MASSEY UNIVERSITY

Development of A Compliant Micro Gripper

by

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Abstract

Manipulating micro objects simply and effectively has been a widely discussed and challenging task in recent literature for many reasons. Limitations in complex micro fabrication techniques mean creating extremely small tools at the micro scale is very difficult. Adhesion forces also dominate at this scale, causing anything and everything to stick together. This means that even when these tiny structures are created and introduced to the micro world, they quickly become polluted with contaminants and struggle to pick and place particles without said particle adhering to the tool. Indirect methods for micro manipulation exist, however these can be damaging to biological material such as cells, due to unseen forces being focused into a small point. Having the ability to safely manipulate and separate these objects from a culture is crucial to understanding their individual characteristics. Therefore a safe and reliable method for micro manipulation needs to be developed.

This project focuses on investigating the current methods used for micro manipulation in order to identify any possible routes towards developing a simple and yet effective means for manipulating micro objects. A modular micro gripping mechanism is proposed in this report, capable of manipulating many different types of objects such as spherical, non spherical or other arbitrary shapes. The proposed micro gripper combines traditional machining techniques with a complex micro fabrication process to produce a modular mechanism consisting of a sturdy, compliant aluminium base in which replaceable silicon and borosilicate glass end effectors are attached. This creates an easily customisable solution for micro manipulation with an array of different micro tips for different applications. A kinematic analysis for the gripper has been provided which predicts the workspace of the gripper given an input actuation. Design parameters of the gripper have also been optimised through various techniques such as FEA (finite element analysis) simulation and the effects of altering individual flexure beam lengths. The gripper is operated by a piezo actuator with a total capable expansion of 19 μm when 150 VDC is applied. This expansion is then amplified by a factor of 8.1 to a maximum tip displacement of approximately 154 μm. Displacement amplification is achieved by incorporating bridge and lever amplifying techniques into the compliant design.

The complete micro gripper is then used to demonstrate manipulation tasks on several different target object types including silica micro beads (spherical and non spherical), a human eyelash and a grain of pollen. These tests are performed to investigate the effect of adhesion forces and also to demonstrate the large size range of capable pick and place objects (6 μm to 500 μm).

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I would also like to thank the Massey technicians involved, such as Ken Mercer, Morio Fukuoka and Anthony Wade. Ken, Morio and Anthony were always just around the corner when ever I had a design question. Each of them has been very forthcoming in offering their vast engineering knowledge and I can safely say that many of the technical aspects relating the grippers control would not be achieved without them. For these reasons I would like to express my tremendous gratefulness to these people.

The design of the micro gripper also required a lot of repeated part fabrication, especially during the early stages. For this I would also like to thank some of the Massey workshop staff including Kerry Griffiths, Clive Bardel and Ian Thomas. Without their experience in mechanical design, many of the grippers complex part fabrication would have been impossible. A special thank you to Kerry Griffiths, who went above and beyond when ever I needed a part urgently made.

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Abbreviations

STORM	Stochastic Optical Reconstruction Microscopy
STED	Stimulated emission depletion
DEP	Dielectrophoresis
PDMS	Polydimethylsiloxane
VCM	Voice Coil Magnet
DRIE	Deep Reactive Ion Etching
MEMS	Micro Mechanical Mechanisms
PZT	Piezo Actuator

Symbols

μm	Micro meters
μN	Micro newtons
nm	Nano meters
nN	Nano newtons

Chapter 1

Introduction

”Nano technology. The science is good, the engineering is feasible, the paths of approach are many, the consequences are revolutionary-times-revolutionary, and the schedule is: in our lifetimes” said Stewart Brand in the foreword of the book ”Unbounding the Future: The Nano Technology Revolution” [1]. Modern engineering has allowed us to step into this bizarre world of micro and nano technology as Stewart had envisioned it. Today we are on the way to developing new solutions offering advancements in biomedical applications [2], micro assembly, cell biology, pathology, virology and taxonomy.

Micro manipulation is the ability to control objects at a micro scale. When exploring the micro scale world, we generally classify objects into three size categories known as nano, micro and meso scales (Fig. 1.1).

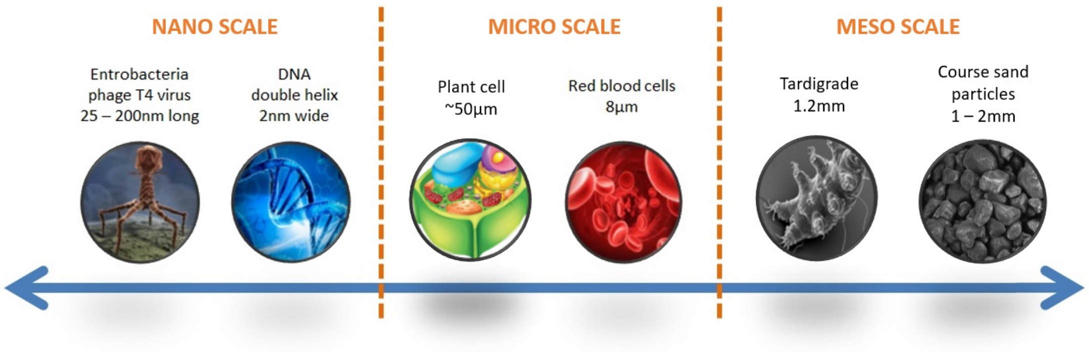

FIGURE 1.1: Objects typically found within a nano, micro and meso scale [3]

Objects sized within 1 μm to 100 μm are known as ’micro’ objects [4]. Typically we find objects such as red blood cells (8 μm) or plant cells (approx 50 μm) at this scale. Any objects above 100 μm are usually visible to the human eye without magnification and are no longer within the micro scale. Instead we classify this group of items as being within a meso scale. As we dive deeper into this invisible world, objects on a nano scale such as DNA or hydrogen atoms become no longer visible by standard optical microscopes. This phenomenon is due to the limitations associated with the diffraction properties of light and typically limits optical microscopy to approximately 0.2 μm [5].

Although there are some optical microscopy super resolution methods to surpass this limit such as STORM (pointilistic or localization based approach) [6], STED (stimulated emission depletion)[7] and structured illumination [8], we often still refer to alternative methods such as electron microscopy which can achieve a resolution of 10nm or better [9].

1.1 General Background

The field of manipulating micro objects simply and effectively has been widely discussed recent literature. Having the ability to perform experiments on single cell organisms is crucial as each cell holds its own individual characteristics. Significant biochemical heterogeneity can exist among cells due to localised damage, mutations, stages in cell life, differences in exposure to external signals and many other reasons [10]. For example, brain cells may express as few as 65% of the same genes as their neighbours [11]. It has also been shown that cells of the same category can have varied responses to vaccines [12]. Vaccines also can take time to produce, especially against emerging infectious diseases. A promising technology for combating this problem is known as antibody therapeutics and involves isolating and reproducing naturally occurring human antibodies however, this process requires a method of selectively targeting and studying a single cell among a large population [13]. The disintegration of cells by rupture of the cell wall is known as cell lysis and is commonly used for cell analysis or protein extraction [14]. Today, cell lysing is typically done by grinding or boiling a group of cells to break the robust cellular walls. The final mixture can then be analysed to get an average reading from the population and is performed in thousands of laboratories every day [11]. This process is both laborious and time consuming. It is done to create a single medical solution for a wide range of individual cases which often means medications can have vastly different side effects on individuals [15]. It is clear that individual cells can be very different from their neighbours which creates the need for a technology that can separate and study a single cell in order to fine tune medical solutions for an individual.

Another application for micro manipulation tools is the delicate micro assembly of parts typically less than 100 μm tasks [16]. Kim et al describes the fundamental requirements for micro assembly as including; a large force to weight ratio, high precision actuation and some sort of feedback sensing capabilities [17]. The team developed a voice coil driven micro gripper with precise force regulation for performing fine alignment tasks of opto-electrical components. Micro manipulation technologies have also been used for the assembly of living bio-hybrid micro robots [18]. Many bacterium (in this case a rod-shaped prokaryotic bacterium) use a flagella or tail as a propulsion method through a medium. In this example the bacterium was used as a biological motor to transport an elongated zeolite L crystal which was attached to the bacterium by using two micro fluidic channels and optical tweezers. This study not only demonstrated a promising strategy for future self propelled micro robots, but also showed how optical tweezers and micro fluidics can be used for micro assembly.

1.2 Micro Manipulation Techniques

The field of micro manipulation has been very popular recently and contains a vast amount of literature. There are many different techniques for micro manipulation ranging from compliant micro grippers [19] [20] to magnetic micro robots [21] however most can be defined into contact and non-contact categories. This section outlines all common methods found in literature and the main issues faced with each of them.

1.2.1 Non-Contact Manipulation Techniques

Non contact micro manipulation involves the manipulation of particles without ever making contact with the object at any point during the manipulation. There are many different non contact manipulation techniques such as optical tweezers [22], sound wave manipulation [23] and electrostatic manipulation [25]. These methods are designed for both biological and non-biological objects in all types of medium (liquid, air, vacuum etc) [26].

Optical Tweezer Manipulation:

Optical tweezers were first introduced by Ashkin in 1986 [22], since then optical tweezers have become one of the more common techniques used for micro particle and cell manipulation due to their ability to precisely manipulate micro objects. When a beam of light passes over a particle, the photons undergo a change in momentum when either refracted, diffracted or reflected [22] [27]. If the refractive index of a particle is greater than the surrounding medium, the change in momentum can be used to trap the particle inside a high intensity beam of light [28]. One of the problems with optical tweezers is the induced heating at the focal point which can cause damage to living tissue [29]. Also, optical tweezers lack selectivity. Any dielectric particle will be attracted to the laser beam meaning that single particle manipulation is often impossible within highly populated samples [30]. The last major limitation involving optical tweezers is photo damage [31]. This can occur in biological materials due to transient local heating (described above), two-photon absorption [32] and photochemical processes that create reactive chemical species within the sample [33].

Because of the inherent damage to biological samples due to the use of a high powered laser beam, it was proposed to indirectly manipulate cells by manipulating dielectric beads to surround and push the cell [34]. This method also included a successful path planning technique and was able to accurately manoeuvre a cell within the sample (Fig. 1.2).

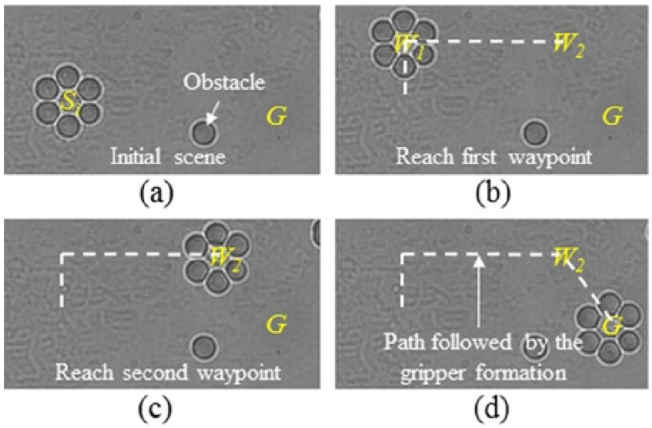

FIGURE 1.2: Indirect transport of a bead using the 6-bead gripper formation: (a) the gripper in the initial state ; (b) the gripper applies the manoeuvre to reach the first way point ; (c) the gripper applies the manoeuvre to reach the second way point ; and (d) the gripper reaches the final goal by applying the manoeuvre [34]

Sound Wave Manipulation:

Sound waves have also been proposed as a non contact method of manipulating particles [23]. In this method, high intensity sound waves were produced to create standing wave interference patterns inside a sample chamber. Particles would then move towards the troughs in the standing waves and could be manipulated by adjusting the frequency. The problem with this method is that the particles could be manipulated through micro fluidic channels in x and y directions only.

Ultrasonic sound waves have also been used for manipulating particles. Ryota et al. developed a method for moving particles through small channels with ultrasonic vibrations [24]. The method worked well for manipulation although 2 dimensional motion is only possible and also, a particle must be suspended inside some form of micro channel.

Elecrostatic Manipulation:

Electrostatic manipulation involves dielectrophoresis (DEP) which is a phenomenon in which a force is exerted on a dielectric particle when it is subjected to a non-uniform electric field [25]. The intensity of the force depends on the frequency of the electric field and the dielectric properties of the particles. All particles exhibit dielectrophoretic properties when in the presence of an electric field. A dielectric particle is an electric insulator that can be polarized by electric fields making it repel itself from areas of high intensity electric fields. This process was proposed as a method of non contact manipulation of cells, where by devices were constructed to control the shape, position and orientation of a collection of particles [25].

Because electrostatic cell manipulation exposes the cells to strong electric fields, the physiology of biological materials can be affected. This is either due to heat from induced current flow or direct interactions of the field with the cells [35]. Electrostatic manipulation works by transferring charge through electrolysis. This leads to a disadvantage as the working distance is short due to the lack of conductivity in the surrounding medium and particles [36].

1.2.2 Contact Manipulation Techniques

Contact micro manipulation involves the physical contact of manipulation tools with the object to be manipulated. In general, contact manipulation is preferred for the study of micro objects that will not be damaged by any resulting contact forces [37]. As we have previously seen, non contact manipulation methods tend to be usable only in a single plane of motion. We also saw that many of the methods subject the sample to damaging forces such as heat, electric fields and high intensity photon streams. Contact manipulation on the other hand, generally does not directly subject the sample to a damaging environment. It also allows for multi plane and rotational movement of particles, providing a much more flexible tool for studying singular objects.

Micro Pipette Manipulation:

The most popular contact manipulation technique uses micro pipettes for either grabbing a cell through aspiration by applying a vacuum to the cell [38] however this can cause significant damage to the cell. Micro pipettes are also used for penetrating and injecting a substance into cells. This process is most commonly performed for artificial insemination by injecting a spermatozoon into an oocyte [39]. Micro pipettes are typically made by heating and stretching thin glass rods, these rods can also be used as end effectors to act as miniature tweezers for picking and placing micro objects [40].

Magnetic Micro Robot Manipulation:

Magnetic manipulation uses magnetic fields to control micro particles that are magnetic. If the particle is not magnetic, a magnetic coating can be applied. Magnetic micro robots have been developed in order to move cells by pushing them along a desired path [21] (Fig. 1.3). In this case the micro robots were coated in nickel with four surrounding electro magnets. The magnets were then used to generate precise magnetic fields to manipulate the micro robots with four degrees of freedom. In this case, cells with a diameter of 20 μm were successfully picked and placed along a desired path. One of the issues was that the nickel coating process often caused the micro robots to have opposite polarity. Also, this process is only possible on a planar surface without any up/down motion.

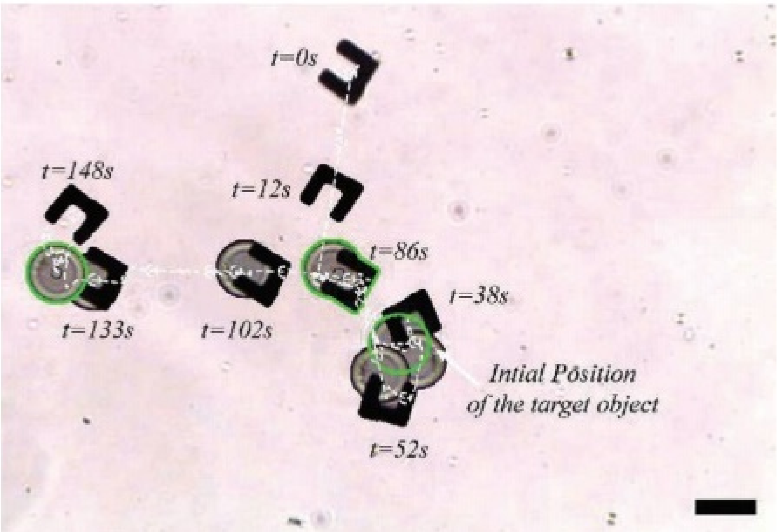

FIGURE 1.3: Nickel coated micro robots manipulating a cell of 20 μm diameter [21]

A similar system was also created using eight surrounding electro magnets rather than four [2]. The purpose of this proposal was to show how five degrees of freedom allowed the micro robots to move up and down instead of being stuck in a single plane of motion. This was intended for minimally invasive ophthalmic procedures which involved manipulating the robots inside the eye. Fully untethered control of the micro robots was demonstrated inside a rabbit eyeball however one of the draw backs to this technology was their limited ability to apply large forces due to their size and the density of magnetic flux passing through them.

Another proposal created a magnetic manipulation system with six degrees of freedom [41]. Unfortunately manipulation was only possible in a very small work space of 2 x 2 x 2 mm of translational freedom with 4 degrees of rotation along each axis.

1.2.3 Compliant Micro Gripper Manipulation

Under actuated gripping mechanisms have become a popular topic in literature as contact type micro manipulators. These involve manipulating multiple gripper fingers with a single input force. They also typically exhibit isotropic properties meaning that if a single finger is opposed, the remaining fingers will continue moving [42]. These properties are desirable when it comes to creating a micro gripper as it minimizes the need for many actuators and also means that the gripper tips are more flexible for grasping unsymmetrical objects. Because of the inherent difficulties with manufacturing micro mechanical joints and fixtures, the majority of micro grippers are under actuated and/or compliant. Compliant mechanisms are monolithically manufactured as a single piece and offer repeatable motion through elastic deformation of structural members meaning there is no friction and backlash involved [43] [44].

A good example of a simple compliant gripper structure is shown in Fig. 1.4 [45]. This gripper was designed using interactive map-based techniques and was not intended for micro manipulation tasks however, it demonstrates the general idea of compliant flexing. From Fig. 1.4, we can see that a vertical input force causes the structure to flex with no moving joints or hinges. The flexing motion then converts from vertical to horizontal movement which closes the tips.

Compliant mechanisms require some form of precise actuation in order to flex. Because of this, there are many different ways of actuating compliant mechanisms in literature including shape memory alloys [46], piezoelectric [47] [48] [49] [50], electro thermal [51] [52], electromagnetic [53] and electrostatic control [54] [55] which are detailed as follows.

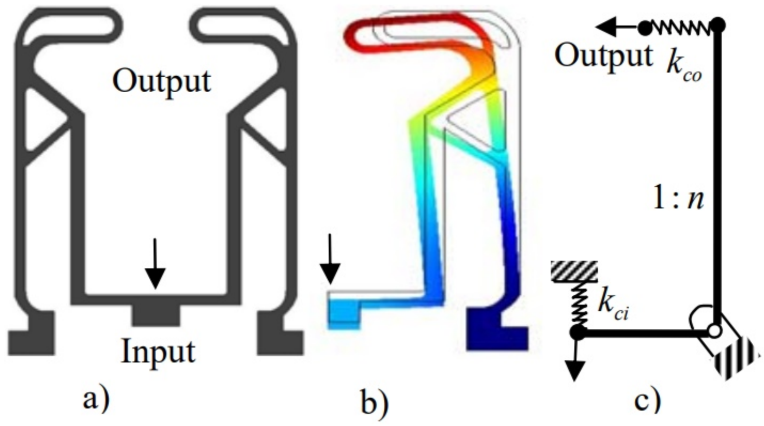

FIGURE 1.4: Illustration of a compliant gripper where a) the complaint gripper, b) flexing of the gripper, and c) a simple vector illustration where springs represent compliance [56]

Shape Memory Alloys:

Nitinol is a nickel titanium alloy that exhibits super elastic properties meaning it can be stretched at room temperature by a small force however when a current is applied, it becomes much harder and returns to its original position [46]. Nitinol, also known as muscle wire, has been used to create a soft gripper by placing it inside a casting of PDMS and glass fibers [57]. This allowed the castings to flex when a current was applied. Nitinol can be stretched by up to 8 percent of its original length however, this dramatically lowers its life cycle. The life cycle can be dramatically improved (millions of cycles) if the material is only stretched by 3 - 5 percent of its original length [57].

