenging situations.
- Professional videographer/filmmakers - interviews and follow-up with a practicing professional: Spyro Serepisos.
- Cinematographers – interviews and follow-up with an experienced cinematographer: Richard Bluck.

Spyro Serepisos runs his own production company, Grizzly Pictures (http://grizzlypictures.co.nz/), in Wellington. He has a range of clients including Gazely Motors, the Institute of Surveyors, Speedmagnet, and Mindset fitness. He specialises in using video and social media to reach target audiences. I was able to work with him on one of his assignments, which was the launch of a new vehicle model at Boomrock (http://www.gazley.com/news-and-events/np300-launch/). This enabled me to use a DJI Ronin gimbal for a whole day in a commercial environment.

Image 8: Spyro Serepisos.

Richard Bluck NZCS is President of the New Zealand Cinematographers Society and has more than 25 years' experience as a cinematographer, camera and Steadicam operator and focus puller. He has worked on Peter Jackson's King Kong and Lord of the Rings trilogy, Master and Commander, District 9, Avatar, The Far Side of the World, The Legend of Zorro, and most recently on the Sir Edmund Hilary documentary film Beyond the Edge.

Image 9: Richard Bluck.

Secondary research included:

- People in my BDes(Hons) Photographic Design class in similar areas of interest.
- Looking at the media companies like Red Bull are using (such as Brain Farm, http://brainfarmcinema.com/).
- Investigating related areas such as adventure cinematography e.g. climbing Aoraki Mt Cook.
- Not looking just at action sport (i.e. including photography relating to wildlife, adventure, motor sports, etc.).

The user needs expressed as product requirements are summarised below:

Prosumer

Issue	Comment	Product need
Typical uses	Using a handheld DSLR with video capability	-
	Making a short video of my daughter learning to ride a bike	Effective stabilisation and light weight
	Short film of the massive party we had last weekend	Compact and unobtrusive
	Panning shots of the major sights when I was on holiday	Effective stabilisation
Likes – current equipment	Just point and shoot, the camera does the thinking	Easy to set up and use
	Everyone is very impressed with the output, very good quality compared to what I have had in the past	Effective stabilisation
	The camera is beautifully designed and ergonomic	Comfortable handle design
	Lovely shallow depth of field and bokeh	Not really applicable, this is more of a camera issue
Dislikes – current equipment	Need to be very careful with that because it is fragile and expensive	Robust protection
	Needing to carry a bag for all the extra bits and pieces like batteries and SD cards	Self-contained unit
	The sound quality is awful, you really have to overlay some music afterwards	Ability to use the latest cameras
	There is quite a bit of bouncing around, a bit hard to watch the output sometimes	Effective stabilisation
	My arms get tired if I have to do hold it in one position for any length of time	Compact and lightweight
Suggested improvements	I'd like to get closer to what a proper filmmaker can do	Effective stabilisation and compact
	I'd like something that looks the part	Good aesthetics, purposeful
	Easy setup, want to turn it on and start filming	Easy setup and operation

Emerging filmmaker

Issue	Comment	Product need
Typical uses	Using a gimbal similar to a DJI Ronin	-
	BMX rider performing tricks at the bike park	Compact, lightweight, and highly protective
	Video analysis of ski school pupils	Effective stabilisation
	Contracted stills and video for ski field company	Compact, lightweight, and highly protective
	Short film: extreme vertical	High level of protection
	Stop motion photography film	Effective stabilisation
Likes – current equipment	The smooth shots are amazing	Effective stabilisation
	I can get footage I never have been able to before, like follow shots	Economic and easy-to-use from any angle
	It looks very high-tech and professional	Needs to be built to a high standard and look compatible with other equipment
Dislikes – current equipment	It is really big and cumbersome and not very practical for shooting, when I do long takes my arms get very tired	Compact and lightweight, good handle design
	I'm worried I'm going to bang into something and drop the whole thing	Good level of protection for the camera, and also that the gimbal itself is not damaged
	Challenging to set up, the instruction manual is pretty poor	Easy setup and operation
	Quite expensive for what it does	Cost competitive
Suggested improvements	Protect my camera equipment better	Good level of protection to the camera and also that the gimbal itself is not damaged
	I would like to be able to get closer to the action	Compact unit
	It would be great if it would fit in my backpack	Compact and lightweight unit
	As cheap as possible	Cost competitive

Professional videographer/filmmaker

Issue	Comment	Product need
Typical uses	Mostly use a DJI Ronin	-
	Promotional shoot for a car company	Equipment needs to be failsafe
	Short video clips for marketing purposes	Versatile, effective stabilisation
	Short documentary	Able to do long takes, i.e. compact and lightweight
	Raw material for TV ad	Quick to set up for lens changes
Likes – current equipment	Follow shots add a huge amount to the quality of the material	Effective stabilisation
	Getting some great footage using 4K video	Effective stabilisation
	The electronic stabilisation works really well	Effective stabilisation
	My clients love me having the latest equipment	Needs to be built to a high standard
Dislikes – current equipment	It has to be all set up before I go on location, too much risk and time involved to do it on site	Easy setup including the ability to change lenses
	Need to have an external monitor to frame shots	External monitor or use camera screen directly if visible
	Can't shoot with the Ronin for more than a few minutes at a time	Lightweight
	The position of the handles means it's hard on the wrists	Comfortable handle design, compact
Suggested improvements	Less weight would be my number one priority	Lightweight
	Auto balancing if that is possible	Auto balancing

Cinematographer

Issue	Comment	Product need
Typical uses	Generally using a Gremsy for this type of work, but also use a Steadicam	-
	Scouting locations	Compact, robust, easy to pack away
	Trial shots to get a feel for what final shots will look like	Effective stabilisation
	Behind-the-scenes documentary	Compact and lightweight
Likes – current equipment	Incredibly small and light weight compared to traditional steady cam equipment	Lightweight
	Quality is pretty good, but not up to professional standards	Effective stabilisation
	Compared to my other equipment, it is low-cost	Cost competitive
	It's self-contained, I don't need a second person to pull focus	Compact unit
Dislikes – current equipment	Can I rely on it?	Needs to be built to a high standard and operate effectively
	It is very difficult to use a Steadicam for any length of time, they are really heavy	Compact and lightweight
Suggested improvements	Something that was easier to set up would be good	Easy setup and lens changes
	Auto balancing if that is possible	Auto balancing

The specific user needs and wants identified and ranked from this process are as follows:

1. Protection of the camera equipment, operator confidence in risky situations.
2. Lightweight so that users can operate for longer.
3. Need to be able to manoeuvre in small spaces.
4. A way for the camera operator to view and compose the frame clearly and effectively.
5. A way to balance the camera faster and more efficiently when initial set up and when changing lenses.
6. Easily transportable and be ready to go really fast - minimum set up times.
7. Elimination of cables and things to get twisted on.
8. Really intuitive design where anyone could use it from clueless enthusiasts to professional cinematographers.

I am designing for someone's lifestyle and being a go-everywhere item of equipment. They are people who are involved with tough and rugged environments where there is not the possibility to set up dollys or other systems and where only a small gimbal device would be able to be used. Because it is opening up new possibilities of what is able to be captured, this product should help introduce a new type of film maker where they are confident in going into difficult shooting environments with confidence that their camera equipment and their self will be able to stay safe.

Protection - impact protection for the camera and lens. Often an operator will be following someone whether that is running, skateboarding, skiing or some type of other risky movement to get the shot that they are wanting, they put the camera at risk of being hit and damaging the equipment. Another issue with protection is when transporting the gimbal plus camera to different locations. Some operators use large Pelican cases with cut out foam. Pelican cases are a large moulded plastic case with a clip seal and foam padding on the inside. Even though this is very effective in protecting the camera is increases its size and weight massively. Also protecting it from the elements in terms of weather resistance, if the weather was so bad it needed to be waterproof then it would probably be unsuitable for shooting.

Lightweight - the amount of time the camera operator can use a gimbal before fatigue sets in is a major factor. Even a few kilos are very hard to hold out in front of you for any length of time. For example, these guidelines from Europe indicate that any weight held out in front of a person should not exceed 3kg for females and 5kg for males:

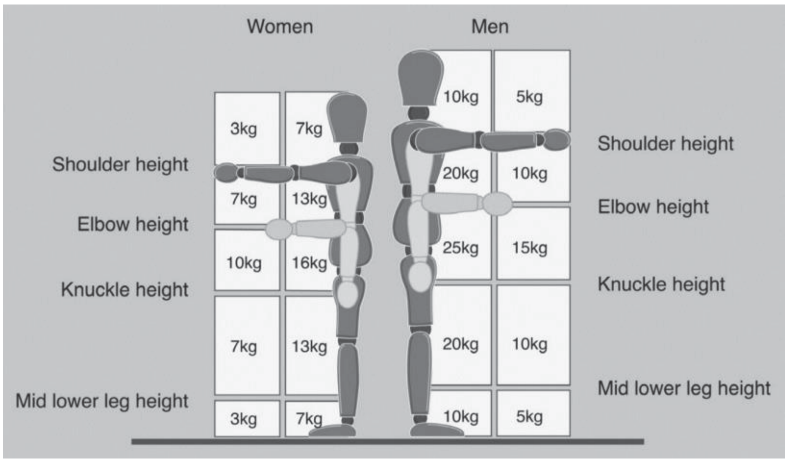


Figure 3: Health and Safety Authority. (2006). Lifting guidelines.

Although the weight is greater if held close to the body, in the situation of using a camera gimbal this would reduce operational flexibility. Some manufacturers have developed harnesses and human exoskeletons to cope with the weight of gimbals. This also effects the life of the batteries so it does not have to move so much weight.

Manoeuvrability - in small and tight spaces; in crowds, in and around buildings, even being passed through widows for a continuous shot.

Initial set up - of the camera is one of the biggest problems that gimbal users face. The gimbal needs to be perfectly balanced for all three axes to function properly. This also includes balancing the camera when changing lens while shooting, as this changes the point of balance, often for more than one axis (obviously for tilt and pan, sometimes also for roll as the roll axis may not be along the centre line of the lens).

Competitive cost - this is always related to quality and reliability, i.e. people are prepared to pay a reasonable amount for a piece of equipment that will not let them down.

Battery life – this is a significant issue - often there are a number of different batteries used by multiple devices on a rig such as microphones, follow focus systems and monitors which can get confusing and a hassle when one battery runs out. This also contributes to the amount of cables that are attached to different devices on the gimbal where they can get tangled up around different moving points and affect the way the gimbal operates.

Composing the shot - being able to view what is been shot which sometimes means the need for a second person, to control the gimbal to make sure it is framed right and that the focus is correct. Or using a good monitor or smartphone can be used, but the most preferable would be the ability to make this possible for a single person.

Secondary considerations

Tool-less design or limitation to the number of necessary tools.

Elimination of complex cable arrangements that can get twisted up when rotating.

Needing a lot of gear to carry around to get good quality audio and other accessories such as follow focus systems and screen monitors.

3 PRODUCT SPECIFICATION

Image 10: Desborough, G. (2014). Murray 1, Whitby.

3.1 VISUAL PRECEDENTS

I looked for visual precedent in the type of equipment my target market was likely to be using and attracted to: photographic equipment, outdoor Bluetooth speakers, and sports equipment and armour.

Filmmaking equipment
This equipment is designed to fit nicely in the hand, it has very high quality finishes, uses space age materials, looks strong and robust, sometimes there are a lot of functional knobs and appendages, it is almost always entirely black though sometimes there are highlights, it is purposeful looking. For example in Image 11 below, Red Cameras cameras have a strong form follows function aesthetic, in Image 12 below, Black Magic Design cameras tend to be more streamlined but they pay a lot of attention to fastenings with hex head screws, and in Image 13, the Alexa Arri Mini camera is a very high quality camera which is been finished in carbon fibre which gives it a sleek, ultimate tech, minimalistic design.

Image 11: Red Cameras cameras

Image 12: Black Magic Design cameras

Image 13: Alexa Arri Mini camera

Outdoor Bluetooth speakers

I specifically chose outdoor Bluetooth speakers as they were the similar size to the gimbal. They had similar internal electronics which were highly important to keep protected. These products display their weather-proofing with rubberised textured services, bold forms, and again extensive use of black with some high-lighting. Form is very much dictated by the functionality. They also pay some attention to detail and fasten-ings.

Image 14: Outdoor Bluetooth speakers.

Sports equipment and armour
I looked at this type of product because something similar could well be worn by people involved in action sports. And also I was interested in how they had dealt with protection from aesthetic perspective. They had similar characteristics to the Bluetooth speakers with rubberised, texturised shells, shock pads, scales, and again black featured with some highlighting.

Image 15: Sports equipment and armour.

The key visual design inspiration that I took from looking at these different products was:

- very functional
- black with highlights of fluoro
- exotic materials including carbon fibre
- high-tech, futuristic, high-quality finishes
- rubberised shockproof surfaces
- not easily marked or damaged
- tactile
- generally matt finish
- scales and armour, chunky
- attention to detail in the fastenings
- hex fastenings that imply precision and high torque
- sleek and streamlined
- built with a purpose in mind, not necessarily pretty.

3.2 COMPETITIVE PRODUCTS ISSUES ANALYSIS

This has mainly been though personal knowledge, and secondary research:

- of the major websites of equipment manufacturers;
- looking for the credits of short films, where the equipment used is sometimes given; and
- looking in the comments sections of films or in forums where questions about equipment are asked.

A summary of the key features and issues with existing products is below. There is a more detailed description of specific models in the Appendices.

- They are large and cumbersome. Most gimbals try to have a reasonably large payload so that they can be suitable for a wide range of camera equipment. This means that the equipment itself can be quite solidly built, and when a camera is attached the whole rig can be heavy, in this context anything over 3 to 4 kg is heavy.

- They can be very tiring to use. Most gimbals have wide fixed handlebars set wide apart so that the machine can be moved around and pointed easily. This puts the user's arms in a wide, unnatural position. Where there is a requirement for a relatively long shot this can make it very hard for the operator. Some operators even say that 'flying' a gimbal is a young person's game.

- They offer minimal protection. Possibly because they evolved from drone gimbals, where a crash was going to destroy everything anyway. They also had the Steadicam for inspiration, which is a large piece of equipment designed to carry a heavy payload and be able to manoeuvre it.

- Some gimbals require significant technical ability to set up, even a knowledge of coding skills for the program that runs them (see example of setup process for DJI Ronin in Appendices).

- They all need to be balanced including being rebalanced each time cameras or lenses are changed. This can be time-consuming and frustrating because effectively you are trying to find a centre of gravity in three dimensions very precisely (see example of setup process for DJI Ronin in Appendices).

- Nearly all gimbals obscure the rear screen of the camera, which means they need an additional monitor.

- Battery drain can be significant with controllers, sensors, motors, and external monitors.

- Many gimbals cannot be placed on the ground without the help of a stand, and if this is part of the gimbal it adds weight.

- They are relatively expensive, at least US $1,500 for something that will perform well (refer to Appendices for specific product costs).

The opportunity in the market could be expressed as: very few gimbals offer very little protection, and equipment with a high level of protection offers poor performance:

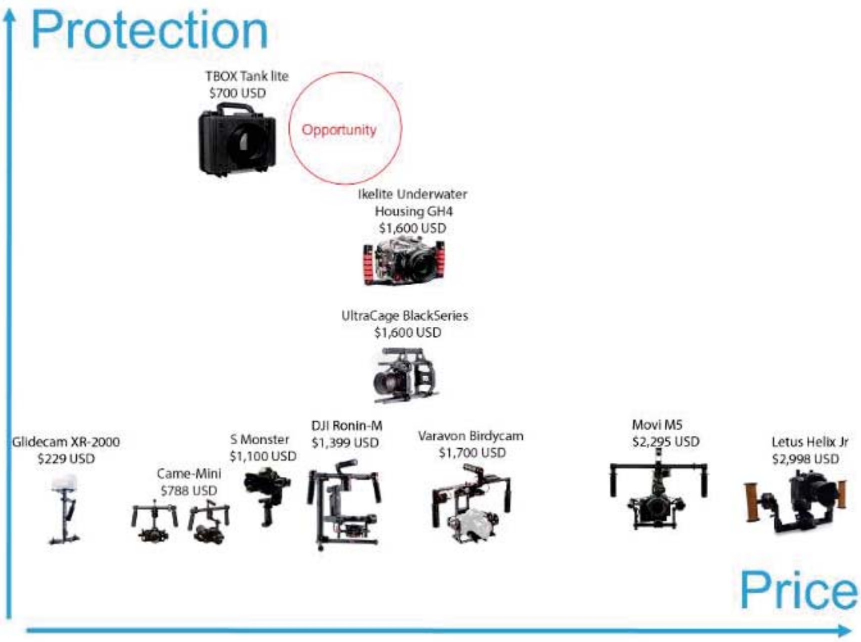


Figure 4: Protection vs price.

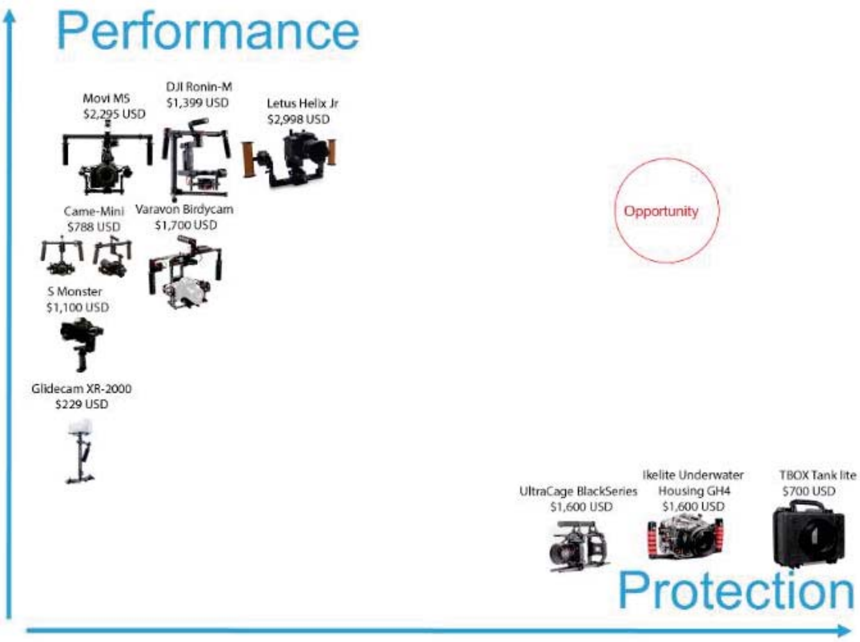


Figure 5: Performance vs price.

3.3 DESIGN GOALS

This project has the objective of developing a 3-axis hand held camera gimbal that provides protection and stabilisation when shooting action sports in challenging environments. Specifically, it would:

- be highly durable and protect the camera it is supporting, i.e. able to survive a drop onto a surface with minimal damage, and increase user confidence knowing their equipment is protected;
- have lightweight construction to extend the time the camera operator can work for without feeling fatigued;
- substantially reduce vibration and maintain good image quality under extreme operating scenarios; and
- have a simple design that is easy to manufacture to keep costs as competitive as possible.

Physical impact protection - The product must provide impact protection to the camera equipment so that it can be used in the most challenging terrain and weather environments. If it is dropped it must have excellent shock absorbing qualities (i.e. the ability to absorb the energy from an impact such as dropping onto a hard surface).

Lightweight - My product needs to be as light as possible to help minimise camera operator fatigue as much as possible. This can be achieved by reducing the size of parts to an absolute minimum and the use of high tech materials and production methods. For example, designing from flat sheet and using bracing. It is being designed so there is no need for a harness or special carry vest, which is the current, cumbersome practice.

Ergonomics and ease of use - It needs to be easy to set up, adjust, use for filmmaking, carry and transport.

Aesthetics - The client is keen to use high tech materials to give it a rugged and military type look. It will be a very personal object that will hopefully be used a lot by the user. It needs to fit nicely in the hand and the materials need a good tactile feel. It needs to look, and be strong and stable. Form will follow function.

Competitive manufacturing cost - The product is for a specialised market so needs to be able to use low-volume manufacturing techniques. It is very likely that it will be refined in an ongoing way so digital design and translation to digital manufacturing is essential.

Camera - The types of cameras that I am specifically looking at are cameras such as the Sony AR7 models, Panasonic GH4 and Black Magic pocket cameras. The Sony and Panasonic models are compact still cameras that have the ability to also shoot high quality video. This type of camera varies in price with different capability and technical specs but range from about 1,700 NZD to 5,000 NZD. Which also gives me a good indication on the amount of money these people are willing to spend.

3.4 PRODUCT SPECIFICATIONS

Final product must be a fully functioning prototype.

Design aspect	Definition
Lightweight	2.0-2.5.kg[6] without payload
Protection	Calculations of the physical strength of materials, and possibly “Mil standard” drop test (MIL-STD-810F 516.5, Blickenstorfer (2016), see Appendices)
Low cost materials and methods	< US $1,000
Payload	1kg[7] and associated physical size: 110mm H x 140mm W x 90mm D
Battery life	To be determined, must be consistent with camera battery life
Easy to carry and manoeuvre	Measured by user acceptance
Technical performance	‘Step test’ and possibly laser test (mounting a laser in the gimbal and using a wall target)
Aesthetics and materials	Measured by user acceptance

My design will not resemble the type of gimbal that is used for drones. They are underslung camera gimbals design for another use and because weight is the primary consideration they tend to offer very little protection. Quality and performance is important to my design. I won't sacrifice performance for cost savings. I would rather it cost more and performs correctly than not perform as it is supposed to.

[6] The DJI Ronin M, one of the most popular gimbals on the market, weighs 2.3kg.

[7] At the start of the project I had initially targeted a high quality DSLR camera which would be about 2kg, but I have updated this in response to advances in technology. Future forecasting is predicting that compact mirrorless cameras which are typically less than 1kg with lens will take over a lot this market space of camera users.

4 CONCEPT DEVELOPMENT

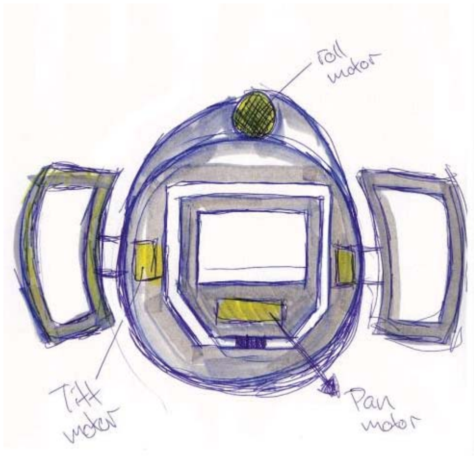


Image 16: Initial concept sketch.

4.1 DESIGN TOOLS

I used some sketching initially to visualise concepts and see how they would operate. However it is quite challenging to do this with a three-dimensional product where tolerances are involved and everything needs to fit together. Therefore I soon progressed to using Adobe Illustrator to sketch and then print parts from flat sheet. The use of flat sheet was one of my design objectives and this was the easiest way to organise concepts and then translate them to a physical prototype.

An important part of digital fabrication is the ability to create and express design concepts in three dimensional form. I had limited experience using CAD modelling software. At Massey University the product known as Rhino is used, which is orientated towards surface modelling. After taking advice from people in the industry, I chose to use a product called Solidworks which is widely used for engineering type design. Solidworks is more complex but is relatively easy to use, and crucially, it enabled me to make and assess analytical (virtual) models in 3D. This is because Solidworks allows 'assembly' of each component and can simulate mechanical motion such as rotation, linear movement, etc.

It took some time to become familiar with Solidworks, and www.lynda.com was very helpful for this. The emphasis on CAD meant I was able to use these files directly for 3D printing and laser or waterjet cutting. It also allowed me to have many iterations and to make working prototypes using low cost materials like MDF and acrylic before moving on to materials like carbon fibre and advanced plastics. Multiple design-build-test iterations was a key part of my product design approach.

SolidWorks has a nesting programme plug-in that breaks an assembly apart and lays it flat. This could then be saved as a DXF and imported into Illustrator and then cut using the laser cutter. This has been a large time saver and also extremely helpful. It meant I could make all of my model in a 3D space with the right thickness and with a few clicks have it nested really well saving materials and time.

4.2 CONCEPT DEVELOPMENT

A gimbal stabilises motion in three axes of rotation: roll, pan and tilt. These three axes can also be referred to as roll, yaw and pitch when describing aircraft or ship movement. Movement along these axes is referred to as roll pan and tilt axis rotation respectively:

Rotation	Axis	Lateral Movement	Aircraft or ship
Roll	x	Forward and back	Roll
Pan	z	Up and down	Yaw
Tilt	y	Left and right	Pitch

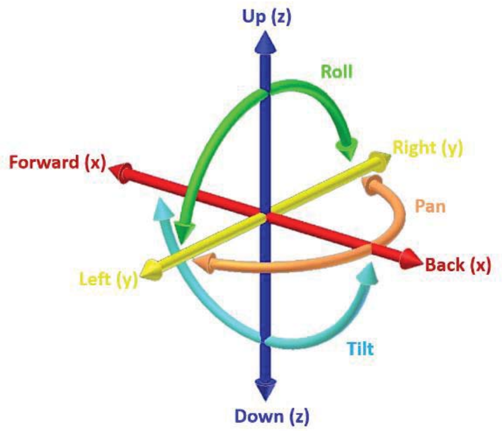


Figure 6: The six axes of movement.

With protection as a fundamental design criterion, I wanted the structure itself to provide protection and to surround the camera. These were my first ideas of how this might be accomplished.

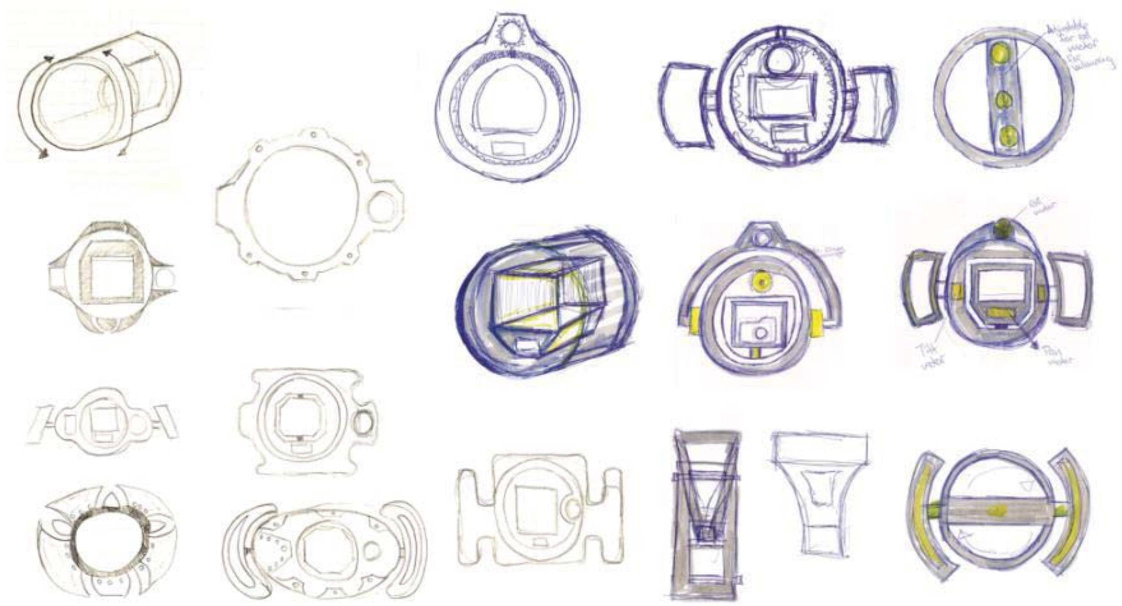


Image 17: Desborough, G. (2015). Initial concept sketches 1.

Establishment of a basic model - geometric layout

In Illustrator I organised the order in which I thought the three axis could go within each other. There are several ways the three axes for pan, tilt and roll can be set up. Working from the inside out, Pan-Roll-Tilt is the chosen option because it is:

- the most compact
- easier to incorporate tilt in the handle
- internal cage provides strength
- provides a flat mounting point for pan motor
- allows for the baseplate to be mounted with good clearances.

I had some crucial components that needed to be incorporated. My most important was the box that I had created that would fit a number of cameras within with an estimated weight limit for a camera and lens combination of 1000-1500 grams.

