THE DEVELOPMENT OF AN ANTI-GRAVITY ARM TO ASSIST IN THE REHABILITATION OF STROKE PATIENTS

A dissertation submitted by

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ABSTRACT

This project shows that it is possible to design and develop a low cost anti gravity arm to assist in the rehabilitation of stroke patients that can interact in a three dimensional virtual reality environment. The study focuses on the development of a passive, natural movement device to maximise the muscles exercised while reducing the complexity and cost of the device.

A prototype anti gravity arm was manufactured. The prototype’s effectiveness was tested with the use of tension bands to provide the motive force in reducing the effects of gravity. It is demonstrated that the anti gravity arm provides a reduction in the effort required by the patient to move their arm thereby providing a stroke patient suffering hemiparesis the ability to exercise their arm. It is shown through previous studies that exercise of the affected arm is the leading contributor to rehabilitation.

The use of forward kinematics demonstrates that it is possible to translate the movement of the anti gravity arm into movement within a virtual world. The project shows that the real world movements can be correctly interpreted by the device and projected onto a computer monitor allowing the movement of a virtual hand within a virtual room. Analysis of the results shows a favourable correlation between the movement of the anti gravity arm and the expected movements depicted within the virtual environment.

By reducing the effort required to move a patient’s arm and providing the mechanism to depict this movement within a virtual environment, the project has indicated that that a low cost anti gravity arm may be an effective solution in rehabilitation therapy.
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INTRODUCTION

1 INTRODUCTION

Stroke affects thousands of Australians every year. The outcomes for stroke vary, but it is likely that the survivor of stroke will suffer a disability. As the number of stroke patients requiring physiotherapy increases, there is a need to help reduce the strain placed on the availability of physiotherapists. It is accepted that for a stroke patient to recover the use of their affected limb, they need to exercise the affected limb as much as possible. To this end the project attempts to determine the viability of developing a low cost anti gravity arm to assist in the rehabilitation of stroke patients.

1.1 PRESENT SYSTEMS

There are various methods in use for the rehabilitation of stroke patients. The accepted treatment is intensive physiotherapist care as soon as practical after the event followed by home based therapy as soon as the patient has recovered sufficiently. This method often results in sub standard rehabilitation as the majority of rehabilitation care is left up to the patient. Any lack of motivation can lead to a drastic decrease in ability.

To help in this, new methods of rehabilitation are being investigated world wide. Methods of interest include the use of active and passive robotic assistance. This assistance may be in the form of planar or natural movement robots. The most expensive and generally most capable of these is the active natural movement device, with the least expensive and generally least capable device being the passive planar device. These devices usually include an interactive display to help maintain patient interest by turning the exercises into games and to help facilitate tracking of results by the physiotherapist. However, many of these systems are hospital or clinic based and this can result in the benefits provided by these devices being limited to the sessions available to the patient.

1.2 PROBLEM DEFINITION

With a view of providing a low cost, home based system, this project hopes to develop an anti gravity arm to allow patients to exercise and monitor their performance at more regular intervals, in their own home. The device should provide for the reduction of
effort on behalf of the stroke patient to move their arm, with the movement available to the patient being as wide as practicable.

The anti gravity arm is to be used in the rehabilitation of stroke patients which may include use under the supervision of a physiotherapist or unsupervised use at home. To assist in this, the device should include an interactive virtual world to help develop exercises and to maintain the patient’s interest.

1.3 PROJECT OBJECTIVES

The objectives defined for the project are to design and develop a low cost anti gravity arm to assist in the rehabilitation of stroke patients. To accomplish this, objectives have been set that allow for a systematic approach for developing the device. These objectives are:

- Research of relevant background information.
- Evaluation of similar systems.
- Detail design of an anti gravity arm.
- Development of software to translate movement of the device into movement projected in a virtual world.
- Analysis of the results, suggesting improvements and future work.

Further more, the device should provide for significant reduction in the effort required by the patient to move their arm. The device should provide for a wide range of motion, exercising the shoulder and elbow but limiting the movement about the wrist to help simplify the design.

1.4 METHODOLOGY

Investigations will be made to determine current practices for stroke rehabilitation. Robotic rehabilitation devices will be researched so that an ideal model can be developed that best fits the project objectives. Once these investigations have been undertaken a computer model will be developed so that an appreciation of the design constraints can be understood. From the computer model, detail design drawings will be developed.
The design drawings will allow for the anti gravity arm to be built by the USQ workshop. Once built, basic mechanical testing of the device can be undertaken. This testing will be used to determine the amount of assistance that can be provided and to check for any changes that may need to be made to the design.

After the basic mechanical testing is complete, software can be developed to interpret the output of sensors that can measure the rotation of the joints so that this movement can be reproduced in a virtual world. Testing of the software will be to ensure that the real world movements are correctly reproduced in the virtual world.

**1.5 CONCLUSION**

The project is to design and develop an anti gravity arm to assist in the rehabilitation of stroke patients. The project will involve the investigation of current stroke therapies, the design of an appropriate anti gravity arm, the design of a virtual environment that reproduces the real world movement of the device and testing to conclude whether the anti gravity arm meets the design goals.
2 LITERATURE REVIEW

A study of papers prepared by various experts in their field is presented here to help define the key areas relating to an anti gravity arm to assist in the rehabilitation of stroke patients. The following literature review will investigate stroke, its causes and effects as well as stroke therapies that are currently practiced. Further investigation will reveal new stroke therapies that have been proposed and what benefits they may provide over more traditional stroke therapy.

2.1 STROKE

A basic definition of stroke is an interruption of blood flow and therefore oxygen to the brain. There are two major types of stroke. The most common form of stroke, called ischaemic stroke, is caused when a blood clot forms that blocks or plugs a blood vessel in the brain. By blocking the flow of blood, sections of the brain become starved of oxygen and glucose causing the destruction of that section of the brain.

The other typical form of stroke, called hemorrhagic stroke, is caused when a blood vessel breaks and bleeds into the brain. As the blood within the artery is under a high pressure, this rupture tears the soft brain tissue and subsequently forms a large clot that squashes the surrounding brain. The clot may then cut off blood supply to that region causing the destruction of brain tissue.

Stroke is the third most common cause of death in Australia (Corbett 2003). Of the 40,000 Australians that have a stroke annually, 70% survive. Of those that survive, 50% will have a disability that will affect their independence in daily activities (Corbett 2003). These statistics show that 14,000 Australians annually could benefit from an enhanced method of rehabilitation.

2.2 OUTCOMES OF STROKE

A common disability that results from stroke is complete paralysis on one side of the body, called hemiplegia. A related disability that is not as debilitating as paralysis is
one-sided weakness, or hemiparesis. Stroke also commonly affects the speech and memory centres of the brain.

A stroke that occurs in the right hemisphere of the brain will affect control of movement on the left side of the body. Sufferers of a right hemisphere stroke are also likely to suffer problems with their spatial and perceptual abilities (Corbett 2003). A stroke that occurs in the left hemisphere of the brain will affect control of movement on the right side of the body. Sufferers of a left hemisphere stroke are also likely to have difficulty with speech and language skills (Corbett 2003).

It is well known how stroke occurs and what the outcomes are. What is not fully understood is what can be done to either eliminate the effects of stroke, through healing and medical intervention, or mitigate the effects of stroke, through rehabilitation. The area of focus here is brain plasticity. Within brain plasticity lays the possibility that the brain can repair itself or other parts of the brain may learn new functions to compensate for the loss of function elsewhere. Taub et al. (1999) have shown through neuroimaging and transcranial magnetic stimulation that massed practice producing sustained activity can induce reorganisation of the brain.

If the brain does have some inherent plasticity, it has to be asked what can be done to utilise this. Wolf et al. (1989) have shown that the forced use of hemiplegic upper extremities (arm and shoulder) does reverse the effect of learned non-use in stroke patients. The views of Taub et al. (1999) and Wolf et al. (1989) imply that a repeated exercise regime focusing on the affected limbs may promote reorganisation of brain structure that would allow a patient suffering from stroke to regain movement and control over their affected limb.