Electro-Thermal Actuation:

Electro thermal actuation works by applying voltage to heat flexure beams which causes thermal expansion. This expansion is then used to actuate the gripper tips. A proposed compliant micro gripper with a force resolution of 19.9 nN and a gripping range of 10 μm explains how thermal actuation can be better than others as they require a much smaller chip area, low driving voltage and generate large forces and displacements [51]. The downside of thermal actuation is the heat involved can travel up to the gripper tips and may affect biological samples. Thermally actuated grippers often require large heat sinks to avoid this problem.

Thermal heating has also been used to decrease the stiffness of structural members for more delicate pick and place tasks [52]. In this case, heating elements were wrapped around parallelogram struts which always provide parallel motion, regardless of stiffness. The authors mention that although reducing the stiffness of flexure beams can reduce the risk of damaging the sample/gripper tips, it is recommended to have some form of force feedback in order to have a reading of the gripping force.

Electro-Magnetic Actuation:

Electromagnetic actuators (voice coil magnets - VCM) have been used in the past as they have a large displacement range and do not require any amplification [53]. Due to the nature of electro magnetic actuators, they are generally quite large. This poses a challenge when trying to integrate such a large actuator into a micro gripper design. This gripper was also only suitable for picking up large objects of approximately 250 μm.

Electro-Static Actuation:

Electrostatic comb drives produce movement from repulsive forces upon voltage being applied to the combs [58]. Comb drives have been used extensively in literature for actuating micro grippers. Chang et al. proposed a rotary comb drive which used a curved comb in order to combine electrostatic and flexure mechanisms [55]. This meant that the flexure beams acted as a spring to keep the gripper normally open while the comb drive provided the force to close it. The gripper design was shown to have a maximum displacement of 96 μm at 100 volts. Another example of an electrostatic comb driven micro gripper is presented in [54]. In this case, the gripper also included a small pipeline that was used to fire compressed air at the object upon release in order to avoid it adhering to the gripper tips and not releasing.

Electro static grippers require a high driving voltage, meaning that the voltage may travel to the gripper tips and could damage biological samples [55]. Electrostatic combs also require complex micro manufacturing and a large amount of space. This is because many combs are required to gain significant actuation force. Another problem with these drives is the ”pull in” effect. Comb drives generally can only be used within one third of their capacitive gap. If the combs are pushed beyond this limit, the actuation will become unstable which is known as the ”pull in” effect.

Piezo Electric Actuation:

Piezoelectric (PZT) actuators are the most common actuation choice due to their precision sub nano meter positioning capabilities [59], high force output to weight ratio [60], fast response time and good performance with the proper control. Nah et al. shows a general example of a flexure based compliant gripper driven by a piezo actuator [61]. In this study, a displacement amplification of 3 times with a maximum stoke of 170um was achieved. The reasoning for using a piezo actuator was to allow fine positioning of the gripper.

There have also been recent advancements in piezo electric material research, one of which shows promise for replacing traditional PZT (lead zirconate titanate) crystals. A recent paper by Ciubotariu et al, showed how PMN-PT (led magnesium niobate-lead titanate) crystals are far superior to PZT [62]. PMN-PT was shown to have roughly the same blocking forces at PZT but with 5 times the displacement. Although PMN-PT actuators are not currently on the market, the raw material is available in different shapes and sizes and could still be used for micro manipulation purposes.

1.3 Commercial Micro Manipulation Systems

There are a number of commercially available micro manipulation systems available for those who desire a straight out of the box solution (Fig. 1.5). One example uses optical tweezers for manipulation and is produced by Thor Labs (OTM211) [63]. This kit provides high resolution force and particle tracking for those who wish to conduct micro research with intuitive software and controls. Narishige Takanome is another form of micro manipulation system that is made as an add on and is compatible with many different microscopes [64]. This system has a large range of rotation and uses micro probes for interacting with objects. Manipulation with these types of systems can take considerable time as they still mostly rely on the abilities of the user for control.

FIGURE 1.5: Commercially available micro manipulation systems for research (Thor Labs OTM211 and Narishige Takanome Micromanipulation System) [63][64]

Other commercially available systems exist for performing high resolution, large batch scale micro assembly such as the FC300R Die / Flip Chip Bonder manufactured by Smart Equipment Technology (Fig. 1.6) [65]. This system is an automated device used for assembling micro circuitry components and currently holds the best component bonding accuracy of $\pm$ 0.5 μm.

FIGURE 1.6: Commercially available micro manipulation system for large batch scale flipflop bonding (FC300R) [65]

1.4 Overview of Problems With Current Methods

The majority of non contact methods are limited to single plane motion. Non contact techniques can also damage the object from excessive photo damage, heat or high current flows [66]. Due to the aforementioned problems, contact manipulation is generally preferred when working with living cells and micro objects. In addition, contact methods generally can handle objects of different shape and size while keeping the cost of manipulation low [67].

Contact micro manipulation also bears its own difficulties, especially due to force scaling laws which mean adhesion forces can make the release of an object extremely difficult [68]. The physical world forces take on entirely new characteristics at a micro scale. In our macro scaled world, we are used to gravity being the most dominant acting force. This is because gravitational forces are proportional to object volume however, as the scale is decreased, adhesion forces which are proportional to surface area become more dominant. Tianming et al. describes this phenomenon in his thesis by imagining a square cube with side lengths of 10cm. If we calculate the gravitational to adhesion force ratio, we get 10 which shows that gravity is the most dominant force however, if the lengths are decreased to just 0.01cm, the ratio becomes 0.01 with adhesion forces being larger than gravitational (Fig. 1.7) [4].

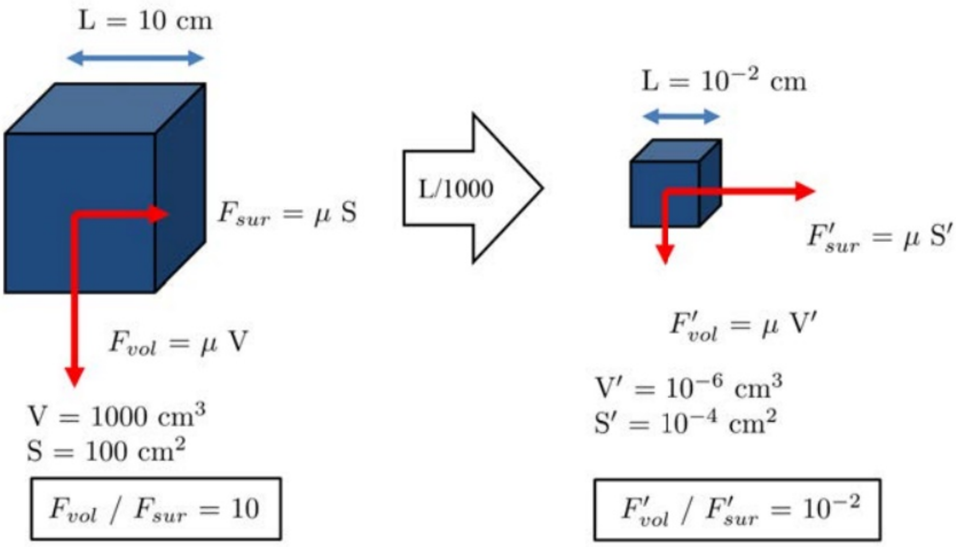

FIGURE 1.7: volumetric vs surface area force ratios in both macro and micro scales [4]

Biological cells are generally sized between 1 - 100 μm with the majority of cells nearer to 10 μm. At this scale, adhesion forces become a problem as objects begin adhering to each other and are difficult to separate. Because of this, many studies have developed manipulation methods for relatively large scale objects (100 - 300 μm) and thereby avoiding the problem of adhesion forces [69] which leads into our next problem. Hao et al developed an electro-statically driven gripper capable of handling objects within 20 - 60 μm [70]. The design is exclusively manufactured at a micro scale which minimizes adhesion problems and also includes complex features such as a comb drive structure, delicate flexure beams and a ratchet self locking system. The issue is that many of these systems in literature capable of cell-size object manipulation are designed in this way and although this technique is an excellent display of MEMS technology, it leaves the entire structure extremely fragile and costly to replace. Replacement is often necessary as gripper tips can become polluted with unwanted particles or to avoid cross contamination between samples. Many micro objects may also require gripper tips of different shapes and sizes which further highlights the need for an easily replaceable design.

The last problem with contact manipulation lies with the inherent difficulties of manufacturing micro mechanical joints and fixtures. This leads to the majority of micro grippers being under actuated and/or compliant which minimizes the need for many actuators and also means that the gripper tips are more flexible for grasping asymmetrical objects [71]. A three finger micro gripper capable of 10 - 800 μm object manipulation was recently proposed by Tao Chen et. al and explored the idea of replaceable gripper tips [72]. Although each tip could be changed, proper alignment of the three gripping fingers required multiple actuators and compliant hinges which adds unwanted bulk, cost and complexity to the system. Another example of a replaceable micro gripper proposed that each gripping tip could be glued to an end effector probe by using a UV resin [73]. The main issue with this method is that it requires a highly precise process and also takes roughly 10 minutes to complete. From these examples it is clear that a good gripper design should not only be replaceable but should also be simple enough that gripping tips can be changed efficiently with little effort.

1.5 Discussion of Techniques

Throughout this literature review, we have examined many different micro manipulation techniques and methods for micro actuation. Figure 1.8 shows a table that examines manipulation techniques most often found in literature versus 7 key specifications that are based on common problems faced. This section will provide a short summary of these techniques along with their strengths and weaknesses.

COMMON TECHNIQUES - PROS AND CONS							
NON-CONTACT METHODS							
METHOD	*CAPABLE CELL (5-10UM) MANIPULATION?*	*DAMAGING TO CELLS?*	*REPLACEABLE*	*SUFFERS FROM ADHESION*	*COMPLEX AND EXPENSIVE DESIGN*	*SINGLE CELL 3D MANIPULATION?*	*DEXTERIOUS MOTION?*
OPTICAL TWEEZERS	YES	YES	N/A	NO	N/A	YES BUT CAN BE DAMAGING	YES
ELECTROSTATIC FORCES	YES	YES	N/A	NO	N/A	YES BUT CAN BE DAMAGING	NO
SOUND WAVE FORCES	YES	YES	N/A	NO	N/A	YES BUT CAN BE DAMAGING	NO
CONTACT METHODS							
METHOD	*CAPABLE CELL (5-10UM) MANIPULATION?*	*DAMAGING TO CELLS?*	*REPLACEABLE*	*SUFFERS FROM ADHESION*	*COMPLEX AND EXPENSIVE DESIGN*	*SINGLE CELL 3D MANIPULATION?*	*DEXTERIOUS MOTION?*
MAGNETIC MANIPULATION	YES	NO	MICRO ROBOTS ARE REPLACABLE	YES (MICRO ROBOTS ADHERE)	YES	NO	NO
COMPLIANT MICRO GRIPPER	RARELY	NO	RARELY	YES	OFTEN	YES	YES

FIGURE 1.8: Table examining the specifications of common micro manipulation methods

1.5.1 Non-contact Techniques

Many of the non contact techniques such as optical tweezers, electrostatic and magnetic, all perform well in a similar environment however, they seem to share common drawbacks. When a substrate is clear of debris and neighbouring particles, non contact techniques function well however, when the substrate becomes more crowded, unwanted particles are also attracted into the manipulation region. This makes these techniques lack the ability to precisely study a single cell/particle among a sample of many.

Instead of relying on a physical connection for applying force to an object, non contact techniques produce strong electric, acoustic, magnetic or optical forces for moving an object. These often contain a lot of potential energy which is focused on a single point in order to get any significant force. Because of this, a lot of the energy is released onto the object in the form of heat due to induced current flow, photo absorption and high static voltages, all of which can be damaging to biological material (Fig. 1.8).

Optical tweezers cannot be used if there is not a direct path of light which limits their use for in vivo applications. A similar problem exists for electrostatic and acoustic technologies as electrostatic manipulation has a very short working range and acoustic waves loose intensity when passing through a solid medium.

Lastly, it was found that all non contact techniques only operate within 2 dimensions. In other words, they can only trap objects on the substrate floor and cannot manipulate up and down. This means that they cannot transfer particles between mediums and have difficulty rotating an object for observing at all angles. Furthermore, optical tweezers are the only non contact technique that can provide dexterous motion. This is because electrostatic and sound wave forces are much harder to precisely control meaning particles cannot be manipulated with great accuracy.

1.5.2 Contact Techniques

Contact techniques are more common in literature for this task as direct manipulation presents an easier approach and offers more precise results.

A common method for contact manipulation is by controlling micro rods or pipettes as tweezers for pick and place operations. The downside of this method is that highly precise motorized stages are required for the movement of each end effector which also adds difficulties for achieving correct alignment of the tools. This method is similar to compliant grippers which also utilize a tweezer like design however they typically do not suffer from alignment issues.

When comparing magnetic and compliant manipulation techniques, it is clear that a compliant gripper is superior for our research objectives for two main reasons. The first reason is that magnetic micro robots cannot provide 3D motion and therefore cannot transfer cells between mediums. Secondly, magnetic micro robots do not offer precise movements as magnetic fields are difficult to control. Unfortunately, all contact methods can suffer from adhesion forces at the cellular scale meaning cell manipulation is difficult however, there are methods to reduce this such as minimizing gripper surface area or using a releasing technique such as vibration. Furthermore, micro grippers have yet to become easily replaceable and usually feature a complex design. One of our research aims is to improve in these areas meaning that a compliant micro gripper will be the obvious choice for single cell manipulation.

Throughout this review, we have seen many different types of actuators for producing micro movements such as magnetic voice coils, piezo electric, electro static and electro thermal actuators. Magnetic voice coil actuators can provide a large stroke and a high force however, they are too large for our application due to the many winds of wire needed in the coil.

Electrostatic comb actuators have been proven to function in a compliant micro gripper however they are also made quite large as many combs are required to reach an adequate force. This also means that extra micro manufacturing needs to be done in order to create the comb structures. They also pose a threat of damaging biological cells as the combs require high operating voltages which may translate through the structure to the gripper tips. Lastly, electrostatic comb drives cannot be used to their full range of motion due to the 'pull in' effect.

Electro thermal actuators rely on producing high temperatures for deforming structural members and subsequently create a displacement/force. Because of this, most grippers in literature are forced to include extra material in order to disperse the heat away from the gripper tips, resulting in a larger structure than necessary. This type of actuator can however be made to suit many different size requirements and with the help of displacement amplification techniques, can produce adequate displacement.

There are many examples of piezo electric compliant micro grippers in literature, all of which require some form of displacement amplification as piezo actuators offer a small stroke of motion. Although the motion is small, the output force can be large depending on the size of the actuator. They also can be made compact and are the smallest known type of actuator used for micro gripping, with some in the range of 3 mm across. Piezo actuators require high voltages for actuation (80 - 150 V). Because they are a separate component from the compliant mechanism, they can be insulated to prevent high voltages travelling to the sample.

1.5.3 Conclusions & Challenges

This literature review has revealed many key insights into the currently existing techniques and methodologies for micro manipulation and the key problems associated with them. We have seen many different manipulation and actuation methods that could potentially be employed in this project. Micro manipulation is also a relatively new topic in literature and still has areas for improvement for example, it was observed that most of the micro grippers in literature are only able to manipulate objects of 100 μm+ as adhesion forces at a smaller scale are challenging to overcome.

From this review, we have eliminated non-contact techniques from this project, as most of the techniques are damaging to biological material which is what we intend to manipulate. Also, they are unable to facilitate 3D motion.

Micro grippers on the other hand, are typically not damaging to cells unless they require high voltages for actuation. This is not entirely true however, as piezo actuators can be insulated from the gripper itself. Piezo actuators are also the simplest method for gripping as they are compact and do not require any complex manufacturing to function. For these reasons, we have found that a piezo actuator is most suitable.

We have also decided to use a compliant mechanism for our gripper as manufacturing a monolithic object is far easier than creating individual parts that require assembly. Compliant mechanisms also offer repeatable motion with virtually zero friction and backlash. The monolithic nature of compliant mechanisms also allows for both gripper tips to be automatically aligned in a single plane which meets one of our initial design requirements. For this and the above reasons, we have chosen to create a compliant design. It is also important to consider isotropic design in order to minimize the amount of actuators required.

1.6 Problem Statement

The examination of literature around micro manipulation has shown that there are three main factors that are currently limiting the technology. The first problem is adhesion forces which cause objects to stick to any tools at a micro scale, making manipulation of cell-sized objects extremely difficult. This means many manipulators in literature are designed to move large objects and cannot manipulate cells. Because of this, micro grippers capable of manipulating particles sized between 5 μm and 50 μm must be extremely small to minimise surface area. Many examples capable of this are either highly fragile and costly micro structures or overly complex with multiple actuators. In the field of micro manipulation, we often are dealing with many different samples which require single use tips to avoid cross contamination. This is a problem because the grippers that are capable of cell manipulation cannot be easily cleaned due to their fragility and are uneconomical to replace often.

1.7 Proposed Solution and Novelty in This Study

To solve the problem of highly fragile and complex micro structures, we propose to minimize the complexity of our design by creating a large and strong compliant mechanism controlled by a single piezo actuator. This means that a large portion of our design will be strong, replaceable and will not require complex micro fabrication.

Secondly, In order to have the small precise motion for manipulating cells, we propose replaceable gripping tips that are manufactured with MEMS technologies and can be easily attached to the larger mechanism. The novelty in this method is that only a small part of our gripper requires micro fabrication which reduces the cost but most importantly, it also means that if the tips were to break or are contaminated, we can replace them without replacing the entire gripper.

Lastly, we plan to improve the usability of the gripper by having custom gripper tips available for separate applications (Fig. 2.1). For example, smaller objects may require finer tips for reducing adhesion forces or concave tips could offer a more firm grip around a spherical object. From what we have seen, this idea has not been used in previous literature and adds further novelty to our method. By incorporating these three elements into our design, the cost of micro manipulation systems will be reduced while increasing the versatility of our gripper across a much larger range of micro objects/sizes than previously seen in literature.

1.8 Research Objectives

In short, the key research objectives we intend to face in this project will include:

- Developing a manipulation method that can work around adhesion forces.
- Developing a manipulation method that is not harmful to biological materials.
- Minimising the complexity of our gripper design for easy replacement and reducing cost.

This research aims to meet these challenges to the best possible degree in the time allotted (approx 1 year).

1.9 Chapter Summary

This chapter has provided an in-depth introduction to the methods and technologies currently in use for the field of micro manipulation. We have also identified many different contact and non contact techniques, along with their individual strengths and weakness. This was necessary before conducting any design work or experiments as we needed to explore and evaluate different options in order to select the appropriate path for this project. From what we have observed, we have settled on the design of a piezo actuated compliant micro gripper as this best suits our intended research objectives.

The following chapters of this thesis will be layed out as follows. Firstly, chapter 2 will detail the materials and methods involved in the design of our system. This will include optimisation techniques, control algorithms, kinematic modelling and fabrication techniques involved. Chapter 3 will begin by first introducing the experimental set-up, followed experiments and then results and discussion. We will then conclude in chapter 4 and discuss our findings, along with any future recommendations for further work.