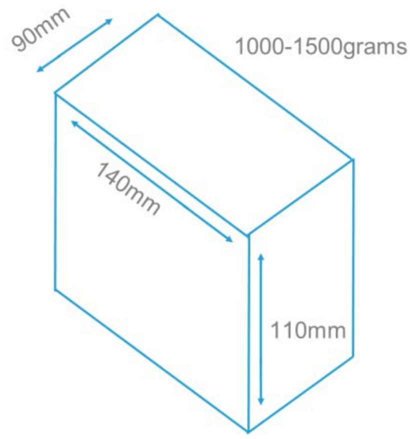


Image 18: Camera box.

The next was the size of components that were going to be within the structure. The motors, the control board and the battery.

I needed to figure out what type of motors I was going to use; this was going to be important for the size so that I could make sure that I had enough clearances between different spinning parts.

Thinking in a three dimensional form in my head and then unfolding these thoughts into nests in a 2D program that I could then cut out using the laser cutter and then glue back together to make an object. I was mainly making shapes that could be stuck to together with hot glue or superglue to create some objects to get an idea of shape and size.

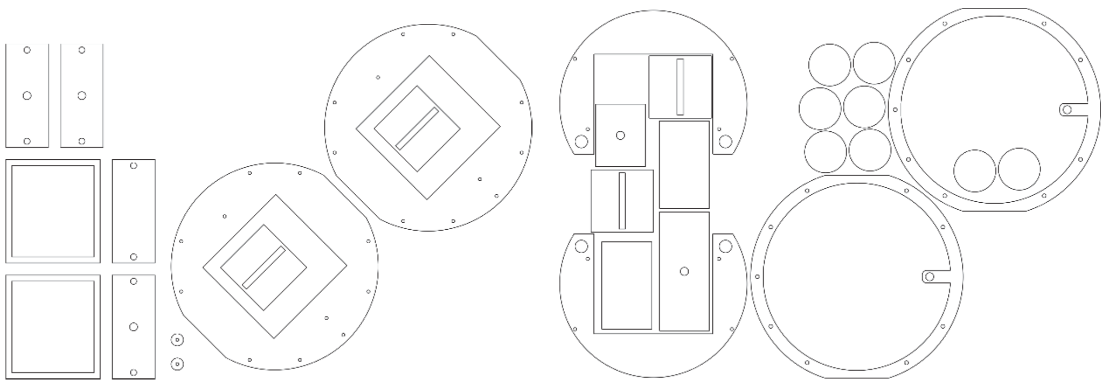


Image 19: Desborough, G. (2015). Initial concept sketches 2.

Key areas to progress with prototyping

1. The way in which an external bearing for the roll axis would actually be achieved.

   Using a hubless wheel in this context, the two main options for the drive are:
   - geared drive – a toothed drive to ring and a motor with a cog. This would have less play than with an integrated system as the drive would not be bearing weight, but still considered to be subject to jitter.
   - belt drive – a cam belt drive similar to the ones in a printer, but with a large driven ring. The belt would adsorb some of the shock from changes in direction. Off-the-self options are available for cogs and belts.

   Clip designs to hold an outer shell or bearing so that the inner ring can run freely within and a separate drive gear attached.

2. Building for maximum structural strength.

3. Operator ease of use, ergonomics, setup and adjustment.

4. Design for manufacturing using low cost methods suitable for low volume manufacturing such as cutting from sheet.

5. Robust design, i.e. allowance for more strength and rigidity, motor capacity, etc. than the minimum required.

Using a spiral development process with multiple design-build-test iterations, I was also conscious of not getting bogged down in the "hardware swamp" (Clausing, 1994). To avoid this, I broke down the product into pan, tilt and roll components, and sub-components, and had an objective of issues to address for each prototype iteration, and a review of design direction after each.

5 PROTOTYPING

Image 20: CAD drawing of three axes of prototype.

5.1 OVERVIEW OF PROCESS

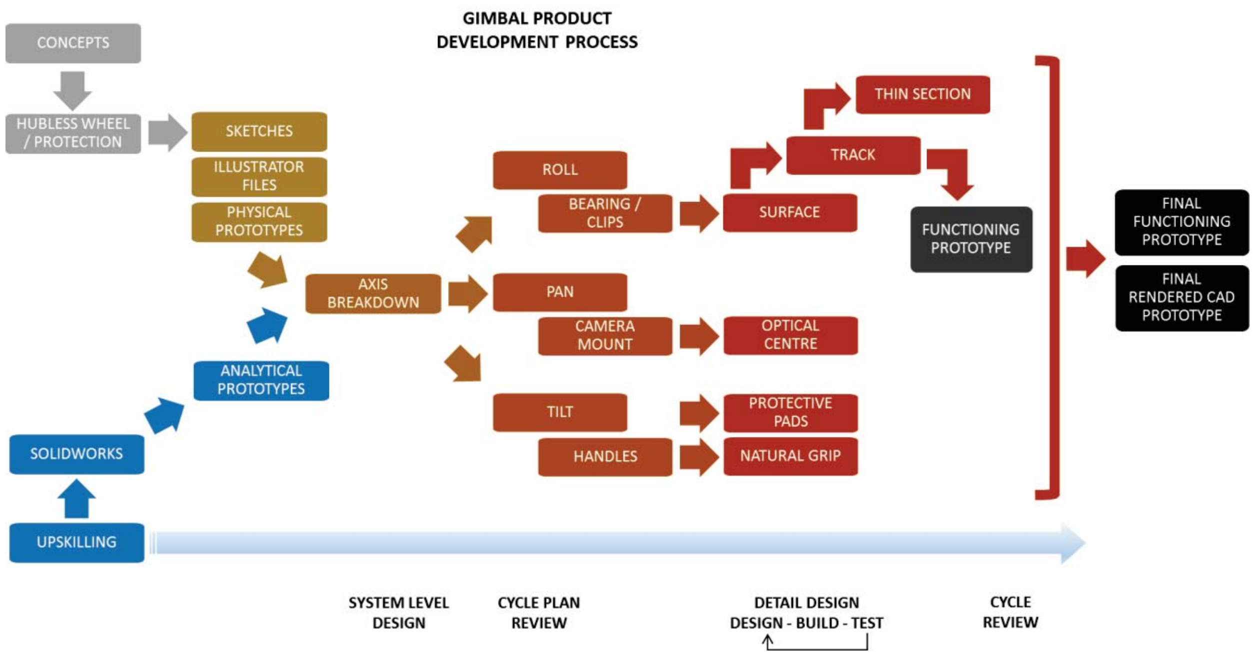


Figure 7: Gimbal product development process.

5.2 MATERIALS SELECTION

I did not have a predetermined view of materials before starting the prototyping. I did however have an intention of using low cost materials to develop parts of the design before progressing to final materials, and that 'high tech' materials such as carbon fibre would appeal to my target market and be consistent with other similar products such as camera equipment.

Carbon fibre was always the first choice for the structural frame because of its excellent strength to weight ratio. Although I used 3 mm acrylic for the early prototypes I was able to drop down to 2 mm carbon fibre because the calculation showed that this would be sufficiently strong.

Generally the use of aerospace-type materials adds significantly to the cost because they are costly in their raw form, and also difficult and costly to machine and manufacture. By using carbon fibre, aluminium, titanium, and the latest 3D printing plastics, the design uses materials in a way that makes the most of the properties, and also does this cost effectively. The most expensive components are the motors, which are likely to fall in price over time, and the bearing, which could be developed as a custom-made component to protect intellectual property.

A summary of their properties is below (technical parameters are in the Appendices):

Material	Properties	Best suited for
carbon fibre	extreme strength to weight and stiffness to weight, very low weight (20% of steel), can shatter under shock load, hard to cut or mill, expensive	Frame
aluminium	very low weight (33% of steel), very strong, very easily cut and machined, reasonable cost	Fastenings, track
titanium	high strength, high shock absorption, low weight (60% of steel)	Fastenings
stainless steel	very heavy in this context, strong, cheap	Bearing
Ninjaflex Semiflex TPE	flexible TPE (thermoplastic elastomer) filament, very high level of shock absorption, low weight (15-20% of steel)	Shock absorbing pads, handles
3DXMax PLA	carbon fibre infused PLA (Polylactic Acid, a thermoplastic polyester) filament, rigid, relatively dense	Mountings, clips
acrylic	excellent finish when laser cut, easily machined, brittle	Gear drive
acetal (Delrin)	easily machined, high strength and shock absorption, light weight (20% of steel)	Bearing
silicon nitride	extreme hardness, light weight (40% of steel), and low Ra (surface roughness) values	Ball bearings

Material Rating out of 10	Strength / weight	Stiffness / weight	Shock Absorbtion	Cutting	Machining	Aesthetics	Cost (10 = best)
carbon fibre	10	8	4	8	6	10	2
aluminium	6	5	7	8	9	8	6
titanium	7	6	9	5	5	9	4
steel	6	6	7	8	9	4	9
Ninjaflex Semiflex TPE	4	2	10	-	-	8	8
3DXMax PLA	6	7	5	-	-	6	8
acrylic	2	5	5	10	6	7	9
acetal (Delrin)	6	6	8	8	9	6	7
silicon nitride	7	8	7	-	-	9	8

5.3 FIRST PROTOTYPE

The first material I choose to use was 4mm cardboard. This was used to establish a basic layout of the three axes. It is very cheap and laser cut very quickly and easily, providing me with 1:1 scale models. I used hot melt glue to help hold them together.

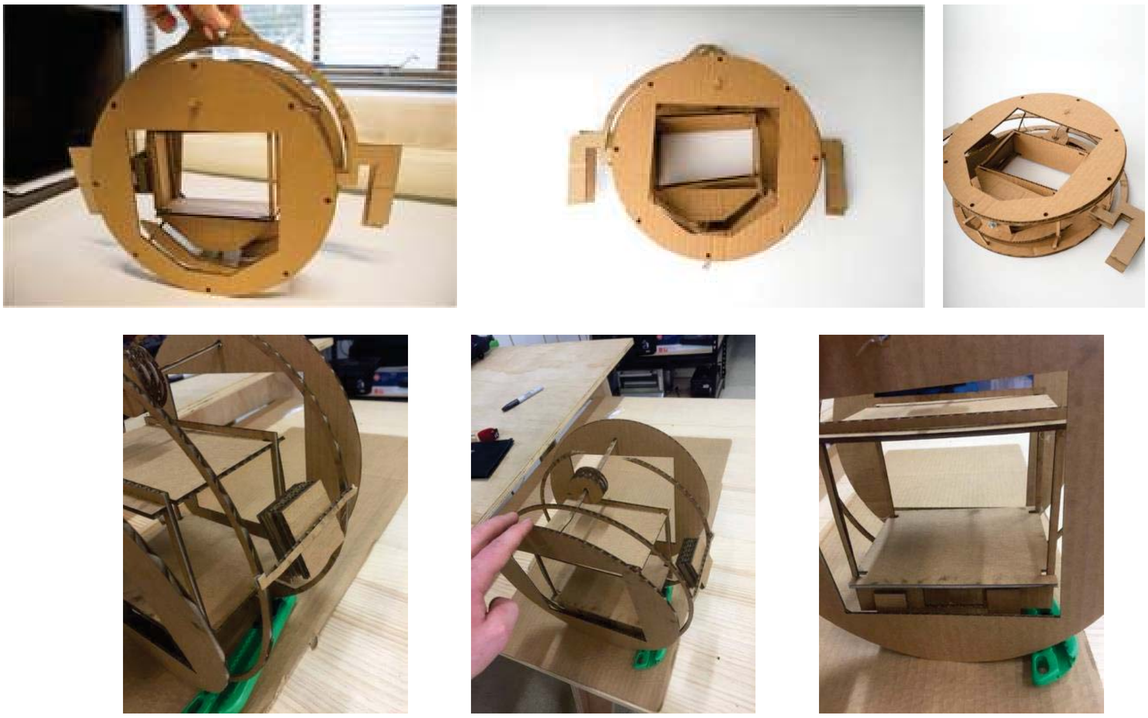


Image 21: First cardboard conceptualisation

This material did have downsides though, it was very flimsy and had no structural strength.

I designed my prototype around the camera box idea that I had created earlier and also made up motors of layered cardboard to help build my prototype. I made sure that the motors that I were choosing were well over spec, because I knew downsizing it would be a lot easier than trying to make things bigger to fit around. I was trying to maximize the use of space as much as I could and was placing motors in places that probably were not going to work (which I didn't know at the time).

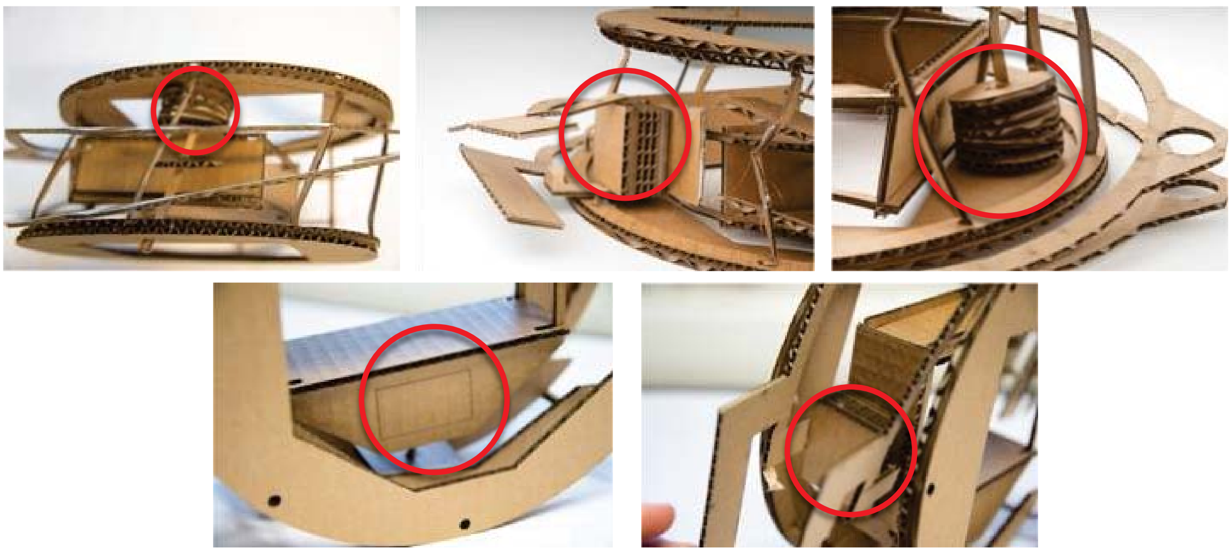


Image 22: Determining position of motors.

I broke the 3 different axes down into elements. I looked at how I could get the pan axis to work and spin within the roll axis.



Image 23: Pan axis clearances.

I was trying to figure out how the components interacted to make sure that I had enough space around this pan axis to spin within the roll.

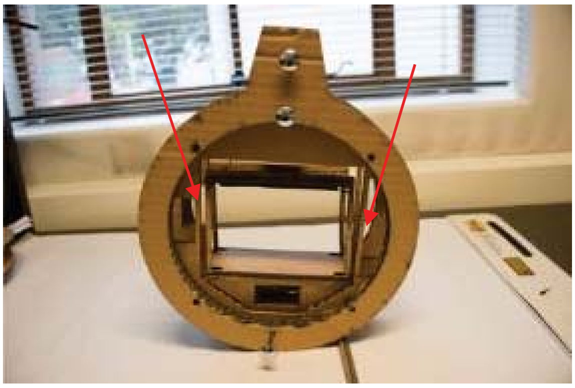
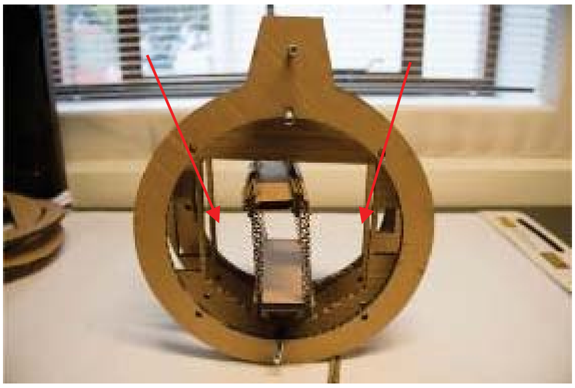



Image 24: Pan axis clearances.

Using this material, it was very hard to achieve a prototype that I had envisioned as it didn't have the structural strength that I required. I could however get a brief look at how each axis was going to spin.

I learnt that I was able to get the size of the total structure reasonably small in comparison to other gimbals on the market and with the size of the camera. It also gave me a good understanding of where I could place each of the motors within each of the axis to maximize space.

I did learn very early on that if one dimension, was changed, especially on the inner most axis that this had a very large flow on effect to the rest of the design.

5.4 SECOND PROTOTYPE

My next chosen material was 6mm poplar plywood

This material was much better at giving me the structural integrity I required. It was also easy to laser cut and only slightly more expensive than cardboard. To help with my structural components I used m6 steel bolts to help provide more rigidity. I again used slots and hot melt glue to join pieces together to give quick visualization of the shape and size. The roll motor was placed at the top where I was expecting to have an external driven axis using spur gears, a circular rack and pinion or a timing belt drive.

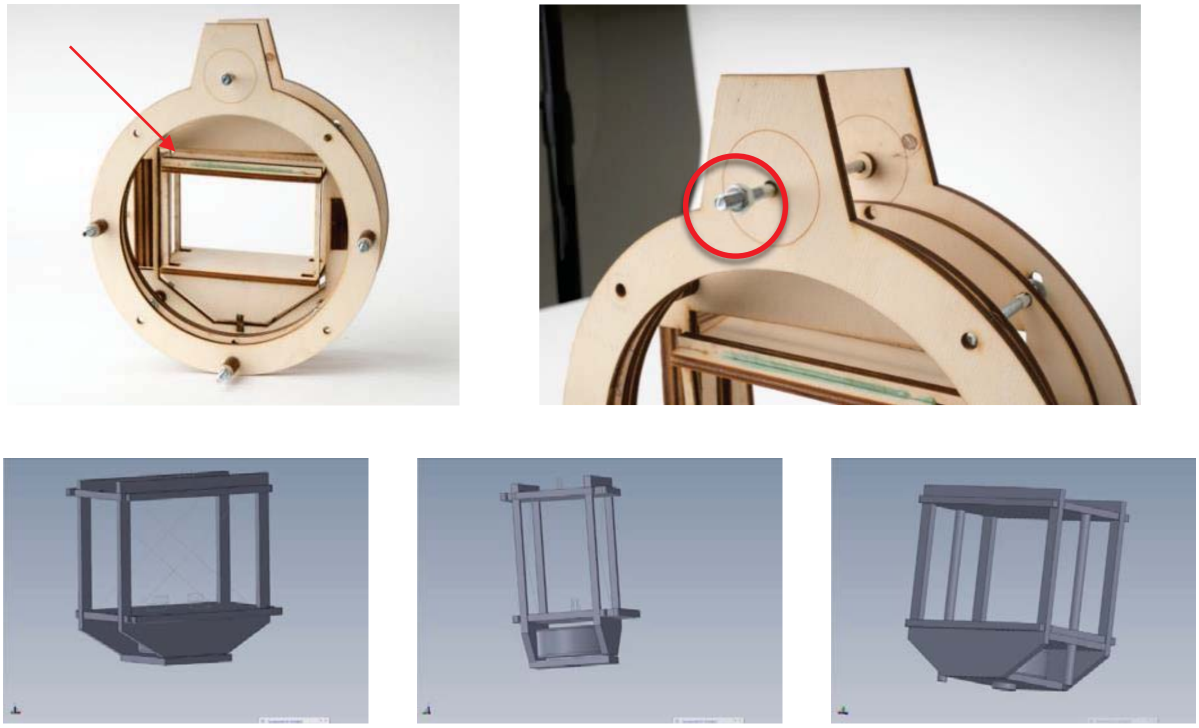


Image 25: Pan axis structure development.

I cut out small rings that I could use as spacers between the front and rear faces of the tilt axis so that I could maintain an even distance around the outer cylinder.

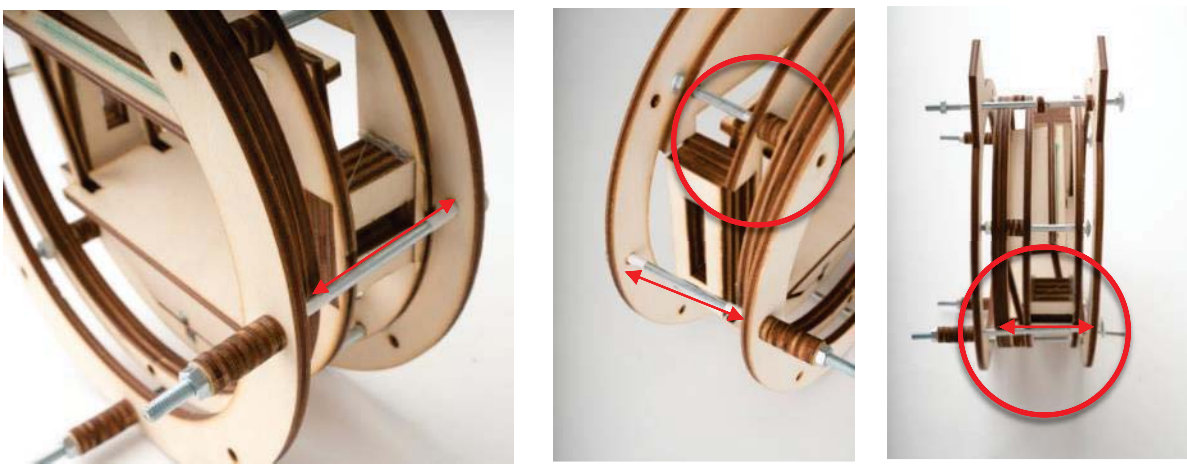


Image 26: Standoffs for tilt axis.

After learning from the initial cardboard prototype I figured out more accurately how much clearance was needed for the axis to spin. Also the slots worked a lot better with the stronger material. I was able to get the pan axis to rotate by having enough clearances top and bottom and also having an allocated space for the motor to be placed and function. The material did make it difficult to see some of the clearances, i.e. there were some components that rotated that weren't clearing parts.

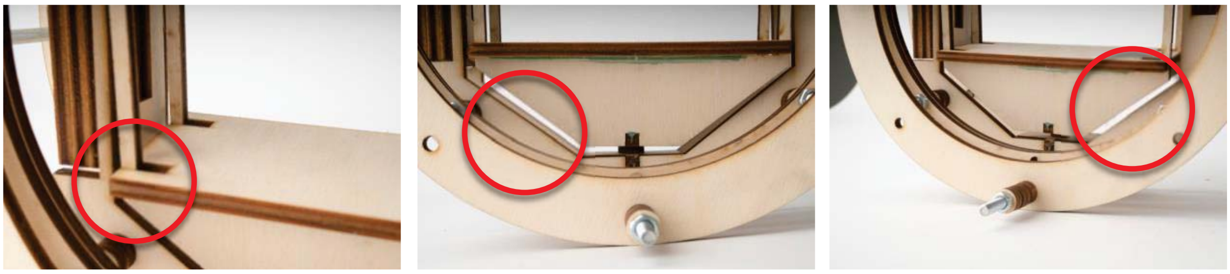


Image 27: Pan axis clearances.

Now that the structure was stronger I was able to place a camera on the inside to get a real representation of the size and scale of the prototype in comparison to the camera. This was very encouraging as I could see that I was be able to make something that was very compact.

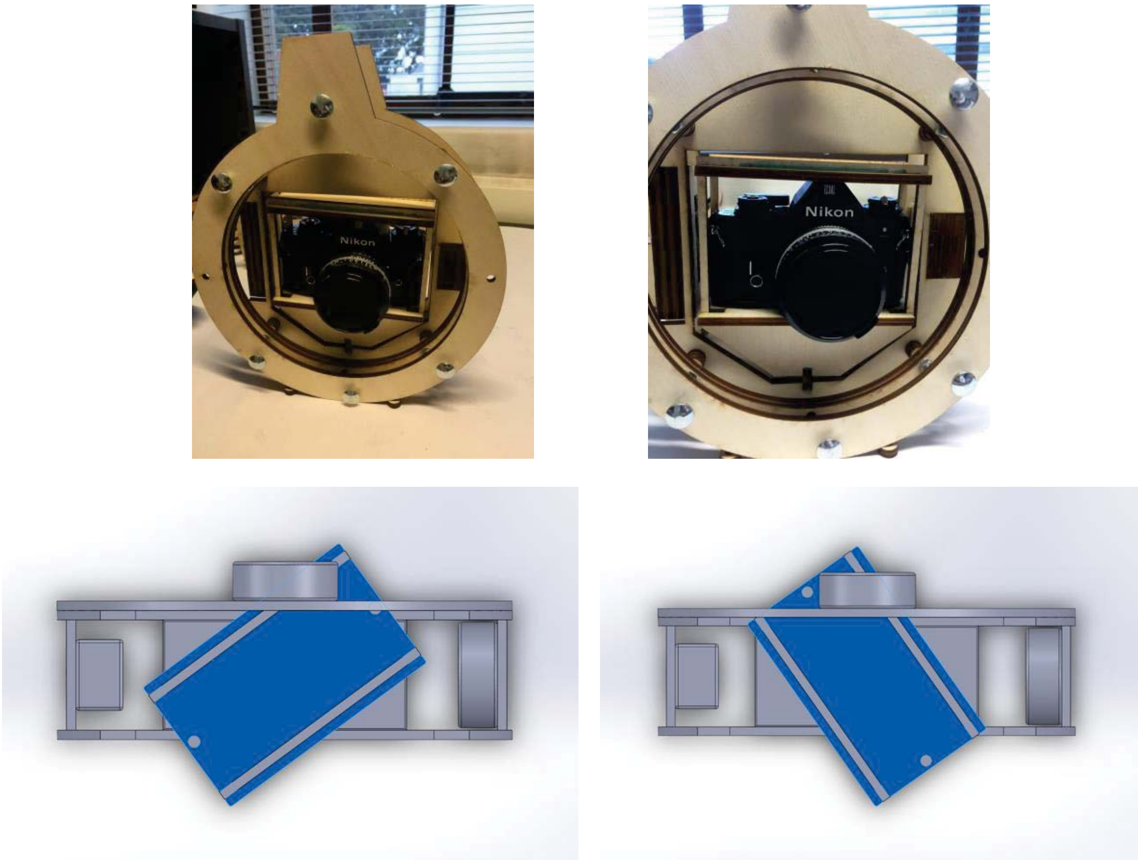


Image 28: Camera positioning and pan axis clearances.

This prototype gave me a good understanding of how the structure could become stronger using steel bolts and laser cut rings as stand offs to help provide much greater strength. It also provided some options for where each of the motors could be placed. I knew through this prototype that the pan axis and the tilt axis were going to be relatively easy to resolve as they were going to spinning on a direct drive system.

5.5 THIRD PROTOTYPE

My next material was clear 3mm acrylic. It provided the structural benefits of the ply wood and it also meant I could see the inter-relationship between components.

Again I made up motors and used structural components like the steel bolts that were successful in the previous iterations.

Image 29: Dummy motors and basic structure development.

I looked at how I could reduce the size of the prototype by placing motors within another axis and having a cut out slot for it to move backwards and forwards. This would limit its degree of movement but would decrease size. This was an issue I needed to examine further.

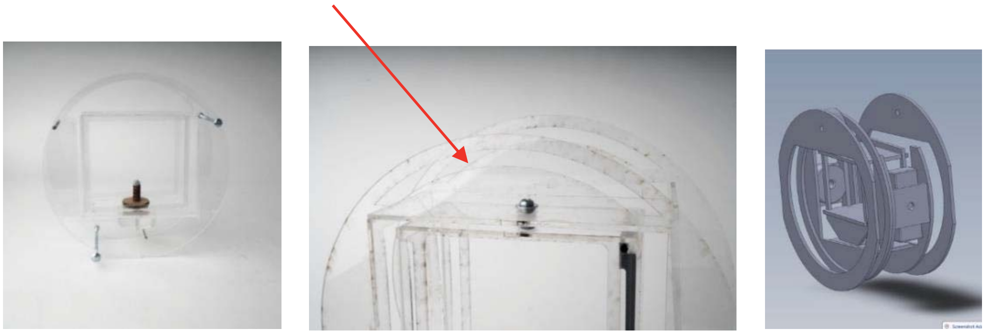


Image 30: Roll axis development.