There are many different methods used to exercise the affected limb to assist in this brain reorganisation. These include physiotherapist manipulation, tabletop exercise, constraint induced therapy and mechanically supported exercise. The main emphasis is on getting the patients to move their affected limb through a wide range of movements for extended periods of time. Mataric et al. (2007) showed that it was not the device itself that was important, more the fact that the patient used their affected limb consistently in a range of different tasks.
2.3 CURRENT THERAPIES

Therapy for stroke patients can be broken down into three categories which are determined by the timeframe of when the stroke occurred. These are acute care, which is the timeframe directly after the event, rehabilitation, generally up to one year after the event and long term support (Minkman et al., 2005). An increasing trend within stroke care is a decrease in the length of inpatient stay with a move towards more community care (Coupar et al., 2007). This move has resulted in the development of therapies that can be effectively managed in the home.

A type of rehabilitation program that clinical trials have shown to provide great benefit to stroke affected limbs is Constraint Induced therapy (CI therapy) (Taub, Lum and Hardin 2005). CI therapy involves task based training for extended timeframes daily, transfer of exercises to real life situations and restraint of the less affected limb from use. While CI therapy provides great benefits to stroke patients its use is limited outside of the original hospital stay and periodic physiotherapist sessions due to the large amount of one on one therapist supervision required (Lum et al. 2005).

(Patton, Stoykov and Kovic, 2005) have suggested that exercises need not be set up to guide the patient’s motion or reduce the errors they make. It is suggested that a more beneficial system may be to disturb the motion so that the patient needs to adapt to overcome this offset. In essence a force field is applied around the target, be it forcing the patients hand away from the target or introducing a coriolis effect around the target. A coriolis effect is applied by forcing the patients hand away from the target in a circular manner. The effect can be visualised as similar to a satellite view of a cyclone. The swirling vortices of cloud that you see represent the forces applied. These forces are strongest near the target and weaker as you extend outwards. What is suggested is that patient specific force effects can be developed so that the patient learns to adapt to these conditions and the resulting after effect corrects their impairment.

Kahn et al. (2001) suggest that a training regime that reduces errors when exercising with a robotic device does not provide any added benefit compared to repetitive reaching training where errors are allowed. This appears to point to the conclusion that it is not particularly relevant as to what rehabilitation regime is adopted, more that there be a continued intensive exercise routine for the stroke affected limb.
For a stroke patient to get the most benefit from an exercise routine and to be able to regain the most movement and functionality from their affected limb, there is a need for an exercise routine to be developed that can be utilised at home for extended periods up to the point where no more functional improvement can be seen. Therefore a desirable goal for the project is to develop a system where the exercises can be carried out at home on the affected limb, have session times extending past one hour in duration and have exercises whose skills can be transferred to real life situations.

The movement that a patient’s arm is moved through in rehabilitation therapy can be placed into two categories. These categories are planar and natural movement. Planar movement, in the terms of this paper, is the movement of the arm in two dimensions only. This description is normally associated with exercises where the patient moves their arm forwards and backwards, left and right. This way the patient exercises the use of the elbow joint as well as limited use of the shoulder. Planar movement may also include the rotation and bending associated with wrist movement.

Natural movement, in the terms of this paper, is the movement of the arm in three dimensions. Natural movement utilises the arm and shoulder to their full extent by reflecting the normal range of motion that the arm may move through. Natural movement may be limited to not including the rotation and bending associated with the wrist as this often simplifies the assistance device.

2.3.1 PHYSIOTHERAPIST ASSISTED EXERCISES

A physiotherapist has the knowledge to analyse a patient’s movement and control abilities following stroke and be able to determine the best course of remedial action. A physiotherapist will initiate therapy as soon as practical after a stroke. This may be as soon as the following day as it is generally accepted that the most marked improvements occur within the first three months following a stroke event (Lindmark, 1988).

Typical physiotherapist exercise in the acute stage would include hand on hand exercise (Johnstone, 1987). This is where the physiotherapist takes direct control of the patient’s limb to move it through a range of positions to perform a task. These tasks may be placing pegs in holes, picking up objects and drawing. The physiotherapist can tell how
the patient is progressing by the way the patient is reacting to the direct stimulation. As the patient regains control of the affected limb, the over corrections and unstable, jerky movement is abated.

Another acute stage exercise suggested by Johnstone (1987) is the stretching of the affected limb. Through lack of use the muscles and tendons tighten. To overcome this, the physiotherapist will manipulate the patient affected limb through a full range of extension exercises. As the patient progresses they may be able to initiate movements of their own accord. To this extent the physiotherapist may introduce manipulatory exercises. These exercises are where the patient picks up, reaches for and squeezes/manipulates different objects. All these exercises are intended to have real life analogies so that the patient can transfer their new learned motor control to their home life.

2.3.2 HOME BASED EXERCISES

Home based exercises are exercises developed by a physiotherapist that are able to be self initiated and conducted at home. Home base exercises have been developed to help reduce the patient load on the physiotherapy system and for the motivated patient to enhance their rehabilitation ability. These exercises are generally simple to complete and require minimal equipment. The exercises are not designed to replace the physiotherapist but to enable rehabilitation to continue without direct one on one supervision and direction.

Table top exercises are a common option for home based exercise (Taub et al. 2006). In table top exercises the patient would lay their affected limb flat on a table with a tea towel underneath. The tea towel is there to help eliminate the friction of the arm rubbing directly on the table. The patient then moves their arm forwards and backwards, left and right. They may try reaching for objects sitting on the table or try and draw patterns on the table.

While tabletop exercises are easy to setup and require no additional equipment, there are some fairly obvious deficiencies with this exercise regime. While the patient is learning control of their arm they are not building the strength required to support the weight of the arm. The control that they do develop is limited to two dimensions as tabletop
exercises are planar exercises. If the patient lacks the ability to overcome the friction between the table and tea towel, the exercises are all but useless and will be more detrimental by reducing the patient’s motivation.

Balls of various sizes are used to exercise the fingers and wrist. The tactile response of manipulating and arranging various sized balls is an exercise that can be completed at home with limited resources (Kamal, 1987).

2.4 RESULTS OF THERAPY

Studies undertaken by Taub et al. (2006) have shown significant outcomes for stroke patients suffering from hemiplegia or hemiparesis of the upper extremities. Through a placebo controlled trial using constraint induced therapy, Taub et al. have shown not only significant improvements over the course of intervention, but a maintenance of this improvement with only a marginal drop over a two year period, figure 2.1.

As constraint induced therapy in its most basic sense is the forced use of the impaired limb, it is feasible that these results will carry over to other therapies where the patient exercises the impaired limb for extended periods of time. These results also correspond with the views of Duncan (1997) that the amount of motor recovery present at one year after stroke is the level at which patients will remain.
Common sense would indicate that the more you exercise the more benefit that is received. This assumption is validated by Langhemmer, Lidmark and Stanghelle (2006) with their results from the study of regular planned exercise versus treatment when necessary indicates that an intensive follow-up programme during the first year after stroke is highly favourable.

2.5 ROBOTIC REHABILITATION

Robots are the ideal training partner. A robot cannot be exhausted, strained or frustrated. A robot is always willing to participate and can be made available any time of day. If a robot can be made available at home then there are no limitations to the number and variety of exercises the patient can do.

There are a number of devices currently under development or that have been introduced to the market that assist in relieving the weight of a stroke impaired arm to assist in rehabilitation. These devices can be broken down in categories of active, where the device can force the movement of the affected limb in multiple directions with various force and passive, where the device has no active control over how much assistance is given at any time after the initial setup.

2.5.1 ACTIVE ASSISTANCE

An active device is one where the device can apply a force to move or restrict the patients affected limb. An active device can use electric motors, pneumatics or hydraulics to apply a force in a similar way that a welding robot may move about to carry out its tasks. With active assistance it becomes possible to have a device that can apply many different types of rehabilitation theory. During one exercise the device may provide active assistance where the device will guide the patient’s limb to target. During another exercise the device may resist the patient’s movements or apply an error that tends to push the patients limb away from the target.

Active devices can come in the form of planar or natural movements. Most active devices are planar in design so as to reduce the complexity of the design and associated
control systems. Due to their inherent cost and complexity, active devices are normally restricted in use to hospital and clinical facilities.

2.5.2 PASSIVE ASSISTANCE

A passive device is one where the device can provide assistance in removing some of the effort involved in movement. A passive device may use springs or some form of elastic band to provide a constant force. The force, once setup, cannot be increased or decreased by the controller, only through the natural tendencies of the medium.