Chapter 2

Methods

2.1 Compliant Micro Gripper

The proposed micro gripper body is made from two key components, the first of which is a compliant amplifying mechanism that acts as a base where a variety of replaceable micro gripping tips can be attached. This component is designed to fit a resin coated multilayer piezo actuator which is pre-tensioned by a set of small screws. The piezo can provide an input actuation of approximately 0 - 19 $\pm$ 2 μm with an input voltage of 0 - 150 Volts and a maximum blocking force of 1700 N. The input displacement is then amplified by approximately 8.1 times at the tips to a maximum stroke of 154 μm (covering a large number of micro objects). The second component is the replaceable gripping tips which are manufactured through DRIE (deep reactive ion etching) technology. These tips are designed to be replaceable and easily attachable to the larger mechanism for a variety of different gripping tasks. For example, finer tips may be required for complex and delicate manipulating where as rounded tips may be more useful for spherical cell gripping (Fig. 2.1)

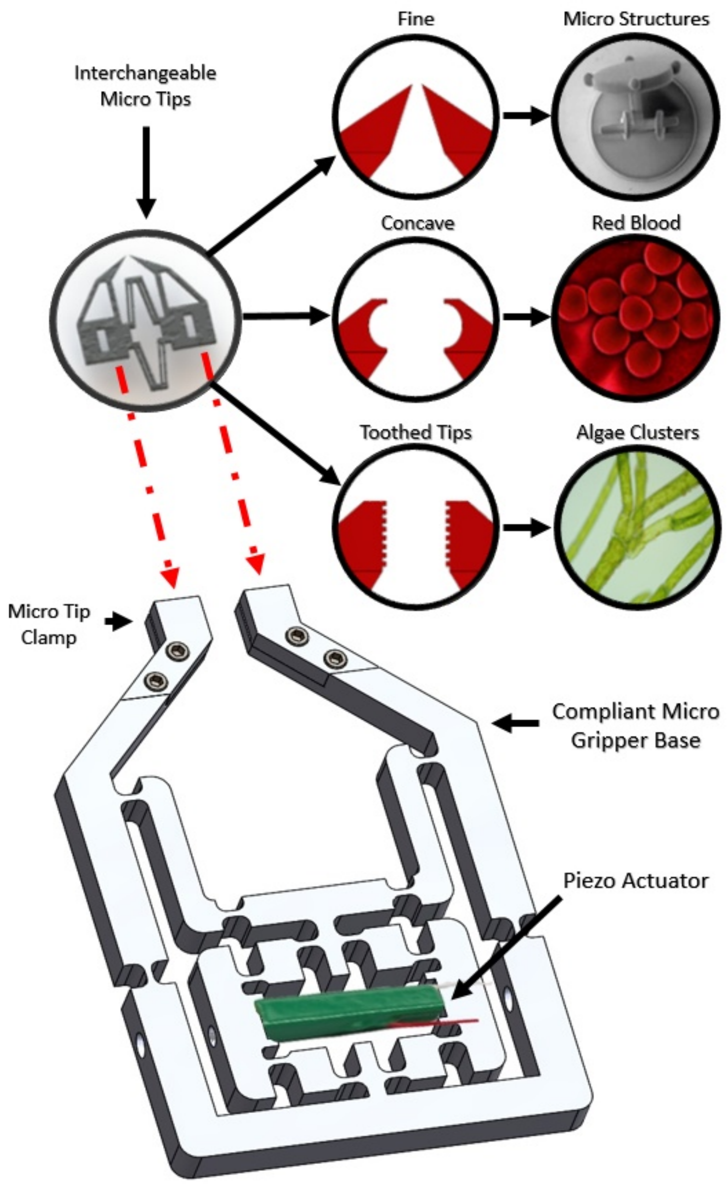

FIGURE 2.1: A modular micro gripper design with three example interchangeable tips for different gripping applications

2.1.1 Base Gripper Amplification

Related Literature Review:

Piezo electric actuators are created as a very simple structure consisting of charged quartz plates that expand upon voltage being applied [75]. Piezo actuators offer a very fast response time, a high output force and sub nanometer positioning resolution [59]. Because of this, they have been used frequently in literature for micro grippers. When designing a mechanism that uses a piezo actuator, pre-stressing of the actuator is required as the movement is extremely small [76]. Piezo actuators also often require some form of displacement amplification in order to get the required amount of force at the gripper tips. A bridge amplifier [77] is a common method of displacement amplification which converts horizontal motion to vertical motion by deflecting two parallel beams (Fig. 2.2) [78]. An example of a piezo electric gripper that employs a bridge amplifier can be found in [48]. In this case, the bridge amplifiers output was connected to a beam buckling mechanism which was intended to create a constant force at the grippers output (Fig. 2.3). When the gripper tips become opposed, the beams begin to buckle, instead of crushing or breaking the gripper tips. The proposed design was able to grip objects however the constant force was only present over a very small range of displacement (while the beams begin to buckle). The smallest object this gripper was able to manipulate was 200 μm.

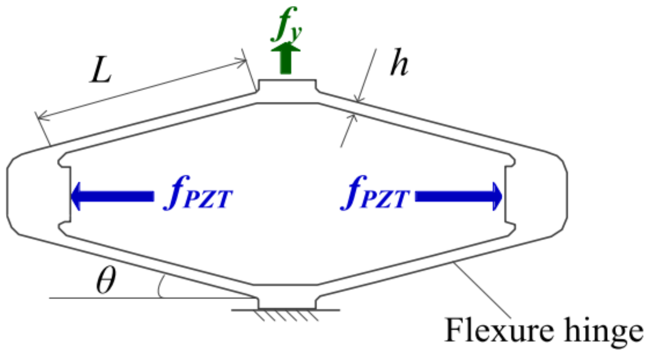

FIGURE 2.2: A simple bridge amplifier mechanism [77]

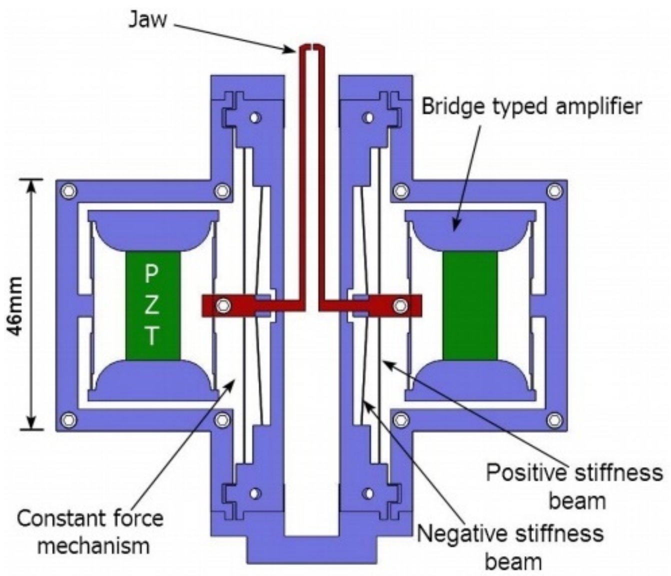

FIGURE 2.3: A piezo electric constant force gripper with bridge amplifier and beam buckling mechanisms [48]

Another example of a piezo actuated gripper used a lever amplifier to gain displacement (Fig. 2.4). This mechanism works by simply placing the fulcrum point closer to the input force end of a lever, subsequently increasing the displacement at the output [47]. In this paper, a displacement amplification of 3.8 times was achieved however this could be increased/decreased by further moving of the fulcrum point.

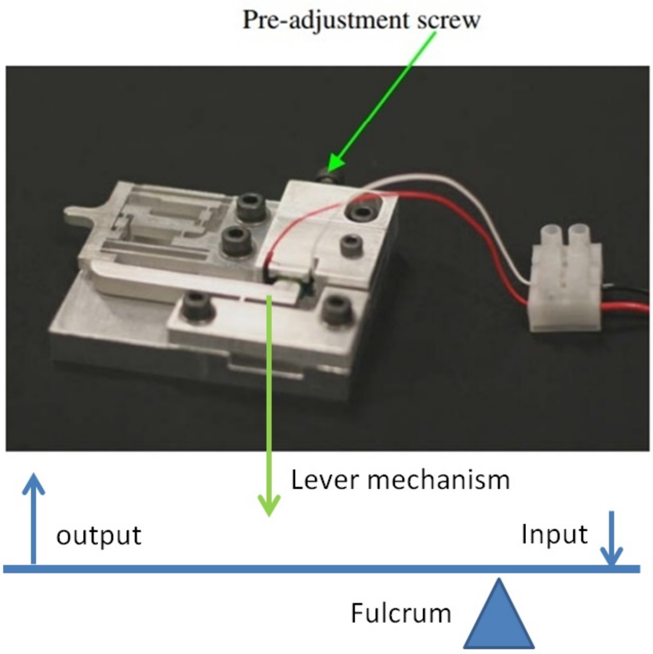

FIGURE 2.4: Compliant gripper with lever amplification mechanism [47]

Proposed Amplification Mechanism:

Two sections of the aluminium structure are designed to amplify the input motion by approximately 8.1 times to the gripper tips. This achieves a large range of output motion with a maximum stroke of 154 μm. The first section utilizes a compliant bridge mechanism [78] which is able to convert horizontal motion from the piezo actuator to vertical displacement. In our case, the bridge was designed to achieve an amplification of approximately 5 times however this varies based on the individual lengths of D1 and D2 which can be seen in Fig. 2.5. This motion is then further amplified by use of a simple levering mechanism which amplifies the motion by a further 3.1 times and translates to the final stroke region where the micro-gripper tips are situated (Fig. 2.5). The base gripper structure is designed symmetrically along the center vertical axis in order to achieve a similar but opposite motion from both actuating fingers and also to avoid shear and bending forces acting on the actuator. This is another reason why precise manufacturing is required, hence why conventional 3D printing often is not suitable.

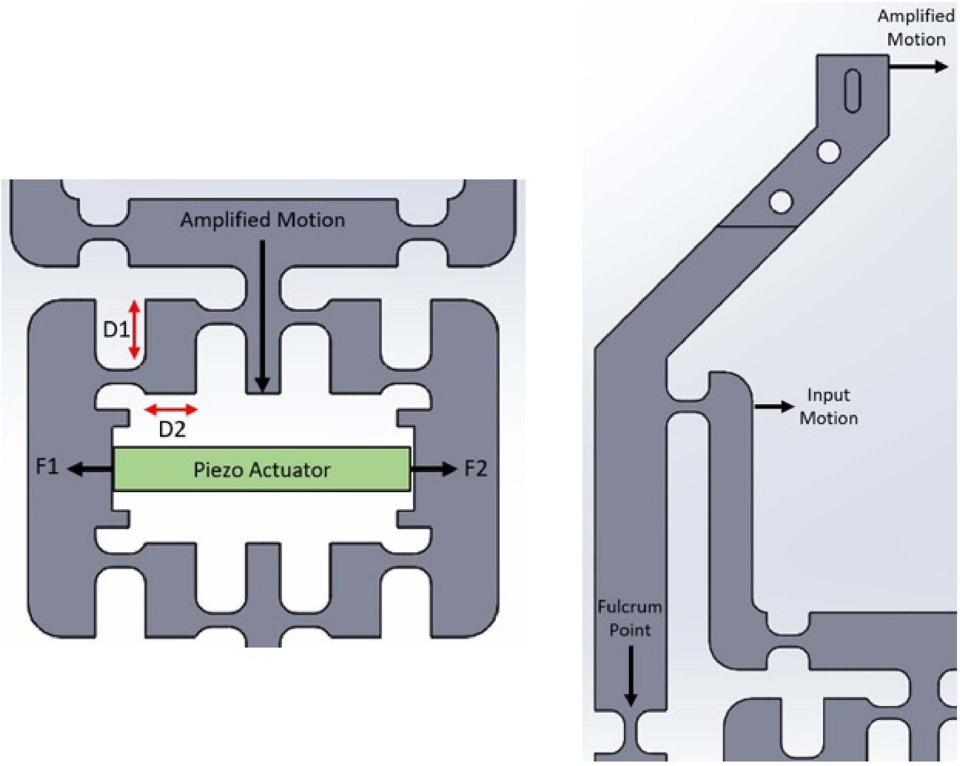

FIGURE 2.5: The bridge and lever displacement amplifiers of the aluminium gripper base

2.1.2 Base Gripper Optimisation

The structure of the gripper was optimized by changing the individual link lengths between flexure hinges and measuring the output displacement for each case (Fig. 2.6). This identified the links that could be adjusted to maximise output displacement. In this case these are links AB and FE, whereas changing the length of BE has no affect. Optimizing link FG was ignored as it corresponds to the length of link FE. When designing a compliant micro gripper it is important to optimize the positioning of compliant beams and flexure hinges to allow sufficient deformation where needed and to minimize the maximum material stress [79]. Because of this, the thickness T_{hinge} of flexure hinges with a length of 3mm and radius of 1mm was also optimized. This was done around the maximum yield stress σ_{max} for the material AL7075-T6, which is equal to 505 MPa. With a safety factor of $SF = 5$, T_{hinge} was adjusted to suit the following constraints:

1) Constraint Equation: $\sigma_{max} \approx \sigma_{hinge} * SF$

2) Subject to: $0.4mm < T_{hinge} < 1.8mm$

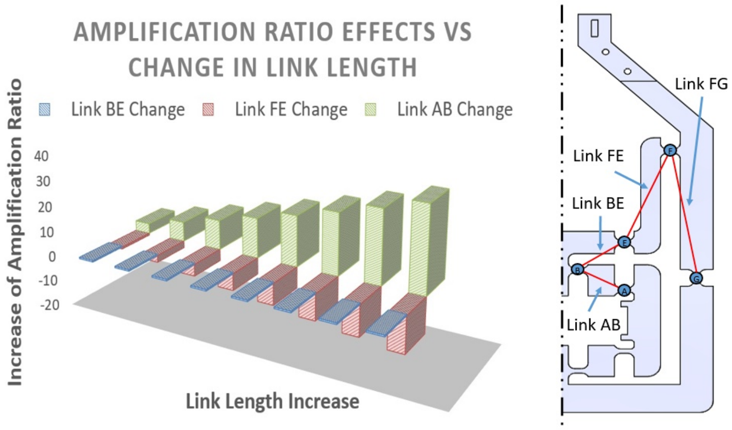

FIGURE 2.6: A simple experiment comparing the effect of individual link length versus output displacement

The reasoning behind having a large safety factor is that the gripper will be pretentioned to different settings which will add extra strain to the hinges. It also allows for some leeway if the gripper actuator were ever upgraded to have increased input displacement. By comparing the hinge stresses versus thickness in Solid Works FEA simulation (Fig. 2.7), the optimal hinge thickness was found as 0.8 mm given a maximum input displacement of 19 μm.

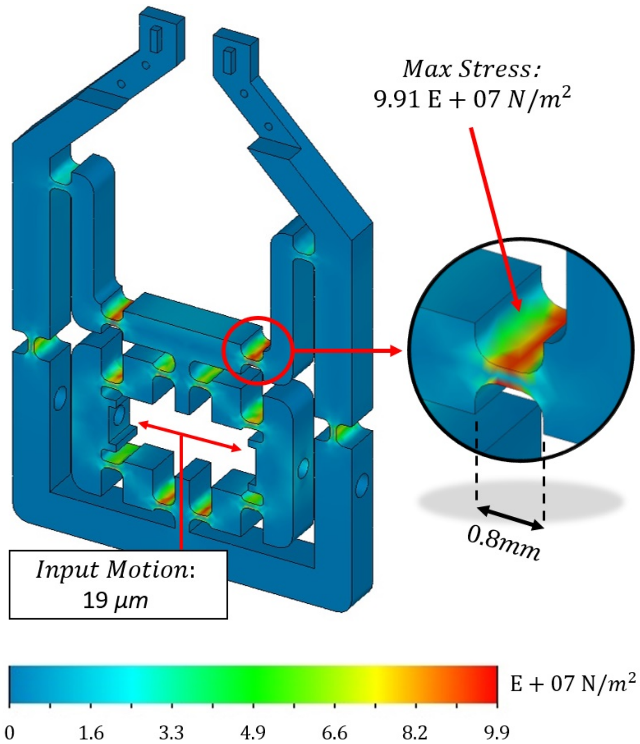

FIGURE 2.7: Finite state analysis simulation of the micro gripper with a flexure hinge thickness of 0.8 mm

2.1.3 Base Gripper Kinematic Modelling

The output of the micro gripper $x(t)$ (Fig. 2.8) can be modelled through a set of geometric relationships based on the initial state of the gripper [80]. Two key displacement amplification techniques were used in the design of the gripper. Firstly, a bridge amplifier [77] which converts horizontal motion to vertical motion by deflecting two parallel beams [78] and secondly, a simple lever to translate the motion to the gripper tips. Because of this, the modelling has been split into two sections, firstly the bridge amplifier with initial design constants u_0, L_0, w and secondly the upper compliant section with a, b, h_0 and L_0^I as defined in Table 2.1.

TABLE 2.1: Compliant micro gripper design constants

Bridge Amplifier Constants	
u_0	7 mm
L_0	3.5 mm
w	7.8 mm
Upper Compliant Section Constants	
a	17.8 mm
b	23.1 mm
h_0	6.3 mm
L_0^I	3.5 mm

Starting at the bridge amplifier, the piezo actuator applies a known horizontal input displacement of $y(t)$ to the system. This causes the structure to flex which decreases the angle θ_1 and subsequently alters the length of L_0, yielding L_1. The output displacement $h(t)$ of the bridge amplifier can therefore be found by taking the difference between the initial (L_0) and current (L_1) lengths (Eq. 2.1). This is then multiplied by 2 as the bottom end of the bridge is fixed and thus transfers its motion to the top.

$$h(t) = |2 * (L_0 - L_1)| \tag{2.1}$$

where:

$$L_1 = (u_1)tan(\Theta_1), \quad \Theta_1 = cos^-1\left(\frac{u_1}{w}\right), \quad u_1 = u_0 + y(t) \tag{2.2}$$

The vertical displacement $h(t)$ is then forwarded into the upper compliant section where it causes the length h_0 to decrease creating a new length h_1. This subsequently alters angles a_0, a_0^I, a_0^{II},

b_0, b_0^I, b_0^{II} and β_0, yielding a_1, a_1^I, a_1^{II}, b_1, b_1^I, b_1^{II} and β_1. By using the micro gripper constants in combination with these changes, the output $x(t)$ (Eq. 2.3) which can be used to calculated the workspace of the gripper, given a certain input, can be calculated as:

$$x(t) = (L_1^{II} + h(t)) \tan(\beta_1) \tag{2.3}$$

where:

$$b_1 = cos^{-1}\left(\frac{a^2 + c_1^2 - b^2}{2ac_1}\right), \quad \beta_1 = \frac{\pi}{2} - a_1^I \tag{2.4}$$

$$c_1 = \sqrt{(h_1)^2 + (L_1^I)^2}, \quad \gamma_1 = \pi - b_1 - a_1 \tag{2.5}$$

$$a_1^I = a_1 + a_1^{II}, \quad a_1^{II} = b_1^{II} = tan^{-1}\left(\frac{h_1}{L_1^I}\right) \tag{2.6}$$

$$a_1 = cos^{-1}\left(\frac{b^2 + c_1^2 - a^2}{2bc_1}\right), \quad h_1 = h_0 - h(t) \tag{2.7}$$

For the purpose of the kinematic analysis, a pseudo-rigid body model (PRBM) model of the micro gripper was created. This displays design variables and geometric relationships associated with the mechanism (Fig. 2.8). This method is commonly used among compliant architectures as it simplifies analysis by assuming flexure hinges as being torsional springs rather than rotational hinges.

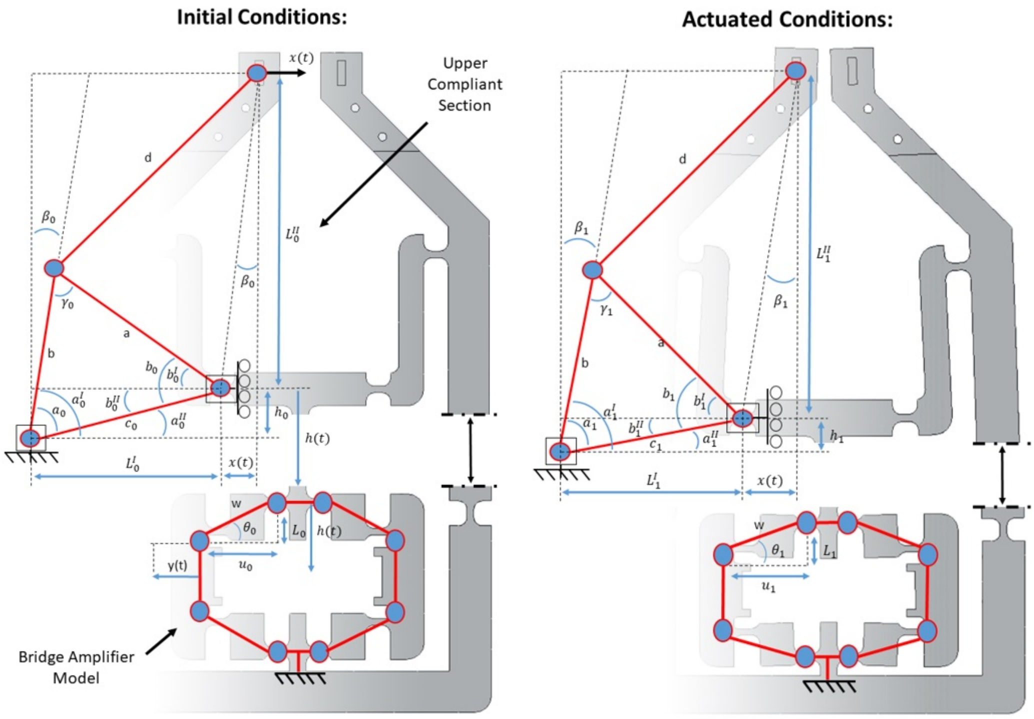

FIGURE 2.8: A detailed PRBM representation of the compliant micro gripper for kinematic modelling

2.1.4 Base Gripper Fabrication

The compliant base component can either be CNC machined from aluminium or 3D printed however currently CNC manufacturing is used as 3D printing can cause inconsistencies in resolution and is also more flexible which may lead to misalignment of the gripper tips (Fig. 2.9). Currently we are using 7075-T6 aluminium plate as the strength and elasticity of this material make it a common choice for compliant mechanisms [74].