From the previous prototype I found that only having one point of contact for the pan axis was not strong enough. Having two made it significantly stronger, therefore I planned to use a thrust bearing in future prototypes.

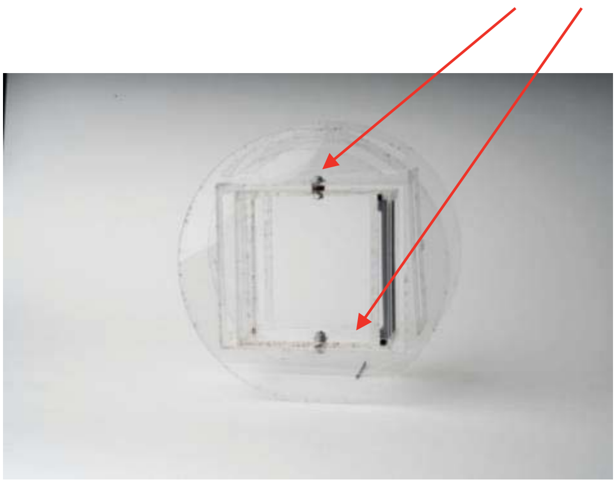


Image 31: Pan axis bearings.

I tried to figure out a way in which I could get vertical movement in the pan axis. By having a 3D printed part it provided a strong material for a camera to be mounted to and also the holes were rods could go so that it could be slid up and down for balancing. I also wanted to see if it could be placed on its side so that the motor and axis configuration could be changed depending on user preference where the inner most axis could in fact become the tilt.

Image 32: Camera mounting plate; pan axis.

I also had a concept for balancing the camera along the optical center of the roll axis to help with setup and lens changes:

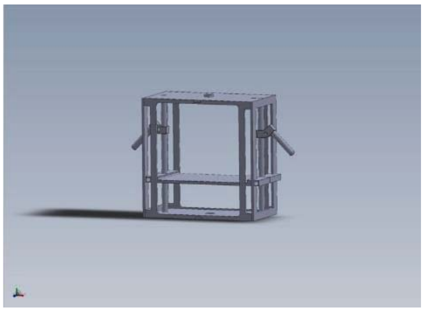


Image 33: Balancing weight 'antennas' for pan axis.

Knowing that my pan axis and tilt axis were going to be direct drive I was confident in them working and being compatible with the software I was planning to use. The axis I really wanted to focus on was the roll axis. How I was going to get it to spin, whether that was controlled or free spinning. And how it was going to be driven clockwise and counterclockwise. After doing a research into different possibilities for the roll axis I began exploring a hubless wheel concept.

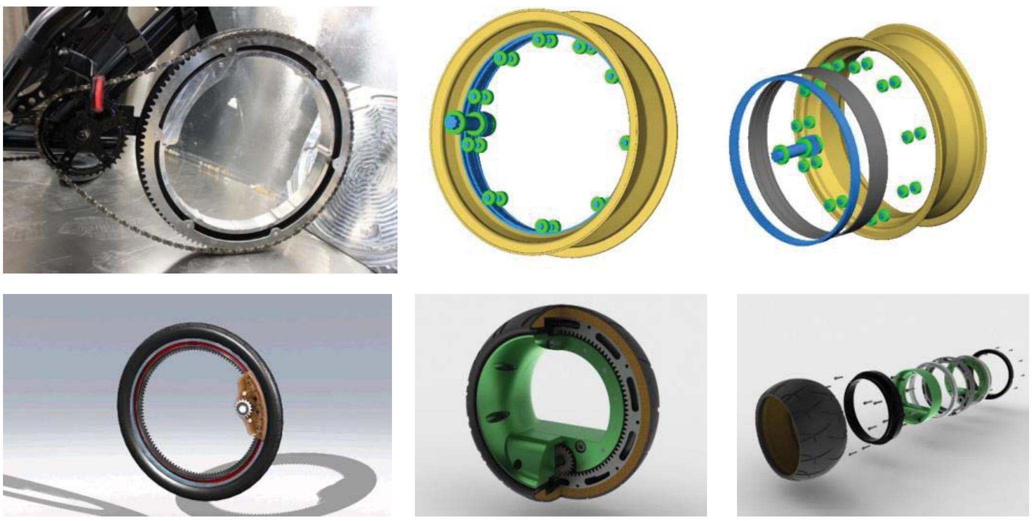
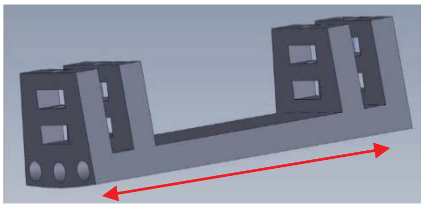


Image 34: Hubless wheel research.

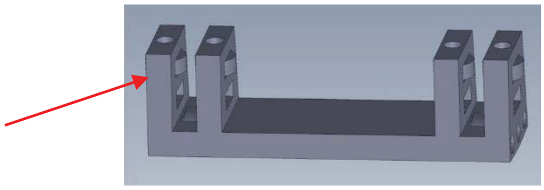
This type of design uses a bearing to spin an internal shell or wheel and then have a gear ring or something similar on the outside to drive the roll movement.

I needed to figure out how to make the internal structure spin. It was essentially a large bearing. I used the 3D printers to make a clip that would run on the surface as it had holes in it from different directions which couldn't be milled using a 3-axis CNC.

I used PLA plastic as it was cheap and quick to print, and small radio controlled car wheel bearings as they were an appropriate size and easy to obtain. Through a few iterations of the clip design I had a reasonable idea of how the clip was going to work and perform with a structure running on the inside.



I made the clip so that it had a specific length that could help support the bolts and mean that that I wouldn't need the small laser cut rings to space the two faces apart.



It had bearings on both the lateral and radial surfaces to contain the inside structure

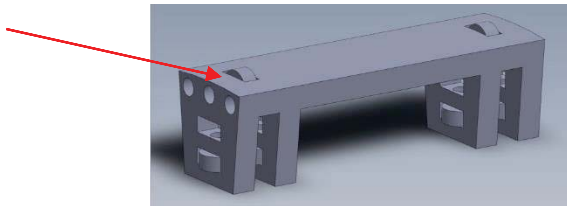


Image 35: Bearing clip development.

As I developed it further I reduced the amount of bearings that were needed

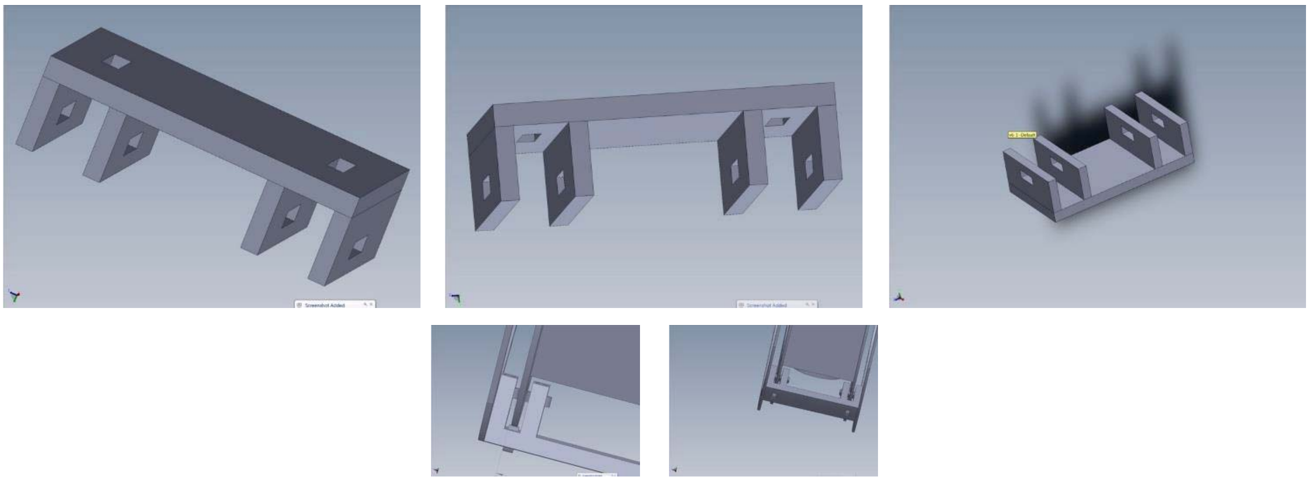


Image 36: Bearing clip development.

I also managed to make it much smaller which speed up print times and materials cost.

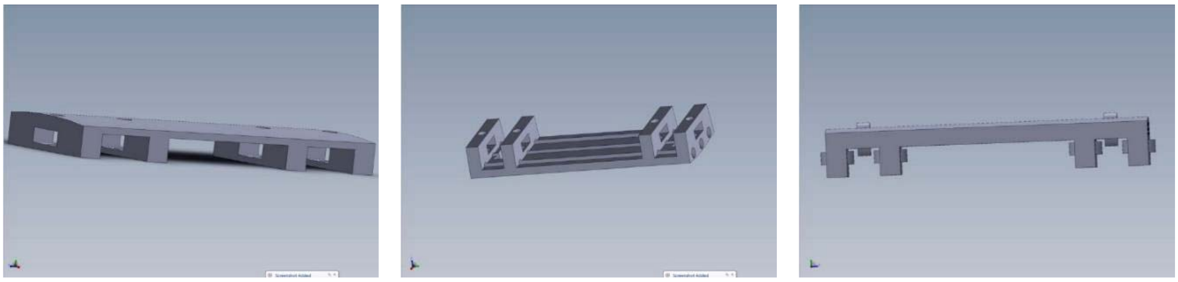


Image 37: Bearing clip development.

An analytical prototype was made which was drawing heavy influence from the hub less concept where I had bearings running entirely around the outside surface of the roll axis I looked at how these could be placed and the number that were needed.

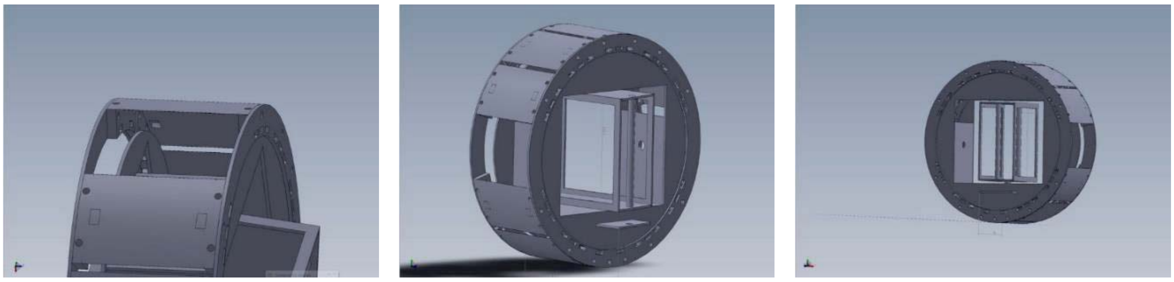


Image 38: Roll axis bearing face.

I then made it so it didn't have two lateral bearings sandwiching the material, which further reduced components, size and material.

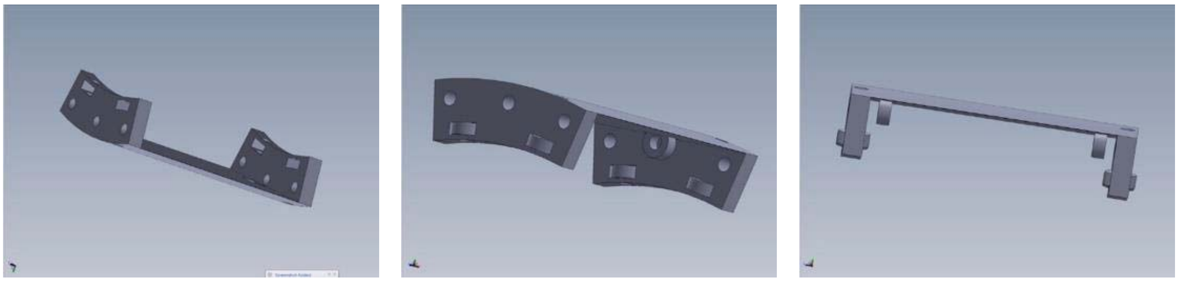


Image 39: Bearing clip development.

I constructed this so it had 3D printed components either side of the tilt axis and went back to using laser cut out rings to space the faces out.

Image 40: Spacers and positioning of bearings.

5.6 FOURTH PROTOTYPE

Further roll axis exploration using an acrylic prototype.

The objective of this iteration was to have an internal cylinder with the bearing clips pushing the bearings up against the front and rear faces of the acrylic, to provide it with lateral strength and to run off the edge of the acrylic to provide radial strength.

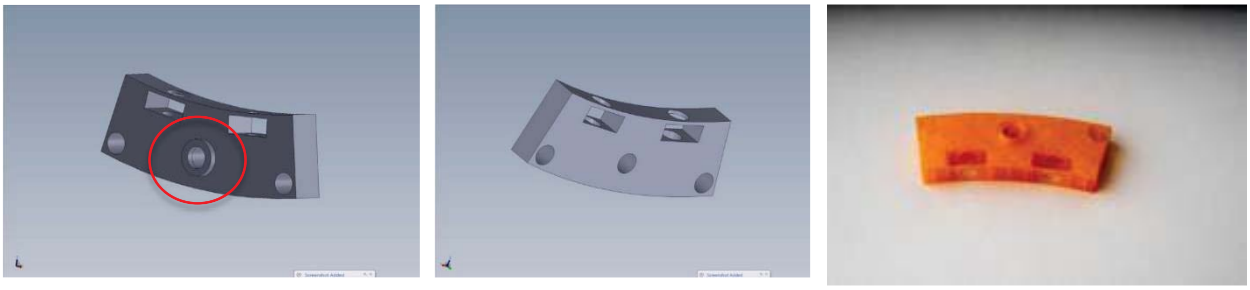
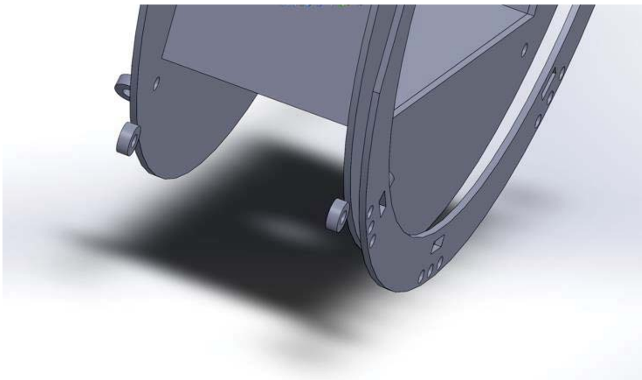


Image 41: Bearing clip further development.

I also included small flanges to help with the bearings spinning and eliminate the need for a thin washer



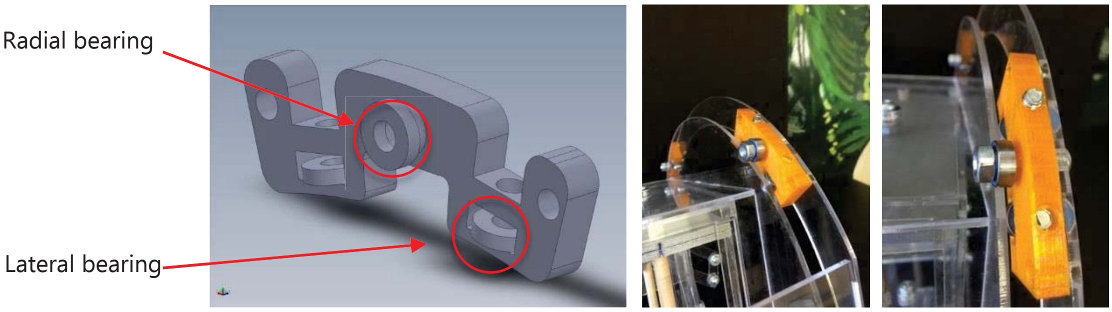


Image 42: Bearing clip specific detail.

I choose to go with four points of contact instead of three to help keep the inner cylinder moving smoothly. It also meant I could place the pan axis where I wanted.

Image 43: Bearing clip mounting.

I went back to using spacers as it meant the 3D printing times were a lot quicker and it meant I could apply more tension to the bolts to make the structure stronger.

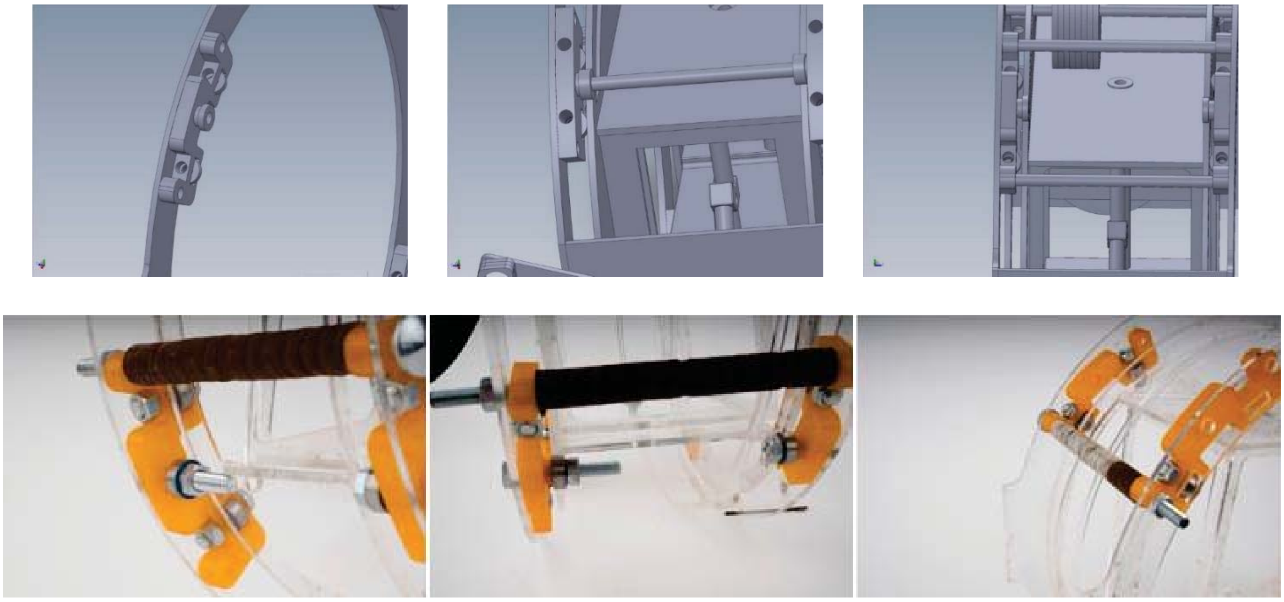


Image 44: Spacer adjustment for bearing clip positioning.

The acrylic material was also quite slippery and the bearings weren't actually 'gripping' the surface.

Image 45: Final bearing assembly.

The models below show how I investigated the optical center balancing and making sure that clearances were sufficient.

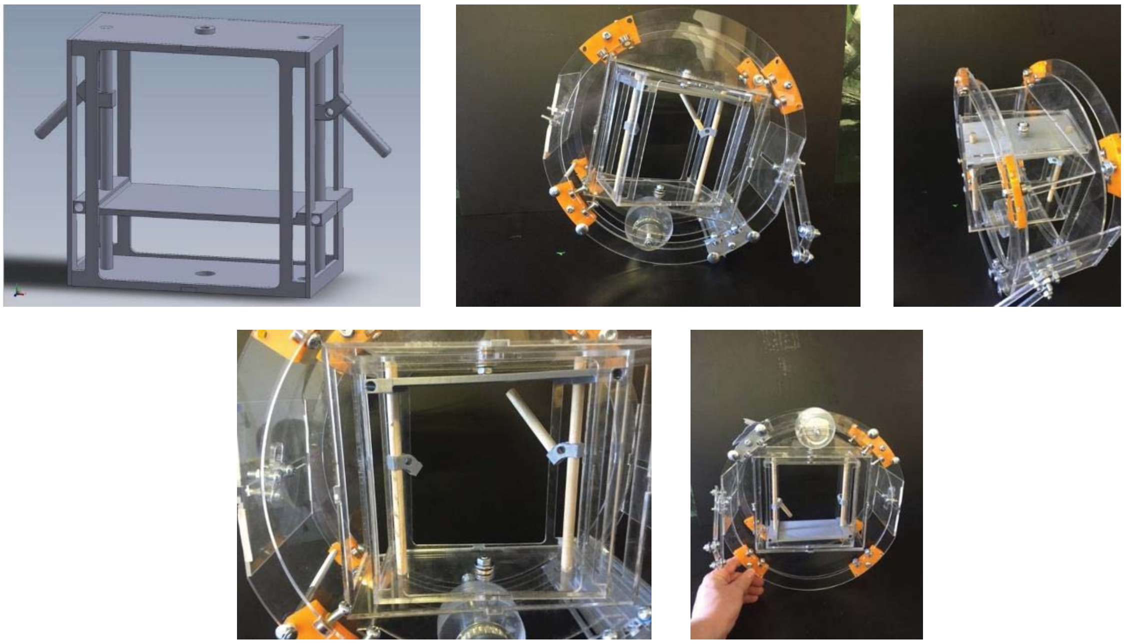


Image 46: Pan axis integration with roll axis.

An analytical prototype using CAD was made to test operating parameters when functioning.

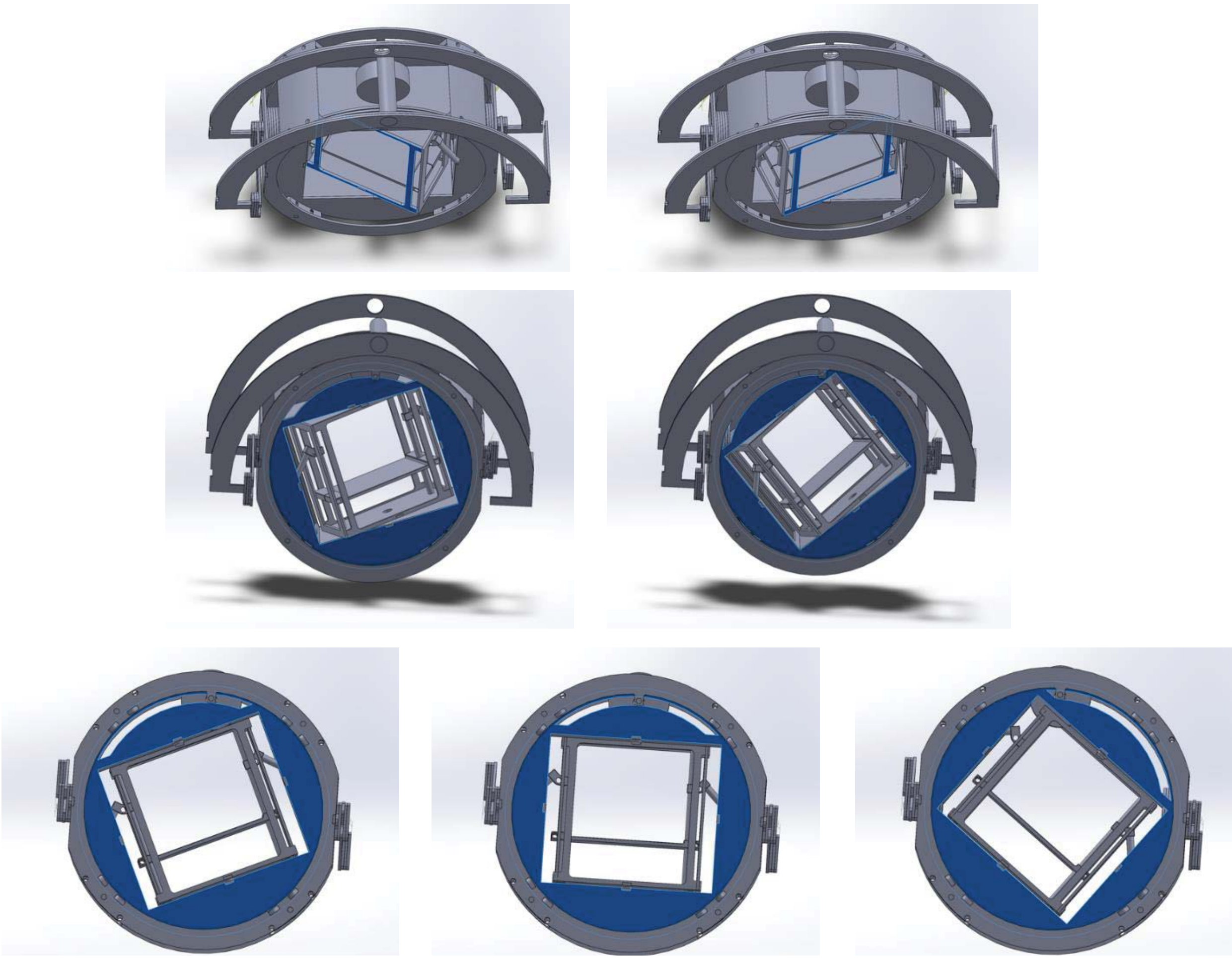


Image 47: Pan, roll and tilt axis clearances in CAD.

The model below shows an early test of how I could incorporate some type of spring system into the handle but this was parked reasonably quickly as it added a considerable layer of complexity that wasn't needed at this stage of development.

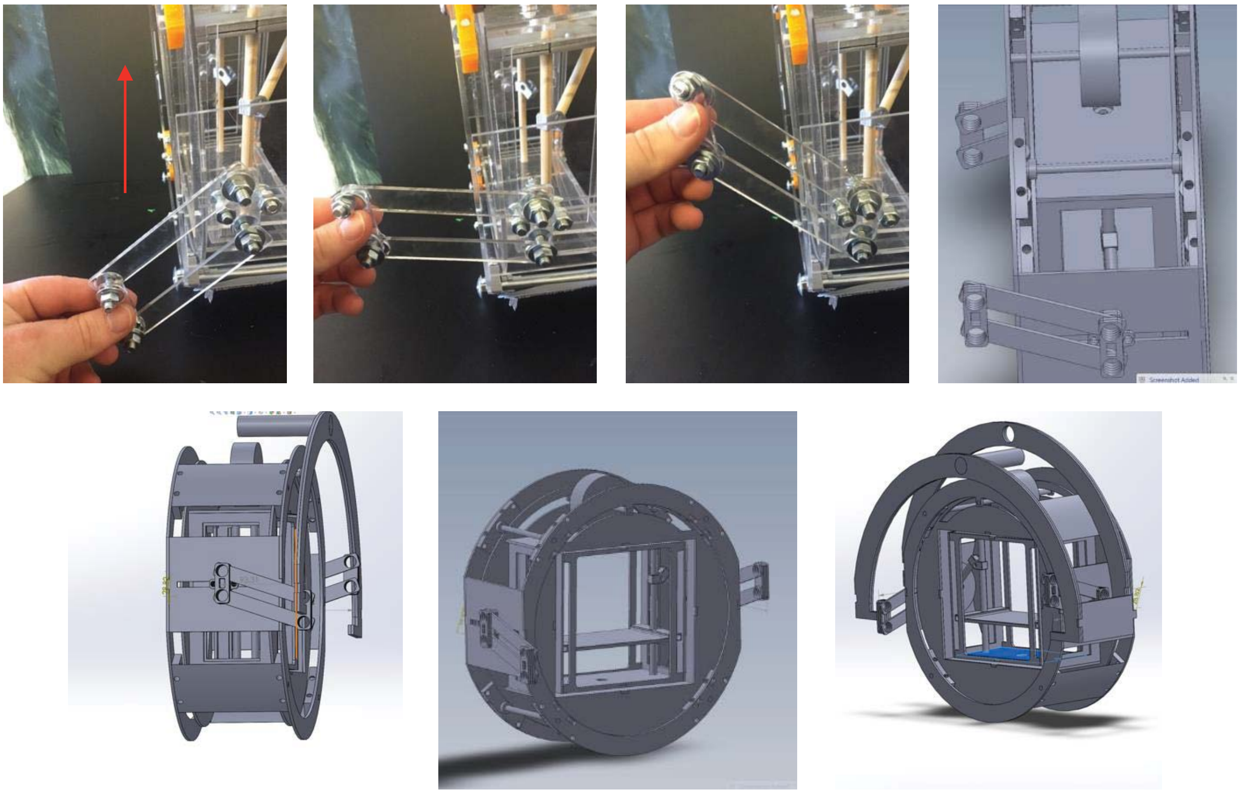


Image 48: Handle option development.