Passive devices can come in the form of planar or natural movements. Generally speaking, because passive devices do not need the additional complexities of control systems they can be more complex in the amount of freedom available to the patient.

2.6 THERAPY ROBOTS

Robot assisted rehabilitation is still considered a new and novel approach for stroke rehabilitation. Most studies that have been conducted have been restricted in either being short term or limited in the number of participants. The generally accepted treatment for stroke rehabilitation is well documented and proven. It is for these reasons that robot assisted rehabilitation has been slow to be introduced. There is however a small handful of researchers that have developed and begun to market robot assisted rehabilitation devices.

2.6.1 MIT-MANUS

The MIT-Manus, (‘Manus’ meaning hand in Latin) is a direct drive, five bar linkage mechanism which can provide two degree of freedom movement for the fore arm and elbow. The MIT-Manus also has a differential mechanism driven by geared actuators to allow three degree of freedom wrist movement (Hogan et al. 1992).

The device can be described by the terms of this paper as an active planar device as it can direct the movement of the patients hand through two planes of motion. The device simulates direct “hand over hand” instruction as a proven rehabilitation technique (Hogan et al. 1992). The MIT-Manus will guide the patients hand with variable
firmness to the target. To promote the development of motor control, the firmness of guidance is reduced as the patient regains control and strength.

The MIT-Manus has an interactive display to help develop activities and exercises and to keep the patient’s interest. The MIT-Manus exercises are setup by a physiotherapist guiding the patient’s hand, attached to the device, through a range of exercises or activities. The device records these movements and can then replay the movement by guiding the patient’s hand in a similar manner to that of the therapist. It is therefore possible to have a patient utilise the device at home by running previously described programs without the physiotherapist needing to be present.

![Figure 2-2 - MIT-Manus Active Planar Device (Hogan et al. 1992)](image)

2.6.2 T-WREX

The T-WREX or Therapy WREX is a natural movement, passive device based on the Wilmington Robotic Exoskeleton. The T-WREX can track the patient’s movements and can represent these movements in two dimensions on a screen display. The T-WREX requires a physiotherapist to set up the device by applying elastic bands to the tension bars which creates a lifting force that acts on the upper arm and forearm until the patient’s arm can float freely. The physiotherapist can then guide the patient through the built-in exercise programs that mimic daily activities. As the patient regains motor control the physiotherapist can decrease the assistance provided by the device by removing elastic bands, thereby reducing the anti-gravity effect of the device.
The T-WREX has five degrees of freedom and can provide an estimated 66% of vertical movement and 72% of horizontal movement (Sanchez et al., 2006). The sensors used to collect angular information are precision potentiometers. Although data in all three dimensions is collected, this is then reduced to two dimensions for feedback in the interactive exercises.

![Figure 2-3 - T-WREX Passive Natural Movement Device (Sanchez et al. 2006)](image)

### 2.6.3 NeReBOT

The NeReBOT (NEuroREhabilitation robot) is a three degree of freedom wire driven robot. The NeReBOT can be considered an active, natural movement device with some limitations. The device uses three electric motors to control the tension in three nylon wires that are connected by magnetic break off points to a forearm split. These magnetic break off points are a safety device where if the load exceeds the preset value of the magnetic connection, the wires disconnect.

As the NeReBOT has only three electric motors to control five degrees of freedom, some limitations are incurred. Each electric motor can only supply a pulling force, gravity can supply a downward force but there is no mechanism to control horizontal movement. Due to the way that the device is configured, the patient’s arm can travel along the horizontal plane with little effort.

To initiate the exercise program a physiotherapist guides the patient’s forearm to a specific point while a constant light tension is maintained by the electric motors. Once
the target position is met the physiotherapist initiates a control program to determine the joint trajectories required for the device to meet this target. The device can then exercise the patient’s affected limb by adjusting the tensions in the three control wires, moving the patient’s arm to and from the target.

![NeReBOT Active Natural Movement Device](image)

**Figure 2-4 - NeReBOT Active Natural Movement Device (Rosati, Gallina & Masiero, 2007)**

The control algorithms that are used, allow the device to determine how much force the device is supplying compared to the amount of force that the patient is able to exert. This data is used in determining the progress of the patient and can assist the physiotherapist in determining the correct exercises to conduct (Rosati *et al.* 2007).

## 2.7 CONCLUSION

It can be seen that stroke is a major cause of disability in Australia. The 40,000 stroke patients annually in Australia, 14,000 will suffer a form of disability. The large number of new patients every year places a great strain on the available physiotherapists. There is a need for rehabilitation services that can increase the quality life for stroke patients and that can help reduce the need for intensive physiotherapist care.
Studies presented here have shown that robot assisted rehabilitation is a feasible and practical method to help in the rehabilitation of stroke patients suffering from hemiparesis. They also suggest that it may be practical to perform physiotherapy session at home while not under the direct care of a physiotherapist.

The studies do not agree on what method of rehabilitation is most beneficial. Many methods exist and they all show promising increases in the ability of the patient to regain use of their affected limb. What can be taken from the studies is that it may not be important which method is used rather the fact that the affected limb is being used. One consensus that many of the studies do agree upon is that it is better to exercise through the widest range of movements to see the best results.
3 DEVELOPMENT OF CONCEPT

There are various factors to be considered before it is possible to select a design that best meets the objectives of the project. Many approaches have been developed to help make an informed decision that goes some way to eliminating personal prejudices against one form or the next. To assist in the decisions required before initiating a complex and costly build, a thorough analysis of possible solutions is required to help analyse and justify the decisions made.

3.1 FORM OF CONCEPT

There are two main parameters that will govern all other decisions in the design of the anti gravity arm. These are the assistance proved (active or passive) and the amount of freedom provided to the patient (planar or natural movement). These two criteria are paramount to the design and need to be weighed up carefully for consideration.

An active anti gravity arm may be considered as the ultimate in design philosophies. It appears that there is so much that can be accomplished with an active device. It would be possible to incorporate a whole range of theories in stroke rehabilitation including disturbing the motion of the patient’s arm using the Coriolis Effect, assisting the patient’s movements similar to direct hand on hand therapy and the exaggeration of errors forcing the patient to over correct. There would be the ability to treat chronic patients with hemiplegia that have no ability to move at all.

The disadvantage of an active system is the large increase in complexity. Depending on the mode of movement used a direct drive system with five degrees of freedom would require five motors with appropriate controllers, using indirect drive this can increase to ten motors and controllers. This factor alone is enough to place an active system out of scope for this project. It is simply not possible to develop an active system on the budget and timeframe allocated. In addition, the programming skills required to get an active device working are well beyond the scope of this project.
A passive anti gravity arm could be considered as a compromised solution. The inherent nature of the design is simplicity. The forces provided by the device are generally only those needed to offset the effects of gravity. This reduces the need for force generation to two devices, one lifting the fore arm and one lifting the upper arm. Due to the fact that a passive device offers constant assistance once setup, there is no need for complex motor and controller combinations. A simple elastic band is enough to provide the force required to offset the effects of gravity.

Research by Reinkensmeyer and Housman (2007) suggest that the additional therapeutic benefit offered by active devices may not correspond to the increase in cost and complexity. It can be suggested that if a passive device can be made at a low enough cost that it becomes reasonable for patients to have one available at home, then a passive device could be advantageous to an active device that is normally restricted to hospital or clinical use. The patient would have instant access to the device and with the proper activities developed the patient would have an entertaining form of rehabilitation that is proven to work.

This reduction in complexity and cost associated with the elimination of five to ten motors and controllers makes a passive anti gravity arm a very attractive solution when confronted with a restricted budget. Research suggesting the additional abilities of an active device may not account for the increase in cost helps to reassure that the solution need not be a compromised one. It is for these reasons that I chose to develop a passive anti gravity arm.

Having narrowed the selection criteria to that of a passive device helps in the decision on the range of freedoms allowed by the anti gravity arm. A passive planar device would be the most simple to design, so long as restrictions were made to limiting movement to shoulder and elbow. In a planar device there would be no need to have a mechanism to offset the effects of gravity by lifting the device as this could all be accomplished within the device structure itself. A simple multi directional skateboard that the fore arm rested on would accomplish the task, yet tracking of movements would become difficult. A self supported scissoring arm that projects in the horizontal frame would be able to provide a range of planar movement and would allow for easy tracking.
Limitations of a planar device include a reduction in the range of motion supported by the device, particularly in relation to the shoulder. The shoulder is only exercised in two degrees of freedom rather than the three degrees of freedom that it can normally travel within. While the patient would be exercising a range of motions and regaining muscle control, it is debatable as to whether this would extend to regaining the ability to being able to support their own arm. Harwin, Patton and Edgerton (2006) when studying the MIT-Manus, a planar device, suggest that more degrees of freedom should be available to allow movement of the shoulder against gravity.