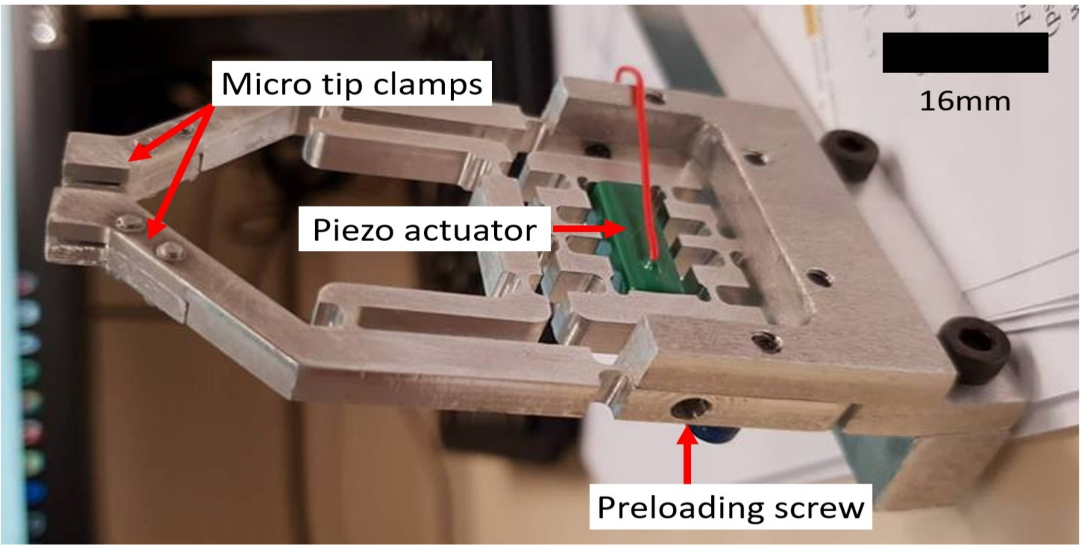

FIGURE 2.9: The CNC machined aluminium compliant base gripper with piezo actuator and micro gripper clamps

2.2 Micro Gripper Tip Fabrication

2.2.1 Silicon Tip Fabrication

As mentioned previously, the gripper is designed to have a variety of interchangeable tips for different applications. These tips are manufactured from 400 μm thick silicon wafers by using DRIE (deep reactive ion etching) technologies. The different stages involved for manufacturing a set of tips is shown in Fig. 2.10. Stage 1 begins with the preparation of a silicon wafer. In order to remove any impurities from the wafer surface, each wafer is first ultrasonically cleaned in acetone for 10 minutes. This is followed by a 10 minute plasma clean to remove any remaining organic particles. Once thoroughly cleaned, we then add a 500 nm thick layer of chromium to each wafer (stage 2). This is done by using electron beam sputtering technologies (specifically a BOC EDWARDS FL400) which uses a powerful beam of electrons to vaporise and deposit the chrome evenly on each wafer. The third stage involves spinning a 1 μm layer of photo resist onto each wafer where the etching pattern will eventually be placed. Once complete, a mask which contains the etching pattern needs to be created. This is done by using CAD software to create a 2D image of the pattern which is then loaded into the mask writer (in our case, a Heidelberg UPG 101 was used). The mask writer will then write the pattern onto a blank mask which is comprised of three layers; glass, chromium and photo resist. Once complete, the mask is then developed in developing liquid to reveal the inverted pattern of the grippers. Chrome etching liquid is then used to remove the unwanted chrome around the mask, leaving only transparent glass and the micro gripper etching pattern. We can now move onto mask alignment (stage 4) where we place the mask and wafer into the alignment device (Karl Suss MA6). After aligning the pattern over the wafer, the MA6 then delivers a powerful 10 second burst of UV light over the mask subsequently transferring the pattern to the wafer photo resist. A quick 1 minute bath in developing liquid then exposes the desired pattern on the wafers. The 5th stage involves first bathing each wafer in chrome etching solution to remove unwanted chrome around the exposed pattern. We then repeat ultrasonic cleaning in acetone to remove the photo resist which is no longer needed, leaving only the chrome etching pattern and silicon. The reason why we have created the pattern in chrome is that the DRIE process etches through chrome much slower than silicon. The idea is that the chrome will protect the silicon from etching in unwanted areas. At this stage we can move to stage 6 by placing the wafer into the DRIE device (Oxford Instruments PlasmaPro100 Cobra) where the unwanted chrome and silicon will be etched away, leaving only the gripper tips remaining.

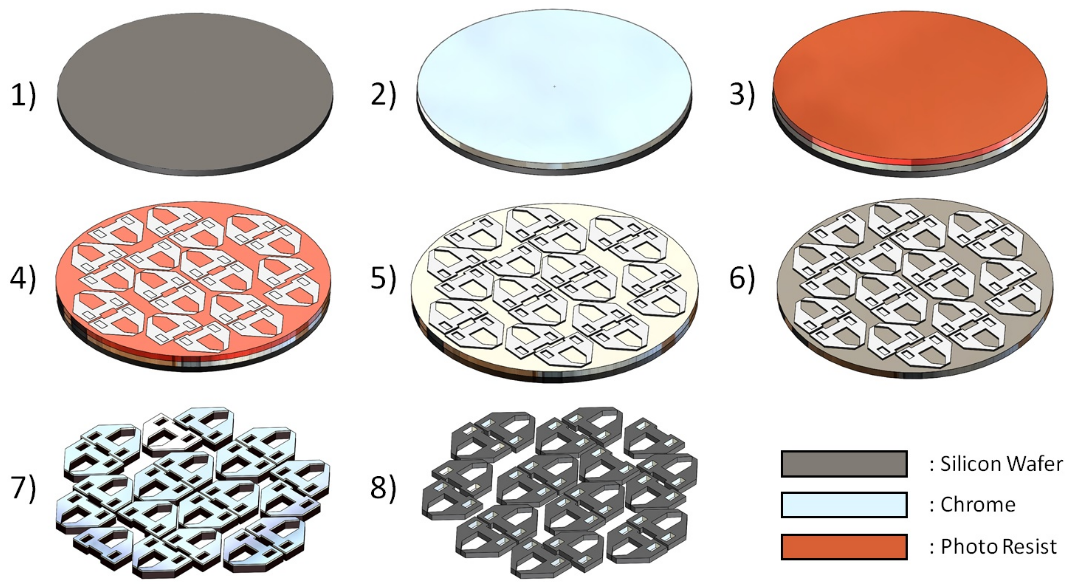

FIGURE 2.10: A sectional view showing the different layers involved in etching a silicon wafer (stage1: blank silicon wafer, stage 2: silicon wafer with chrome layer, stage3: silicon wafer with chrome and photo resist layer, stage 4: gripper pattern exposed into photo resist layer, stage 5: gripper pattern in photo resist developed, stage 6: chrome around developed gripper pattern removed, stage 7: silicon etched away leaving only gripper tips with chrome layer, stage 8: chrome removed leaving only silicon gripper tips.

DRIE Capabilities:

The reasoning as to why deep reactive ion etching was used is due to the sub micron resolutions that can be achieved with this technology. Unfortunately, it was found that this resolution drastically reduces as etch depth increases. This made creating custom tip designs very difficult and also impossible in some cases. Etching through an entire wafer depth of approximately 400 μm always resulted in the fine tip patterns being destroyed due to inwards etching and chrome degradation. In order to achieve any kind of micron-range tip structures, the pattern was first etched to a depth of 60 μm to 100 μm on the wafer top. The wafer is then flipped and etched again to remove the remaining 340 μm from the bottom side down. By doing this, it was found that the minimum achievable feature length was approximately 40 μm with the minimum tip diameter for sharp edges being approximately 1 μm. This can be seen in Fig. 2.11 where four 100 μm thick tip types are shown. In the case of the round and toothed tips, a diameter of 40 μm between features was the smallest that could be achieved. Smaller features can be created however any gripper tips created below 60 μm thick were simply too fragile for handling and shattered immediately upon contact.

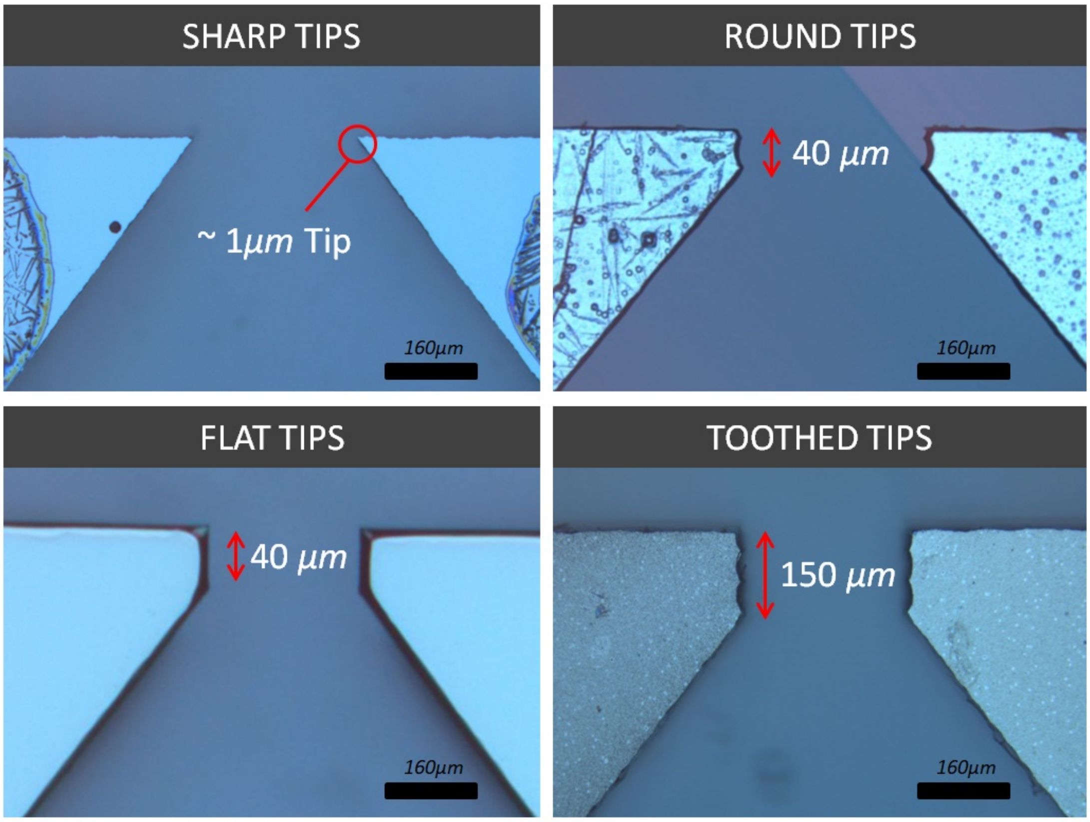

FIGURE 2.11: Four different tip types (sharp, concave round, flat and toothed)

Silicon Etching Rate:

Etching through silicon is a lengthy process as ionised plasma attacks and strips away individual atoms at a time. In this case, the etch depth is approximately 400 μm which is the total thickness of a 76 mm silicon wafer. During the etching process, it is important to know exactly what rate the silicon is being removed. If the time is set for too long, the wafer will be etched away and will no longer shield the wafer chuck, meaning the device will begin etching itself causing permanent damage to the chuck. This also means the remaining tips will continue to etch unnecessarily and will gradually become thinner and more fragile. Knowing the exact etching rate is also important when fine etching is required. In order to get the precise removal rate of the device, an optical profilometer was used to measure the depth of a pattern that had been previously etched for 6 hours. The results showed a depth of approximately 279 μm had been achieved and therefore meant a rounded rate of 47 μm per hour (Fig. 2.12) and a total time of 8.5 hours per wafer.

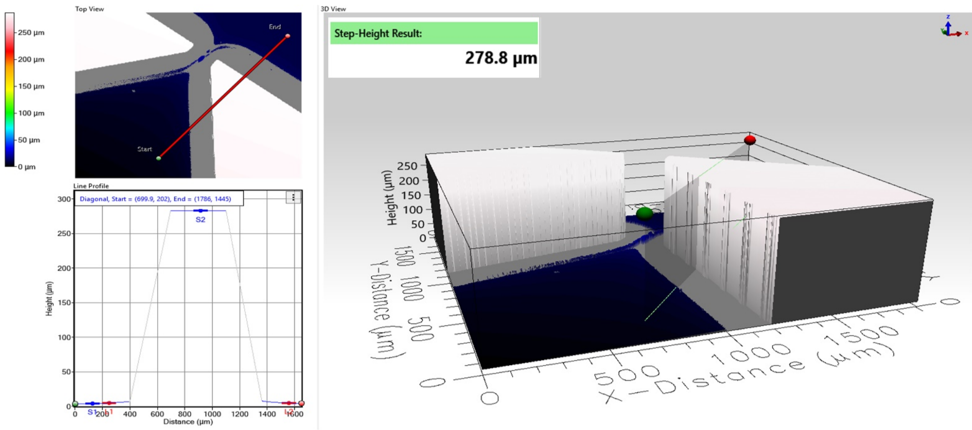

FIGURE 2.12: Silicon wafer etching depth after 6 hours measured with an optical profiler

Side Wall Etching Implications:

When manipulating micro objects, it is important that the manipulators have the smallest possible surface area in contact with the object to reduce adhesion forces. When etching, a combination of helium, CHF3 (fluoroform) and SF6 (sulphur hexafluoride) gases are used to form an ionised plasma which attacks the silicon wafer from an almost vertical direction. It is very difficult to obtain a perfect vertical sidewall when deep etching, meaning sidewalls are often angled inwards which becomes worse as the depth into the material increases. Furthermore, as the depth approaches the bottom of the wafer, we see the angle reverse to form an outwards tail

(Fig. 2.13). This effect is present regardless of the tip shape or size however is more prominent in deeper etches.

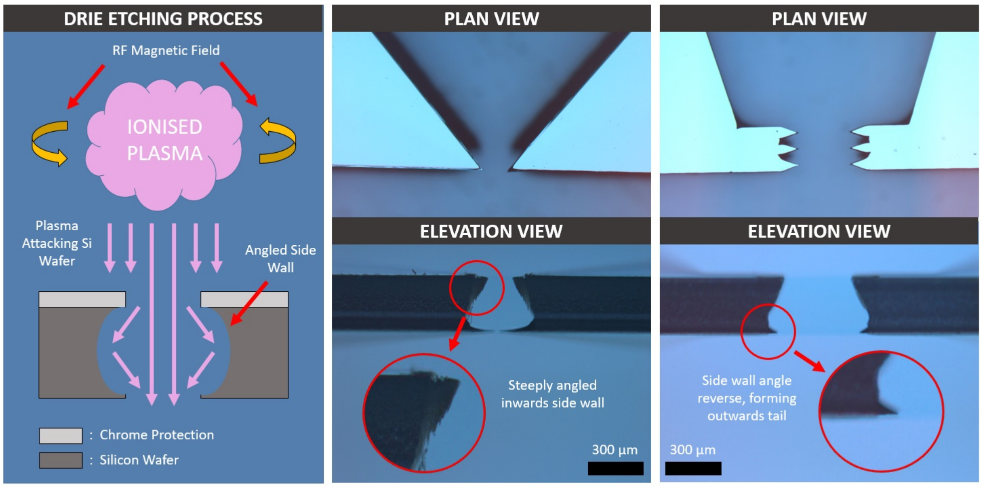

FIGURE 2.13: Angled side wall issue with deep reactive ion etching

Part of the angled side wall effect works in favour with the gripper as it means the tips themselves converge to a point of minimum surface area, reducing adhesion forces. It is the the final reversal of the angle and tail formation that poses an issue. Firstly, it limits the z-direction reach of the tips as the tail hits the substrate floor before the actual micro tips. This means any object must be manipulated in between the concave tip structure which drastically increases the surface area in contact with the object (Fig. 2.14). This can be avoided by flipping the tips upside down however, the tail then obscures the actual tip view when using an optical microscope. It was found that a simple solution to removing the tail is to flip each batch of silicon tips and briefly etch through approximately 60 μm from the other side which causes the tail to be etched away, leaving only the gripper tips converging to a point of minimum surface area.

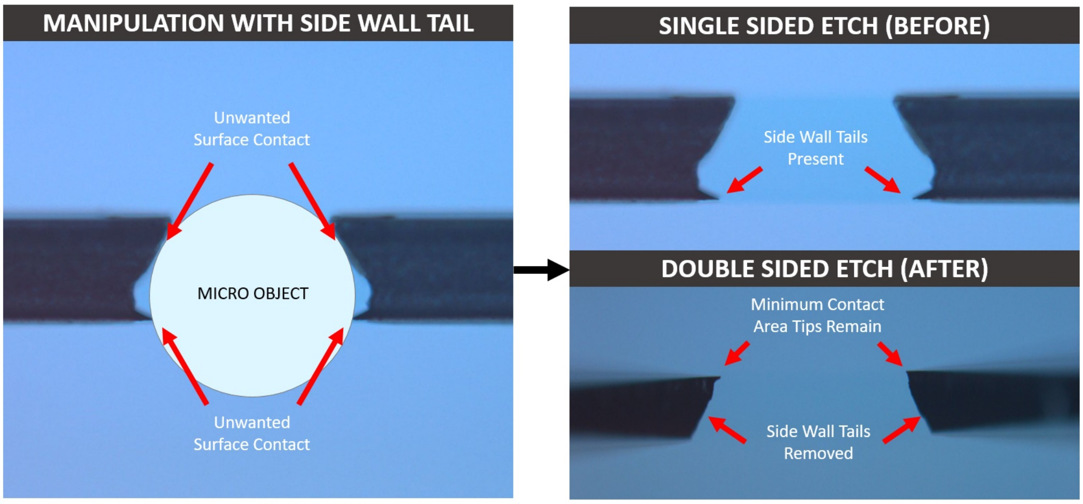

FIGURE 2.14: Angled side wall tail removal

2.2.2 Brass Tip Fabrication

In order for the silicon micro gripper tips to be correctly aligned, they are manufactured as a single part. This means that they must have a way to flex with the compliant base gripper as it is actuated. Initially the silicon micro gripper tips were manufactured with a set of compliant springs however, the fragile nature of the material proved too delicate causing the springs to shatter upon actuation (Fig. 2.15).