I was looking at how I could minimize size by balance the roll motor with the roll axis. I would then need to make a cut out slot in the tilt axis for it to have a certain degree of movement. I was also being much more efficient using nesting and using my material to its maximum potential.

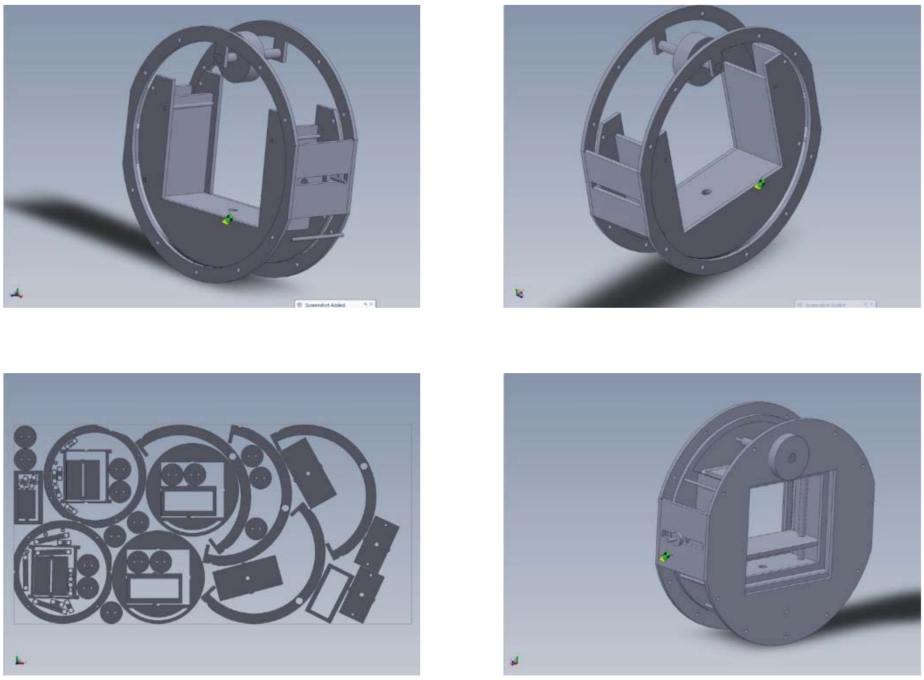


Image 49: Positioning of motors; nesting for better use of materials from flat sheet.

5.7 FIFTH PROTOTYPE

Acrylic and PETG prototype to refine the running surface and develop the inner cage.

I wanted to develop the idea of an internal structure that spun that also provided more protection for the camera. I developed the 3D printed clip idea further where I wanted the bearings to be running on more of a cylinder. I used PETG to cut into long strips that specifically had slots that would then wrap around a laser cut disk to mate perfectly. This was to help increase gluing surface and provide a stronger bond.

Image 50: Gluing PETG roll axis running surface for bearings.

I cut out a jig using the large CNC machine which I was going to use to help clamp the plastic in place. I used this for several methods including putting it in an oven to see whether I could bring it to its glass transitioning temperature.

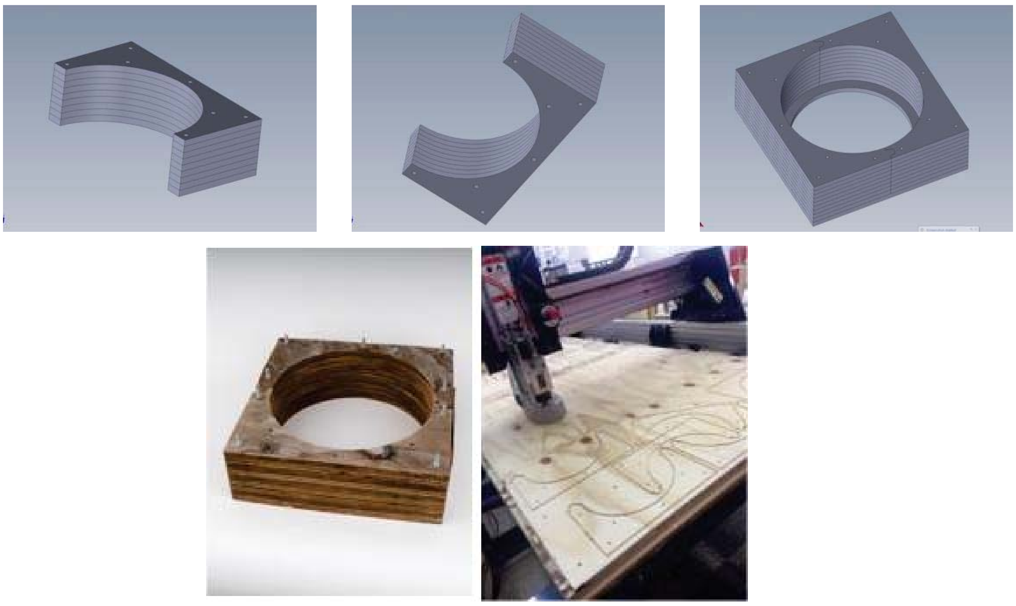


Image 51: Mould for gluing roll axis.

I tried using a range of different epoxy glues all with similar success, i.e. that it was providing a strong bond again the PETG and the acrylic.

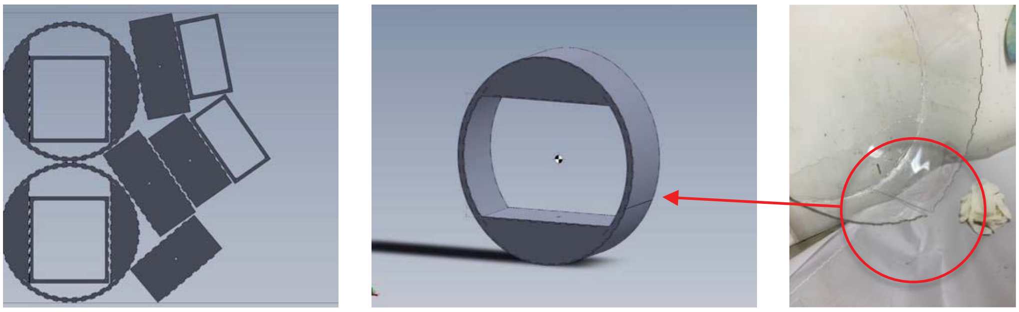


Image 52: Issues with PETG surface.

I was having problems with the join of the plastic. This ridge was resulting in a significant problem where the bearings were running smoothly until it reached that point and because of the number of bearing clips it had a very small amount of movement before it impacted on the rotation.

To resolve this issue I used an XL belt drive that wrapped around it to make it stronger and give it more support. Next I needed to resolve the timing belt configuration. I figured out the diameter that the XL gear disk needed to be and also used this to help provide support which was promising.

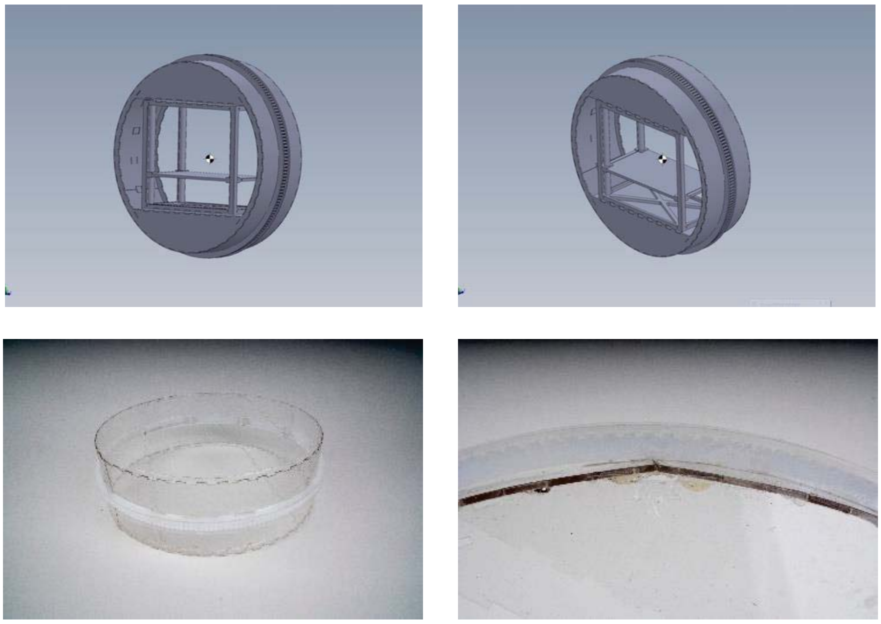


Image 53: Belt drive options for roll axis.

I developed the inner cage so that I used a cross section piece of 3D printed PLA to help with strength and also created a different mounting plate that could easily be moved on the pan axis.

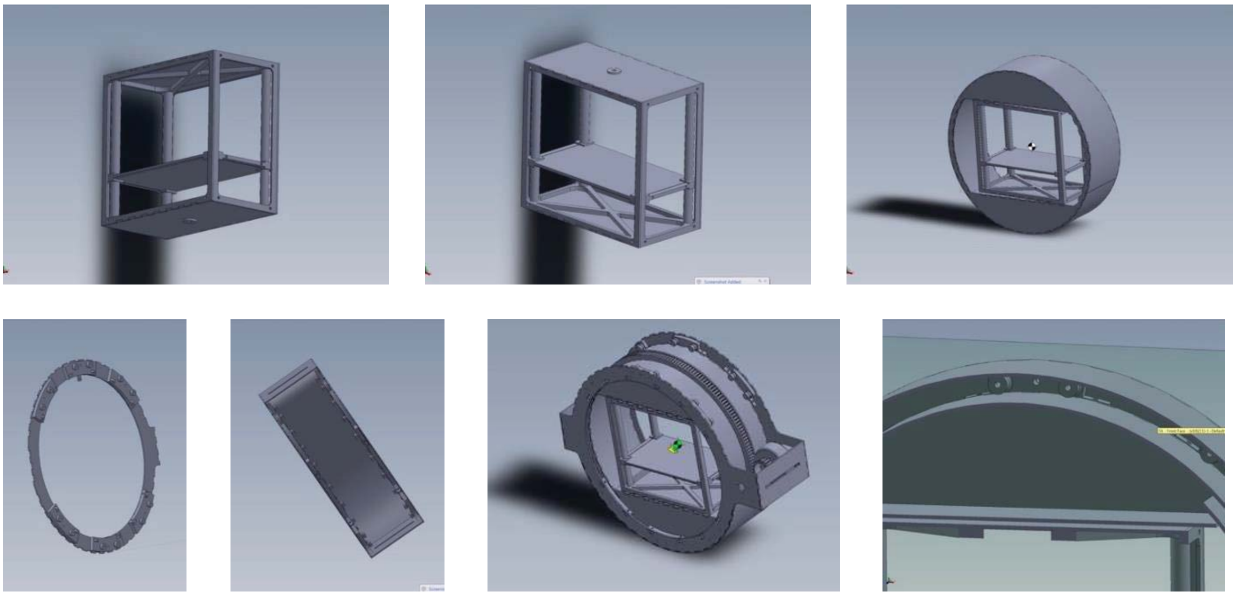


Image 54: Pan axis camera mount height adjustment options; bearing running surfaces.

Moving the motor from the top down to the side to help with balancing the tilt axis.

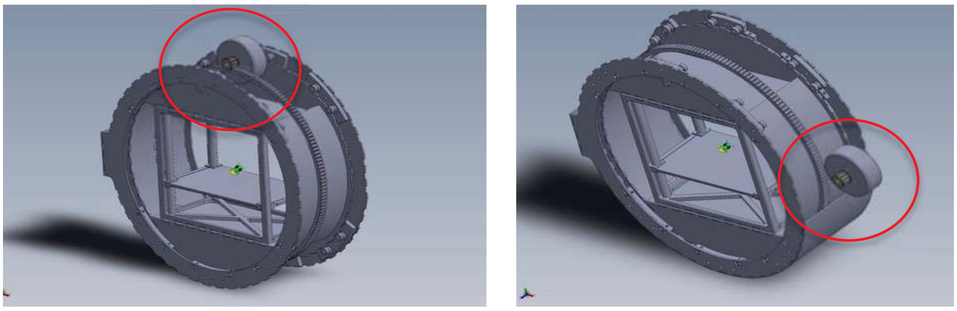


Image 55: Roll motor positioning.

I also wanted to translate this PETG wrapping to the tilt axis which would then make it two cylinders running inside each other.

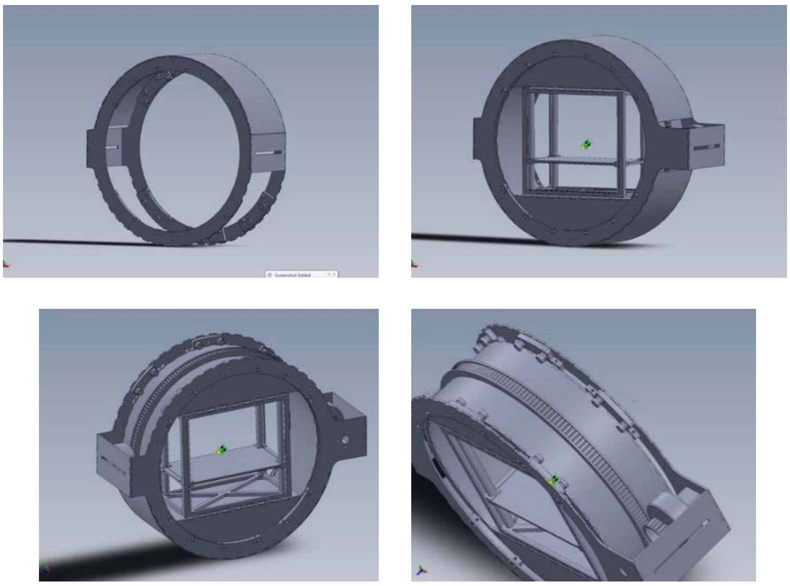


Image 56: Drive system for roll axis.

New bearing clip development, where material was removed and the bearings spaced further apart.

Image 57: Bearing mounting.

Then looked how I could make 3D printed parts that could be used for things like holding specific motors and mounts, including removing material and testing whether strength was maintained.

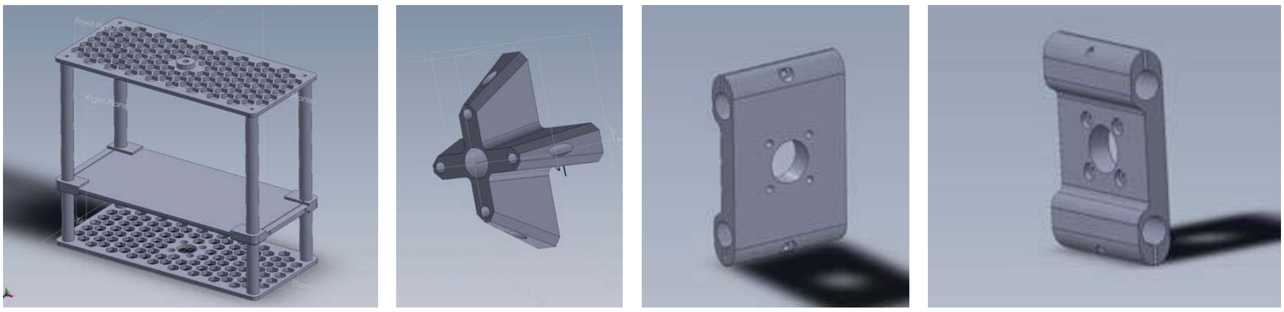


Image 58: Pan axis weight reduction, motor mounting components.

I experimented with three clips for weight reduction but found this brought in unneeded variables.

Image 59: Reduction in number of clips.

5.8 SIXTH PROTOTYPE

PETG exploration of vacuum forming as a cylinder making process.

After talking with workshop staff they suggested that I could try vacuum forming the PETG which would get rid of the 'ridge'.

I made up a male mold on the lathe and the process actually worked quite well with the bearings spinning freely. They were however skidding slightly because of the materials properties of the metal bearing against the smooth plastic. I was then able to laser cut the slots that I needed on the top face.

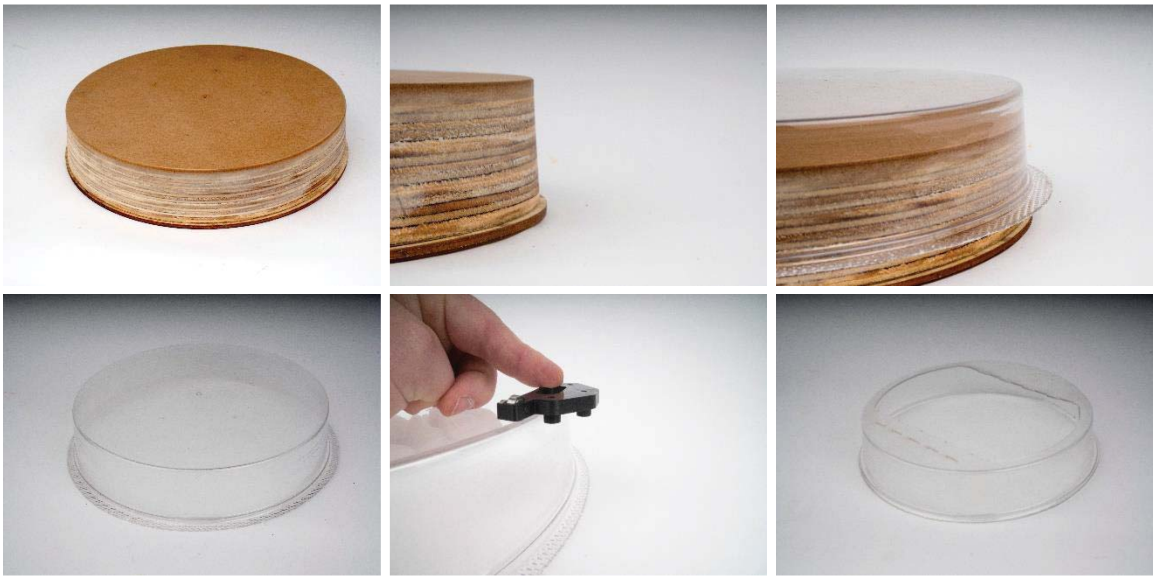


Image 60: Exploration of vacuum forming.

5.9 SEVENTH PROTOTYPE

Acrylic and PETG to develop the option of the bearing running on a track.

At this point I reviewed the design direction. If I headed down more of the path of vacuum forming this meant a likely end point of carbon fibre lay-up molding in which the process becomes a lot slower, more time consuming and generally more expensive. That wasn't the design direction I had planned.

I reconsidered how I could get the bearings running on a higher accuracy concentric surface and decided to focus on creating a specific track. First I looked at making it with a v groove bearing and making a v groove ring for it to run on, this had advantages of providing lateral and radial support.

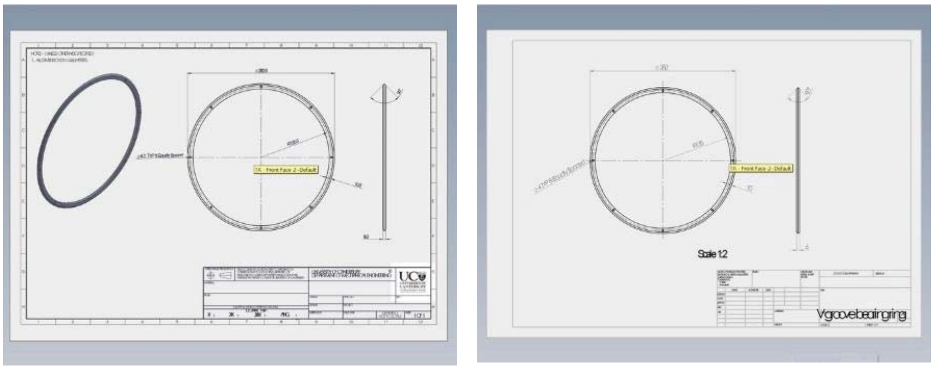


Image 61: Bearing options.

Going in this direction was going to require some specialist machining to get a track running right and very expensive bearings imported from overseas and for those two reasons it wasn't pursued further.

Thinking about a very similar idea I just used deep groove bearings. I made a bearing that was using an aluminum shaft and then running a bearing on the outside. I made inserts with tightly cut laser cut rings that fitted inside the rod and also were tight enough to thread a bolt onto to make stronger stand offs.

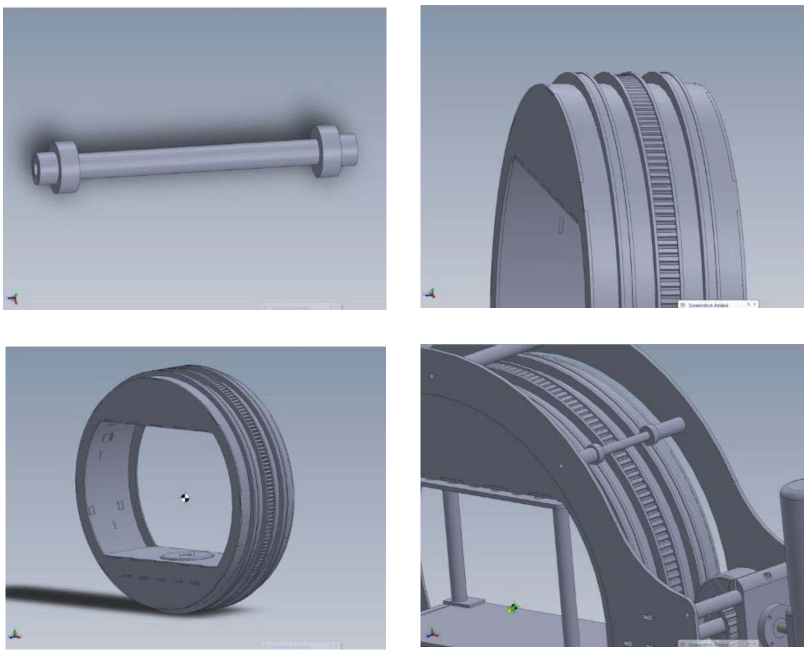


Image 62: Bearing track and drive.

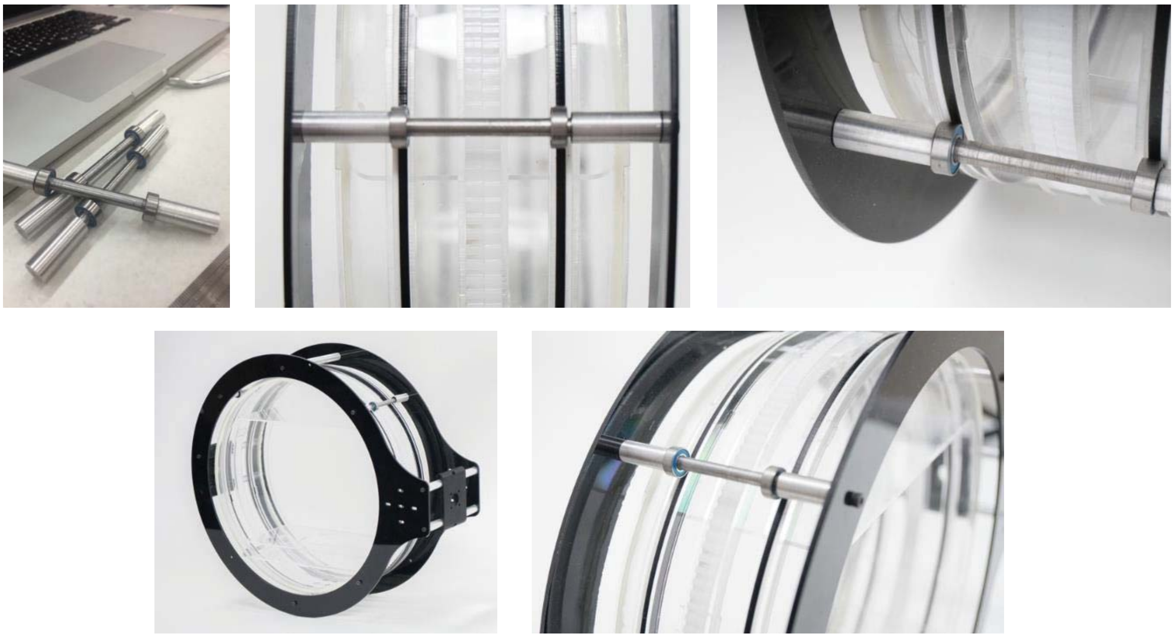


Image 63: Bearing running in track.

This design used flanges either side of the track so the bearings would run straight, which was more successful than previous prototypes, and required a lot less adjustment to get it spinning freely. However, I found that there was significant friction caused by the lateral load of the bearings against the flanges. This is where I also started making 3D printed motor mounts and figured out how to make my large XL pulley gear.

5.10 EIGHTH PROTOTYPE

Acrylic prototype to develop the area of bearings running on a track. And trying to cancel out the need for gluing or forming PETG to achieve a consistent surface.

First I tried running the flanged bearings on a pieces of laser cut acrylic that was cutting using a high PPI setting to increase smoothness. This worked pretty well but I was finding there to be some binding between the two materials. The decision was made to make the track from aluminum.

This was a major iteration and a milestone in the project as I felt I was close to resolving the bearing track and wanted to progress several other areas. As I was starting to introduce the electronics I called on the expertise of my brother, who is a final year engineering student, to assist, as the electronics was not a strong area for me.

I changed the shape of the outer tilt axis so that it could be placed down on a flat surface.

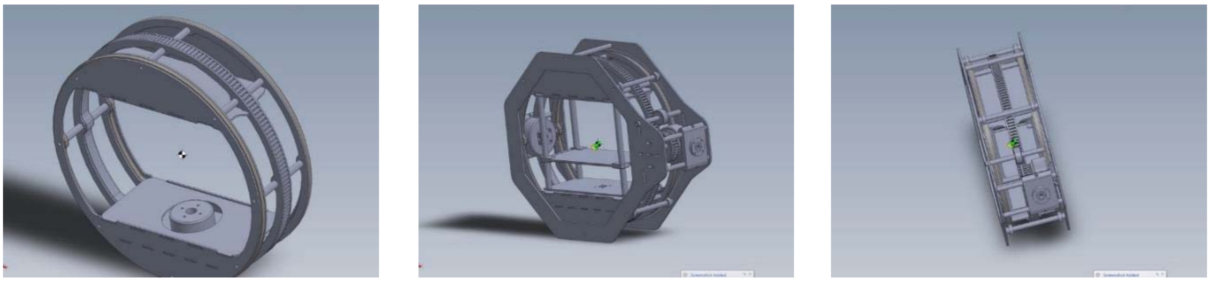


Image 64: Square base tilt axis.

I started to use carbon fibre tube to start getting a feel for the material.

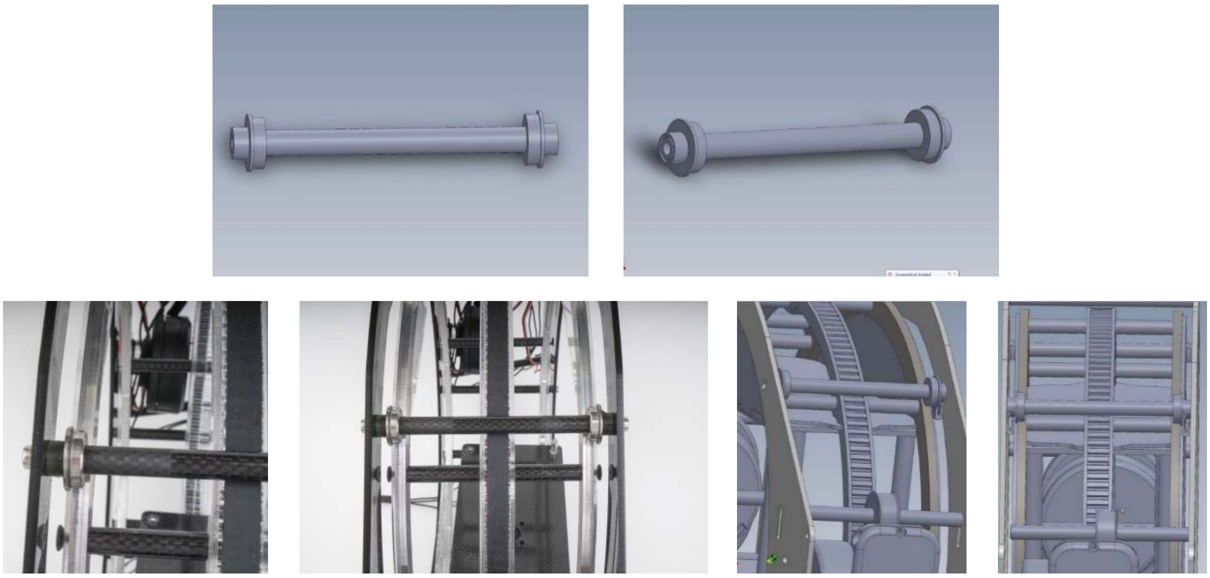


Image 65: Use of carbon fibre tube standoffs.