A passive natural movement anti gravity arm would allow for the widest range of movement in the patients arm. The patient would be able to move their arm through four of the seven degrees of freedom as allowed by the structure of the human arm. Depending on how the device was designed there would most likely be limitations imposed on the full range of motion. For example; the patient may no be able to reach directly overhead while using to the anti gravity arm.

A natural movement device would need some form of mechanism to support the fore arm and upper arm as well as the weight of the device itself. The design of the device and the force required to support the arm would need careful consideration. It would be preferable if the effort required moving the arm was the same regardless of the attitude that the arm is currently in. Adding more freedom to the anti gravity arm increases the requirements for tracking. Five degrees of freedom implies at least five sensors to detect movement. These factors introduce added complexities in a passive device.

After studying the various other devices being developed to rehabilitate stroke patients and the analysis of the advantages and disadvantages of active versus passive and planar versus natural movement, I decided that the basic format for the anti gravity arm would be a natural movement passive assistance robot.
3.2 MOVEMENT

A human arm has seven degrees of freedom, three in the shoulder, one in the elbow and three in the wrist. The degrees of freedom are:

- The up and down movement or pitch of the shoulder.
- The side to side motion or yaw of the shoulder.
- The rotational movement or roll of the shoulder.
- The bending motion of the elbow called pitch.
- The up and down flexing of the wrist called pitch.
- The side to side flexing of the wrist called yaw.
- The rotational movement of the wrist called roll.

These seven degrees of freedom are what allows the human arm such dexterity of movement. The scope of this project is to allow for the widest range of motion for the first four degrees of freedom. By eliminating the need to accommodate the three degrees of freedom associated with the wrist it is possible to significantly reduce the complexity of the design while still maintaining a large range of motion for stroke rehabilitation exercises.

3.2.1 PHYSIOLOGY OF HUMAN ARM MOVEMENT

When you move your arm, you incorporate the combined movements of the different degrees of freedom provided by the joints in your arm. It is seldom the case that a movement results in a series of singular joint movements, rather a combination of joint movements that work together to move your hand to the correct target position in the least amount of time. For an anti gravity arm to be of assistance it needs to be able to work with the patient and follow the natural motion of movement for an arm.

The shoulder has three degrees of freedom which can be expressed in mechanical terms. The pitch, yaw and roll of the shoulder are a direct result of the ball socket type joint of the humerus and glenoid cavity shown in figure 3.1. Pointing your arm directly away from you and moving the arm up and down results in the rotation of the humerus in the glenoid cavity, pitching the arm up and down. Maintaining the direction of your arm but moving the arm side to side again results in the rotation of the humerus in the
The movement of the clavicle can be used to introduce two additional degrees of freedom in the arm. This concept can be understood by hunching your shoulder up and down. This results in additional pitching of the shoulder. Hunching your shoulder forwards and backwards results in additional yaw of the shoulder. While doing this, you are not using the pitch, yaw or roll movement of the head of the humerus and glenoid cavity, rather the sweeping and raising motion enabled by the clavicle.

The elbow is a much more simplified joint and is shown in figure 3.2. Hanging your arm straight down, the movement of the elbow can be seen as being restricted to pitching up and down through approximately 180°. This movement can be thought of as starting with the humerus and radius/ulna horizontal. The elbow can now pitch as the
Developments of concept

Radius/ulna rise from the horizontal, pass through the point of being perpendicular, finally coming to rest on top of the humerus.

![Anatomy of Human Elbow](image)

Figure 3-2 - Anatomy of Human Elbow (A.A.O.S., 2007)

Descriptions of the movements of the wrist are neglected as they are beyond the scope of the project.

3.2.2 MOTION OF A NATURAL MOVEMENT DEVICE

A natural movement device must attempt to mimic natural human arm movement as much as possible. It has been shown that the movement of the shoulder joint is a complex arrangement of complimentary movements about the clavicle and the head of the humerus intersecting with the glenoid cavity.

To accommodate this movement, the anti gravity arm will need to be able to support each degree of freedom available in the clavicle and the humerus and glenoid cavity joints. Starting with the clavicle, the anti gravity arm will need to be able to allow the shoulder itself to be raised and lowered, defined as the pitch of the clavicle, and to be moved forwards and backwards, defined as the yaw of the clavicle. This is illustrated in figure 3.3.
The shoulder joint is more complex with the inclusion of roll within the humerus and glenoid cavity joint. This roll associated with the humerus and glenoid cavity is quite small. As wrist movements are not being addressed, the fore arm will be confined to a fixed attitude with the palm of the hand facing the floor. In this position it is next to impossible to distinguish roll of the shoulder from a combination of pitch and yaw about the shoulder. In light of this, I have made the assumption that roll of the shoulder can be ignored as it will most likely be constrained by the manner in which the patient’s arm interacts with the anti gravity arm support.

The shoulder movements that now need to be catered for have been reduced to pitch and yaw. The anti gravity arm will need to allow the patient’s humerus to pitch forwards and backwards to accommodate reaching motions. The anti gravity arm will need to allow the humerus to yaw left and right resulting in a sweeping motion of the patient’s arm. These motions are illustrated in figure 3.4.

The elbow is a simple rotation joint that can pitch the radius and ulna approximately 180° about the end of the humerus. The limitations in the relationship between the radius and ulna to the humerus should be maintained in the anti gravity arm. If the anti gravity arm elbow joint was able to pitch past the horizontal in relation to the humerus then it is likely that the patients arm would come into contact with the device during certain movements or that the weight of the device might cause an injury to the patient by over extending this joint. If the anti gravity arm elbow has the same limitations as a human elbow, then as the patient’s elbow reaches the extension limit, the anti gravity arm elbow will do the same and further sweeping movement would be passed on to the yaw of the shoulder. This is similar to what happens in a human arm.
Another movement not directly related to the elbow joint, but one that affects the forearm is a combination of pitch and yaw about the shoulder. This action, combined with the fixed attitude of the forearm results in a pseudo elbow yaw. This can be examined by holding your forearm in a fixed attitude with the palm facing the floor. If you lift your hand, it appears that the elbow has found a new degree of freedom. What is happening is the shoulder is changing its pitch and yaw resulting in a rotation that reflects as yaw on the elbow joint. This motion of elbow pitch, pseudo yaw and the associated limits are best explained by figure 3.5.
To allow an anti gravity arm to interact with a human arm, limiting this movement to that of the shoulder and elbow, requires that the anti gravity arm be able to accommodate five degrees of freedom. These are the pitch and yaw of the clavicle, the pitch and yaw of the humerus and glenoid cavity and the pitch of the elbow. It has been assumed that the roll of the shoulder will be eliminated by the fixed attitude of the fore arm when supported by the anti gravity arm.

3.3 MECHANICAL STRUCTURE

The design of a passive natural movement anti gravity arm needs to facilitate the movements of the patient’s arm as they exercise a wide range of motion. The anti gravity arm must neutralise the weight of the device itself as well as the changing weights of different patient’s arms. It should take comparatively little force to move the patient’s arm when the device is fitted.

The design of an anti gravity arm shoulder joint requires the ability to accommodate movements that the patient may try to make. The shoulder joint must accept patient movements that use the pitch and yaw of the clavicle as well as the pitch and yaw of the humerus and glenoid cavity. The device should be able to accept movement occurring in a single degree of freedom or in multiple degrees of freedom at once. The movement of the device should work in conjunction with the movement of the arm, in no way restricting this movement but following the movement of the arm while allowing the ability to track these movements.

It would be very difficult to try and design a single joint that could manage to raise and lower, reach forwards and backwards while twisting and tilting all the while maintaining accurate measurements of all angles of movement. It is reasonable to take steps to disassemble this joint so that each degree of freedom is contained within one particular area only. By doing this, it is possible to reduce each degree of freedom to a simple rotating shaft. This simplifies the design and allows for easy measurement of angles.