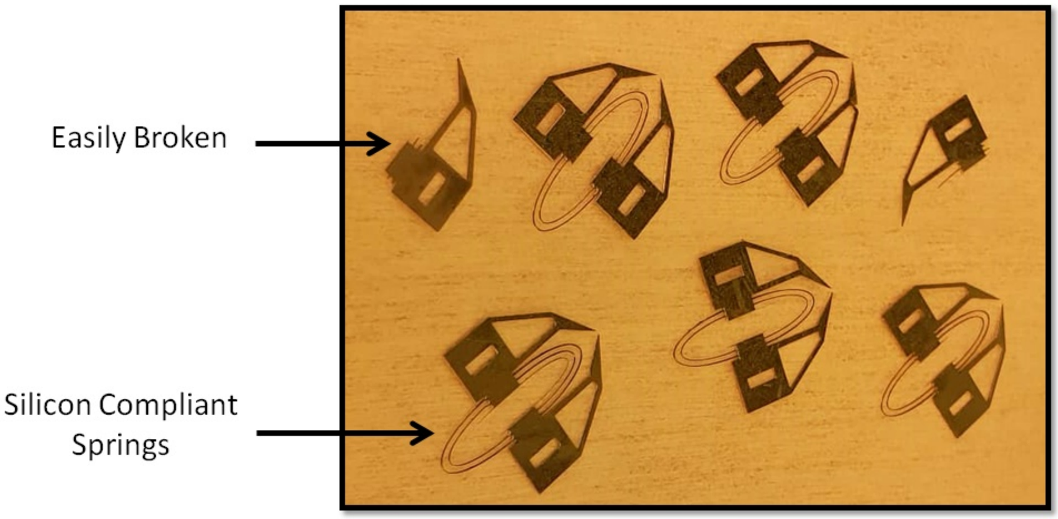

FIGURE 2.15: Silicon etched tips with fragile compliant springs

Because of this, more flexible 0.3 mm thick brass tips were created with a micro mill upon which the silicon tips would be attached. This is done simply by using loctite glue and because the brass and silicon tips are dimensionally identical, they naturally align upon gluing due to surface tensions. To keep the silicon tips as a single part, a small beam connects the tips while manufacturing which makes them rigid. This beam is then broken once the tips are glued to the brass, allowing them to flex with the compliant brass tips (Fig. 2.16).

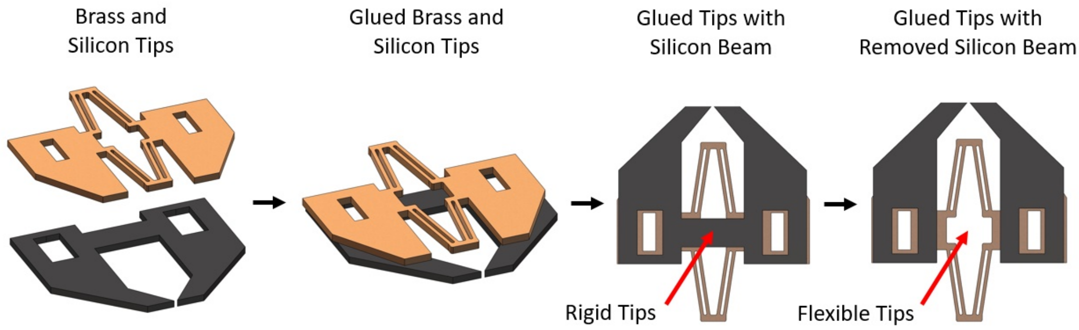

FIGURE 2.16: The process of gluing the silicon tips to the brass

2.3 Gripper Tip Alignment

Achieving near perfect alignment (within 1-2 μm) of the micro gripper tips is crucial for stable manipulation of small spherical objects, such as micro beads or cells. If the tips are not applying a force normal to the equator of the micro object, it is very difficult to adequately grasp it, such that the object can be raised and moved from the substrate floor (Fig. 2.17)

To examine the problems associated with gripper tip alignment, a pair of borosilicate glass end effectors were attached to the compliant base micro gripper. These end effectors are created with a Narishige PC-100 pulling device which heats, softens and stretches a glass rod. Eventually the rod breaks at a point with a diameter of approximately 1 μm and can be used as a pair of end effectors. When attached to the gripper, a screw and pivot system was developed in order to slightly move each end effector up or down until correct alignment was achieved. As seen in Figure. 2.18, the tip will pivot either up or down depending on the screw adjustment.

Z-axis alignment (up/down) was possible with this method, however it was not very accurate due to the large pitch of the screws used. X-axis alignment (left/right) must also be considered as each end effector is fixed separately to the compliant base. To counter this effect and avoid creating an overly complex alignment design it was decided to create the gripper tips as a single part. This meant that the tips would be naturally aligned in the x-axis however, z-axis alignment would still be required due to slight flexing of the tips when attached to the rigid compliant base

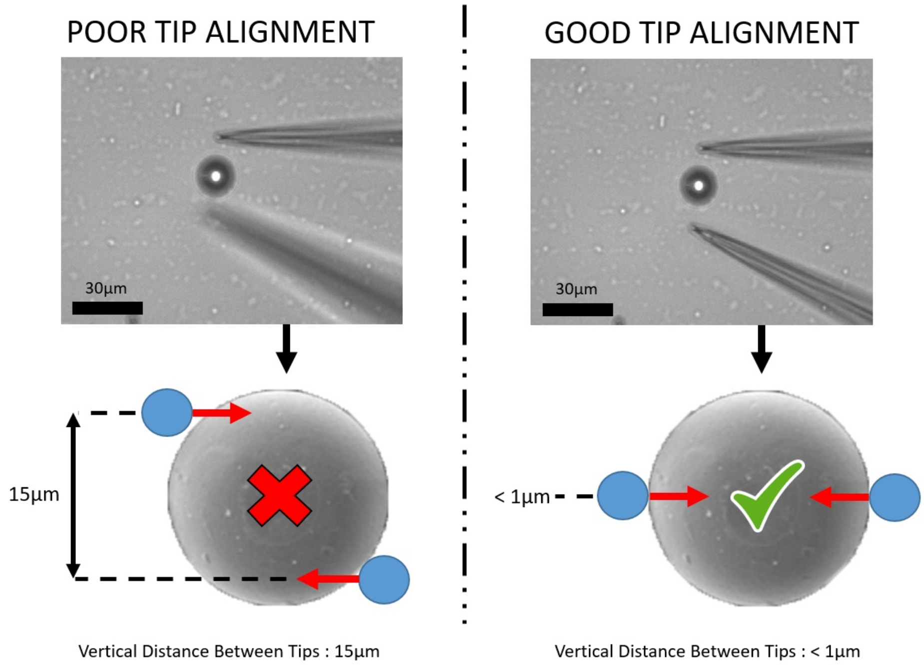

FIGURE 2.17: The importance of adequate tip alignment in grasping micro objects

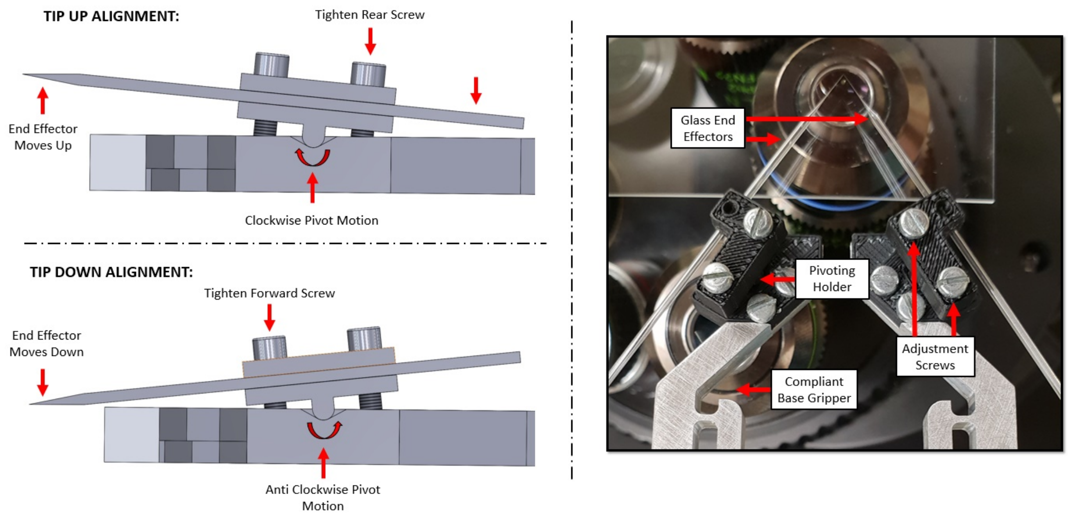

FIGURE 2.18: Initial glass end effector screw and pivot alignment

gripper. For this, a simpler alignment solution was devised which consisted of only two screws (one for each side). A set of extremely fine M2.5 x 0.20 adjustment screws were used (Thorlabs F2D5ES8) to achieve a greater alignment resolution per turn. When turned, the screws make contact with the gripper tips, causing them to slightly flex downwards in the z-axis (Fig. 2.19).

In order to have the ability to use both single piece gripper tips and also glass end effectors, the end effector housing design was later modified. Instead of using a levering method, a single fine adjustment screw was used to slightly press down on the end effector (Fig. 2.20). Another fine

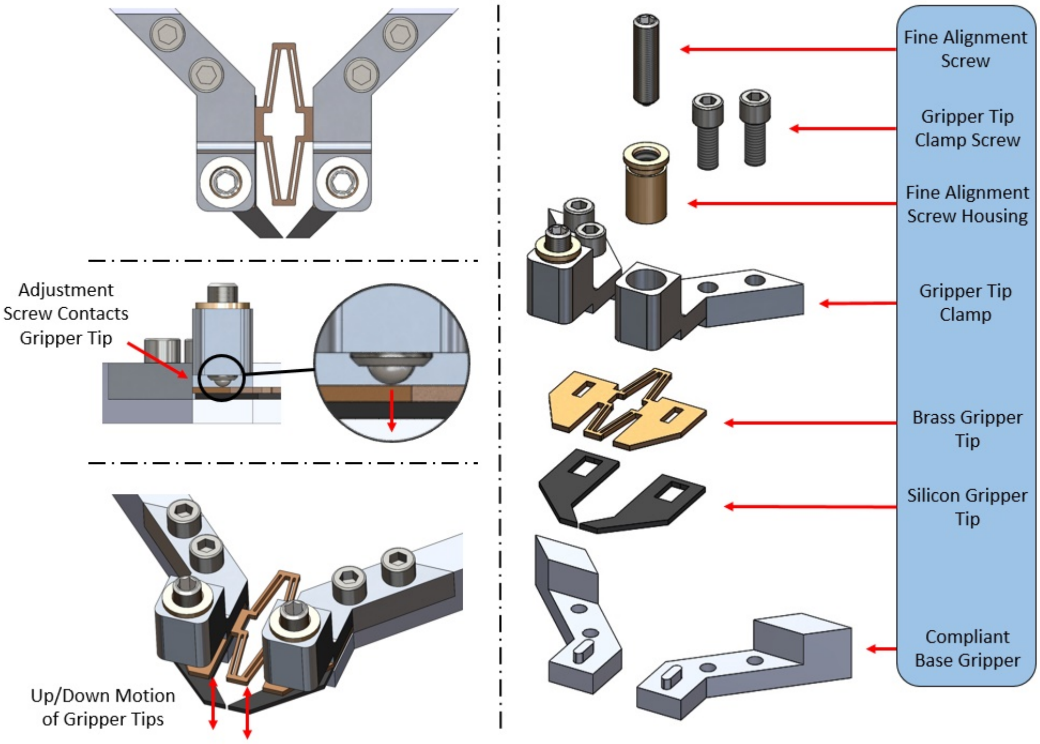

FIGURE 2.19: Brass and silicon gripper tip alignment solution

screw was also used to press against the back side of the end effector. This meant that when tightened/loosened, both z-axis (up/down) and x-axis (forward/backward) alignment was now possible.

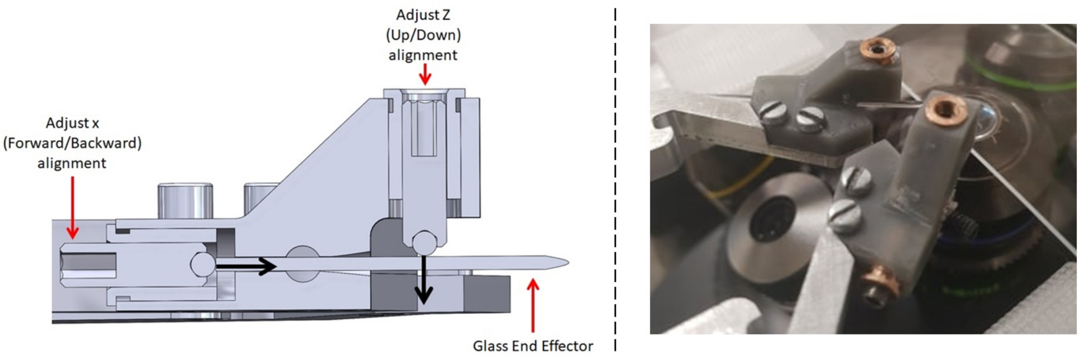

FIGURE 2.20: A sectional view of the new end effector mount along with actual view

2.4 Gripper Control

The following section will discuss the control methods used for actuation of the micro gripper.

Piezo Actuation:

In order to drive a piezo actuator, a stable high voltage of 0 - 150 VDC is required. For this, a Matsusada PZJ high speed piezo driver is used to control the piezo with 0.1 V precision. The driver is adjusted with a raspberry pi 3 linux operating system with an ADS1258 attachment. The ADS1258 offers a 16 bit DAC which we use to send an analogue voltage between 0 and 10 VDC to the piezo driver in order to adjust the high voltage.

Actuation feedback:

With any closed loop control system, some form of feedback is required to get an idea of the current system state and how far it is away from reaching a set point. In this case a single 120 Ω Kyowa strain gauge is glued to the piezo actuator to get a reading of expansion. The gauges are connected to a simple Wheatstone half-bridge circuit which measures changes in resistance as the strain gauges expand. The idea of the Wheatstone half-bridge circuit is to initially balance the resistance of the bridge to approximately 120 Ω. When the bridge is balanced, approximately 0VDC is read when measuring the voltage across the middle of the bridge. When the strain gauges are expanded, their resistance increases effectively unbalancing the bridge. This causes the voltage measurement to slightly increase between 0 - 1.5 mVDC over the entire expansion of the piezo actuator (0 - 19 μm). In order to obtain any usable information from this small change, a 24 bit ADC (analogue to digital converter) is used to sample the data with high resolution. The ADS1258 is again used as it also includes a 24 bit ADC which provides a high precision measurement across the bridge with a resolution of micro volts. Closed-loop control is accomplished by comparing the current actuator strain with a set of previously calibrated strain values and resulting expansions. The entire closed loop control can be visualised in Fig. 2.21, where the input is a given gripping set point and the output is the expansion of the piezo actuator.

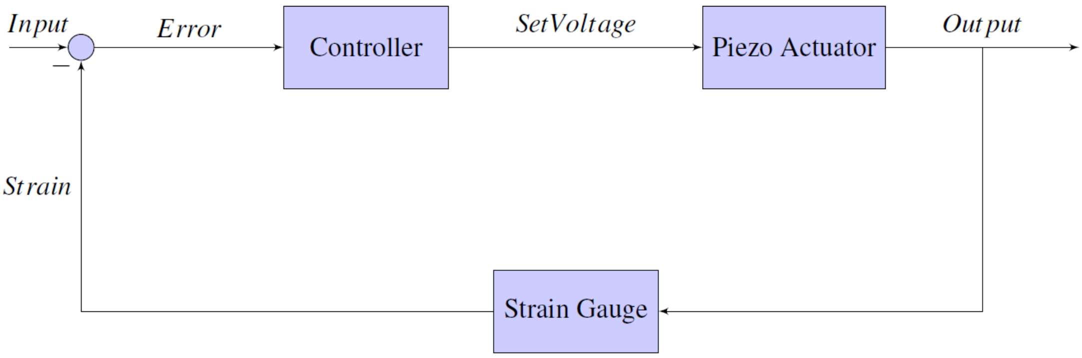

FIGURE 2.21: Simple diagram representing the closed loop actuation control system

2.5 Summary of Methods

In this chapter we have seen a detailed explanation of the techniques and methods used for designing, manufacturing and controlling the micro gripper. This included reasoning as to the design decisions made in the process. We have also seen multiple optimisation techniques which increased overall performance and stroke range of the gripper. Kinematic modelling has also been described which has given us a mathematical model of the compliant gripper. Lastly, the methods for controlling the entire system have been outlined which enables us to have precise control over gripper position.

Chapter 3

Experiments and Results

This chapter will present the experimental results obtained from testing the micro gripper on different target objects. To start with, section 3.1 will explain how the closed loop gripper control was calibrated and the problems faced with doing this. Secondly, section (3.2) will display a series of manipulation tests for each type of shaped silicon micro gripper tip. The target objects in this case are randomly selected spherical and non spherical micro beads within a size range of 100 μm to 500 μm. The results of these experiments will then be discussed in order to highlight any possible benefits of manipulation with different gripper tip shapes. Section 3.3 will then branch out from the previous experiment to demonstrate how the micro gripper can be used to manipulate more common biological micro objects, in this case ranging from 60 μm to 100 μm. Lastly, section 3.4 will briefly explain the importance of cellular-sized object manipulation and presents a new method for achieving this by using borosilicate glass micro end effectors. Manipulation is then successfully demonstrated on spherical silica micro beads, ranging from 6 μm to 20 μm. This section will also include a few experiments, which will categorize and discuss the issues related to alignment and adhesion at this scale.

3.1 Experimental Setup

In order to properly manipulate a sample using the micro gripper, very precise motorized micro stages are required. In this study, a set of 3-axes motorized stages (OSMS80 and HPS80, Sigma Koki) with a controllable resolution of 0.5 μm are used. These stages are controlled serially by a driver (SHOT304, Sigma Koki) from a PC. A custom machined bracket is attached to the stage, in which the micro gripper is fastened to. The gripper is actuated by a NEC/TOKIN AE505D18H18F resin coated piezo actuator which is driven by a Matsusada PZJ-0.15Px3 driver (Fig. 3.1).

The ADS1258 16 bit DAC and 24 bit ADC is connected to a Raspberry Pi 3 inorder to control the entire system remotely from a windows computer. This is done by using two Cytron 433 MHz radio UART transceiver modules , one of which is connected to the Pi and the other to the computer. The Pi can now communicate strain gauge data wirelessly to the computer for viewing and vice versa, the PC can send commands to the Pi for operation of the gripper. A diagram describing this communication can be seen in Fig. 3.2.