In the early stages of the handle development I experimented with trying to make a 5th axis where I used small radio controlled car shock absorbers to try and make a shock absorbing arm. This was something that wasn't really working and something that introduced several new problems particularly excess weight and additional complexity so there was no further development in this area.

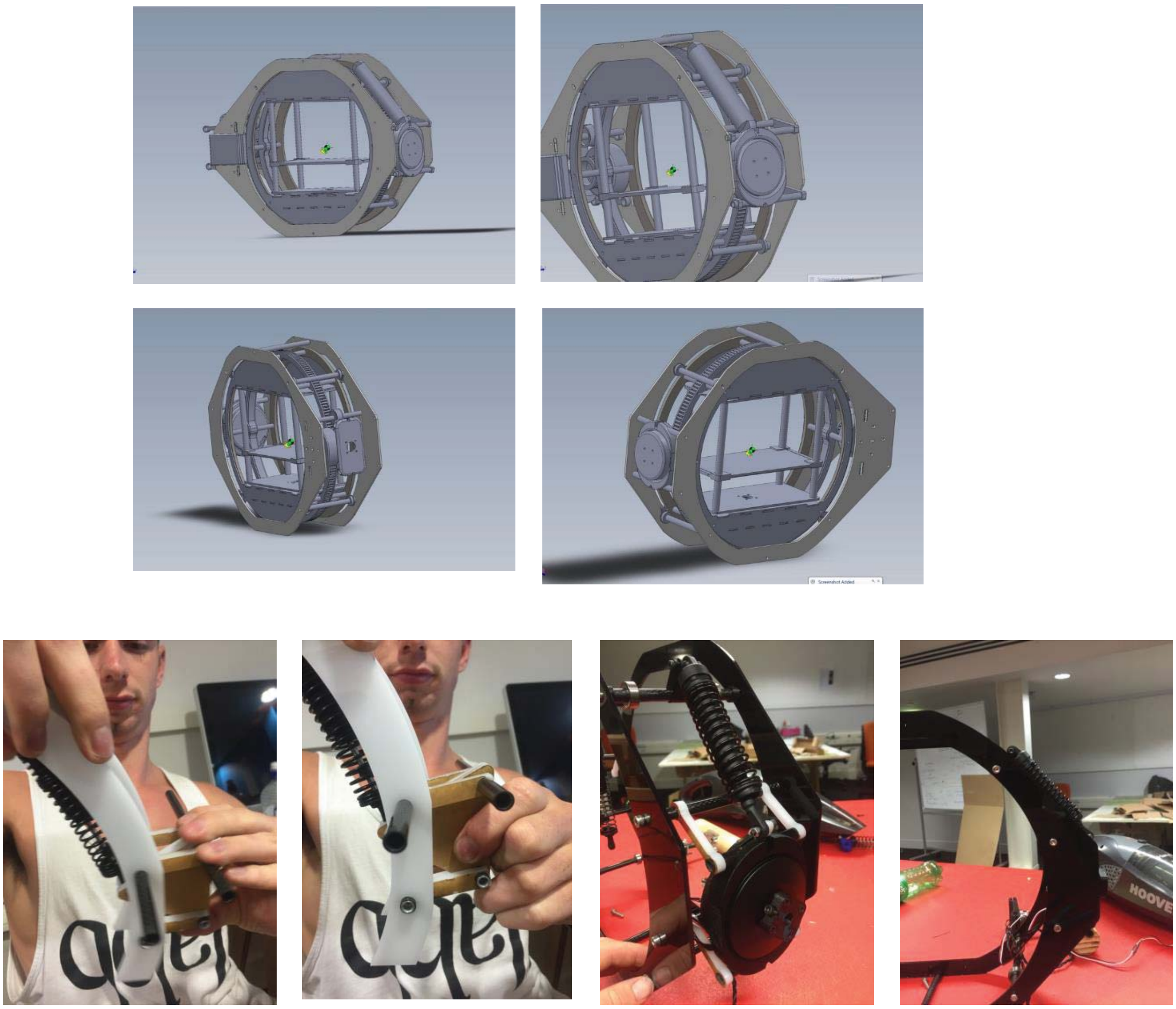


Image 66: Exploration of shock absorbing handles.

There was quite a lot of friction caused by the acrylic so I changed the material to aluminum. I used the water jet cutter and milling machine in the workshop to mill out a round disk. When testing this the bearings ran very smoothly with not too much adjustment which was exactly what I was trying to achieve. This was a major milestone and we could now get the electronics and get the prototype working, first with one axis then all three.

An important area of this prototype was the electronics. The prototype required three brushless motors, a control board and a battery.

The control board system chosen was the 32 bit Alexmos Pro Board. This control board has many features to help with usability, Bluetooth connectivity to help fine tune programming when out in the field, added lithium polymer (LiPo) battery support to make sure the batteries are not completely discharged and dual IMU sensors to help with stabilisation performance.

The motors chosen were three GB5015EN motors which are powerful and small brushless motors with encoders with Hall effect sensors. These sensors give the control board the ability to know the absolute position of the motors which gives greater accuracy, high stabilisation performance, and significantly extends battery life.

A lithium polymer (LiPo) battery was chosen as they provide high energy storage to weight ratios, are capable of fast discharges, and come in large variety of shapes and sizes help fit within a specific space in my prototype.

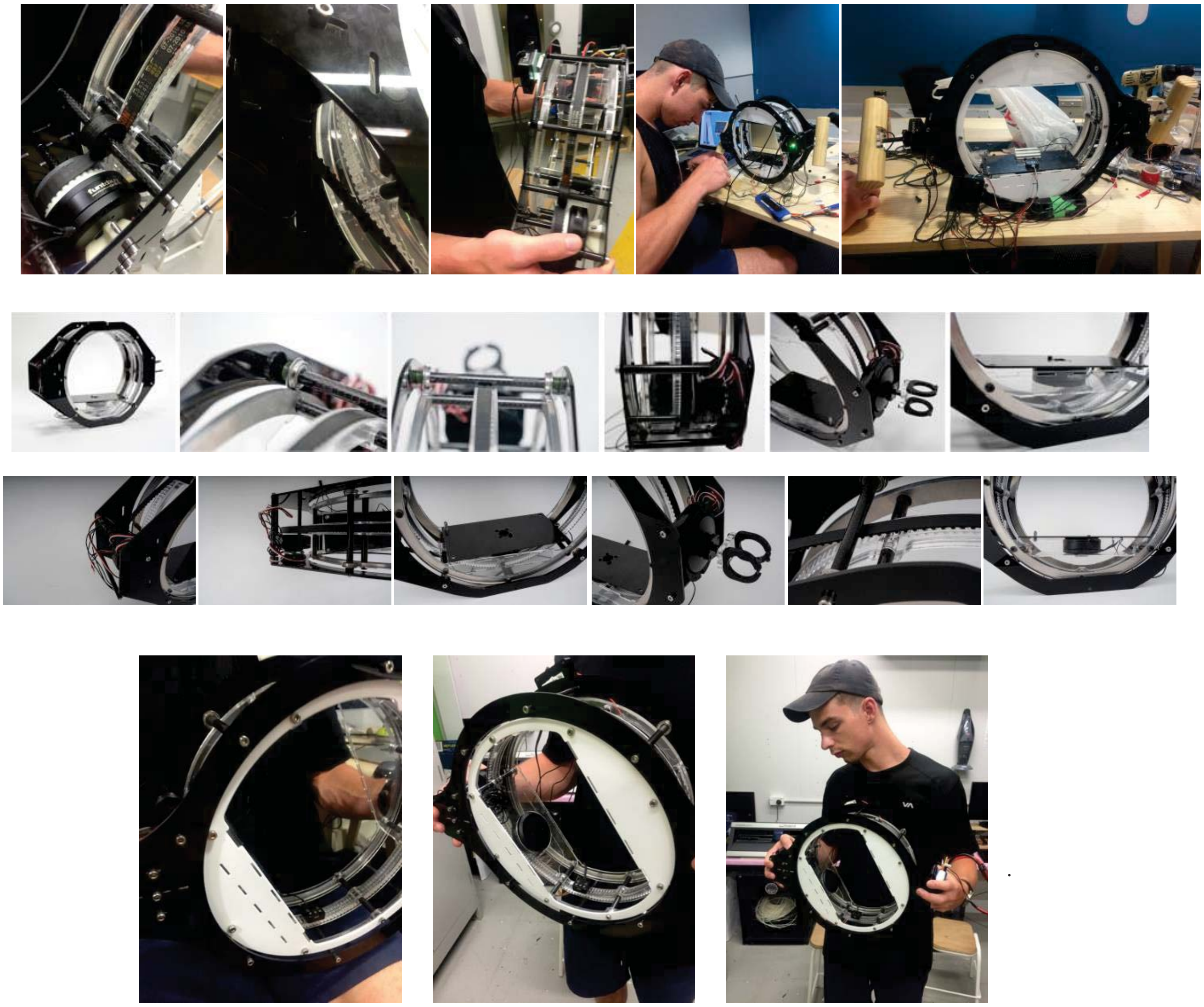


Image 67: Integration of electronics for functioning prototype.

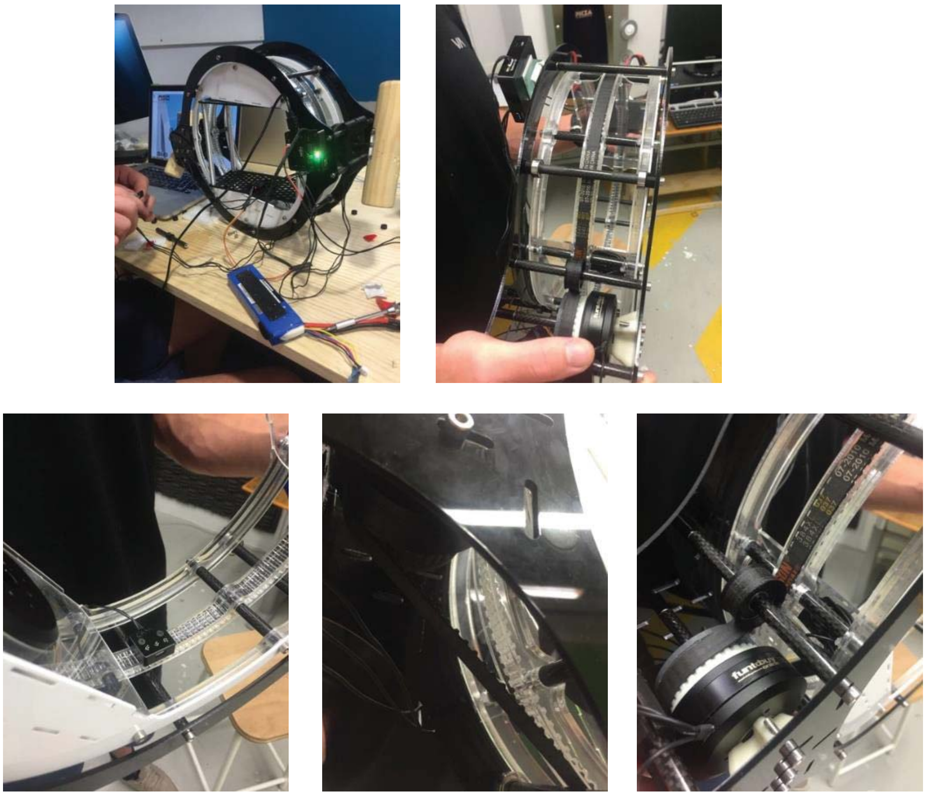


Image 68: Tensioning system for belt drive.

Jimmy assisted me with electronics and also to start thinking about materials suitability and how to build in strength. His expertise in calculating clearances and making sure parts mated correctly was also very helpful. Jimmy's knowledge in Solidworks also helped a lot where he was able to speed up my workflow and understanding of the programme.

There is a large electronic aspect to this project that it is important to note that I was not trying to became an expert in this so that is where I specially required Jimmy's expertise in this area to assist with programming.

Handle design. The handles were an important part of the usability so I explored some concepts for this area.

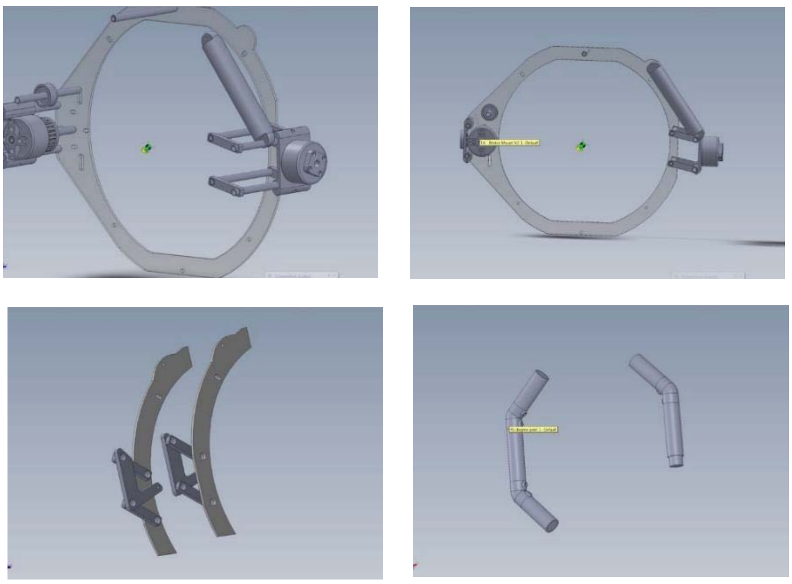


Image 69: Handle design and mounting options.

For a conventional handle, I tested a range of different shapes and sizes to try and find a comfortable handle. I found through user testing and anthropometric research that a pipe with about a 35-40mm diameter was the most comfortable to grip. A wooden handle of 35mm in diameter was used for the first user testing stages

Image 70: Handle development.

I first experimenting with some simple forms made from polystyrene using the hot wire cutter. I was looking at a how I could mould something to fit more comfortably with the hand. I felt as though I was making a quite organic looking shapes and this could be something that could be quite good contrast to the aesthetics of the other parts of the gimbal.

Image 71: Early handle designs.

After doing some more research into ergonomics and anthropometrics I looked into things like how power tool grips worked and how baby seat carriers were formed to be ergonomically effective.

I still found that the best thing to grip was a circular cylinder of about 35-40mm in diameter which provides natural fit to the hand.

Image 72: Handle cushioning structure.

Image 73: Handle form development.

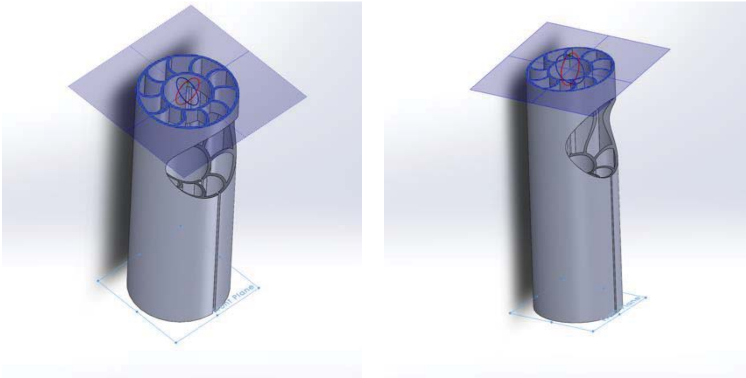


Image 74: Final prototype handle cushioning structure.

I wanted to expand of the idea of just a tube. I came up with an idea of making a very lightweight and strong core with the use of a mouldable material around the outside to mould to a person's particular hand. I choose to use 16mm carbon fibre rod and the Ninjaflex Semiflex material where it was about 20mm thick where I had made an internal structure that would help provide some cushioning and moulding the to the structure and the person's hand.

Other benefits of the handle being this shape and size was that it was providing very good shooting benefits, where the user could hold the gimbal with very relaxed and natural wrist and good completely change his grip when shooting high and low shots.

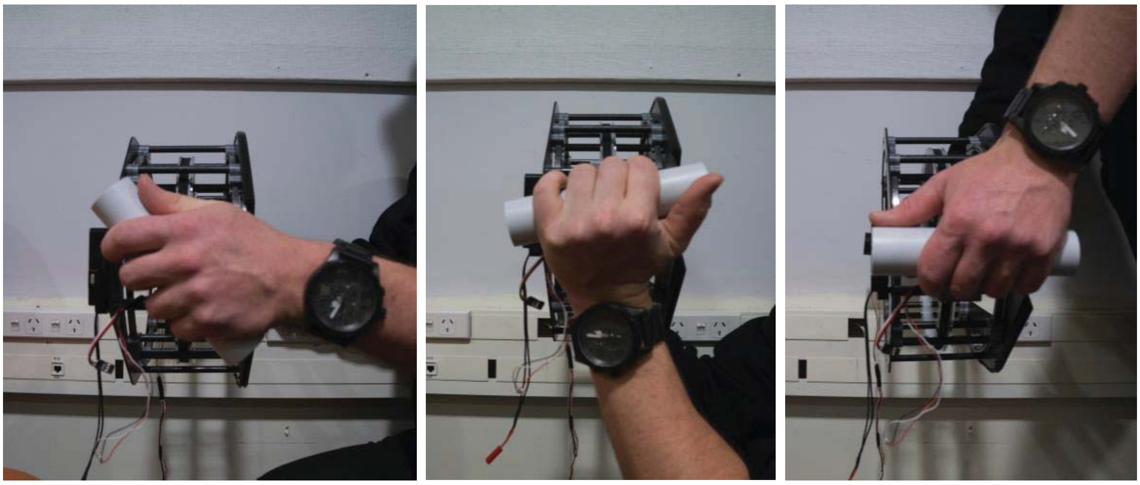


Image 75: Hand and wrist position with handle.

5.11 NINTH PROTOTYPE

Acrylic and thin section bearing to achieve a final solution for the roll axis bearing. Last prototype before manufacturing in final prototype materials. Refining clip design, handle design.

Now that I had a smoothly functioning prototype I reviewed how to improve the roll axis further. There are thin section roller bearings made in an appropriate diameter, i.e. a bearing with a very large inner diameter bore, very thin in cross-section, very compact and lightweight. However, they are very expensive, over US $800 each, which would have exceeded my target budget. After some searching I was able to source these from an engineering company in China for a more reasonable cost.

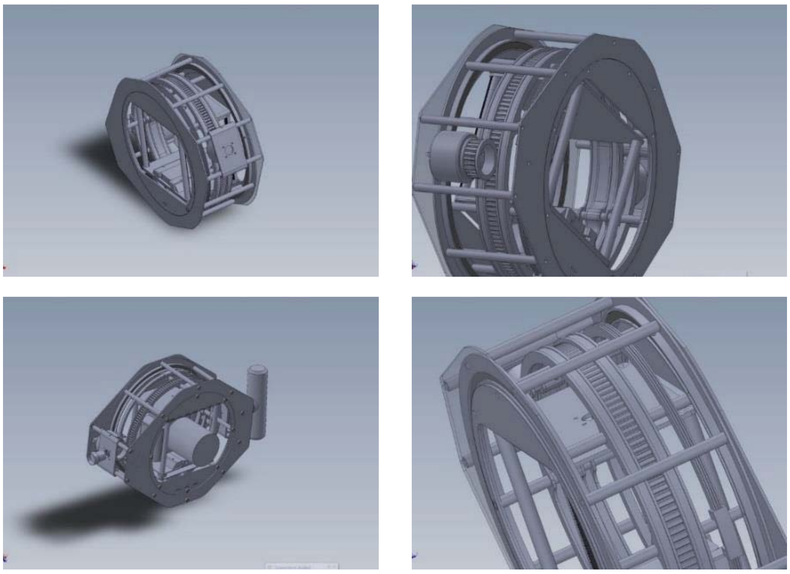


Image 76: Roll axis drive using thin section bearing.

These provided much greater accuracy where there was no adjustment needed to get them spinning freely. By using these I was able to decrease the outside dimensions by about 50mm which improved the overall weight and compactness.

To mount the bearing, I made 3D printed clips from PLA that could attach to the inner and outer faces of the bearing.

Image 77: Clip development for thin section bearing.

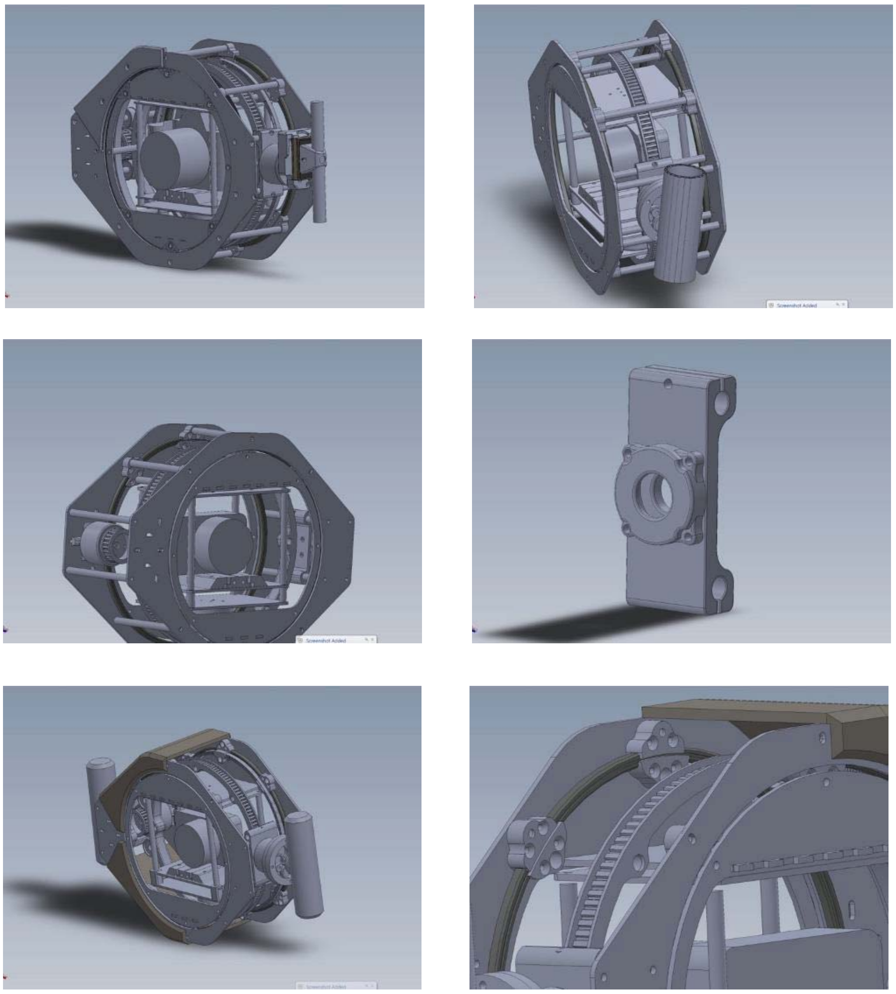


Image 78: Last prototype before final materials prototype, including shock absorbing pads.

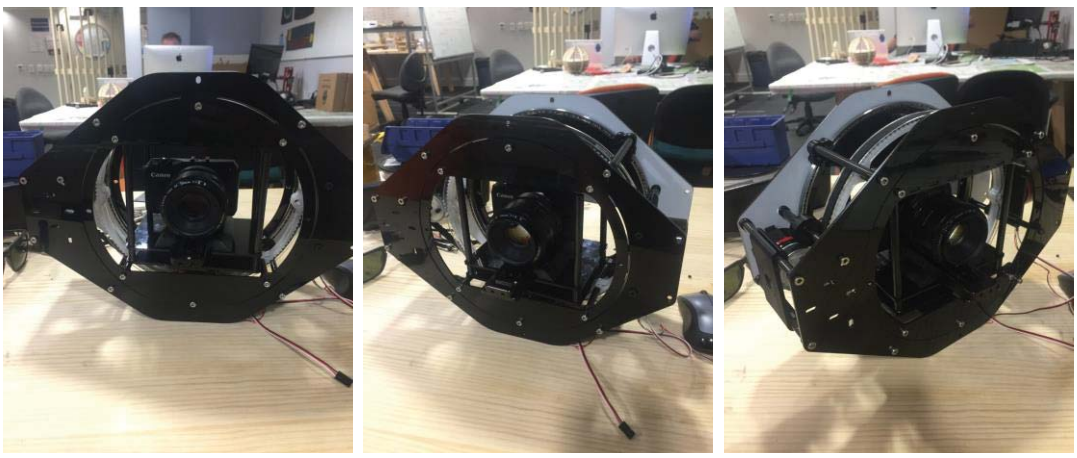


Image 79: Last prototype in acrylic before final materials prototype.

5.12 TENTH AND FINAL PROTOTYPE

I wanted to then recreate this prototype in a more finalised material.

I choose a matte finish 2mm carbon fibre sheet because of its strength and weight qualities. This also provided very significant structural benefits. I have used a 3D printed filament called Ninjaflex Semiflex which is a thermoplastic polyurethane. It provides excellent shock absorbing properties which I have maximised through printing techniques. I also used a slightly different 3D printed PLA where it had infused carbon fibre material which provided much stronger parts.

Image 80: Final materials prototype.

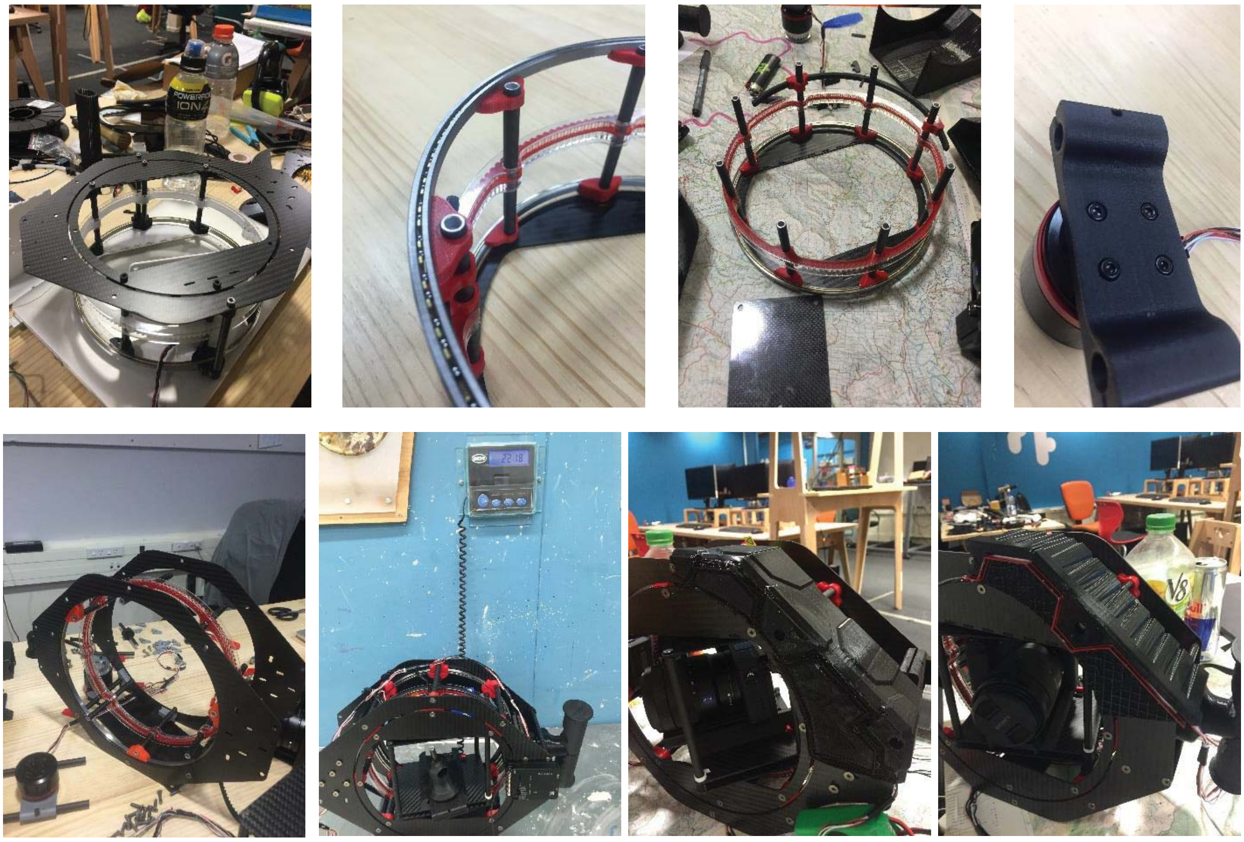


Image 81: Changes to clip colours and pad design for aesthetic enhancement.