The pitch of the clavicle can be accommodated in two ways. It is possible to include an arm rotating on a horizontal shaft that will follow the rise and fall of the clavicle, shown in figure 3.6. It is also feasible that this can be eliminated altogether by mounting the
shoulder joint a distance above the patients arm. By doing this I am accommodating the rise and fall motion, but as I am only interested in measuring the position of the hand in relation to all movement, this rise and fall will have a flow through effect on the position of the hand without the need to directly measure it.

![Figure 3-6 - Accommodating Clavicle Pitch](image)

Yaw of the clavicle can be accommodated by rotating about the vertical in a motion similar to figure 3.7. This rotation would allow for the hunching movements that can be made by the shoulder, but once again this may be able to be eliminated as this movement does not have a direct effect on the position of the hand. A benefit of incorporating clavicle yaw would be the ability for the anti gravity arm to automatically adjust to differences in patient arm length or patient positioning when using the system.

![Figure 3-7 - Accommodating Clavicle Yaw](image)

The anti gravity arm shoulder joint must be able to move with the pitch and yaw of the patient’s shoulder. To accomplish this, the joint must facilitate movement about two
axes simultaneously as well as singularly. Use of a ball type joint would provide for this combination of movement in a small package that could easily be purchased off the shelf. The problem arises when one tries to track the movement of the ball type joint.

A solution is to separate the movements into two rotating shaft type joints that are normal to each other. This allows for easy angular tracking, but does increase the size of the packaged solution. The pitch of the shoulder has the shoulder joint rotating about a horizontal shaft shown in figure 3.8a. The yaw of the shoulder has the joint rotating about a vertical shaft shown in figure 3.8b.

The elbow joint of the anti gravity arm must allow for pitch of the patient’s elbow as well as the pseudo yaw mentioned previously. In the attitude that the patient’s arm will be held in, the pitch of the elbow corresponds to horizontal motion, while the pseudo yaw corresponds with vertical motion. As such it is a simple matter to develop the elbow joint by replicating the shoulder joint. The motion of shoulder pitch becomes pseudo elbow yaw and shoulder yaw becomes elbow pitch.

By incorporating these concepts into a model that can allow for yaw of the clavicle, pitch and yaw of the shoulder and pitch and pseudo yaw of the elbow a basic model of the anti gravity arm can be drawn as in figure 3.9. While not including all the finer details, the model does help in the visualisation of the problem and what form an appropriate solution may take.
3.4 FORCE GENERATION

The users of the device are patients with limited muscular strength and control. It is reasonable then to take measures to reduce the forces required to move the anti gravity arm. In studying the concept drawing it becomes apparent that motions revolving about the vertical will be able to support their own weight and that of the patient, but motions revolving about the horizontal will cause the arm to droop. To resolve this and to provide the required support to the patient, some form of force will need to be exerted at the points of horizontal rotation. By applying a force that is calibrated to the weight of the device and the individual patient, it is possible to lift these sections and so provide a feeling of weightlessness to the patient.

To provide the force required to lift the apparatus and the patient’s arm, different methods of force generation have been investigated. The requirements I set out for the force generation device was that it provide a constant force over a large range of movement, have a constant force over a range of environmental conditions, be easy to adjust and that the force generation device be compact its physical size. The reasoning behind the need for constant force generation is that I wanted the force provided to be as linear as possible over a full range of movement provided by the apparatus. I did not want the force provided to vary due to environmental conditions, such as changes in temperature as this would cause differing results from one day to the next. This may
affect the ability of the physiotherapist to interpret the correct results as the patient progresses through the exercises.

Springs were initially investigated as they are a common commodity and are generally the first item thought of when requiring simple force generation. Springs come in a wide range of sizes and shapes and are specified by their manufacturer with a known force that they can provide.

The problem with springs is that while it would be quite easy to find a spring that would match the requirements of the apparatus in the unloaded state, it would become quite cumbersome applying multiple springs to try and match the different weights of individual patients. Once you start getting three or four springs mounted in a small space they tend to grow laterally in size and take up quite a lot of room.

Elastic bands were investigated as they are a cheap source of force, are commonly available in a wide range of sizes and take up very little room even when stacking multiple elastic bands in the same general location. A major benefit of elastic bands over springs is the ability to stack elastic bands in close proximity, even on top of each other until the correct amount of force is applied. This lends itself well to adjusting the apparatus to suit different patients.

In an effort to find an elastic medium that was stable against changes in temperature and extended use, I found a range of tension bands offered by AustBAND. These tension bands are used for exercise and rehabilitation and offer a variety of resistances ranging from light through to extra, extra heavy. The bands are available at a low cost of approximately $4/m from Clarke Rubber.

The tension bands consist of dual layer tubing that is colour coded for varying resistances. The tubing comes in rolls and needs to be cut to size. The tubing is very flexible and can easily double its cut length when stretched.

In an effort to eliminate the need for someone to physically adjust the device before use, air muscles were researched as a form of automatically adjusting the force supplied by the device. An air muscle is a pneumatic device that works in a manner similar to that of a human muscle with a very large power to weight ratio. An appropriately designed air muscle can lift up to 400 times its own weight.
An air muscle consists of an internal expandable tube, surrounded by a strong braided tubular mesh sleeve. As the inner tube is stretched, the braided tube contracts and elongates up to a set limit imposed by the external tube. When air pressure is applied to the inner tube it first expands until it hits the external braided tube. As they touch, the expansion of the inner tube forces the external braided tube to expand radially and contract axially. This axial contraction continues as air pressure is applied until the air pressure stabilises or the external braided tube has reached the limits of radial expansion. Thus you have an actuator which will stretch when air pressure is reduced and contract when air pressure is increased.

To use air muscles to provide the anti gravity force for the device it would be necessary to have two control valves, one for the upper arm and one for the lower arm. Each of the valves would be suitable to control multiple air muscles if needed as long as they are on the same circuit. With the control valves connected to the micro controller it would be possible to set the anti gravity arm up with the press of a single button. By knowing the attitude of the arm in a relaxed floating state, it would be possible to apply air pressure to the air muscles until that attitude is reached. The air muscles would then be able to provide a continuous force throughout the exercise program.

An attractive advantage of using air muscles is that it would be quite reasonable to transform the anti gravity arm into an active device with the addition of two more air muscles controlling the horizontal elbow and shoulder movements. Some judicious control structure would enable the controller to raise and lower the fore and upper arms as well as independently move the elbow and shoulder left or right.

One disadvantage of air muscles is that they can only provide a one way force. An air muscle can contract only. They require a secondary force to expand the muscle ready for the next movement. When in use for the passive anti gravity arm, this is of no concern as the weight of the device as well as the patient’s arm are more than sufficient to provide this extending force. In the active state it would be necessary to either have a matched opposite air muscle or have the single muscle act against an opposing spring.
3.5 FRICTION REDUCTION

Friction will play an important part in the usability of the device. If the force required moving a joint is too great, the device will be of little benefit. There is a need to reduce friction as much as practical so that the forces required for moving are as low as possible.

The most basic method of removing friction is the sliding bearing also known as the plain bearing. Sliding bearings are a cheap method for the reduction of friction but they do have limitations. A sliding bearing has three well defined levels of lubrication which are defined by the Strubeck Curve (Juvinall & Marshek, 2000). A typical Strubeck Curve is shown in figure 3.10. At slow rotations the friction is represented by (I) with the bearing in the boundary lubrication phase. As the rotational speed increases, the bearing progresses to the mixed film lubrication phase as represented by (II). At fast rotations as represented by (III) the bearing is in the hydrodynamic lubrication phase.

![Figure 3-10 - Typical Strubeck Curve (Hironaka, 1984)](image)

The important information to be taken from the Stribeck Curve is that friction is highest at slow rotations. This has a profound effect on the anti-gravity arm as all rotations will be small and so inherently slow.
A rolling element bearing is a friction reduction device where the outer race, fixed to the body of the device, is separated by balls or rods from the inner race, which is fixed to the shaft of the device. The balls or rods transform the sliding friction into one of rolling friction. This has the benefit of reducing friction at low speeds, but may incur the penalty of reduced life at very high rotational speeds. A typical spherical ball bearing is shown in figure 3.11.