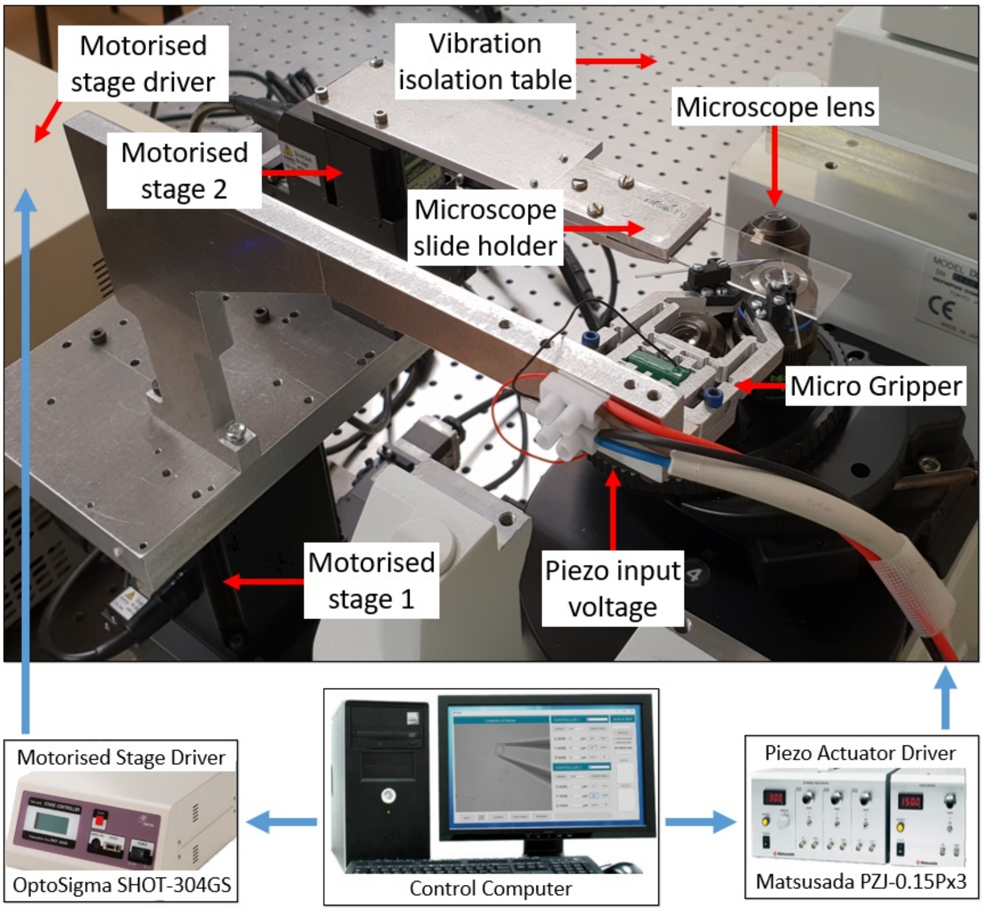

FIGURE 3.1: The experimental setup of the micro gripper

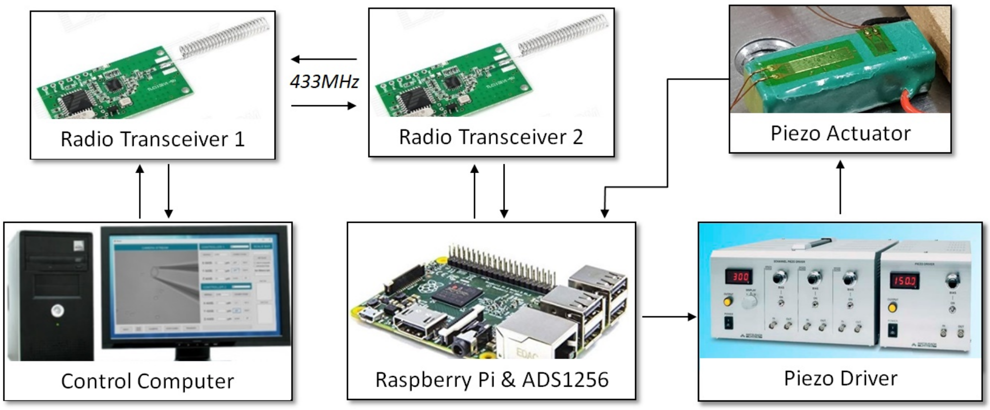

FIGURE 3.2: The methods of transferring data around the system

3.2 Gripper Control

In order to close the loop in the control of the gripper, a high precision strain gauge was attached to the piezo actuator to attain a real-time reading of its expansion. Extremely small changes in the piezo actuators length could then be detected with a 24 bit ADC. The entire 0 μm - 19 μm expansion is measurable as a change of 0 mV - 1.5 mV across the strain gauge and is used as feedback for our closed loop system.

3.2.1 Control Calibration & Hysteresis

To calibrate the system, a set of data relating strain to gripper expansion was gathered with a simple experiment. A program was created to automatically expand and retract the actuator by incrementally adjusting the input voltage in steps of 1 volt (0.12 μm). This was done to cover the entire range of the actuator while simultaneously recording the strain at each point. The results for two expand/retract cycles can be seen in Fig. 3.3. These graphs reveal that there is considerable hysteresis when comparing the expansion and retraction of the actuator. Hysteresis such as this will not affect the gripper control, it merely means that any control system must be mindful of the actuator travel direction when relating strain to actuator voltage. This effect is a natural part of using piezo actuators and therefore it is pointless trying to reduce it. The fact that this level of hysteresis is visible in the data is actually a good sign to some extent, as it confirms the strain gauge is accurately measuring the expansion.

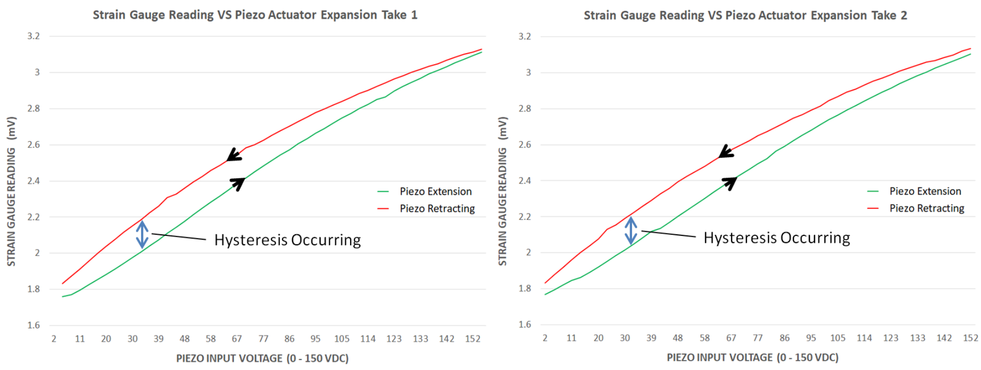

FIGURE 3.3: The results from two expand/retract cycles of the piezo actuator showing strain gauge voltage versus piezo input voltage

Furthermore, a small amount of error was found to be present when comparing the strain results from different actuator expand/retract cycles. In order to account for this, the actuator was expanded and retracted a total of 10 times with strain data being recorded. Each set of data was then averaged together to get a more precise calibration however, when examining each test, very little difference is visible between results. The graph in Fig. 3.4 shows the results for two actuator cycles side by side. The data from these two tests showed the greatest amount of variance amongst all 10 tests. Even so, the largest error between the expansion and retraction cycles was found as being 0.5% and 0.2% respectively. When this error is converted to actuator expansion, the difference becomes 0.075 μm when expanding and 0.03 μm when retracting. When translated to the gripper tips, this error is amplified and becomes 0.61 μm and 0.24 μm for expanding and retracting respectively. Due to the small size of this error, it was considered negligible when manipulating objects within our size range (6 μm to 500 μm) as it had no noticeable effect on the use of the micro gripping system.

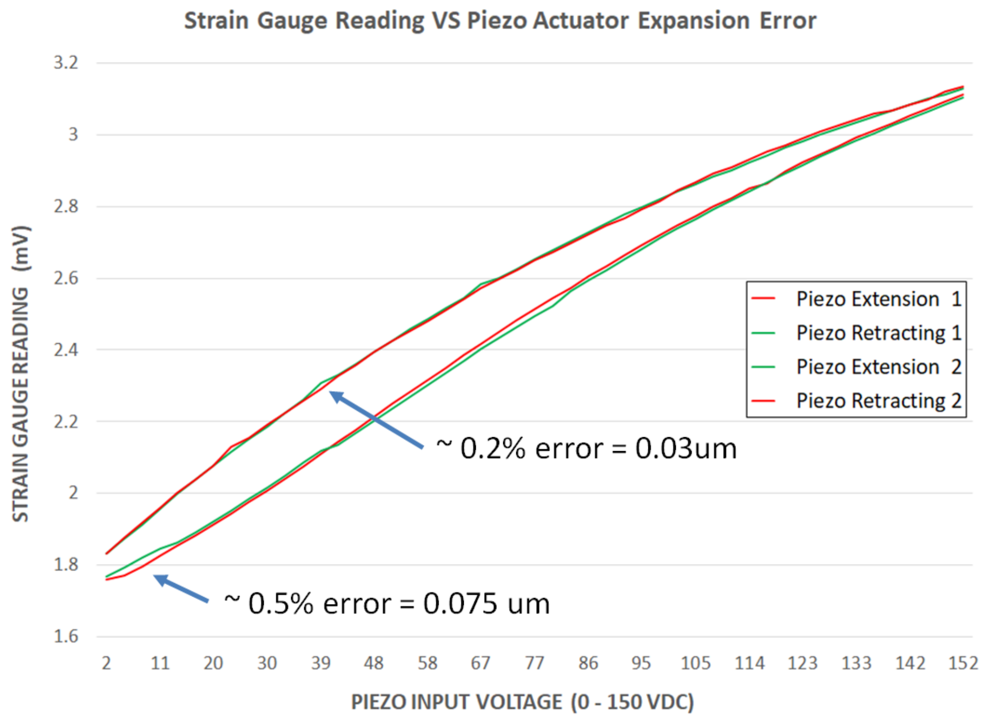

FIGURE 3.4: Graph showing the maximum differences when comparing two expand/retract cycles side by side. Data shown represents recorded strain versus input piezo actuator voltage

3.2.2 Gripper Control Conclusions

The simple experiment in this section was used to generate calibration data that the gripper control can refer to when comparing a current strain voltage to actuator expansion. A large hysteresis was discovered when comparing actuator expansion to retraction however, this was deemed to be unavoidable and not to affect the control program. Lastly, a very small amount of error was discovered that exists between actuator expansion cycles. The error is most likely due to unavoidable factors such as peizo temperature or gauge drift which may cause these measurements to slightly change per cycle. In the end, this error was deemed to be negligible in terms of application as our working scale is simply too large to be affected.

3.3 Shaped Gripper Manipulation Results

A simple experiment was conducted to compare the functionality of four different silicon tip types when manipulating spherical and non-spherical micro beads.

3.3.1 Method

The micro beads used in this experiment are made from glass and are approximately sized between 100 μm to 500 μm. Unfortunately it is not possible to manipulate smaller objects with silicon at this stage due to manufacturing limitations. Because the micro beads are relatively large, we do not have to worry about the issue of adhesion forces at this stage and therefore, experiments are conducted in a dry environment.

In order to conduct experiments, a glass slide is first cleaned with isopropl alcohol and placed on the microscope. A small sample of micro beads is then deposited onto the slide followed by the gripper being slowly lowered until making contact with the substrate floor. In order to achieve correct alignment, each tip is then slightly raised and moved towards the micro object. This process is repeated until both objects are in focus and the tip is making good contact at the approximate equator of the micro bead (Fig. 3.5).

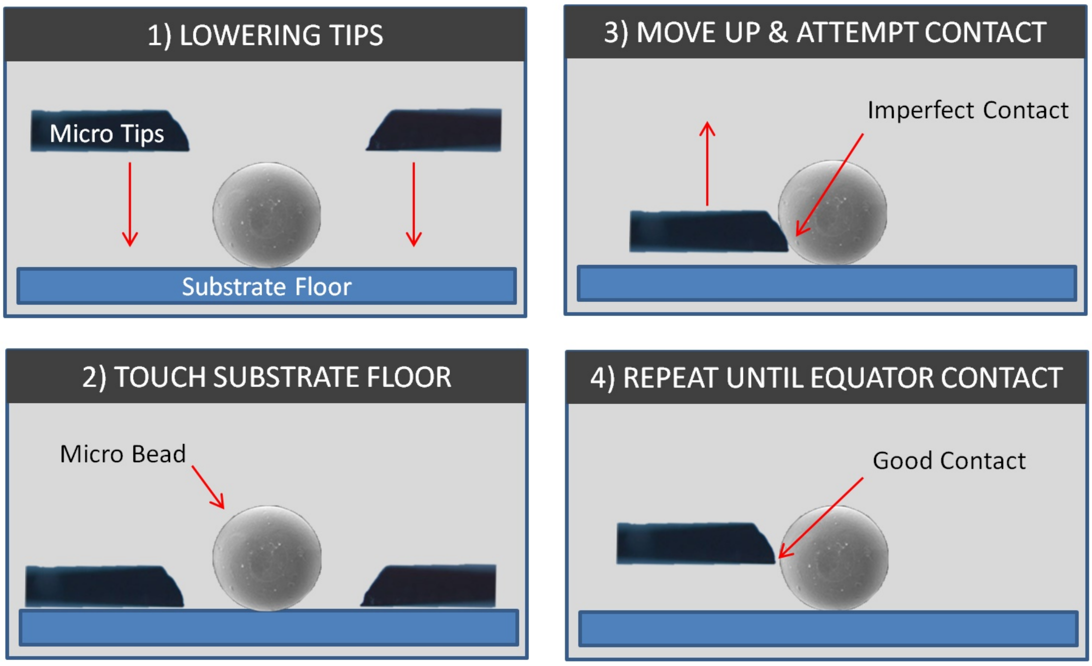

FIGURE 3.5: The process of correctly aligning the silicon micro gripper with a micro bead

Each tip was then used to perform a number of pick and place tasks on 20 randomly sized micro beads. The first task is measured as success/non-success and involves grasping the bead and lifting it of the substrate floor to confirm good contact. A non successful result occurs when an improper contact causes the bead to either drop, or be launched out of view. The number of attempts before a good grip is achieved is then recorded. The second task is also recorded as a pass/fail result and requires the bead be moved by 5mm in both x and y directions, then released back to the substrate floor. If the bead is not able to traverse this distance safely, a non-success is recorded. The total time to achieved these tasks is also recorded along with the different bead sizes.

3.3.2 Results and Discussion

Manipulation Time:

The following graphs show the average time taken to complete a successful micro bead pick and place task for all tip types. This is done to gauge the efficiency of using shaped tips on different target objects (Fig. 3.6).

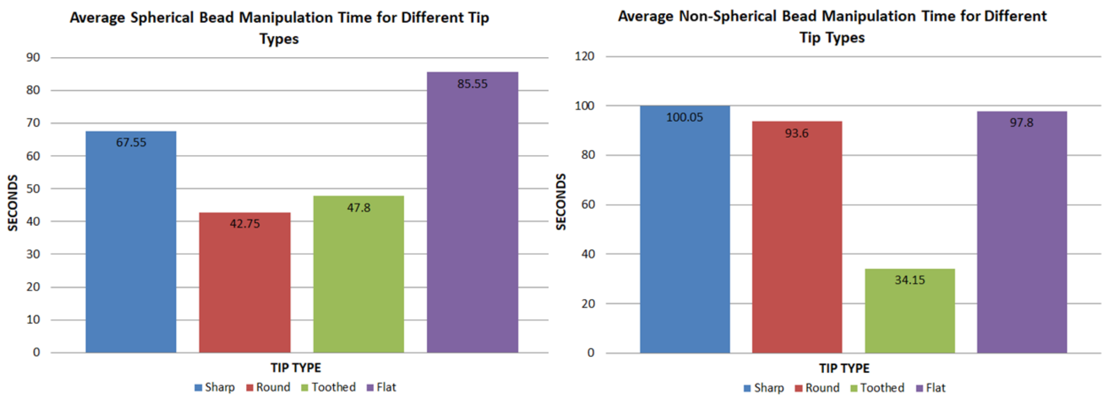

FIGURE 3.6: Graph showing the average time taken to correctly align, pick and move spherical and non-spherical micro beads with silicon micro tips

From this data, two main possibilities can be drawn for spherical object manipulation. Firstly for spherical beads, round tips on average take the least average time (42.75 seconds) to complete the tasks. This is closely followed by toothed tips, which took an average time of 47.8 seconds. This result was somewhat expected, as a spherical bead tends to comfortably and firmly fit in between the concave curves (Fig. 3.7). It also suggests that for spherical target objects, a round tip shape is the most efficient for manipulation. Secondly, flat tips on the other hand seem to show a considerable increase in average time (85.55 seconds). This was mostly due to the difficulties in grasping the target object, as the bead would often be uncontrollably flicked away. The sharp tips come in roughly somewhere between the results at 67.55 seconds.

When compared to non-spherical objects, the results clearly show that toothed tips are the most efficient with less than half the average time (34.35 seconds) of sharp, round and flat tips which took 100.05, 93.6 and 97.8 seconds respectively. This is most likely due to the toothed tips having multiple points of contact to an object, making it more suited for interlocking with an un even surface.

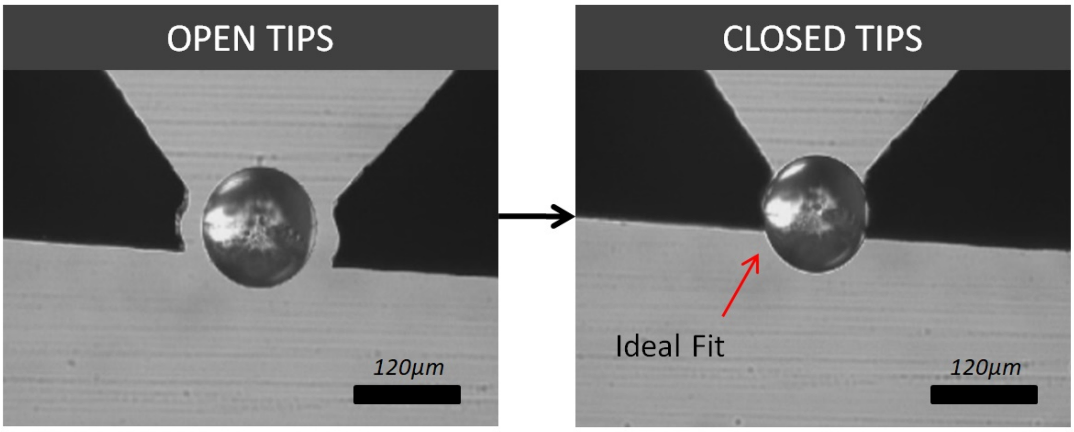

FIGURE 3.7: Round tips gripping a spherical object

Grasp Attempts:

The amount of attempts before having a firm grasp on each micro bead was recorded and plotted on the graph below (Fig. 3.8). This was done to highlight if a particular tip shape showed any signs of being easier to use when dealing with spherical and non spherical beads.

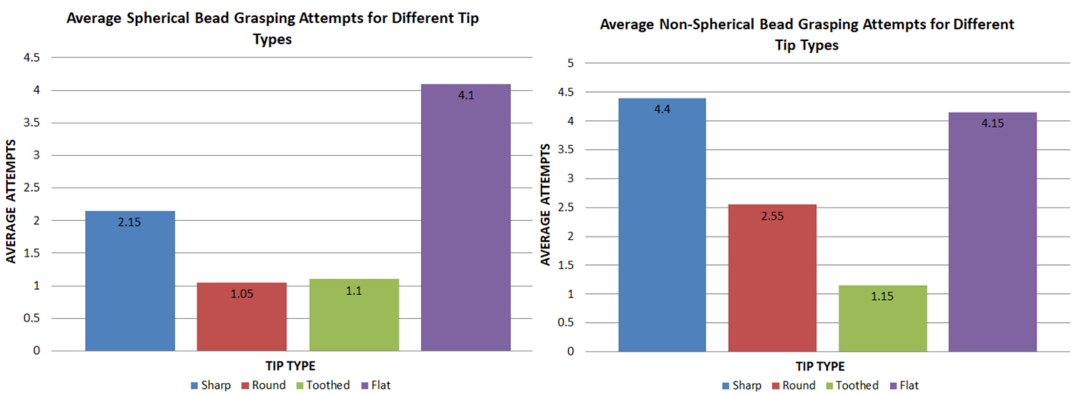

FIGURE 3.8: Graph showing the average number of micro bead grasp attempts before achieving a firm grip

The results show that the amount of grasping attempts closely follows the shape of the manipulation time graph. This is expected as more grasp attempts greatly increases the time taken.

The data shows that round tips are not only the most time efficient, but are also the easiest to use when dealing with spherical objects. We can also see that toothed tips follow round tips very closely with an average attempt rate of 1.1 as opposed to 1.05. This difference is likely negligible and means round and toothed tips function very similarly when grasping sphrical objects.

This is a different case for non-spherical objects with toothed tips showing an attempt rate less than half of the round tips and 4 times less than sharp and flat tips. This result, along with the small manipulation time, clearly suggests that toothed tips offer a vastly more efficient method for manipulating non-spherical objects.

Manipulation Success:

Manipulation success was also recorded as either successful or non-successful for both grasping and moving the target object. This information was recorded to illustrate the fact that there are two main factors to consider when dealing with pick and place success. For example, although it may appear that an object has been gripped, there is a chance that it may become dislodged from the tips when any translational movement is attempted. Therefore grasping and moving both play a part in pick and place success.

The graph below shows the average grasping success rate for spherical and non-spherical objects (Fig. 3.9). This data shows that grasping a spherical object is generally successful when using sharp, round or toothed tips with success rates of 85%, 95% and 95% respectively. Flat tips however, show a much lower success rate of 60%. For unknown reasons, flat tips tend to cause spherical beads to launch themselves out of view when grasped. It is theorised that this is due to an inconsistent surface area on the tips. When grasping, this may cause the bead to slip at certain stages, subsequently releasing the stored energy in the tips and catapulting the bead.