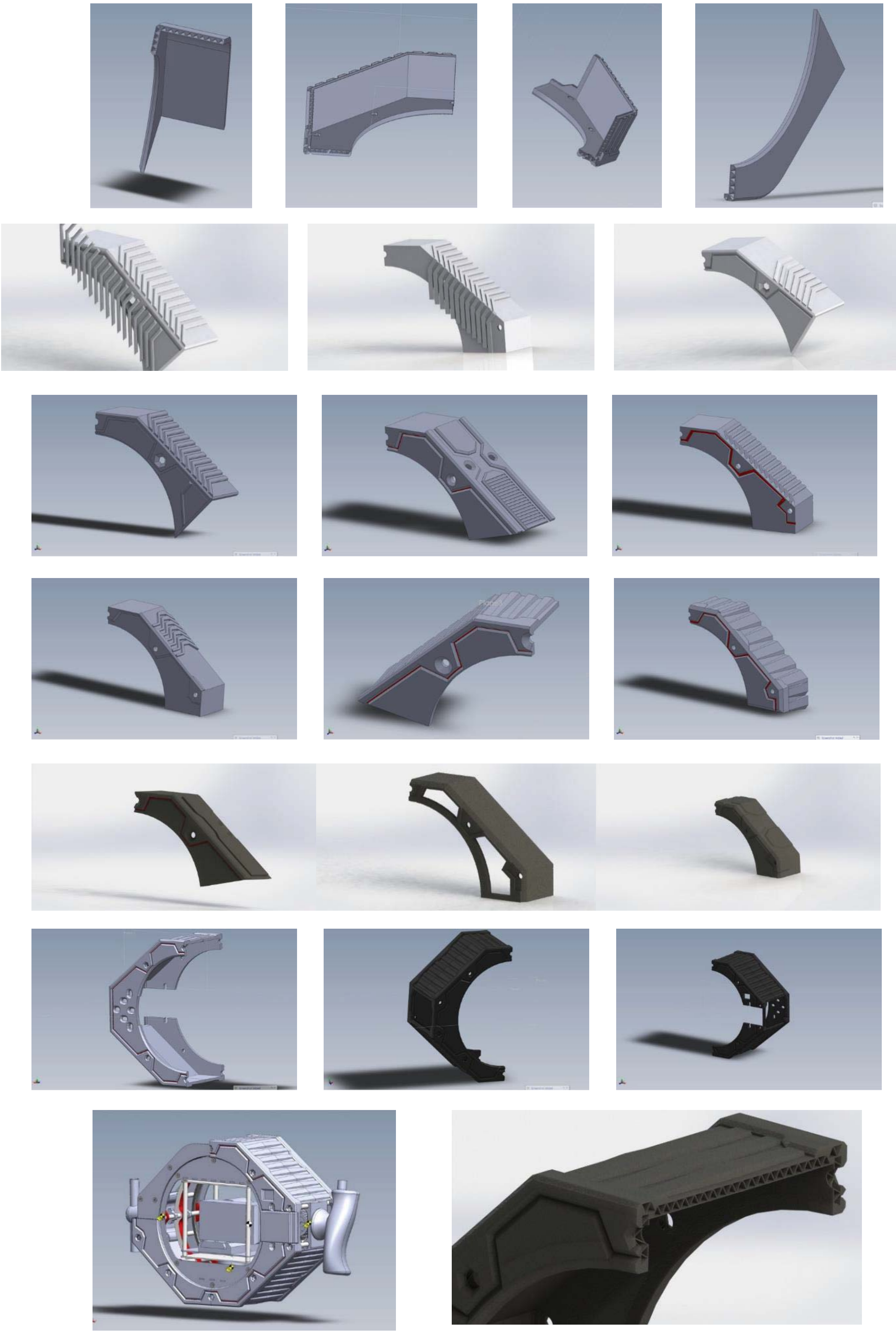


Image 82: Shock pads development; attachment to gimbal; cellular structure.

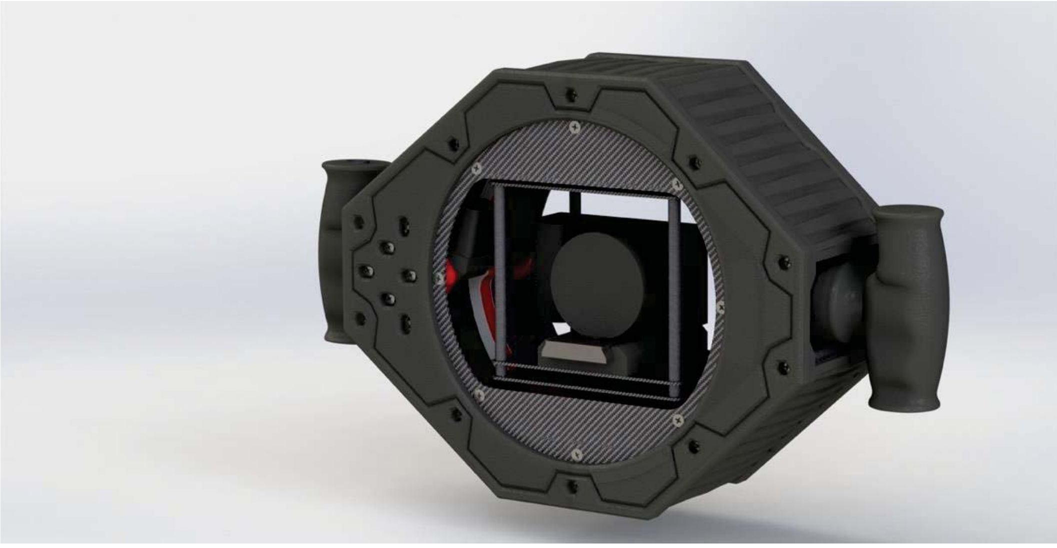


Image 83: Prototype 10 final render.

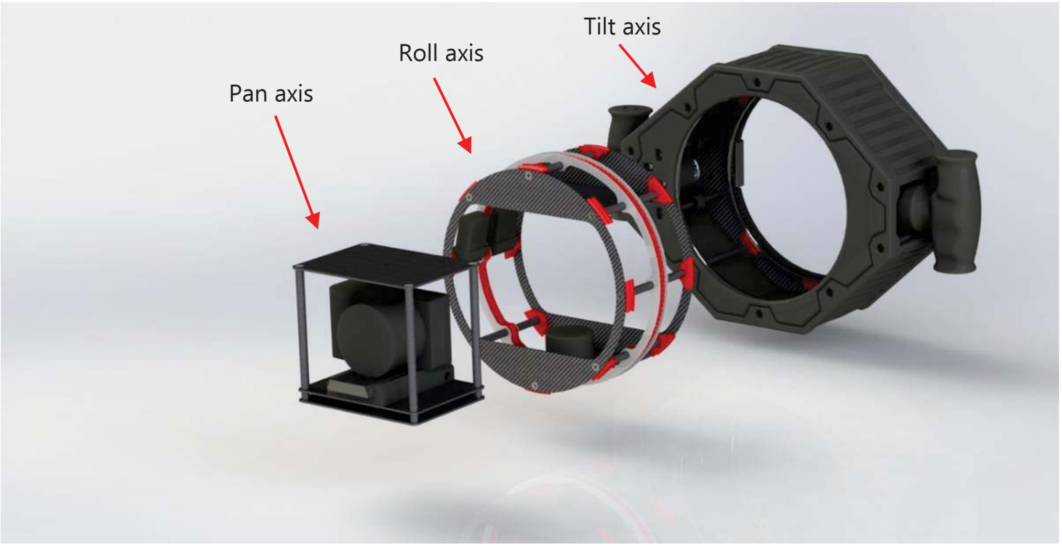


Image 84: Axis breakdown.

Image 85: Shock pads.

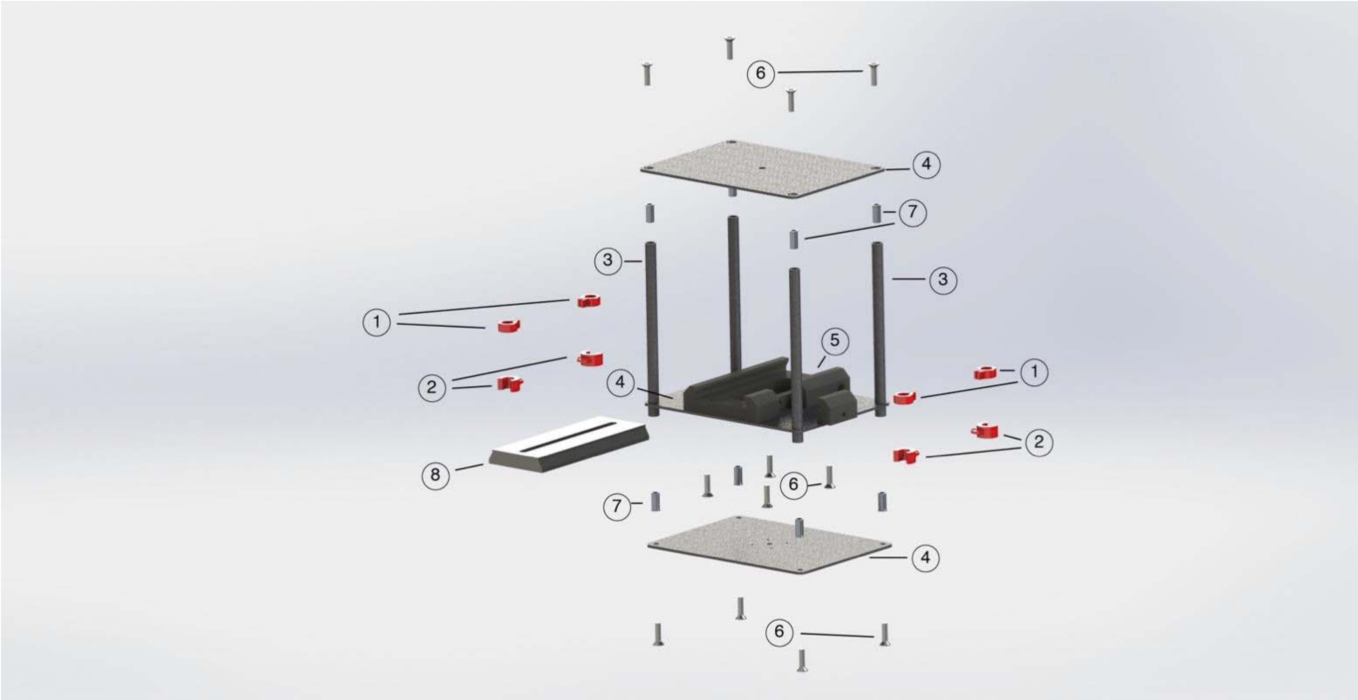


Image 86: Pan axis exploded view.

1 – Optical centre height adjustment clamps (PLA 3D printed)
2 – Optical centre height adjustment spacer (PLA 3D printed)
3 – Spacer rods (8 x 6 mm carbon fibre)
4 – Matte carbon fibre sheet 2mm
5 – Camera mounting plate (carbon fibre infused PLA 3D printed)
6 – Countersunk machine screws M4 x 16mm titanium
7 – Aluminum inserts 6mm x M4
8 – Camera baseplate (carbon fibre infused PLA 3D printed)

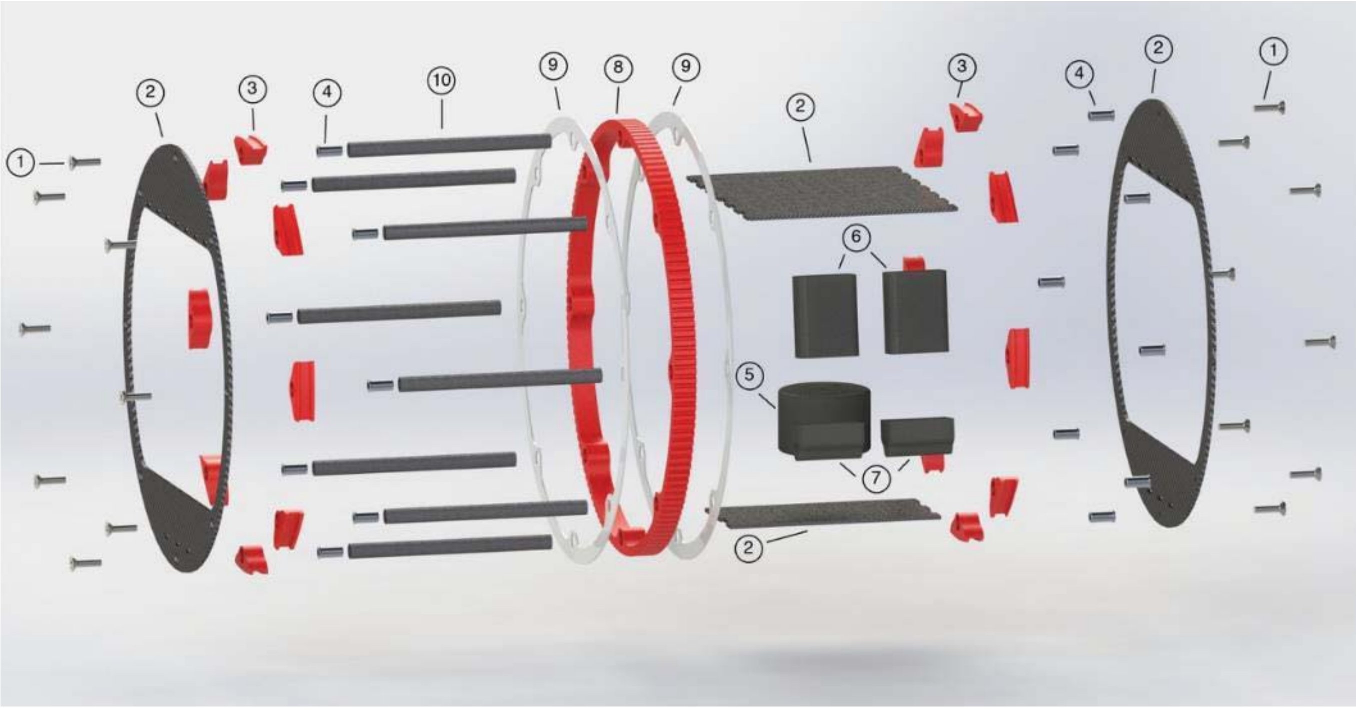


Image 87: Roll axis exploded view.

1 – Countersunk machine screws M4 x 16mm titanium
2 - Matte carbon fibre sheet 2mm
3 – Inner bearing clips (PLA 3D printed)
4 - Aluminum inserts 6mm x M4
5 – Pan axis motor GB5015EN
6 – Spare batteries / Counterweights Sony NP- FW50
7 – Battery Holders (PLA 3D printed)
8 – XL Profile gear rings (Acrylic 6mm)
9 – Gear ring flanges (PETG 1mm)
10 – Spacer rods (8 x 6 mm carbon fibre)

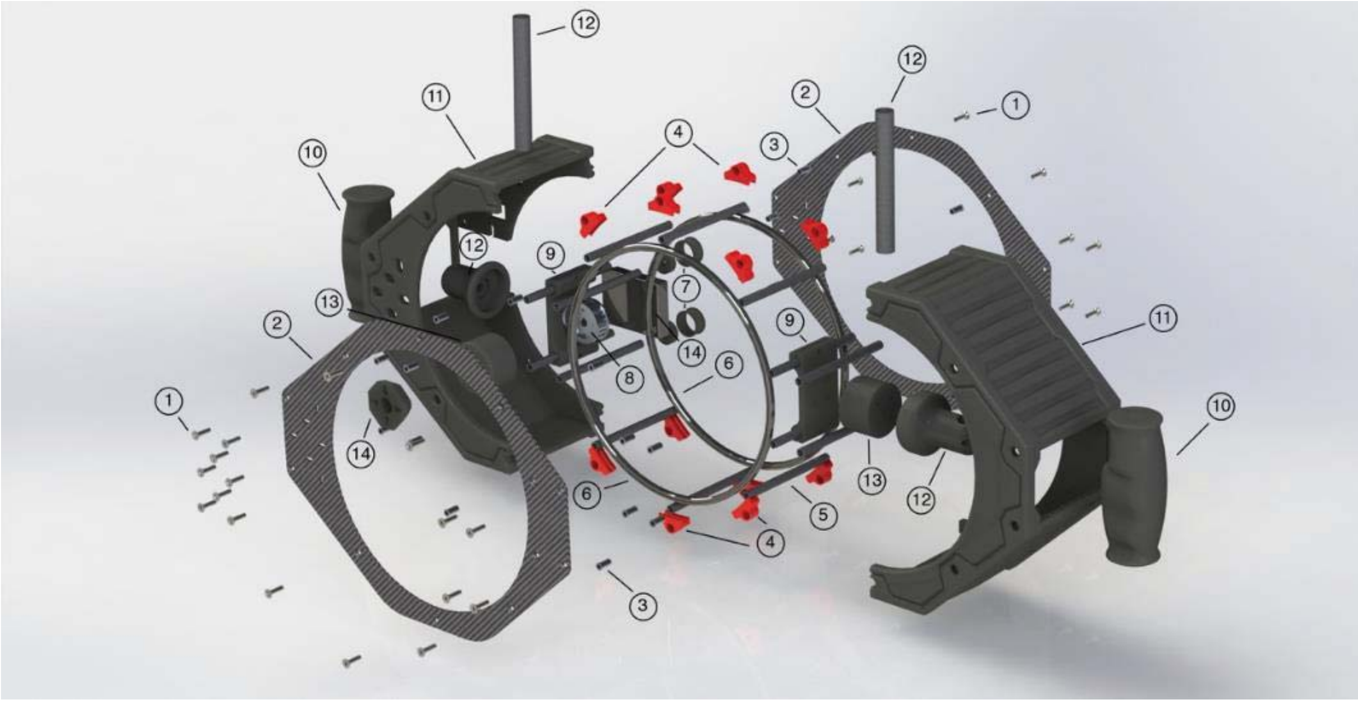


Image 88: Tilt axis exploded view.

1 - Countersunk machine screws M4 x 16mm titanium
2 - Matte carbon fibre sheet 2mm
3 - Aluminum inserts 6mm x M4
4 - Outer bearing clips (PLA 3D printed)
5 - Spacer rods (8 x 6 mm carbon fibre)
6 – Thin Section Bearing KA100CPO – 10-inch
7 – Bearing idlers (PLA 3D printed) and bearings
8 – XL Profile aluminum pulley
9 – Motor mounts (carbon fibre infused PLA 3D printed)
10 – Handles (NinjaFlex Semiflex PLA 3D printed)
11 – Shock absorbing pads (NinjaFlex Semiflex PLA 3D printed)
12 – Motor to handle mount (carbon fibre infused PLA 3D printed)
13 – Tilt and Roll motors GB5015EN
14 - Roll motor mount (carbon fibre infused PLA 3D printed)

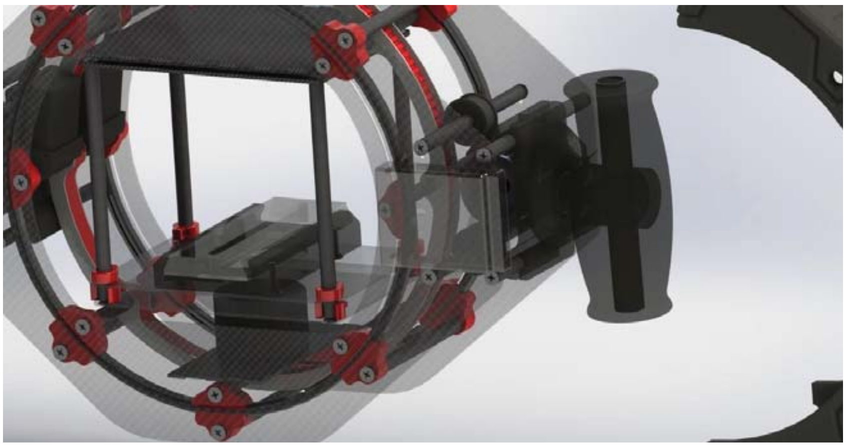


Image 89: Bearing clip detail.

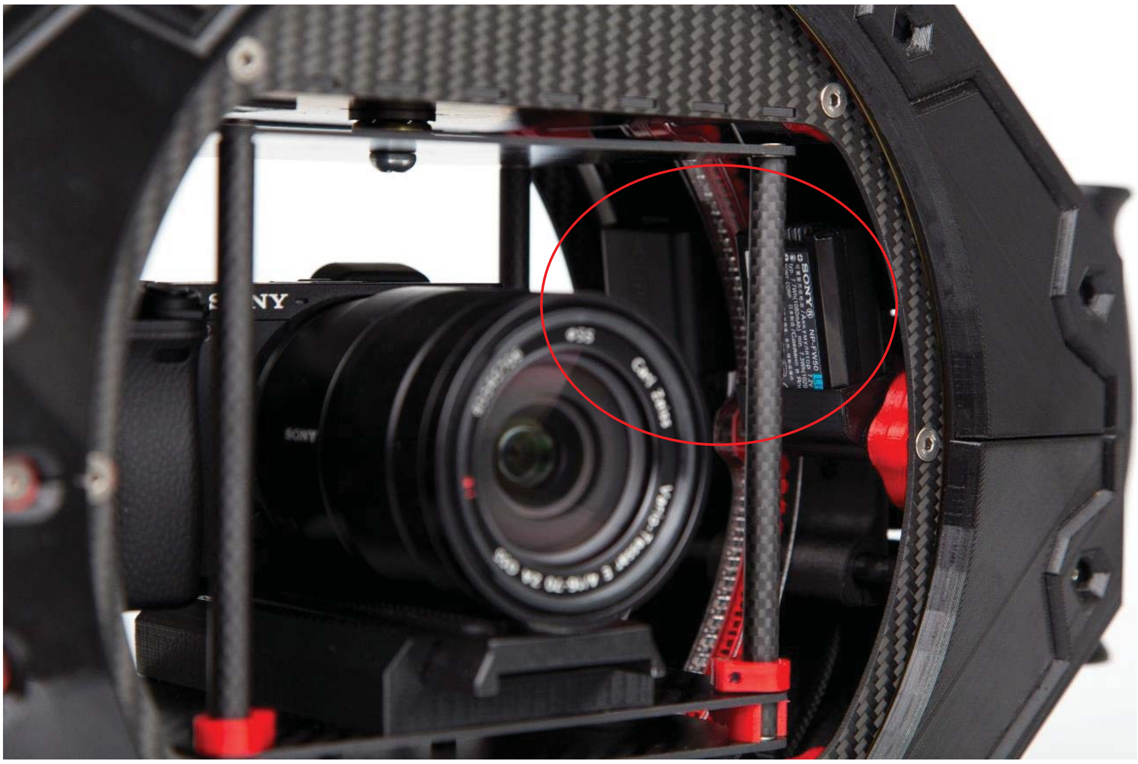


Image 90: Counterweights in roll axis.

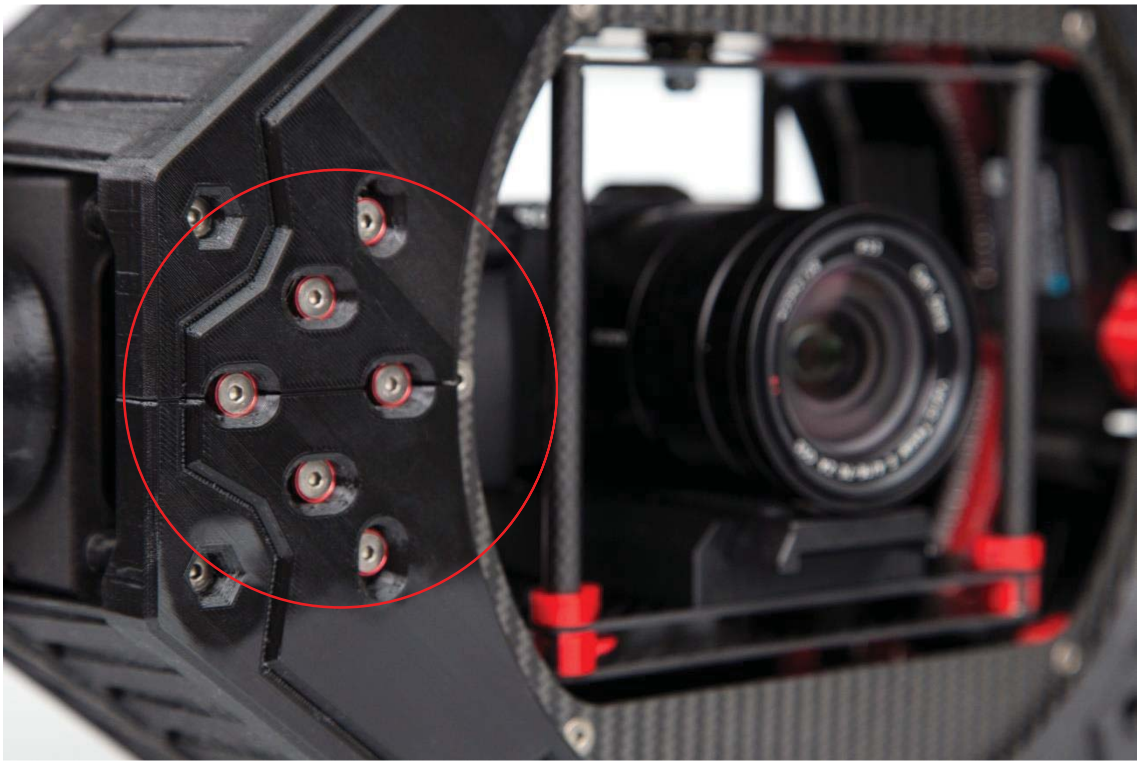


Image 91: Belt and idlers tensioning.

Image 92: Belt and idlers tensioning.

Image 93: Roll axis height - preset clips to maintain optical centre; camera safety release button.

Image 94: Inertia Measurement Unit (IMU).

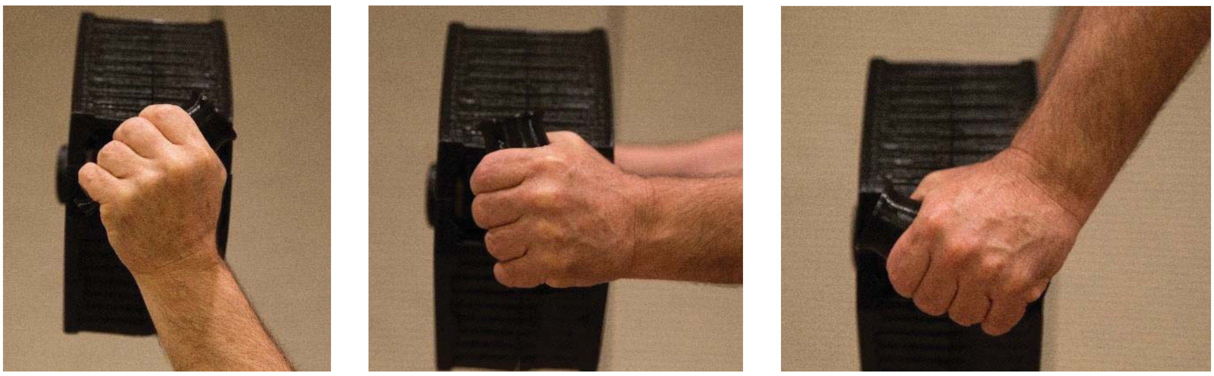


Image 95: High, neutral and low shot - position of hands.

Image 96: Camera and lens balancing setup steps.

a) place camera in gimbal;
b) balance camera by adjusting counterweights for roll axis;
c) attach lens then rebalance for pan axis and tilt axis.