![Figure 3-11 - Spherical Ball Bearing (Wikipedia, 2008)](image)

Two common forms of rolling element bearings are the spherical ball and cylindrical roller bearing. The spherical ball bearing is designed to be compact in size with the ability to carry both radial and axial loads. The cylindrical roller bearing is larger in size for a comparable hole dimension but can carry substantially larger radial loads with a limited ability for carrying axial loads when compared to a spherical ball bearing. A cylindrical roller bearing has higher friction under axial loadings.

The bearings used in the anti gravity arm will be under a combination of radial and axial loads. Radial loads are those acting perpendicular to the shaft. Axial loads are those acting parallel to the shaft. The loads applied will not be large as the device only needs to carry its own weight and that of the patient’s arm at very low rotational velocities.

### 3.6 POSITION SENSORS

To be able to determine exactly what position the apparatus is in at any one time, one needs to be able to measure the angle that each degree of freedom is currently in or at a minimum how far it has it moved from the last known position. There are various ways
to achieve this. One option would be to know where angle zero is and then measure from there. Another way would be to assume a relative zero position and relate all movement back to that. This is an important differentiating factor as sensors that can perform the former are significantly more expensive than those that can do the latter.

In choosing the correct sensor to determine the position of each degree of freedom, I have set certain guidelines that must be met. The sensor must be able to measure a rotational change. The sensor should be able to be run from 3.3V DC with a low current draw and should require only one input to the micro controller. The sensor must be low cost, preferably under $30 per sensor.

A potentiometer is a three terminal resistor that utilises a sliding contact to perform the function of an adjustable voltage divider. The voltage divider function performed by the potentiometer may be linear or logarithmic in nature. The change in voltage of a linear potentiometer is proportional to the distance travelled by the contact. The change in voltage of a logarithmic potentiometer closely follows logarithmic laws. When used as a position control sensor, the preferred type of potentiometer is linear.

A potentiometer can be classified with respect to the maximum resistance offered by the potentiometer, the tolerance of the resistance, the repeatability of a specific resistance given specific travel of the contact and the number of turns the potentiometer contact may traverse before reaching a stop. A one turn potentiometer refers to a potentiometer contact that can traverse approximately 270°, while a three or ten turn potentiometer will provide a figure much closer to 360° per turn. In general terms the lower the tolerance, the smaller the repeatability error percent and the more turns, the more expensive a potentiometer will be. A potentiometer may range in cost from below $1 to $50 or more.

By fixing the body of the potentiometer the body of a device and rotating the contact connected to the shaft of the device, it is possible to use a potentiometer to measure a change in voltage as the shaft rotates. If you have a linear, ten turn, 10kΩ potentiometer, every degree of rotation the potentiometer value will result in a change in resistance of 2.78Ω.
A rotary encoder is an electro-mechanical device used to translate mechanical motion into electrical data. An encoder converts the mechanical rotation of a shaft into a digital code. There are two main classification of rotary encoder, absolute and relative.

An absolute encoder can be of mechanical or optical construction. A mechanical absolute encoder uses a series of concentric metal rings. These metal rings have sections that are removed to allow a contact to conduct only at certain points of rotation. Within these concentric rings a sliding contact rotates. As the contact moves, different parts of the contact are conducting, while others are not. This creates a distinct binary code for a specific angular position. The precision of this angular position is relative to the number of tracks within the encoder. A very simple three track encoder would have a precision of 45°. An example of how a three bit absolute encoder works is shown in table 3.1. An optical absolute encoder works in a similar manner using transparent and opaque glass with light passing through instead of metal rings and contacts.

<table>
<thead>
<tr>
<th>Contact 1</th>
<th>Contact 2</th>
<th>Contact 3</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>off</td>
<td>off</td>
<td>off</td>
<td>0° to 45°</td>
</tr>
<tr>
<td>off</td>
<td>off</td>
<td>on</td>
<td>45° to 90°</td>
</tr>
<tr>
<td>off</td>
<td>on</td>
<td>off</td>
<td>90° to 135°</td>
</tr>
<tr>
<td>off</td>
<td>on</td>
<td>on</td>
<td>135° to 180°</td>
</tr>
<tr>
<td>on</td>
<td>off</td>
<td>off</td>
<td>180° to 225°</td>
</tr>
<tr>
<td>on</td>
<td>off</td>
<td>on</td>
<td>225° to 270°</td>
</tr>
<tr>
<td>on</td>
<td>on</td>
<td>off</td>
<td>270° to 315°</td>
</tr>
<tr>
<td>on</td>
<td>on</td>
<td>on</td>
<td>315° to 360°</td>
</tr>
</tbody>
</table>

A relative encoder can be mechanical or optical in construction as above but has two outputs that are 90° out of phase. Relative encoder output is shown in table 3.2. As the encoder rotates the output transitions through a half step. To get the correct data from the encoder it is imperative that the encoder outputs be read before they change. It can be seen that if the encoder is rotated too fast that it is possible for the data to be misinterpreted. If the micro controller read only phase one and phase three it would not be possible to determine if the device moved clockwise or anti clockwise. Just as likely, the device could be moving so fast that the encoder is read every five phases and so the micro controller sees the device as stationary when in actual fact the device is moving at great speed.
Table 3-2 - Relative Encoder Binary Output

<table>
<thead>
<tr>
<th>Phase</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

An encoder’s resolution is determined by the pulses per revolution (PPR) offered by the metal or glass disks. Lower PPR encoders which may only differentiate down to changes of 5.625° may cost as little as $8 whereas an encoder that can measure in fractions of degrees can cost upwards of $800.

A hall effect sensor is a device that uses the change in a magnetic field to produce an electrical pulse. As a ferrite object is passed through the field of the sensor an electrical pulse is generated. When used as position sensors a multi-toothed ring is passed through the field of the sensor to produce electrical ticks at each measurable increment. To be able to determine direction as well as change in position two sensors need to be used out of phase to result in a similar output to the relative encoder shown in figure 3.12 previously.

Hall effect sensors range in price from $15 to $100. Other costs that need to be factored in are the manufacture of the timing ring that passes through the hall field. The accuracy of the sensor will be determined by how many timing notches are applied to the timing ring and how many sensors are mounted together. With this in mind it can be seen that the space requirements of an accurate position control hall effect sensor become rather large.

### 3.7 DATA ACQUISITION

Taking analogue data from the sensors and converting this into useful digital information requires the use of an analogue to digital converter (ADC). An ADC can be purchased as a stand-alone component or as an included component within a micro controller. Due to the nature of the project and the likelihood that the scope of the project would change in the future, I decided that the best approach would be to look at micro controllers that offer a good ADC solution with the power and functionality to perform additional tasks.
DEVELOPMENT OF CONCEPT

An ADC can be specified by the accuracy of its measurements and the time taken to complete these measurements. An example of this is an 8bit ADC that can convert an analogue signal into a fraction of the supply signal correct to 8bits. This means that if the signal has a range of 0-3V then the ADC would be able to break this value down into 256 segments, with each ADC value representing a voltage of increase of 0.0117V. A 10 bit ADC can break this value down into 1024 segments each representing a voltage increase of 0.00293V.

The speed of an ADC is determined by the time it takes to complete one full conversion at the converters maximum accuracy. Therefore it is possible to increase the speed of an ADC calculation by reducing the accuracy of the calculation. A quick test to see if the speed of the ADC will be adequate is to check that the ADC is able to complete 25 conversion cycles for every half second. This requirement is based on the generally acknowledged idea that updating a moving image of a screen 25 times per second eliminates flicker and that the micro controller will need to do additional tasks apart from running the ADC such as output to an RS232 connection.

As there are five degrees of freedom that need to be measured, there need to be five ADC channels available for conversions. It is important that there actually be five channels available. Many micro controllers, especially those already mounted on a development board will have some form of pin sharing. This means that some of the ADC pins may be permanently connected to another component such as a button or an LED.

There are a variety of micro controllers on the market, each with their own advantages and disadvantages. Many of these micro controllers are available on the same development board with the same component list. Any of these would make an acceptable choice and a lot of the decision comes down to personal preference. The major micro controller architectures in use today include the ARM, ATMEL and PIC architectures. Each of these architectures has their followers and much advice can be found online.

The ARM range of micro controllers is a 32bit family of RISC (Reduced Instruction Set Computer) chips. The ARM7 2138 series has a CPU frequency of 60MHz with 32kBytes of RAM and 512kBytes of Flash memory for storage. The micro controllers
include two, 10bit eight channel ADC’s, six Pulse Width Modulators (PWM), two 32bit timers and various other devices built in. ARM7 micro controllers are a very powerful yet low cost design.