This bead launching effect also occurs with non-spherical beads, with a flat tip success rate of just 45%. Sharp and round tips also suffer from this effect when grasping non-spherical objects with success rates of just 65% and 55% respectively.

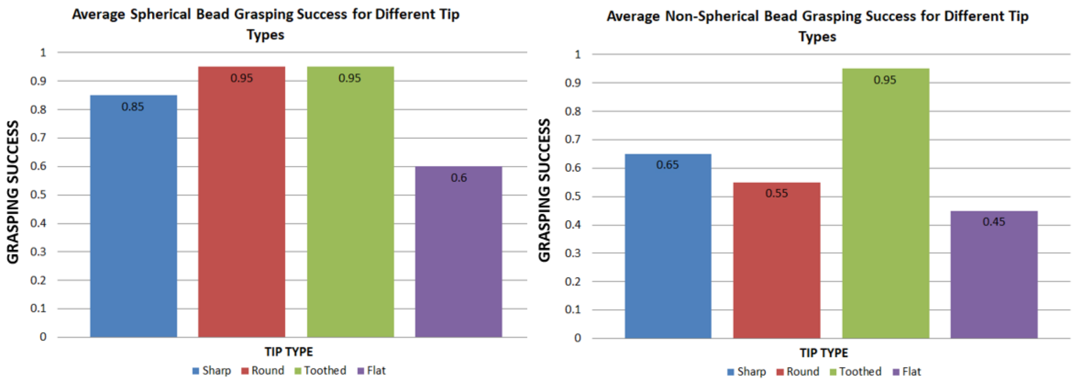

FIGURE 3.9: Graph showing the average grasping success for spherical and non-spherical micro beads

The results from the grasping success were also recorded to show the rare case in which an object becomes dislodged from the micro tips when translational motion is attempted. The results are extremely similar to grasping success due to the fact that if grasping fails, translation motion also subsequently fails.

From the graph below (Fig. 3.10), we can see that movement fail rate makes up for only 5% of attempts when using sharp tips on spherical objects. The remaining tips have a 100% success rate as the results are no different from the grasping success. Non-spherical beads however, show a much larger moving fail rate of 30% and 10% for sharp and round tips. Toothed tips on the other hand fail to move the object only 5% of the time, with flat tips being 100% successful.

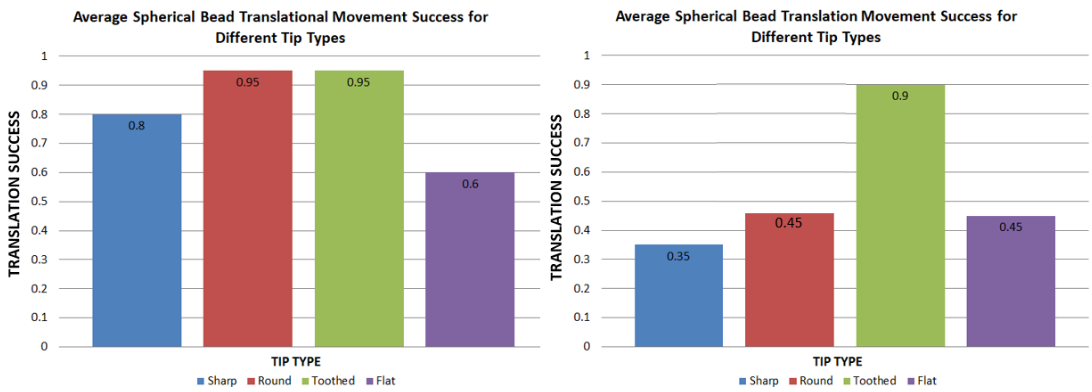

FIGURE 3.10: Graph showing the average success rate when performing translational motion on spherical and non-spherical micro beads

3.3.3 Shaped Tip Conclusions

To summarise the above results, it was found that certain gripper tip shapes can in fact increase the efficiency and effectiveness for manipulation of multi-shaped target objects. Firstly, when dealing with spherical objects, round tips showed the highest success rate (95%) for both grasping and translating. They also showed a significantly smaller average amount of grasp attempts when compared to sharp and flat tips, however were closely followed by toothed. This trend was also followed in the time taken data.

Toothed tips also showed a noticeable increase in performance for non-spherical objects across all tests. Manipulation time was proven as less than half the time of all others. Grasping attempts followed a similar pattern with up to 4 times less than sharp and flat tips. Success rate for both grasping and translating was also proven as being very reliable (95%). This was especially shown for non-spherical objects where grasping success is almost double that of other tip designs. Translational success was equal to round tips however is again more than double that of sharp and flat.

For these reasons, it is concluded that round tips offer the best overall performance for spherical objects with toothed-tips for non-spherical. Unfortunately, manipulation of objects less than 100 μm was not possible in this case, therefore these results can only be proven in an environment where adhesion is negligible.

3.4 Biological Manipulation

Manipulation of micro beads is a good method for showing the dexterity and functionality of a micro gripping system, however in reality there are many other types of micro objects with different surface properties and densities such as parasites, oocytes, micro structures or cells. To examine the differences in manipulating these kind of objects, two simple experiments were performed to both pick and place an eyelash, then a single grain of pollen.

3.4.1 Hair Manipulation

Different micro tips can also be used as tools at a micro scale, for example, a sharp tip can act as a cutting or puncturing device when we need to examine the interior of an object. This was demonstrated on a piece of hair which is approximately 60 μm thick. A sharp tip was first aligned with the eyelash, gripped it and then cut through it (Fig. 3.11).

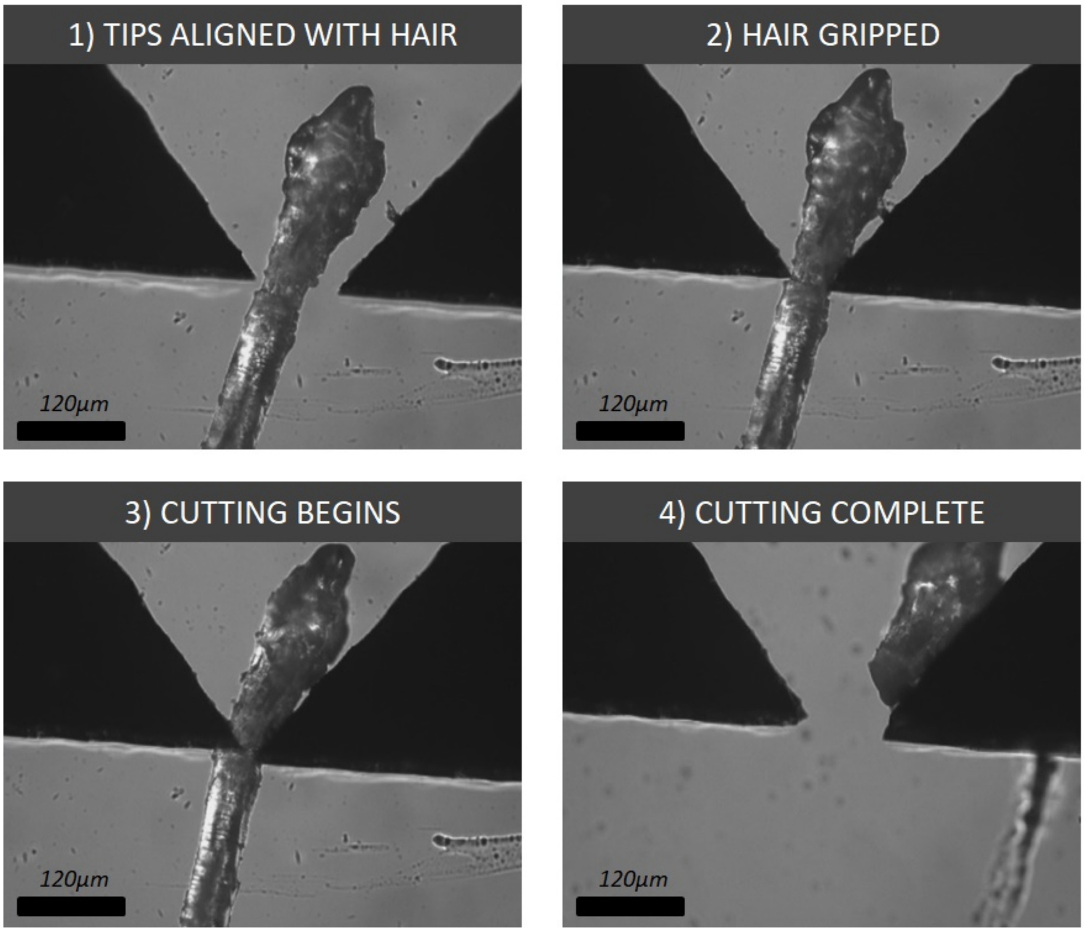

FIGURE 3.11: Process of grasping and cutting an eyelash with sharp silicon tips

Upon grasping the hair with sharp tips, it was very difficult to avoid incurring cutting damage. In order to safely manipulate something such as hair with out damaging it, a gripper tip that has more surface area in contact with the object can be used. In this case, a flat tip is used to show how the eye lash (in this case 100 μm thick) can now be translated without damage (Fig. 3.12).

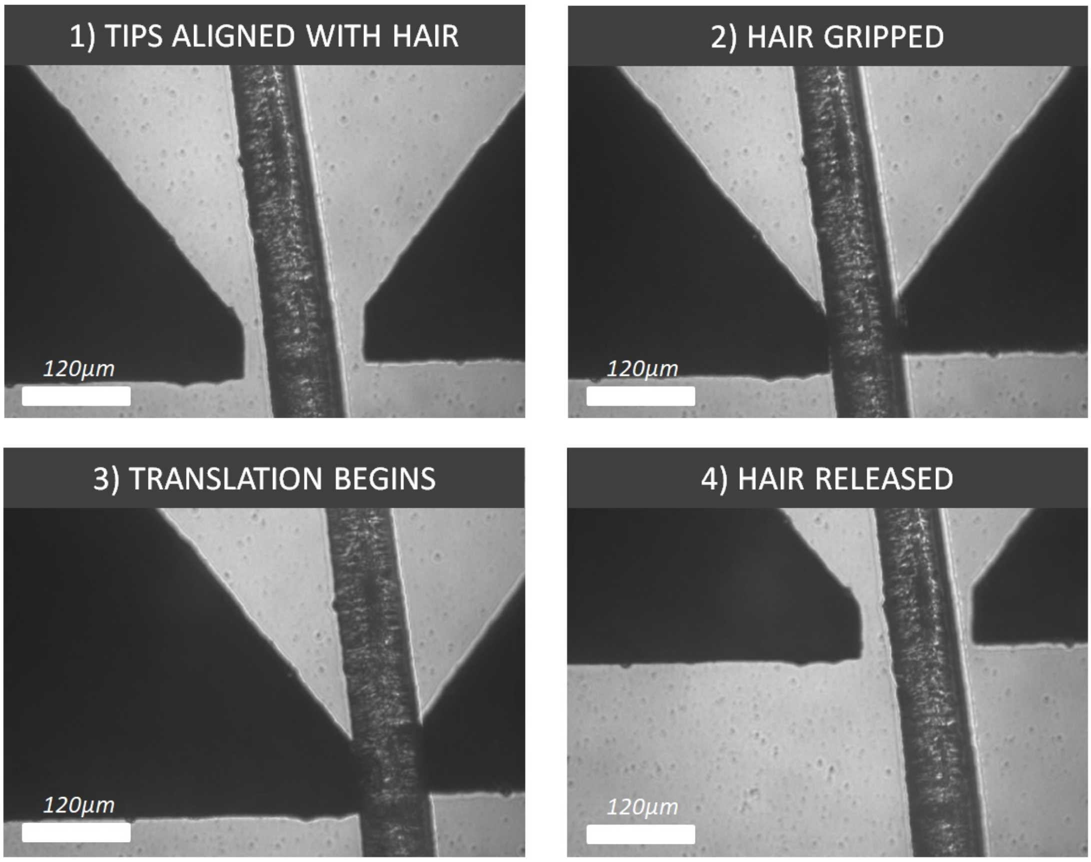

FIGURE 3.12: Process of grasping and moving an eyelash with flat silicon tips

3.4.2 Pollen Manipulation

Another easily accessible common micro object can be found from almost every flowering plant and is known as pollen. Pollen grains are sized within the capable range (3 μm to 100 μm) of which the silicon tips can manipulate. They are also relatively spherical which according to the previous experiment, makes round tips the most effective for manipulation. To demonstrate this, a 60 μm grain of pollen was placed under the micro gripper and successfully grasped, moved and released within the viewing area (Fig. 3.13).

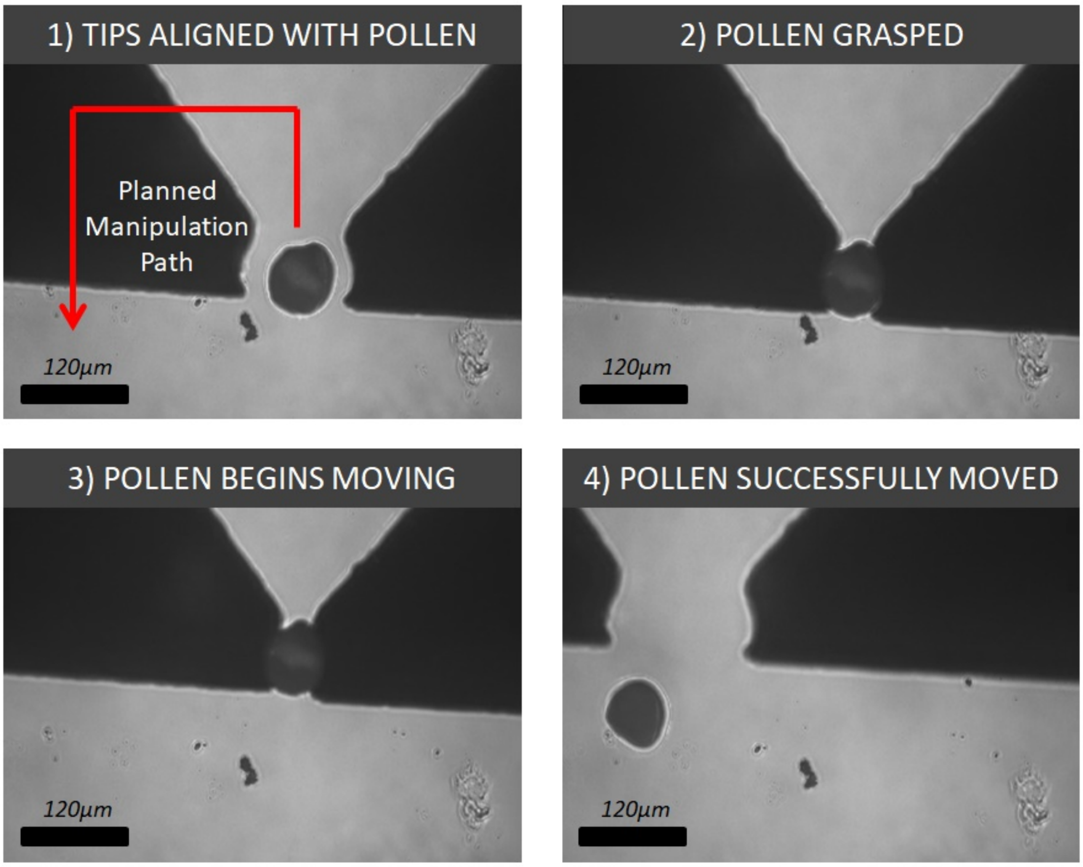

FIGURE 3.13: Process of grasping and moving a grain of pollen with silicon round tips

3.4.3 Biological Manipulation Conclusions

Biological objects are generally much softer and less dense than glass micro beads. Initially, sharp tips were used to attempt manipulation of a 60 μm thick human eyelash. Due to the small surface area and lack of force control, the eyelash was accidentally cut into two pieces. This demonstrated how certain tip shapes can be used as tools at a micro scale (for example cutting or puncturing). It was also shown that the eyelash can be safely manipulated by increasing the tip-object contact area with a set of flat tips.

The results from the previous experiments when manipulating glass beads, concluded that round tips are more suitable for use with spherical objects. Because of this, round tips were used to pick and place a semi spherical 60 μm grain of pollen. Although this is slightly smaller than what has previously been manipulated, the test was successful without causing any damage to the pollen and with problems due to adhesion forces still remaining unseen.

3.5 Smaller Scale Manipulation

Thus far, all manipulation has been achieved using etched shaped silicon micro tips. These experiments have yielded important information on the functionality and efficiency of different tip shapes for a range of different micro objects. Up until now, successful manipulation has been demonstrated on both spherical and non-spherical micro objects, ranging from 60 μm to 500 μm. Unfortunately due to manufacturing limitations, manipulation with these tips has been limited to this size range. Many other micro objects such as micro machines or biological cells, can extend well below this size range and often are found within 1 μm to 20 μm for example, the human red blood cell is approximately 8 μm in diameter. It is therefore important for the micro gripper to be also capable of manipulation within this smaller size range. Thus far in literature, this size range has generally been avoided because of two key reasons. The first reason is manufacturing gripper tips at this scale is very difficult however, the main reason is that adhesion forces begin to dominate at this scale, causing many things to uncontrollably stick together. This presents a challenge with manipulating at this scale, as micro grippers begin to require extremely small contact area with micro objects. If the contact area is too large such as the case with the silicon gripper tips, small objects become extremely difficult to release and stick to the gripper tips. Future work will include refining of the silicon gripper tips in order to reduce this contact area however for the time being, fine borosilicate glass end effectors are used. To demonstrate the capabilities and limitations of the micro gripper when it comes to this size range, a set of pick and place tasks are performed on silica micro beads sized within 1 μm to 20 μm.

3.5.1 Manipulation Time

The purpose of using borosilicate glass end effectors as a micro gripper is to show that very small micro object manipulation between 1 μm to 20 μm is possible with the current compliant gripper system. At this scale, grasping each micro bead became very challenging as the size decreased. To show this, a sample of randomly sized silica micro beads (within 1 μm to 20 μm) was prepared, this time in a liquid environment to reduce any unwanted electrostatic or capillary adhesion forces. A single bead for each size range (starting at 20 μm and decreasing evenly) was then selected for grasping. The time taken to achieve a stable grip was then recorded and repeated a total of 20 times for each bead size with the results shown below (Fig. 3.14).

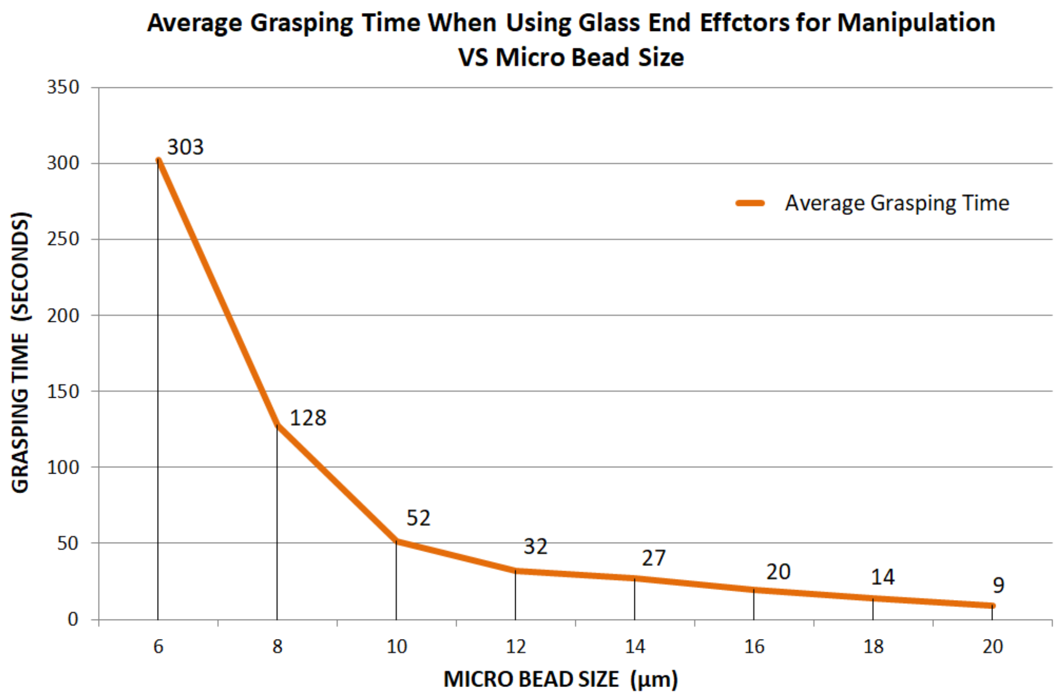

FIGURE 3.14: The average time taken to achieve a stable grip on different sized beads with glass end effectors

Across the range of 20 μm to 12 μm, the average time was found to slightly increase in a relatively linear fashion from 9 seconds to 32 seconds respectively. This result was expected as a decrease in object size naturally requires a finer alignment and thus more user effort however, this began to change as the bead size went below 12 μm. From this point the average grasping time is shown to begin exponentially increasing. This can also be seen from the sudden increase in slope when viewed from the graphed data (Fig. 3.14). By the time the bead size had reduced to 6 μm, the average time had increased by more than 9 times (303 seconds) since the 12 μm bead (32 seconds).