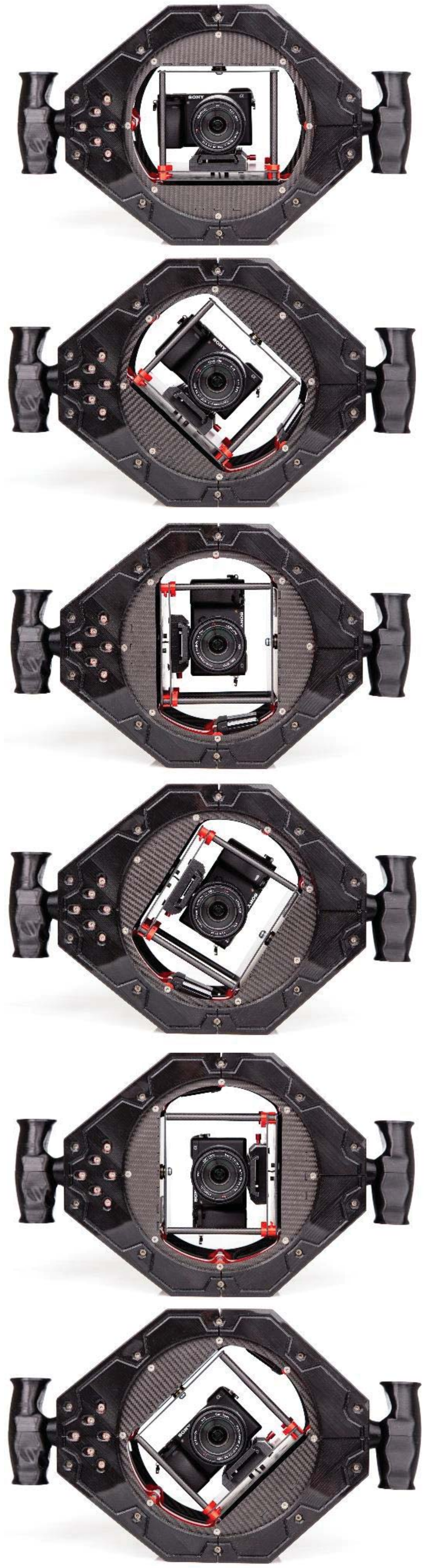


Image 97: Roll axis rotation on optical centre of lens.

Image 98: Product shot, front.

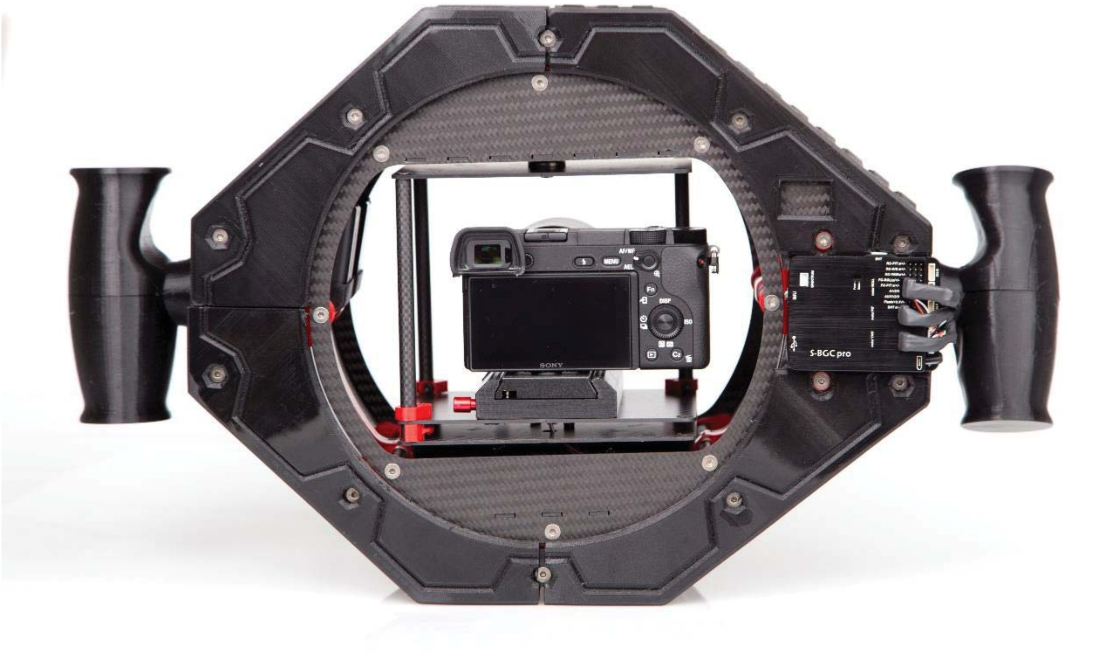


Image 99: Product shot, back.

Image 100: Hero shot of final prototype.

5.13 USER TESTING

As soon as I had a prototype that was functioning, I began field testing. This was particularly to confirm:

- weights balance and ergonomics
- that the electronic stabilisation was working properly
- user reaction to aesthetics.

I used a range of different cameras, including an iPhone. The resulting footage was less important than checking that the unit was operating in a technical sense. So several of these tests were filming people walking or running around the Massey campus. I was particularly interested in the 'step test', i.e. the operator filming someone running up steps while running up the same steps themselves.

We also had a field test in a skate park because that was more of a real-life situation where we were trying to follow a faster moving subject, shooting on foot and from a skateboard. During that test I managed to drop the acrylic prototype with my friend's camera in it. It performed brilliantly: it broke and the camera was fine!

5.14 BALANCING PLATE (FABLAB PROJECT)

For my FabLab project I developed a component that could be used in the final product as an enhancement. This is an option for future development of the gimbal.

For gimbals to work properly the gimbal must be perfectly balanced so that the stabilising motors can function purely to move the camera into the correct position. If there is any weight imbalance at all this puts extra strain on the motors and can cause them to jitter or 'hunt' as they attempt to respond to the gyroscopic input.

Setting up a camera for perfect balance is a time-consuming and trial-and-error process because the only way to find the point of balance is to adjust and test. This is happening along three axes and adjustment for one can make the others incorrect. The rebalancing needs to be redone when lenses are changed, mainly along the longitudinal axis, i.e. for tilt, because a lens is symmetrical lengthways. This means that once adjusted for tilt after a lens change, the centre of gravity should be correct for pan, and possibly for roll depending on the orientation of the lens to the camera.

The Balancer Pro is a baseplate that sits within a 3 axis camera gimbal. It enables the camera operator to perfectly balance the camera's centre of gravity within the gimbals. This is a vital element to making sure the gimbal is working as it should to stabilise the camera along all three axes of movement.

It is fabricated from laser cut 3mm clear acrylic, and uses 15mm aluminium rods. The rods are used for a lens support system which enables the user to attach a range of other systems such as remote follow focus systems, matte boxes, and other accessories. The rods are a crucial element to keeping the sliding movement parallel.

The movement is controlled using a joystick which sends information to a group fabricated Babedunio which then interprets that information to make the stepper motor drive the rack and pinion configuration. The joystick combined with a stepper motor provides the perfect solution for rapid and accurate adjustment of these axes.

It is designed to be compatible with most of the existing gimbal products in the market. It could be sold as an accessory or used directly by one of the existing manufacturers if compatible with their software. This product is designed to dramatically speed up and improve the lens changing process so that the operator can focus on shooting!

6 SUMMARY AND CONCLUSIONS

Image 101. Desborough, G. (2014). Blair 2, Whakapapa.

6.1 DESIGN REVIEW

Protection
The camera (and the other componentry of the gimbal) is protected by an extremely rigid carbon fibre cage and a set of fitted 3-D printed shock absorbing pads with a cellular structure. The pads are designed to absorb impact at the corners and emerge pretty much unscathed. They also provide general dust and weather protection for the camera and components.

Roll axis
The external roll axis is a fundamental part of the design. To achieve this specialised thin section steel bearing has been used. With this type of bearing there is a possibility it could deform if not secured very securely on both sides. This has been done by having it attached directly to a carbon fibre frame, and those frames cross-braced from one side to the other with carbon fibre rods.

The geared belt drive is specifically chosen so that it can transfer the drive from the motor to the roll axis, with a small degree of shock absorption and minimal amount of play. An exact tooth profile is necessary for the belt, the pulley, and the teeth around the roll axis. Because of the different ratios the controller needs to be programmed to allow for this.

Light weight
Weight is reduced to an absolute minimum by using the lightest possible materials that still perform in terms of strength and rigidity. Having a layer of protection is necessarily going to add weight, but the gimbal, because it is very compact, is still comparable to, or less than, the weight of competitor products.

Cost
The cost of using advanced materials has been kept relatively low by starting with flat sheet or 3-D filament and cutting or printing direct from that rather than moulding or machining. Because all of the design is digital there is the possibility of getting some of the cutting or 3D printing done overseas, i.e. in China.

A significant proportion of the cost is the cost of the motors and bearings. It is expected that these could be reduced by buying larger quantities. The bearing itself is such a fundamental part of the design that it may be worth considering manufacturing my own bearing out of acetal, with acetal or silicon nitride balls. Because these are about 20% and 40% respectively the weight of steel, this would more than offset the need for the bearing to be larger for strength reasons. Even if relatively expensive, it could be worthwhile to have a custom-made bearing to protect intellectual property.

Ergonomics
Having a smaller, more compact gimbal is a huge head start in making it more easily usable. It makes it much easier for that weight to be held out in front of the operator, and for the gimbal to be moved to the appropriate position for the subject. The operator can easily see the rear screen of the camera, which is a huge advantage in terms of framing the shot, and with modern cameras even seeing what the actual shot taken will look like. The handles are designed to swivel and rotate easily with the wrist, which is much more comfortable than traditional gimbals with a wide 'handlebar' grip.

Aesthetics
Carbon fibre and titanium are preferred materials for any product claiming to have high performance. The fit and finish of the fastenings is designed to looked functional, i.e. recessed or protruding where appropriate. Nearly all of the external materials are matte finish so won't show finger marks. Highlighting with coloured material where possible to be consistent with other related equipment. The 3D printed shock absorbing pads have a streamlined appearance but a textured finish appropriate for their function. The handles are 3D printed so that they respond to grip, and have a cushioning structure for tactility and comfortable long-term use.

Setup and balancing
Most cameras are lopsided, i.e. the centreline of gravity is not in line with the centre of the lens. This is because generally there is a battery as part of the handgrip. Virtually all gimbals deal with this by having the camera centred based on mass and not having any counterweighting. Having the centreline of rotation lined up with the centre of the lens reduces the amount of set up and balancing required, and also makes lens changes possible without any further adjustment, apart from fore and aft adjustment.

6.2 DESIGN FOR MANUFACTURING

Design from flat sheet and using computer controlled cutting to achieve highly accurate cutting which is very easily to replicate for low volume manufacturing.

Injection moulding as a final production method was not considered suitable from the outset due to the low volumes expected.

Complex components are 3D manufactured and waterjet cut. CNC machining, which is expensive, has been avoided through careful choice of materials, i.e. specific 3D print materials, and use of these alternative technologies.

CAD modelling allowing direct transfer to low volume manufacturing, dramatically reducing the need for control drawings.

Minimal gluing with most parts screwed together for assembly.

6.3 DESIGN FOR ENVIRONMENT

Consumer interest in whether the products they buy can be recycled is growing (GPI, 2014), so I have considered this as part of the design process. The three main ways my product can be made more suitable for recycling is in production methods, assembly methods and the choice of materials.

3D printing or additive manufacturing should be inherently more sustainable because there is no waste from machining, cutting, or moulding support structures and the process can use around 50% less energy than conventional manufacturing (Kreiger & Pearce, 2013). However it is not possible to say that my 3D printing and other manufacturing will be more sustainable overall because a number of factors are involved, including total energy consumption and recycling comparisons (Schneider et al, 2014).

Most of the gimbal is screwed together using machine screws, meaning that it could be easily disassembled for recycling. There is a minimal amount of gluing, particularly the aluminium inserts for the carbon fibre rods, and these can be extracted if sufficient force is applied (well beyond any forces expected in use).

Materials recycling

- Carbon fibre can be recycled and new carbon fibre produced from it for approximately 70% of the cost and using only 5% of the electricity required to produce virgin carbon fibre (Wood, 2013, Polek, 2012). The technology has been driven by the aircraft manufacturers, a Boeing 787, for example, has about 18 tonnes of recyclable carbon fibre.
- All grades of aluminium are easily recycled because it has multiple uses, for example it can be recycled into hardware components. Titanium can be recycled by specialist scrap metal merchants (Titanium Exposed, 2012).
- Most types of 3D printing filament can be recycled (Molitch-Hou, 2013, Advantage Environment, 2013).
- Acrylic can be recycled, although not easily (Singh, 2011).
- Electric motors can be recycled as scrap metal, but circuit boards cannot easily be recycled without disassembly.
- There are also two materials that are not in the latest prototype, but which I may use and future, ascertain and silicon nitride. Acetal can easily be recycled, and can actually be used to improve the performance of other plastics (Plastics Today, 1998). It does not appear that silicon nitride can be recycled once fired.

6.4 PERFORMANCE AGAINST DESIGN SPECIFICATION

CAMERA PROTECTION

- Extremely strong rigid frame and tube bracing give crush protection.
- External shock absorbing pads.
- Each axis is protection layer, three in total.
- 3D plastics: shock absorbing Ninjaflex Semiflex TPE, 3DXMax carbon fibre impregnated PLA for rigidity and strength.
- Bearing clips designed to break before bearing is affected.
- Broken components individually replaceable.

WEIGHT

- Target of under 2.5kg has been met using carbon fibre, titanium, no separate monitor, high performance battery.
- Would be lower with lattice-type 3D parts, Finite Element Analysis[8].
- Motors and bearings are a weight limitation, unless technology advances or they were made from different material.
- No lower weight limit if strength and performance are not sacrificed.

COST / PERFORMANCE

- Prototype is performing well and producing excellent quality footage.
- Jitter / play in the drive mechanism is almost non-existent.
- 3D printing and cutting from sheet makes previously expensive parts (injection moulding, CNC routing) dramatically cheaper.
- Thin section bearings are about a third of the cost, so this could be an area for further development.

AESTHETICS / USABILITY

- Form strongly driven by functionality.
- Carbon fibre and titanium are also very important for aesthetics and to appeal to target market.
- Matte carbon fibre and a smooth uncluttered functional look.
- Handle design moulds to the hand and can be rotated to any angle for a natural relaxed grip.
- Coloured highlights where structurally possible (i.e. that part strong enough in coloured material).
- Flat base so it can be placed between shots.
- Roll axis is able balance the camera in the optical centre so there is minimal camera movement, which minimises setup and lens changing time.
- No need for an external monitor.
- Can be set up for left or right handed people.

[8] a method for optimizing the structure (and reducing the weight and size) of a component using computer modelling of how it would react to real-world forces.

Gimbal Costs (USD)		Quantity	Cost Each USD	Total Cost USD
Electronics	Alexmos Pro Control Board	1	$ 150	$ 150
	3 GB5015 Motors	3	$ 50	$ 150
	Lithium polymer (LiPo) Battery 11V	1	$ 10	$ 10
Materials	2mm Carbon Fibre Sheet (20pcs)	2	$ 40	$ 80
	10” Thin Section Bearing (50pcs)	2	$ 130	$ 260
	8mm Carbon Fibre Rods	2	$ 18	$ 36
	6 x M4mm Aluminum Inserts	68	$ 0.13	$ 9
	M4 x 16mm Titanium Bolts	68	$ 0.80	$ 53
	6mm Acrylic Sheet	1	$ 10	$ 10
3D Printed Materials	3DXMax carbon fibre infused PLA grams	100	$ 0	$ 3
	NinjaFlex Semiflex TPE grams	50	$ 0	$ 5
Machining	Laser Cutter per hour	0.17	$ 68	$ 12
	Water Jet Cutting per hour	0.17	$ 68	$ 12
	3D printing per hour	3	$ 15	$ 45
	Total			$ 834

Gimbal Weight (g)		Quantity	Weight Each g	Total Weight g
Electronics	Alexmos Pro Control Board	1	65	65
	3 GB5015 Motors	3	188	564
	Lithium polymer (LiPo) Battery	1	150	150
Materials	2mm Carbon Fibre Sheet (20pcs)	2	120	240
	10” Thin Section Bearing (50pcs)	2	230	460
	8mm Carbon Fibre Rods	14	7	100
	6 x M4mm Aluminum Inserts	68	0.5	34
	M4 x 16mm Titanium Bolts	68	0.8	54
	6mm Acrylic Sheet	1	80	80
3D Printed Material	3DXMax carbon fibre infused PLA grams	100	1	100
	Ninjaflex Semiflex TPE grams	650	1	650
	Total			2497

Figure 8: Summary of final prototype costs and weight.

My target for payload was approximately 1 kg and the camera and lens combination I am currently using has the following weights:

Item	Dimensions	Weight
Sony A6300 (Sony A7RII is 625g)	120.0 x 66.9 x 48.8 mm	404g
Sony 35mm F1.8 OSS lens (Sony 16-70mm F4 OSS Zeiss is 308g)	64.7 x 64.7 x 45.0 mm	154g
Sony NP-FW50 Battery x 2	31.8 x 18.5 x 45.0 mm	85g
Nikon ME-1 stereo microphone	38.0 x 79.0 x 87.0 mm	92g
Total		735g

Figure 9: Summary of camera equipment weights.

6.5 LEARNINGS

What went well

- Up skilling in digital fabrication and CAD design in the FabLab course.
- Getting in outside expertise for electronics and troubleshooting.
- Keeping in regular contact with my supervisors.
- Having a clear objective of what I wanted to achieve, and how.
- Being able to focus my prototyping on solving specific problems.
- Many iterations of prototyping, regrouping when something wasn't working.
- Keeping everything digital in such a fast moving area, e.g. new 3D filament coming onto the market.
- Having the model close to final form before cutting from final materials.

What didn't go so well

- Having a mechanical design that needed to function at quite a high level to demonstrate the design concept.
- Getting a bit sidetracked with existing markets and trends – a moving target.
- Critiques, was not well prepared enough for some of them.
- Not being able to integrate the component I developed in the FabLab course.

7 FUTURE DEVELOPMENT

Image 102: Desborough, G. (2014). Jackie 1, Waikanae.

7.1 POSSIBLE FUTURE DEVELOPMENT

- Incorporate balancing plate from FabLab project.
- Further weight reduction by using a plastic bearing of some type and/or Finite Element Analysis.
- Development of a custom-made plastic bearing.
- Could have extra accessories easily attached such as microphones and monitors to view quality on media.
- Incorporate a wireless transmitter that can control all camera functions through a smart phone or a tablet.
- Time-lapse functions.
- Improved audio.
- Some type of tag on an athlete where the camera would always have the person in shot.
- More extensive waterproofing or weatherproofing.

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Image 105: Desborough, G. (2012). Whakapapa snowmaking.

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11 APPENDICES

Image 106: Desborough, G. (2014). Blair 2, Whakapapa.

11.1 CAMERA MOVEMENT TECHNIQUES

This is a short summary of the different type of shots that are required for small scale production and shots that can be achieved with specific equipment. Such as a tripod with a fluid head that can achieve very smooth panning shots for a very steady base, or a slider where the camera can be moved in the specified direction along an axis to achieve a smooth tracking shot. The types of classic camera movements that a gimbal can be used for:

Dolly	Move the camera closer or further away from the subject.
Truck	Move the camera left/right across the subject.
Pedestal	Raise or lower the camera in relation to the subject. You can also move diagonally by tilting the tripod head that the slider is mounted on.
Walking & Running	Move freely around the environment.
Follow	Follow a moving subject.
Dynamic	The camera can be moved and oriented in virtually any direction (high, low, side to side, tilted up/down, etc.).

11.2 MARKET TRENDS

11.2.1 Stabilising equipment trends

Hand-held stabilisation was pioneered by the Steadicam in 1975 (Tustin, 2016) and it is only in the past 2-3 years that electronic and camera technology has enabled small, lightweight gimbals.

The Steadicam has for a long time been the 'gold standard' for professional filmmaking where a shot from a moving position is required and a dolly[9] isn't appropriate (Steyn, 2013). It is a mechanically balanced device based on a spring loaded parallelogram and with low friction bearings. It costs approximately US$40-50,000 (Tiffen, 2016) and is aimed at supporting large traditional cinema cameras of up to 20kg with a typical total weight of 30kg. It requires a trained, skilled, and strong operator. The manufacturer of the Steadicam, The Tiffen Company, has strongly defended their IP and there are few direct competitors.

Image 107: Tustin, 2016. Segway mounted Steadicam; Detail of arm.

Perhaps the most difficult shot for a handheld operator is to film someone while running up or down steps. One of the most recognised scenes in motion picture history was such a shot in the movie Rocky, which was released in 1976 (Tustin, 2016). I have used the 'steps test' as a key performance measure for my own design.

Image 108: United Artists. (1976). "Rocky" Steadicam shot.

Three-axis gimbals first gained popularity as a way to stabilise aerial footage from remote-controlled drones[10] and have been adapted to be used with handles. The pioneer in this area was a Freefly Systems

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[9] a mounted camera running on a track.

10 Drone is the common usage and used in this paper, Unmanned Aerial Vehicle (UAV) or Remote Piloted Aircraft System (RPAS) are equivalents.

(http://freeflysystems.com/), founded in 2011 and based in Washington USA. In 2013 they released the Movi 10, regarded as a game changer in terms of using what was then very advanced electronic stabilisation technology in a product that weighed about 2kg and has a 2kg payload, sufficient for medium quality cine cameras and video-capable DSLRs (Lee, 2013; Mrozek, 2014). When launched the Movi 10 was priced at US $15,000. In 2014 they released a more affordable version, the Movi 5 at US $4,000 (Chollet, 2014).

The company DJI (Da-Jiang Innovations Science and Technology Co., Ltd., (http://www.dji.com/) based in China is another pioneer in the manufacture of gimbals, particularly their DJI Ronin model released in 2014. They are one of the largest drone manufacturers in the world, with 65% of the consumer drone market and revenues understood to exceed US$1 billion (Drone Guru, 2015).

Image 109: DJI marketing material. (2016). DJI Ronin in use.

Since then several manufacturers have entered this space, See Appendices for a listing of current manufacturers and examples of products.

In summary the Steadicam has been the go-to option for hand stabilised shooting for 40 years, but recent advances in technology have produced a new breed of much smaller and lighter equipment that is rapidly encroaching on its capabilities.

11.2.2 Camera and filmmaking trends

This section discusses the development of camera technology that has occurred in parallel to stabilisation equipment.

In 2008, Nikon released the D90 and Canon the 5D Mark II (Barnett, Etchells, & Weidelich, 2008; DP Review, 2008). They were the first mainstream DSLR cameras with 1080p HD[11] video capabilities. Their larger sensor sizes and access to a full range of lenses opened up new possibilities for photographers and filmmakers. The video recorders of the time were either technically limited camcorders or expensive professional cine cameras (Reichmann, 2009). The combination of sensor and lenses allowed filming in low light conditions and with shallower depth of field, which can give the video a much more 'movie like' look.

[11] HD generally refers to 1080p (1080 lines, progressive scan) video which is 1920 × 1080 pixel frame size or 2.1 megapixels per image. 4K or ultra HD video generally refers to 3840 x 2160 pixel frame size or 8.3 megapixels per image.

Image 110: (2008). Nikon D90 and Canon 5D MkII.

However, they still lacked good quality audio, autofocus while recording video, recording duration, and suffered from rolling shutter distortion. The distortion is caused by the mirror being lifted during filming and each image being scanned horizontally, which can distort fast moving foreground objects.

Image 111: Jonen. (2007). Rolling shutter distortion. Retrieved from https://en.wikipedia.org/wiki/Rolling_shutter#/media/File:Jamtlands_Flyg_EC120B_Colibri.JPG

Mirrorless cameras address many of these issues and are lighter and more compact due to advances in electronics and less need for mechanical parts. Over time the sensor size in pixels has increased, and autofocus technology has improved to the point where they are now genuine filmmaking (as well as still photography) cameras. In 2013 Sony released the groundbreaking full frame 4K capable A7 (DP Review, 2013). Current competitors are the Blackmagic Production Camera 4K, the Samsung NX-1, and Panasonic GH4. Like gimbals, there have been major advances in the past two years. The range of lenses available for these cameras, in both APS-C and full frame format, has also steadily increased.

Image 112: (2013). Sony A7

The lower end of the camera market has declined significantly due to the increasing capability of mirrorless cameras, and the ubiquity of cameras in smart phones, and mirrorless is replacing DSLR (Braga, 2013; Price, 2015) and below (PR Newswire, 2015):

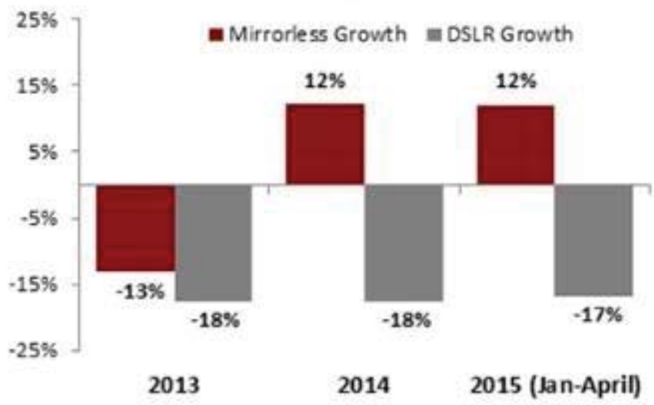

Figure 10: Interchangeable lens camera growth 2013-15.

Some mention also needs to be made of the GoPro (www.gopro.com) and other ultra-compact cameras, which also have associated stabilisation technology. GoPros are ruggedised wide angle video cameras with auto everything adjusted to deliver high contrast MP4 video. Unlike a DSLR, they have no interchangeable lenses, just a good quality fixed wide angle lens. There is no viewfinder, so you won't know framing until later. Sound quality is very poor. So they are addressing a completely different market and I have not considered them as a camera that would be used on the type of gimbal in this project.

In cinematography and all filmmaking, the hand-held stabilised shot has been a major technique for decades, as shown in this compilation of the best Steadicam shots: https://vimeo.com/60974401. Advances in size, weight, and technical capability of equipment mean there are many new possibilities like low angle shots, moving between obstacles, or following the subject downstairs then pass on the camera through a window to continue on the street. For action sports the primary objective is to capture the action and excitement, including tricks. This can mean riding alongside, cable cams, or shooting from a moving vehicle.

For the gimbal in this project, when used for action sports it would be relevant for both still and moving images. High definition video is now at the point where every frame is an acceptable image quality for a still photograph (Butler, 2015; Cox, 2014; ESGI Blog, 2015). This does not mean that they are the same in terms of storytelling; in the words of professional photographer Alex Webb, "I think that video and still photography are very different animals. The former tends toward narrative, the latter toward suggestion. It's like comparing novels and poetry" (as quoted in Shu, 2014). However, for action sports the subject moves so fast that it is often difficult to capture a 'money shot' still image without using a short burst of video or high frame rate.

11.2.3 'Lifestyle' sports and new media channels

Young people increasingly define themselves through sports that include a whole 'lifestyle', including dress, behaviour, language, and attitude to life (Beal & Weidman, 2003; Wheaton, 2004). These sports:

- are relatively recent
- utilise technology-rich equipment and are often innovative;
- often involve significant commitment in time and money;
- have 'living for the moment' and freedom, and are often anti-commercial and anti- institutional;
- are individualistic;
- are non-aggressive in contrast to contact sports, but involve risk and danger; and
- are often consumed in the outdoors or use existing urban spaces.

People who associate with these activities do so because they are seen as exciting, risky, cool, technologically cutting edge, and entertaining (Self et al, 2010; Brymer, 2010). There are a whole range of these sports, from surfing and skateboarding through to free climbing and ultimate frisbee. My focus as noted earlier is on the equipment needed to capture images of a subset of these sports: snowsports, BMX, and skateboarding.

Image 113: Desborough, G. (2014). Murray 2, Whitby.

This trend is part of my context because these consumers are often very interested in technology, have high discretionary spending, and making, distributing and consuming images is part of their lifestyle (Kaplan & Haenlein, 2010; Pew Research, 2014). Participants want to be seen as experts, be true to the culture of their sport, and look the part. Their identities are typically built through images and video posted on social media. This raises issues of immediacy, rapidly rising quality expectations, and the way an identity is constructed online using images.

Many users realise the importance of quality and professional footage if they want the quality and skill of their work to be recognised and something that they are proud of. This will give them 'likes' and followers that they want to impress. Using high performance equipment can help these users become more skilled and successful. Video media is therefore evolving rapidly, with apps like snapchat and Instagram which have 10-15 sec windows in which the user can upload a short video clip. I believe these small and instantaneous video clips will become a new way that 'images' are viewed, and a stepping stone to making and viewing short films.