The ATMEL range of micro controllers offer a large selection of chips ranging from 8bit through to 32bit families. ATMEL micro controllers can offer similar specifications to that of ARM7 micro controllers with the exceptions of reduced memory and lower speeds. A typical ATMEL micro of similar cost to an ARM7 micro would be the ATmega128. The ATmega128 offers 4kBytes of RAM, 4kBytes of data EEPROM and 128kBytes of Flash memory for storage. The micro offers a single 10bit eight channel ADC. The ATmega128 can run at speeds up to 16MHz.

The PIC range of micro controllers, like the ATMEL offer a large selection of chips ranging from 8bit through to 32bit families. Once again a PIC micro controller can offer similar specifications to that of ARM7 micro controllers with reduced memory, reduced speed and a reduced availability of on board components. A PIC micro of similar cost to an ARM7 and ATMEL chip would be the PIC16F87X. This chip can run at speeds up to 20MHz and includes a single 10bit ADC with four channels. Available memory is low with 368Bytes of RAM, 256Bytes of data EEPROM and 14kBytes of Flash memory storage.

All three of the above micro controllers are available in the same development board package which includes a sixteen character, two line LCD display, five buttons, an LED, various proprietary connections and a 240V relay. The cost for each micro in this standardised development package is approximately $140. The development board can be seen in figure 13.12.

![Figure 3-12 - MT Development Board (ARM, ATMEL and PIC) (Dontronics, 2008)](image-url)
3.8 CONCLUSION

The design of the anti gravity arm should cater for the movements of the clavicle, shoulder and elbow. Restricting the movement of the wrist will allow for a simpler device and will not restrict the exercises available to the patient excessively. The structure of the anti gravity arm will mimic the human anatomy so that the device will be constructed with a clavicle, shoulder and elbow. This methodology should help to ensure that the device will be able to move with the patient’s arm and not restrict the movement of the patient.

To provide the anti gravity assistance, some form of mechanical energy will need to be exerted on the device lifting the upper arm and lower arm. The method of force generation should have a linear effect on the arm in that the force supplied should not change as the device is moved through a range of motion. The method of force generation should be compact and easily adjustable to cater for the differences in the anatomical size of patients.

As the device is designed to reduce the effort required to move the arm of a stroke patient, the movement of the joints of the device should be as fluid as possible. To accomplish this, a form of bearing would be required that can remove friction while still being able to support the forces generated by the anti gravity arm when in use.

To measure the movement of the anti gravity arm, sensors will need to be place at the points of rotation. These sensors need to be able to measure a rotational change and be able to track these changes accurately. To translate this data into meaningful information a micro controller will need to be able to read this information, either through an analogue to digital converter or by reading the transmitter code of the sensor. The micro controller should be able to communicate with a personal computer to allow for integration of the movement of the anti gravity arm into a virtual environment.
In designing the prototype, I wanted to make the design ‘modular’ in that it would be able to accept a wide range of different settings as I was not sure what concepts or setups would be most beneficial. This type of design philosophy would allow me to test a range of different setups without the need for the re-engineering of parts. While this has increased the weight of the device, this type of design philosophy has helped reduce the time needed to test different ideas. The final design is shown in figure 4.1 to allow the reader to familiarise themselves with the design before an in depth study is undertaken.

**Figure 4-1 - Anti Gravity Arm Prototype**

4.1 **PROTOTYPE STRUCTURE**

From the concept design, it was decided that it was possible to eliminate clavicle pitch from the prototype design. The benefit of being able to measure the rise and fall of the clavicle did not out weight the added complexity that this additional degree of freedom would impose. Clavicle yaw would be included based on the assumption that the added complexity of an additional joint would be compensated for by the ability to adapt to the
size and positioning of different users without the need for physical adjustment of the device.

The clavicle of the anti gravity arm is a 150mm long beam that is the connecting structure between the stand that the anti gravity arm is supported by and the start of the shoulder structure. As the clavicle is the main support for the entire weight of the device as well as needing the ability to support the weight of a stroke patients arm, the clavicle is designed to house four 26mm spherical ball bearings, two mounted at opposite ends on opposing sides. This can be seen in figure 4.2. The bearing shells are supported on the lips visible in the model.

![Figure 4-2 - Anti Gravity Arm Clavicle](image)

Connection to the stand is made by an 83mm long, 10mm diameter shaft that is designed to incorporate a sensor mount to the underside of the clavicle, a 1.5mm lip to support the bearing centre and a 50mm bearing support shaft with a 20mm threaded end. These features can be seen in figure 4.3. The sensor mount is an 8mm diameter hole that is 10mm in depth to allow for the soft mounting of the rotating shaft of a sensor. Soft mounting is when the shaft of the sensor is not permanently fixed to the hole of the mount but is removed from a physical connection by a rubber sheath. This method was chosen to allow for inconsistencies in the mounting of the sensors and to help eliminate the chance of shaft wear of the sensor due to offset mounting.
A second shaft mounted opposite to the stand shaft and running in the opposite direction is the upper shoulder shaft. This shaft is used to place the clavicle and stand well clear of the patient. To facilitate this, the upper shoulder shaft is of similar construction to the stand shaft with the exception of an added length totalling 220mm. The upper shoulder shaft can be seen in figure 4.4.
The bearing supported connection of the upper shoulder shaft and the clavicle provides for shoulder yaw. Sensor mounting is similar to that in the stand shaft allowing for measurement of shoulder yaw. The upper shoulder shaft is now fixed to the shoulder by a threaded end and lock nut.

The shoulder is a 150mm x 60mm x 20mm block of aluminium that needs to provide for shoulder pitch. It accomplishes this by mounting horizontal shafts within a vertical cut out. The vertical cut allows for a wide range of adjustment in testing. These features can be seen in figure 4.5.

![Figure 4-5 - Anti Gravity Arm Shoulder](image)

The pitch of the shoulder is translated to vertical movement of the upper arm by rotating the control arms about a sensor shaft and a tension shaft. The tension shaft is an 83mm long, 10mm diameter shaft designed to be supported by a fixed connection to the shoulder cut out, be able to support a bearing mounted control arm and to provide a support for the force generation required to lift the upper arm. Fixing of the shaft to the shoulder is accomplished by a reduced diameter section of 8mm that can be inserted through the shoulder cut out and secured with a locknut and washer. The bearing is then mounted on the original 10mm diameter section supported on one side by a locknut and washer and on the other by a 1.5mm lip. A reduction in diameter to 6mm allows for secure mounting of a force generation device which is capped by a return to the original 10mm diameter. This may be seen in figure 4.6.
The sensor shaft is of similar construction to the tension shaft with the removal of the force generation mount, replaced by a soft sensor mount. This allows for the measurement of the pitch of the shoulder. The sensor shaft can be seen in figure 4.7.

The complete shoulder assembly with the tension and sensor shafts at their extremes of adjustment is shown in figure 4.8.
The upper arm portion of the anti-gravity arm corresponds with the humerus bone. In designing the upper arm I had to consider the forces that would be applied to the control arms as force was applied to neutralise the effects of gravity. As the upper arm supports the entire weight of the patient’s arm as well as the device, it was likely that twisting and other undue stresses may be applied to the control arms. Due to these considerations I implemented dual control arms for the upper arm structure. The assembled control arm structure can be seen in figure 4.9. The upper arm structure connects to the shoulder joint via the tension and sensor shafts and translates horizontal rotation of the shoulder into the raising and lowering of the arm.
As there is a wide variety in the shapes and sizes of people, it can easily be seen that the length of the humerus between patients may vary. To accommodate this, the construction of the control arm has been broken down into the arm shaft, the end shafts and the arm heads. The arm shaft is a 200mm long, 15mm diameter steel shaft with internal threads at the ends. The end shafts are 85mm long threaded steel shafts that can be threaded into the ends of the arm shaft. The arm heads are bearing supports that can be threaded onto the end shafts. The arm heads are shown in figure 4.10. The arm heads are made from aluminium and have a 26mm cut out that is a press fit for the selected bearings. By incorporating these adjustable ends it is possible to adjust the length of the control arms from 285mm to 375mm as measured from bearing centres.