This sudden increase is due to one key reason, in that a smaller bead will require finer tip-object alignment in order to properly grasp the bead around its equator. The problem is that this also requires a more precision alignment system in order to realise these subtle changes. In this case, alignment is gauged by comparing the focus of both the bead and end effectors with an optical microscope. As the bead size dips below 12 μm, the limits of this microscope become more apparent causing subtle changes in alignment to become no longer noticeable. This can be seen in Fig. 3.15, where the size of the 6 μm bead is almost indistinguishable from the end effector tip size. It is for this reason that manipulation difficulty drastically increases when grasping very small micro beads as much of the alignment becomes a trial and error process.

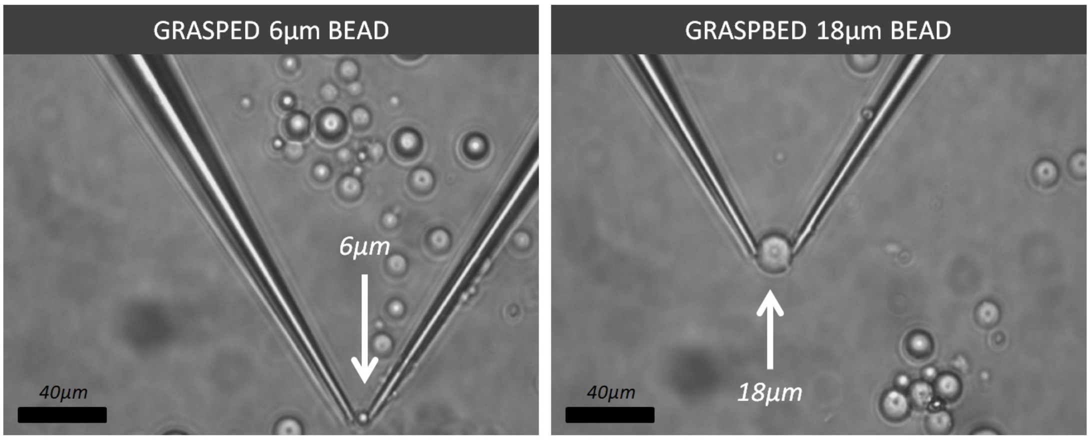

FIGURE 3.15: Grasping a 6um bead versus an 18um bead with glass end effectors

3.5.2 Adhesion Problem

Adhesion forces have previously been discussed as a potential limiting factor in the success of pick an place tasks as the target object becomes smaller. In the first experiment, etched silicon gripper tips were successfully used to pick an place objects sized from 60 μm to 500 μm and were incapable of manipulating anything smaller. Because of this relatively large scale, no noticeable effects due to adhesion were witnessed however, this is no longer the case.

Adhesion Characterisation:

With the addition of fine glass end effectors to the compliant gripping system, the capable target object was improved to a minimum target of just 6 μm. Adequate object grasping has been shown as one difficulty within this size range however, adhesive forces now pose a second difficulty when it comes to object placement. This is demonstrated in Fig. 3.16, where the gripper repeatedly grasps, then opens around a single 18 μm micro bead. When the gripper opens, the bead will randomly adhere to either the left or right side of the gripper, as both end effectors are almost identical and share a very similar contact area with the bead.

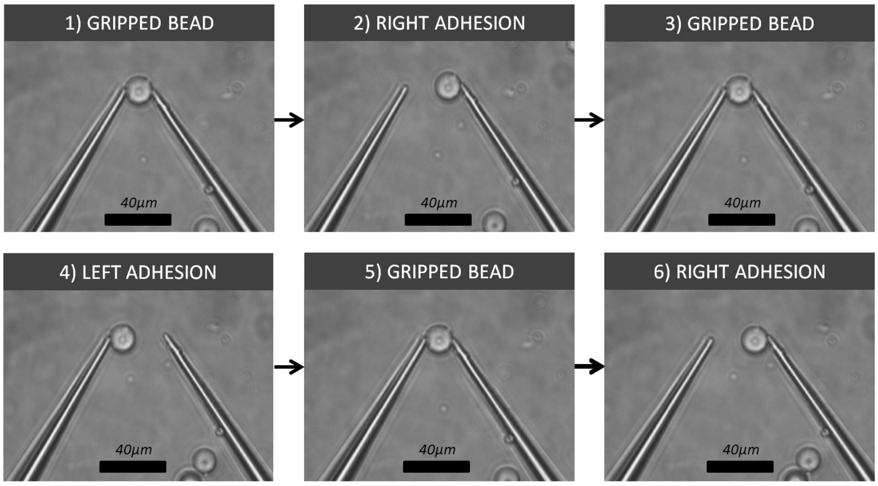

FIGURE 3.16: Repeated grasping of an 18um micro bead showing random adhesion to either side of the gripper tip

Ideally in theory, the bead should have a 50-50 adherence rate to the left and right end effectors respectively. In order to examine this, a short experiment was performed to record which side a micro bead would adhere to when opened and closed a total of 20 times. The experiment was repeated across the same combination of bead sizes as previously used (6 μm to 20 μm) with the results shown in the graph below (Fig. 3.17).

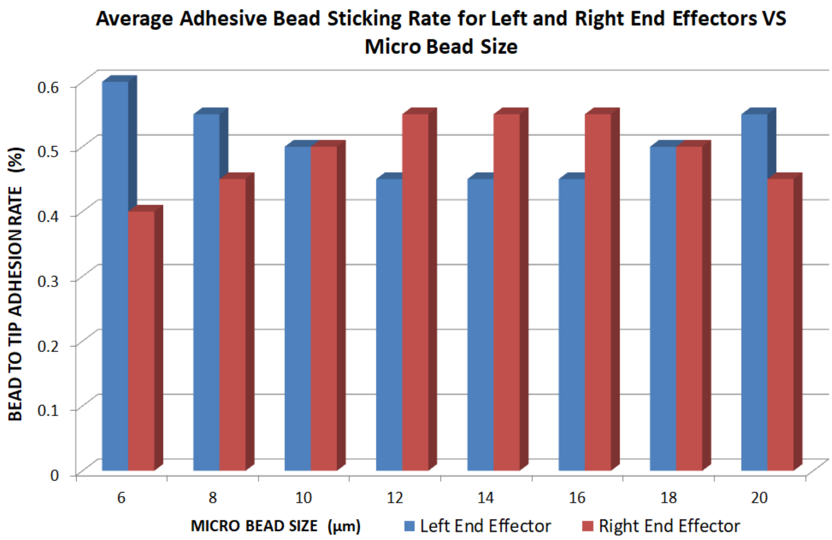

FIGURE 3.17: Graph showing the average bead adherence rate to both the left (blue) and right (red) end effectors for different sized micro beads

The results revealed two key conclusions. Firstly, as expected the average left-right ratio was very close to being 50-50 across all sizes of micro beads. The largest difference from this was a 60-40 ratio with 6 μm beads. A slight difference like this can be expected as both sides of the gripper will never be perfectly aligned or identical. Secondly, all sizes of micro bead adhered to either the left or right gripper 100% of the time. This means that placing any of these beads will be impossible without some form of release strategy which leads us to our next and final experiment.

Bead Release Strategy:

In order to pick and deposit these beads to a location in the sample, a simple method to prevent the bead from sticking to the gripper upon release was discovered. When the gripper tips are abruptly opened at high speed, the bead will often detach from the gripper tips and remain in position on the substrate floor. This is in part related to the end effectors being almost identical. When the tips open at high speed, the adhesive force holding the bead to the end effector is less than the force required to accelerate the bead to the speed of release. Because the tips are reasonably similar, at the time of release the accelerating force from each end effector is equal and opposite. Because the adhesive force from either end effector is too weak to remain adhered to the bead while accelerating, the net force acting on the bead becomes zero causing each end effector to break away at exactly the same time, subsequently causing the bead to remain stationary at the point it was once grasped. This can be seen happening in Fig. 3.18 where the bead is seen to be released just a single camera frame after being grasped.

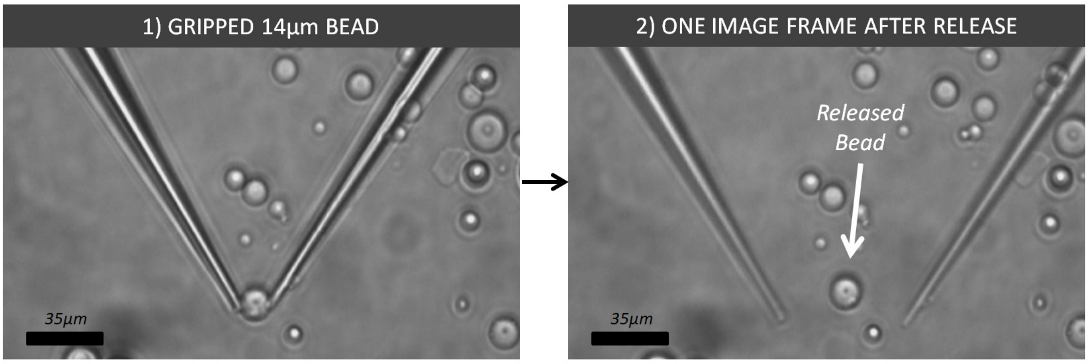

FIGURE 3.18: Image showing high speed release with a 14um micro bead grasped by glass end effectors then released a single camera frame later

Because the release speed is finite, there is a possibility that smaller beads may lack the necessary mass to break adhesion and therefore remain adhered to the tips, even under high velocity. To test this, a similar experiment was carried out however, in this case the success was recorded as either released or adhered to the gripper without any reference to the left or right end effector. Each bead size from 6 μm to 20 μm was released at high speed over the course of 20 trials with the results shown below (Fig. 3.19).

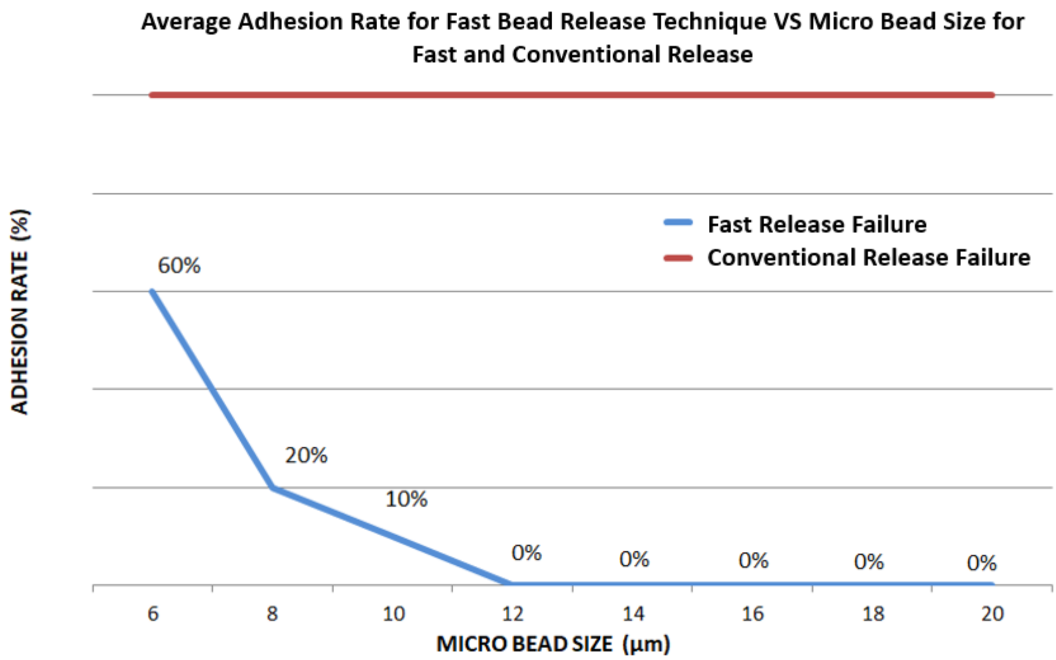

FIGURE 3.19: Graph showing high-speed glass end effector micro bead release success rate for different sizes of bead

The results show that for bead sizes from 20 μm to 12 μm, all were released successfully. Release success begins to drop beyond this point with 10%, 20% and 60% of 10 μm, 8 μm and 6 μm beads adhering to the gripper respectively. Conventional release is also shown in Fig. 3.19 as having a 100% adhesion rate (0% release success) for each bead size.

3.5.3 Small Scale Conclusions

One of the primary aims for this project was to develop a modular micro gripper with easily replaceable gripper tips for different manipulation tasks. The initial idea was to achieve all manipulation of both large and small scale micro objects by using a vast variety of different etched silicon tips. Unfortunately due to manufacturing limitations, it was impossible to create silicon tips with the required features small enough to manipulate objects below 60 μm. Although the silicon tips still proved useful, another one of the grippers early research aims was to have the ability to manipulate cellular sized objects (1 μm - 20 μm) and therefore a solution was needed. This lead to the development of a new set of mounts for the complaint micro gripper, designed to house and align a pair of glass end effectors for manipulation in this size range. This allowed the gripper to maintain a modular design with both silicon shaped tips and glass end effector capabilities.

These experiments demonstrated that the successful manipulation of cellular sized objects with glass end effectors is possible. The problems relating to previously unseen adhesion forces were examined and characterised which also resulted in a simple yet effective release method being developed. This proved to be very reliable for releasing objects ranging from 20 μm to 12 μm. Beyond this point, the success rate was found to significantly drop. Successful release however, is still possible across all capable size ranges with the smallest manipulatable object size (6 μm) successfully releasing approximately 40% of the time. Although 40% may seem like not very often, the reality is that object manipulation within this size range is extremely difficult. When compared to related literature, the size range, release success, modularity and functionality of our current compliant micro gripper far outweighs many of the examples.

Chapter 4

Conclusions & Recommendations

The research outlined in this report has focused on the development of a compliant micro gripping tool for manipulation of different object shapes and sizes. Micro grippers (and many other MEMS) have recently been a very active topic among scientists due to the sub-nano meter manufacturing abilities that are available in today's modern laboratory equipment. In chapter 1, a detailed examination of the current literature relating to compliant micro gripping technologies was presented. The potential for improvement was made clearly apparent as many of the current problems relating to micro manipulation were revealed. The information gathered was then used to form the basis of four key research objectives for the development to follow. In order to create a novel and unique solution, the objectives were heavily designed around the current problems and gaps found in literature. To conclude this report, the remainder of this chapter will provide a brief discussion for each research objective, remarking on how it was achieved, the level of success it had, and any possible recommendations for future work.

4.1 Design Complexity

Many of the micro gripper designs in literature were shown as having very complex designs. In many cases this is due to the compliant gripper structure and actuator being manufactured entirely at a micro scale. This inherently makes these grippers very difficult to manufacture. It also means their functionality is limited, as they cannot be easily rearranged for different manipulation set-ups or target objects. It was therefore decided that the first research objective was to develop a simple and easy to use design.

Ultimately this was achieved by creating the gripper in two pieces, consisting of a larger base gripper in which more precise gripper tips could be attached. The compliant base gripper was extensively used throughout this project and appeared to function very well in all given circumstances. Due to its compliant nature, there was a concern that it may suffer fatigue failure at some point. To avoid this, many FEA simulations were run to decide the optimal hinge thickness based on the amount of flexure. This optimisation was successful as after repeated flexing, the gripper has suffered no permanent deformation or fatigue. Manufacturing complexity was also reduced by creating the base from aluminium sheet with a simple milling process. Although complex micro fabrication was unavoidable in order to create the shaped silicon tips, it was greatly reduced by designing them as an attachment, rather than an entire gripper.

Another benefit for the gripper being made as two pieces is modularity. This has been shown countless times in this report by the grippers ability to house a wide array of attachments for different gripping tasks. Successful manipulation on many different target objects was demonstrated by the attachment of shaped silicon micro tips and also borosilicate glass end effectors. Furthermore, the process of fixing these attachments was found to be effortless, despite their delicate nature. Achieving proper alignment however, was often difficult and required careful fine tuning of the attachment. This was expected due to the lack of precision in manufacturing the base and therefore certain alignment tools were built into the attachments however, fine tuning this was still a very tedious process and could potentially be improved in the future.

Because of these reasons, it can be concluded that minimising the design complexity of the gripper has been successful. This is especially made apparent when compared to grippers in literature with similar object-size manipulation capabilities.

4.2 Replaceability

To an extent, replaceability can be related to design complexity, in the fact that many of the incredibly complex micro grippers in literature cannot be easily replaced. During manipulation, gripper tips often require replacement due to reasons such as contamination or accidental breakage. As mentioned before, generally grippers capable of cell-sized object manipulation are manufactured entirely at a micro scale. this essentially makes them a 1-time use gripper and very expensive to replace due to complex fabrication processes.

Because of the reasons above, replaceability was carefully considered in the design of our gripper. Another reason for designing the gripper as two pieces, was so that the majority of the system (the compliant base) stayed reusable. This leaves only the micro tips requiring replacement, rather than the entire gripper. This two-piece design worked very well apart from a few alignment issues as mentioned in the previous section.

Although replacement of some areas in a micro gripper are inevitable, this has been significantly reduced in our system. Both silicon and borosilicate glass micro tips can be replaced however, it may be worth pursuing a simpler method for fabricating shaped micro tips, as this is still a very time consuming process.

4.3 Target Object Manipulation

Target object size is very important for any micro manipulation system. The smaller the object capable of being picked and placed, the more desirable the system will be. Having the ability to manipulate a single cell as opposed to an entire culture, can be crucial to understanding its individual characteristics. Many of the grippers reviewed in chapter 1 lack this ability, therefore one of our grippers objectives was to manipulate objects within this range.

Silicon tips were initially planned to be the primary method of manipulation. Unfortunately due to manufacturing limitations, it was impossible to create silicon tips with the required features small enough to manipulate objects below 60 μm. In order to manipulate smaller objects, a set of glass end effectors were used. This was proven to work well for objects ranging from 6 μm - 20 μm. The downside of using this method is that more alignment of the tips is required, as each end effector is physically separate from one another, as opposed to the silicon tips which are manufactured as a single piece. Although a good manipulation range was achieved, either refining the alignment method or developing single piece tips capable of this range is recommended.

Adhesion also became a problem at this range with the target objects sticking to the gripper tip 100% of the time. In order to overcome this, a fast release method was used to break the tips free and deposit the target object to the substrate floor. Although this method is not ideal as it could potentially be damaging to an object or the tips, in this case it was shown to work well. Further reducing adhesive forces could potentially be realised in the future by reducing manipulator size, effectively lowering object-tip contact area.

Bio-compatibility was also briefly considered as many biological objects can be soft and fragile. This was shown when manipulating a human eyelash with a set of sharp tips. When grasped, the eyelash was almost instantaneously cut. Flat tips with decreased object-tip surface area were then used to pick and place the hair without damaging. This test showed the importance of tip selection when dealing with softer objects to avoid damaging them accidentally. It is also possible that implementing some form of force sensing in the future could also prevent cutting from occurring.

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