This has implications for my analysis of target markets including having a piece of equipment containing a camera as a constant companion, perceptions of technology as a support for their lifestyle objectives, and so on. For example, they may be a mountain biker where they need to carry their equipment in a backpack up hills to get the best possible shot of their friend where there is the possibility of falling off but knowing the camera would be fine. A snowboarder who needs it to be lightweight and highly protective considering the environment they are in. I want it to be compatible with their existing equipment which would be highly technical, use new materials and the latest technologies.

I want to try and make this product part of the go-everywhere equipment that is always with the user. For the camera to live inside this structure to protect it when using it and transporting. To help the user get the best quality footage and be a vital part of their equipment where this thing can do more than just be a gimbal. To be able to eliminate the need for sliders and dollys and other bulky camera equipment. I want it to have intuitive software that allows the user to use this gimbal to its full potential.

11.3 PERSONAS OF POTENTIAL USERS

The target market for the product is consumers who are either involved in action sports in some way - as a part-time filmmaker, participant, coach, or parent – or need to film in a difficult or risky environment. I have further divided that into prosumers, emerging filmmakers, professional videographer/filmmakers, and cinematographers.

Prosumer - an enthusiast who buys products (almost always technical) that fall between professional and consumer grade standards in quality, complexity, or functionality. They:

- have a high discretionary spend
- see their activity as a hobby, and acknowledge that some hobbies are expensive
- value quality, and love aesthetics
- are intrigued by technology
- are influenced by marketing
- want the latest, like to show off their gear and 'keep up with the Joneses'
- look for multi-use solutions, e.g. an all-purpose camera with a versatile zoom lens.

Image 114: Prosumer.

Emerging filmmaker -someone who is probably a sports participant who is also interested in filmmaking, and wants to film their friends and build some followers. They:

- are prepared to spend on the right piece of equipment but need to save up and will choose carefully
- are influenced by word of mouth/peers
- are expressing their art
- are very conscious of the risk of damage as this has higher stakes
- know that creating and distributing imagery that reflects their identity is integral to their lifestyle
- form follows function.

Image 115: Emerging filmmaker.

Professional videographer/filmmaker – defined as someone who is getting paid for their work but not producing an artistic work. They:

- would tend to take video clips, film events, etc.
- want their equipment to be failsafe, because they are getting paid and the event may not be repeatable

- will analyse and understand technical specifications and see their equipment as a working tool
- may have client expectations of the type of equipment used, i.e. high level gear
- will be very familiar with every aspect of operation as they are using their equipment a lot.

Image 116: Professional videographer/filmmaker.

Cinematographer – defined as someone who is producing an artistic work. They:

- want failsafe equipment, but it is likely to be part of a wider equipment set
- uses equipment for a specific purpose, i.e. this equipment might be used for doing rough takes
- are conservative, perhaps because of bad experiences, and responsive to peer pressure
- will know technical specifications intimately and how to make best use of performance
- may be less interested in what it looks like
- will be very familiar with every aspect of operation as they are using their equipment a lot.

Image 117: Cinematographer.

I have also developed some more detailed personas of potential users.

Image 118: Persona 1.

Andrew is a professional freestyle ski coach doing back to back seasons in New Zealand and Colorado USA.

Andrew is a 28-year-old born in New Zealand and has been skiing since he was 5 years old. A couple of years ago Andrew had a serious injury that put his freestyle skiing on hold and he now coaches up and coming kids in freestyle as he has a really good knowledge of how tricks are performed.

Every year he has about 15 kids aged between 12-17 come from America for a summer camp at the end of New Zealand season where they have extensive coaching for a 3-week period. The camps are very expensive but the kids come over to have an awesome time, do heaps of skiing and learn new tricks to take back so they have a head start on their northern hemisphere season.

The camp includes a lot of video analysis and quick live feedback, with the coaches able to show the kids straight after they have done a jump the video and slow down and point out different aspects of the tricks they need to improve. This has been highly successful and the kids love seeing themselves and it also gives them good footage to video edits and the coaching staff can supply an edit for each of the kids.

Last season one of the coaches did a follow cam jump with a camper and had a nasty fall as he lost concentration on takeoff. He hurt himself quite badly with some broken ribs and also the expensive camera he was using was badly damaged. They have just purchased the latest generation camera equipment and are wanting something that can protect the camera from this happening again but also be portable and not too heavy to cart around on the hill when going up and down chair rides.

His key user needs and issues are:

- protection
- size
- weight.

Image 119: Persona 2.

Petra is an event cinematographer who is self-employed and does work all around New Zealand.

She shoots at a number of weddings but also really likes shooting larger events especially music festivals and concerts. She has a large range of camera equipment including large DSLRs and small compact cameras for tighter spaces.

Weddings are usually reasonably straightforward where she has a decent amount of time to capture the moment of the couple’s day and can make a really nice 3-5min video showcasing it. She uses a lot of equipment to get these shots including, tripods, slider a glide cam and sometimes using a jib arm to get some higher angle shots when there is a large group in a smaller area such as when dancing at the end of the night. She finds her glide cam can get pretty tiring at the end of the day if she is using it a lot so she switches between her equipment quite a lot.

Her other passion is she loves the atmosphere of festivals and music concerts but has had a number of problems when working in crowds where she has had her equipment bumped and damaged and has major problems getting any quality footage that she can use to do camera shake.

She is looking for a solution that can help with some of the problems that she has especially when using them in a tight environment where there are lots of people around and it and prone to getting knocked and bumped by people.

Her key user needs and issues are:

- performance
- protection
- weight.

Image 120: Persona 3.

Richard is a 22-year-old student studying at Victoria University in Wellington.

He has grown up in Wellington and is passionate skateboarder. He works part time at a local skate shop and is saving up for a new camera a keen hobby that he is developing.

Skateboarding is part of his lifestyle and he has a tight group of his high school mates that started skateboarding at a young age. As they have grown up they have all become better and better with a few in the group managing to secure sponsorship agreements through winning competitions.

They have always done a bit of filming with each other but Richard has recently spent more time filming than skating as has really enjoyed capturing the moments of his friends. And the satisfaction of putting together some good clips for his friends. They have been using quite cheap camera gear to make these and putting them together on a laptop at home. His friends are quality skateboarders but the video quality of the clips are letting them down. They are shot with cheap digital cameras that have poor autofocusing and quite low resolution and not much manual control, also the amount of jitter in the shots sometimes make them hard to watch.

He has received really good feedback and has impressed a lot of people of Facebook and Instagram saying that he has talent in this area but knows if he had better equipment and tools that he could produce much better video edits. Richard had been saving up for a new camera that he has recently bought, he has spent about $1500 on a new mirrorless compact camera. It offers him much better video performance and something that he can stick in a small backpack that he usually skates with in town with a drink bottle and some other basic tools. It was important that he didn't buy a massive big camera that would be annoying to lug around with him as they often skate around to different spots.

Richard is looking for some equipment that can take his filming to the next level, he has looked at a number of options such as sliders and at counterweight Steadicam. He wants it to be cheap and also something that can be knocked around a bit been thrown in a backpack when travelling around. Richard has already had a few close calls where he has falling off his skateboard while filming and nearly damaged his new camera.

His key user needs and issues are:

- price
- protection
- performance.

11.4 EXISTING PRODUCT OVERVIEW

11.4.1 Gimbal manufacturers

Name	Location	Size	Major models	Weight	Payload
Steadicam (The Tiffen Company) http://tiffen.com/steadicam/	New York, USA	Unknown, part of bigger group making filters and other camera accessories	M-1 // G-70x // Exovest (USD 49500) M-1 // G-50x // Ultra Vest (USD 41750)	? ?	? / 31.8 ? / 22.7
Freefly http://freeflysystems.com/	Washington, USA	70 employees	Movi 5 (USD 2995) Movi 10 (USD 7995) Movi 15 (USD 11995)	2.15 2.17 2.47	2.27 5.44 6.80
Varavon http://varavon.com/collections/gimbals	Gyeonggi-do, South Korea	Unknown	Birdycam II (USD 1119)	2.80	2.20
DEFY www.defywithus.com	Arizona, USA	Unknown	Did make gimbals, now mainly cablecams: Dactylcam Lite Kit (USD 4995) Dactylcam Pro (USD 20000) Head only: Ethos (USD 10000)	? ? ?	1.60 8.20 8.20
Shape http://www.shapewlb.com/en/isee-gimbal.aspx	Quebec, Canada	15 employees	ISEE (CAD 1299)	?	0.90
Comodo (Bowens) http://www.comodorigs.com/	Essex, UK	Unknown	Orbit (GBP 599)	2.00	5.00
Wondlan (no website)	China	Unknown	LE 304 (EUR 1199) LE 402 WF (EUR 3895)	? ?	4.54 15.00
SwiftCam (www.swiftcam.com)	Hong Kong	Unknown	X3s (USD 799)	3.07	2.00
DJI http://www.dji.com/product/ronin	Shenzen, China	US $1b sales, consumer and professional drones are a major product category, 3300 employees	(Ronin USD 2499)	2.20	2.00
Gudsen http://tomantosfilms.com/7376/moza-gimbal-review/#more-7376			Moza Lite2 Basic (USD 1099) Moza Lite2 Pro (USD 1599)	2.20	4.00
Gremsy (www.gremsy.com)	Vietnam	Unknown	H3 (USD 1395) H7 (USD 2295) H16 (USD 3995)	1.98	3.18

Figure 11: Major gimbal manufacturers (key manufacturers shaded).

11.4.2 Key products in the gimbal market

Image 121: Revo ST-1000.

Revo ST-1000	Comments
Type	Gimbal and counterweight
Overall	Probably the simplest possible system to counterbalance a camera, can be difficult to set the centre of balance exactly
Base cost, cost of accessories, replacement parts, servicing	NZ $150
Price versus performance assessment	Very cheap and simple, reasonably effective
Field of view and maximum deflection along the axes of pitch, roll and pan	Probably 10-15 degrees, 10-15 degrees, and 360 degrees
Maximum weight of camera	2.20kg
Weight and dimensions	Not specified, 254 x 406 x 114mm
Operating constraints and comments	Is a counterbalanced system only, would be tiring to use for any length of time due to hand position

Image 122: Manfrotto Fig Rig.

Manfrotto Fig Rig	Comments
Type	Gimbal and counterweight
Overall	Quite simple and effective, low price
Base cost, cost of accessories, replacement parts, servicing	NZ $376
Price versus performance assessment	Would have limited stabilisation capability
Field of view and maximum deflection along the axes of pitch, roll and pan	Approximately 45 degrees, 45 degrees, 180 degrees.
Maximum weight of camera	Not specified
Weight and dimensions	1.00kg, 475mm diameter
Operating constraints and comments	Is more of a mounting frame than a true stabilisation rig

Image 123: Freefly Movi 5.

Freefly Movi 5	Comments
Type	Motorised three axis
Overall	Top of the line product for professionals, sophisticated interfaces and control settings, silent drive
Base cost, cost of accessories, replacement parts, servicing	NZ $5,875
Price versus performance assessment	Very high performance but at a high price
Field of view and maximum deflection along the axes of pitch, roll and pan	180 degrees, 180 degrees, and 360 degrees
Maximum weight of camera	2.27kg (camera cage dimensions: 130 x 180 x 120mm LxWxH)
Weight and dimensions	2.150kg
Operating constraints and comments	Probably regarded as the gold standard for this type of rig. Camera mounting cage would provide some protection.

Image 124: Ghost Products The Ghost.

Ghost Products The Ghost	Comments
Type	Motorised three axis
Overall	3 axis gimbals system, can achieve a similar standard of video to motorised systems in some situations
Base cost, cost of accessories, replacement parts, servicing	NZ $2,935
Price versus performance assessment	Aimed at professionals, low cost compared to comparable models
Field of view and maximum deflection along the axes of pitch, roll and pan	Not specified
Maximum weight of camera	2.25kg
Weight and dimensions	1.430kg, 450 x 320 x 200mm
Operating constraints and comments	A large bulky unit that does not offer much protection to the equipment.

Image 125: Defy G5.

Defy G5	Comments
Type	Motorised three axis
Overall	Used by Red Bull
Base cost, cost of accessories, replacement parts, servicing	NZ $4,470
Price versus performance assessment	Mid-range professional unit. Note Black Magic video camera shown.
Field of view and maximum deflection along the axes of pitch, roll and pan	45 degrees, 70 degrees, 360 degrees
Maximum weight of camera	2.72kg
Weight and dimensions	2.260kg, 50 x 180 x 200mm
Operating constraints and comments	Very similar in layout to the Free fly Movi 10 but heavier and considerably less cost – it isn't clear whether this is because of the quality of the componentry, profit margin, aimed at a different market, or less R&D recovery.

Image 126: Shape ISEE II.

Shape ISEE II	Comments
Type	Tilt-axis gimbal stabilised on the pitch and roll axes
Overall	Shoulder mounted so therefore has a different shock absorbing system – the flex in a person's arms isn't available
Base cost, cost of accessories, replacement parts, servicing	NZ $6,495
Price versus performance assessment	High end unit, not on the market yet
Field of view and maximum deflection along the axes of pitch, roll and pan	Not released
Maximum weight of camera	Not released
Weight and dimensions	Not released
Operating constraints and comments	Is a relatively expensive and complex-looking unit. Shoulder mounting makes the weight issue less significant but reduces the ability to shoot flexibly, e.g. from a low angle.

Image 127: Photohigher AV200 IDD.

Photohigher AV200 IDD	Comments
Type	Two axis motorised or three axis with kit
Overall	Designed for aerial work. Is a New Zealand company.
Base cost, cost of accessories, replacement parts, servicing	NZ $1,495. Requires a $495 kit for pan and to be hand held (shown at top)
Price versus performance assessment	Design allows for shooting straight down. Does not have a pan axis which would mean that this would be up to the operator if handheld. Note Red Epic camera shown on the left (USD 40,000).
Field of view and maximum deflection along the axes of pitch, roll and pan	180 degrees, 70 degrees, 360 degrees
Maximum weight of camera	Not specified
Weight and dimensions	.59kg but this does not include the handheld kit, which does not have a weight specified.
Operating constraints and comments	Has a lateral movement absorption given by the air when used on a quadcopter. There has been greater attention to weight reduction with the lattice construction, because of the need for absolute minimum weight in the air.

Videos showing existing products:

DJI - Introducing the Ronin (only to 1.20min)
https://www.youtube.com/watch?v=bcjSdzYb9LY

Behind the scenes of Nick Goepper's BIGGEST slope style tricks (only to min 1.55min)
https://www.youtube.com/watch?v=SvIsa2wMSiY

Nick Goepper breaks down his winning slope style tricks (whole video)
https://www.youtube.com/watch?v=KhIGT9ndwKg

Defy G5 with cable cam
https://vimeo.com/109032357

11.4.3 Setup process for DJI Ronin

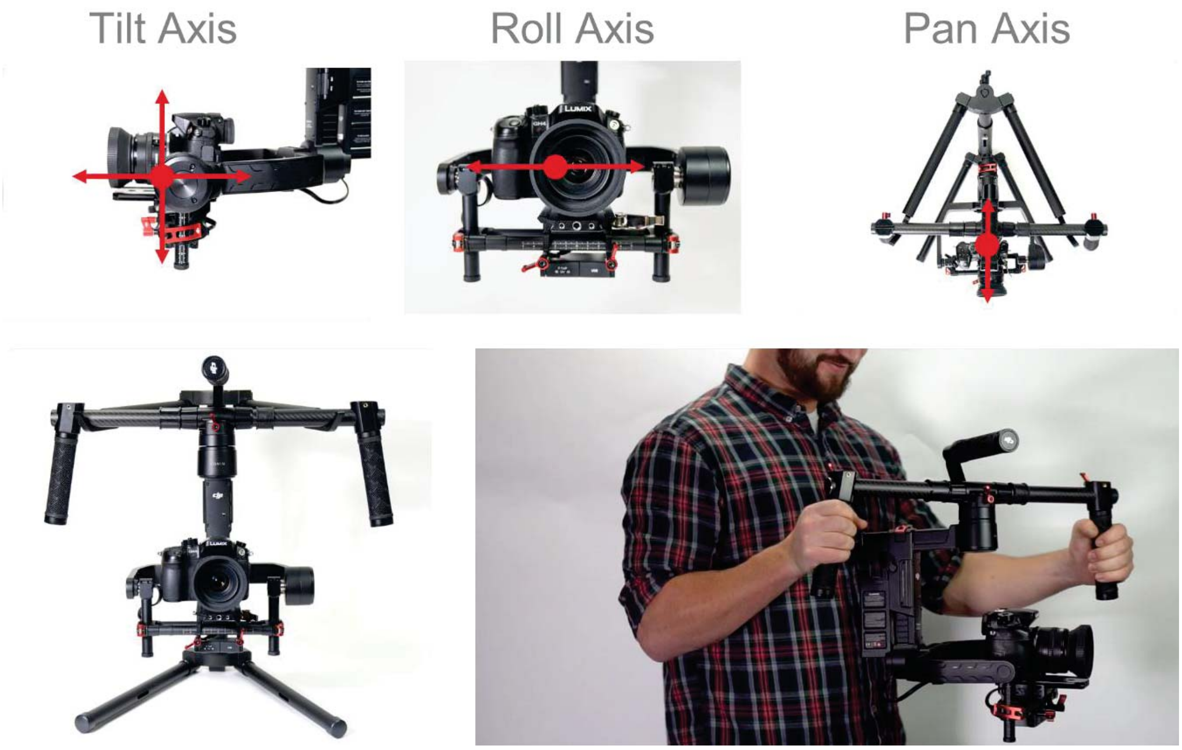

Image 128: Setup process for DJI Ronin.

(video of above process: https://www.youtube.com/watch?v=c6ygxVcIpro)

11.5 MATERIALS RESEARCH

Typical Materials Properties

Material	Tensile strength MPa	Density g/cm^3	Specific strength Kn m/kg	Youngs Modulus GPa	Density g/cm^3	Specific stiffness 10^6 m^2/ms^{-2}
Carbon fibre	4300	1.6	2688	181	1.6	113
Steel	500	7.8	64	200	7.8	25
Aluminium	570	2.7	211	69	2.7	26
Titanium	1300	4.5	289	113	4.5	25
Ninjaflex Semiflex TPE	43	1.2	36	2	1.2	1.7
Standard PLA	57	1.2	48	3	1.2	2.4
3DXMax CFR PLA	48??	1.2	40	5	1.2	4.0
Acrylic	70	1.2	58	3.2	1.2	2.7
Acetal (Delrin)	60	1.4	43	2.8	1.4	2.0
Silicon nitride	375	3.2	117	300	3.2	94

Figure 12: Typical materials properties.

Sources: http://www.engineeringtoolbox.com/engineering-materials-properties-d_1225.html; http://www.engineeringtoolbox.com/young-modulus-d_417.html; or derived from data on manufacturers websites.

Cost Comparison for Carbon Fibre Sheet

(specification: 2.0mm ± 0.2mm, 3K, 100% carbon fibre (no fibreglass), 5 layer, orientation 90/45/90/45/90)

Source	Units	W mm	L mm	Area m2	Currency	Rate / unit	Freight	Total	Exch. Rate	Cost NZD	GST	Less GST	$/m2	Gimbals	$ / gimbal
Dragonplate (USA)	1	305	610	0.1861	USD	149	40	189	0.66	$286	N	$286	$1,539	2.0	$143
Carbon Fiber Australia	2	500	500	0.5000	AUD	239	40	518	0.94	$551	N	$551	$1,102	1.0	$551
NZ Composites (NZ)	1	350	630	0.2205	NZD	200	25	225	1.00	$225	Y	$196	$887	1.0	$196
Erismet (Estonia)	2	450	450	0.4050	EUR	76	40	192	0.59	$325	N	$325	$804	1.0	$325
ZY Hobby - Ebay (China)	2	300	500	0.3000	USD	60	0	120	0.66	$182	N	$182	$606	1.0	$182
CA Composites (China)	2	400	500	0.4000	USD	50	55	155	0.66	$235	N	$235	$587	1.0	$235
CA Composites (China)	25	400	500	5.0000	USD	41	60	1085	0.66	$1,644	N	$1,644	$329	12.5	$132
CA Composites (China)	2	300	600	0.3600	USD	46	55	147	0.66	$223	N	$223	$619	2.0	$111
CA Composites (China)	25	300	600	4.5000	USD	39	60	1035	0.66	$1,568	N	$1,568	$348	25.0	$63

Figure 13: Cost comparison for carbon fibre sheet (key supplier shaded).

Sources: personal communication and manufacturers websites (http://dragonplate.com/; http://www.carbonfiber.com.au/; http://www.nzcomposites.com/; http://erismet.ee/eng/carbon-fiber-sheets/; http://www.ebay.com/usr/zy-hobby; http://www.cacomposites.com/).

Summary of Cutting and Marking Properties of Plastics

Name	Other Names	Type	General Cut Quality	General Mark Quality	Barcode Mark Successful	Safety
ABS		Thermoplastic	Poor-Fair: Slight discoloration of cut edge	Poor-Fair: Slightly engraved marks	No	
Acrylic (Cast)	PMMA, Plexiglass	Thermoplastic	Excellent: Clean vaporization with fire polished edge	Good: Frosted white mark	Sometimes: Depends on background color	
Bakelite		Thermoset	Poor: Some Charring	Good: Low power: White marks; High power: Charred engraved marks	Sometimes: Depends on background color	
Fluoropolymers	PTFE, Teflon, ETFE	Thermoplastic	Good: Some melt	Fair-Good: Clean engraved marks	No	
FR4/FR2	PCB	Thermoset	Poor: Brown Charring; sometimes degating is successful	Good: Dark marks on uncoated surface; Light marks on solder masks	Yes	
Nylon		Thermoplastic	Good: Moderate melt	Fair-Good: Engraved marks with some meltback	No	
Nylon (Glass filled)		Thermoset	Fair-good: Some discoloration of cut edge	Good: Dark marks	Yes	
Polycarbonate	Lexan, Calibre, Makrolon, Panlite, Makrolife	Thermoplastic	Poor: Brown Charring	Good: Low Power: White/Transparent Mark. High Power: Brown/Yellow marks	Yes	Thick smoke when cut
Polyester	Mylar, PET, PETE, PETG	Thermoplastic	Good: Some melt; PETG needs high assist gas pressure approx. 60psi	Fair-Good: Engraved marks with some meltback	Sometimes: Depends on background color	
Polyethylene	HPDE, MDPE, LDPE, UHMW	Thermoplastic	Fair-good: Moderate to large melt	Fair-good: Engraved marks with melt-back	No	
Polyimide	Kapton	Thermoset	Poor: Brown/Black Charring	Fair-good: Dark marks with some soot residue	Yes	
Polyoxymethylene	POM, Delrin, Polyacetal	Thermoplastic	Good: Some melt	Fair-good: Clean engraved marks	No	Formaldehyde gas
Polypropylene		Thermoplastic	Good: Some melt; Sometimes slight discoloration	Fair-good: Deep engraved marks & slight melt-back	Sometimes: (2D codes)	
Polystyrene		Thermoplastic	Fair-good: Moderate melt & residue	Fair-good: Engraved marks with some melt-back	No	
Polysulfone		Thermoplastic	Fair-good: Moderate melt & residue	Fair-good: Engraved marks with melt-back; Wet residue	No	
Polyurethane		Thermoplastic	Fair-good: Moderate melt & residue	Poor-Fair: Slightly engraved marks	No	HCN GAS
PVC	Vinyl	Thermoplastic	Poor: Brown/yellow charring; VERY HAZARDOUS outgassing	Good: Brown/Yellow marks; Some residue	Yes	HCL GAS: DO NOT CUT!
Rubber		Thermoset	Good: Vaporizes with some residue	Good: Deep engraved marks with some residue	Sometimes: (2D codes)	Dense sooty smoke

Figure 14: Summary of cutting and marking properties of plastics (key products shaded).

Source: Synrad Corporation (laser cutter manufacturer) http://www.synrad.com/synradinside/pdfs/LaserProcessingGuide_Plastics.pdf)

Electronics Research

Control board research

There were two main options for choosing a control board, a 32 bit Alexmos Pro control board and Phobotic Control Board. The Alexmos board had lots of features that made it more suitable for my prototype. Things like

- Dual IMU sensors to increase stability performance.
- Bluetooth to help with fine tuning from a smartphone.
- Built-in sound beeper
- Current sensor to measure battery power consumption
- Encoded Motor Support
- Geared drive functionality

It also had a bigger forum with more online support if I was to get stuck, it was also $199 USD.

The Phobotic had some benefits which the Alexmos did not have such as

- Fully automatic PID tuning (has to be clamped in place for tuning to work)
- Operation at any angles
- Onboard setup interface to indicated stabilisation performance and battery performance.

The Phobotic was also significantly more expensive costs $399 USD for the consumer board. After weighing up the options it was decided to go with the 32bit Alexmos Board I was a lot more confident that the gear drive system was going to work with this controller.

Motor Research

I wanted to use encoded motors as they provided much greater stabilisation performance, battery life and torque ratings. I wanted to make sure that I had up spec the motors so that they were not struggling to push the weights required. It would be much easier if future developments to downsize rather than upsize.

I choose the GB5015EN which had a torque rating of 2 - 3.5kg rating which was a lot more than I needed. The GB5010EN which was one model down had a rating of 1 - 2 kgs but was only 40 grams lighter and was about the same size so I choose the more powerful to make sure it wasn't under powered.

Lithium polymer (LiPo) Batteries

LiPo batteries have three main characteristics that make them ideal for this project: rather than other rechargeable battery options such as NiCad or NiMH.

- light weight and can be made in almost any shape and size.
- large capacities, meaning they hold lots of energy in a small package.
- high discharge rates to power the most demanding electric motors.

11.5.1 Drop test standard (MIL-STD-810F 516.5)

Makers of equipment, including phones and laptops, often say that their product is tested to “Mil standard” for a drop test. The following is based on discussion in Blickenstorfer (2016) to provide some detail on what this actually means.

MIL-STD-810F 516.5 often appears in ruggedness specs. This tests a device's ability to survive a variety of impacts and shocks. MIL-STD-810F Method 516.5 defines the purpose of the shock test to "provide a degree of confidence that materiel can physically and functionally withstand the relatively infrequent, non-repetitive shocks encountered in handling, transportation, and service environments."

Procedure IV -- Transit Drop -- is especially popular with rugged computing equipment vendors and commonly called "drop test" or "drop spec." The test requires that items weighing 100 pounds or less survive a total of 26 drops on each face, edge and corner. The 26 drops can be divided among up to five samples of the same test item, which probably means used the first until it fails, then start with the second, and so on, although the language is not clear. Drop distance generally depends on "how materiel in the field might commonly be dropped." Table 516.5-VI (Transit Drop Test) shows that items weighing less than 100 pounds with a largest dimensions of less than 36 inches, i.e. virtually all mobile computers, must be dropped from 48 inches because "a light item might be carried by one man, chest high; thus it could drop 122 cm (48 inches). It also appears that the test is conducted with the equipment off.

What other MIL-STD-810F tests are there?

The MIL-STD-810F is a very comprehensive document. As a result, a statement saying a device is "MIL-STD-810F tested" doesn't provide enough information. The MIL-STD-810F is an almost 600-page document with tests for about two dozen things that can affect a piece of equipment. The tests are:

500.4 Low Pressure (Altitude)
501.4 High Temperature
502.4 Low Temperature
503.4 Temperature Shock
504 Contamination by Fluids
505.4 Solar Radiation (Sunshine)
506.4 Rain
507.4 Humidity
508.5 Fungus
509.4 Salt Fog
510.4 Sand and Dust
511.4 Explosive Atmosphere
512.4 Immersion
513.5 Acceleration
514.5 Vibration
515.5 Acoustic Noise
516.5 Shock
517 Pyroshock
518 Acidic Atmosphere
519.5 Gunfire Vibration
520.2 Temperature, Humidity, Vibration, and Altitude
521.2 Icing/Freezing Rain
522 Ballistic Shock
523.2 Vibro-Acoustic/Temperature

Each test has various procedures and methods, and each may or may not be relevant to a particular application. Major rugged equipment manufacturers have their own testing labs where they can conduct MIL-STD-810F testing. This is generally done in conjunction with testing in an independent lab.