![Figure 4-10 - Anti Gravity Arm Heads](image.png)

The addition of the second control arm to help distribute the forces generated in use has produced the side effect of keeping the shoulder and elbow parallel. This outcome has increased the complexity of the Denavit-Hartenberg calculations used to compute the location of the anti-gravity arm in three dimensions. This added complication will be discussed further in chapter 6.2.

The upper elbow forms the connection between the shoulder and the elbow and the connection between the elbow and the forearm. The shoulder control arms connect to the upper elbow in a similar manner to that of the shoulder by mounting via bearings onto a tension shaft and a sensor shaft with the sensor mount removed. Connection to the forearm is of a similar manner using a tension shaft and a sensor shaft. The design
of the upper elbow is comparable to that of the shoulder but is manufactured from 175mm x 45mm x 20mm aluminium block. The upper elbow includes two threaded holes at the bottom of the structure to allow for mounting to the lower elbow. The upper elbow can be seen in figure 4.11.

![Figure 4-11 - Anti Gravity Arm Upper Elbow](image)

The lower elbow is attached to the bottom of the upper elbow by two bolts. The lower elbow is 142.5mm x 45mm x 20mm aluminium block with a cut out at one end for the mounting a bearing. This cut out has a lip to support the bearing shell. The lower elbow is duplicated and mounted one on top of the other by an elbow shaft supported by the mounted bearings. To save weight and allow for the smallest closing angle, the depth of the lower elbow is reduced from 20mm to 10mm close to the bolt locations. This reduces the overall depth of the lower elbow to 20mm. The lower elbow can be seen in figure 4.12.
The elbow shaft connects the two lower elbows to form a rotating joint. As each lower elbow has a bearing mounted, the elbow shaft needs to be able to accommodate the width of two bearings. The design of the elbow shaft is a 42mm long, 10mm diameter shaft. The bearing mount is 20mm long with a 15mm reduced section thread for securing the bearings by a locknut and washer. Opposing the thread is a 1.5mm lip to secure the bearings on the opposing side. A 10mm long sensor soft mount is incorporated into the end of the shaft. The design can be seen in figure 4.13.

The range of motion for a human elbow joint is approximately 135° of rotation about the vertical axis. To accommodate this, the anti-gravity arm elbow joint is able to rotate approximately 160° about the vertical axis. The assembly of the elbow joint is best explained through figure 4.14.
By simplifying the design of the elbow joint I have induced an error in that the elbow can never be fully straightened. In practice this is of no real concern as the flexibility of the other joints, specifically the shoulder can overcome this limitation.

The lower arm is the only point of contact that the anti-gravity arm has with the patient. By aligning the patient’s elbow to that of the anti-gravity arm, then strapping the patient’s arm to an arm support, the anti-gravity arm can support the patient’s arm, relieving the effects of gravity.

The design of the lower arm is similar to that of the upper control arms with the exception that the free end does not need a bearing. As there is no bearing the fore arm utilises a modified arm head with a thread replacing the bearing support. The modified arm head is shown in figure 4.15.
The modified tension shaft replaces the bearing support structure with a threaded end. This threaded end is used to fix the modified tension shaft to the modified arm head. The modified tension shaft is shown in figure 4.16.

The lower control arm can be seen in figure 4.17. The lower control arm is designed to be adjustable in the same manner as the upper control arms with a range of 285mm to 375mm. The lower control arm allows for the raising and lowering of the fore arm to accept the pseudo elbow yaw mentioned previously.
4.2 PROTOTYPE COMPONENTS

To complete the development of the anti gravity arm additional components required investigation and testing. The generation of force to lift the upper arm and fore arm, a method to reduce friction and a method of data acquisition are discussed in the following sections. The selection of these components allows for testing and use of the prototype.

4.2.1 PROTOTYPE FORCE GENERATION

Methods of force generation selected for use include elastic bands, tension bands and air muscles. It was found in early testing that three standard office elastic bands of 50mm x 2mm dimensions could lift the lower arm section of the apparatus and eleven of the same type could lift the upper arm section. This was in the early testing stages with the control arms mounted in their upper positions, meaning that less force was required to lift the apparatus.

To test the ability of elastic bands to maintain force integrity over extended time frames, the elastic bands were placed under pressure by mounting them on the anti gravity arm to provide the force required to level both the upper arm and fore arm. After leaving the elastic bands in this tensioned state for 24 hours it was found that the elastic bands had lost a significant portion of their strength and the upper and lower arms were no longer level but were drooping at a significant angle.

Further investigation has revealed a marked change in strength in varying temperatures. Using the elastic bands during ambient temperatures below 10˚C it was found that the elastic bands would produce a greater effect on the anti gravity arm than during similar
testing at higher ambient temperatures. The conclusion made was that as the temperature rose, the elastic bands became more elastic and so were able to offer less resistance to elongation. Subsequently more elastic bands were be required to get the anti gravity arm to float.

Tension bands were chosen as the next logical progression as they are similar to elastic bands without the negatives associated with their use. The tension bands used were manufactured by AustBAND. The manufacturer does not supply any empirical data on the resistive force of the bands. I chose the medium and heavy bands for testing in an effort to use the minimum amount of bands with acceptable control of precision in the force provided. Two different methods were tested for mounting on the anti gravity arm.

For the first test I cut the bands into lengths of 250mm and looped each end to form a 25mm loop. These were secured with a cable tie on each end. I now had a tension band of length 150mm long with a loop at each end for connection to the tension supports. This test performed well although it was found that a substantial number of bands were required to lift the upper arm.

To resolve this a second method was developed where the tension bands were cut to 300mm lengths then looped to form one continuos loop of 150mm in length. The ends were cable tied together. It was expected that this setup would reduce the amount of required bands by half but this was exceeded. Due to the reduction in overall length when looped, this new method showed an increased resistance to stretching and so the required total was reduced to approximately one third.

The best approach to setup the anti gravity arm using tension bands has been to use the continuos loop bands to take up most of the force, then the looped end bands with the medium bands used for minor adjustments. This gives the best linear feel to the arm as the patient moves through a full range of motion. Using too many of the heavy bands in the looped configuration leads to a stiff device as they are near their limit of stretch. This may be eliminated by using a longer length initially of 350mm rather than 300mm. This theory has not been tested due to a lack of material being available.
4.2.2 PROTOTYPE FRICTION REDUCTION

Reduction of friction is accomplished by spherical ball bearings. These bearings were chosen for their ability to handle both axial and radial loads as well as having the lowest rotating friction when operating at very low speeds. To simplify the design and construction process a common size bearing was used throughout. A 10mm internal diameter, 26mm external diameter spherical ball bearing was selected after a thorough examination of the SKF bearing selection chart as seen in table 4.1. The bearing (model 6000-2RS C3) was selected due to the internal diameter or hole size that would allow for an adequate shaft diameter and a load limit that was deemed appropriate. The load limit was calculated by the mass of an average human arm (6% of the 95th percentile male mass) multiplied by the maximum assumed acceleration of 1g.

\[
F_{\text{limit}} = m_{\text{arm}} a_{\text{arm}}
\]
\[
= 0.06 \times 97.5 \times 9.81
\]
\[
= 57.4 N
\]

Assuming the weight of the device will be equal to that of a human arm it is easy to see that the forces applied on the bearings will be low. Even if the acceleration has been under estimated by a factor of ten, the forces applied are still below the basic load ratings of the selected bearings.

Table 4-1 - Spherical Ball Bearing Specifications (SKF, n.d.)

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4.2.3 PROTOTYPE SENSORS

The sensors selected are the Bournes 3590S, 10 turn precision potentiometers. These potentiometers were selected due to their low cost and high resolution of measurement. The potentiometers have a tolerance of 5%, linearity of 1.25% and a resolution of 0.02%.

4.2.4 PROTOTYPE DATA ACQUISITION

An LPC-MT-2138 development board from OLIMEX was selected for data acquisition and control. The LPC-MT-2138 features an ARM7 micro controller with sixteen 10bit ADC’s, a two line, sixteen character LCD for visual feedback and an RS-232 serial connection for data transfer between the development board and a personal computer.

The ARM7 micro controller can run at speeds up to 60MHz in either 16 or 32bit address mode. Use of 16bit addresses saves on memory space but its use includes a processing speed penalty. As the memory storage included on the development board is large in comparison to the expected program size, 32bit operation will be used.

4.3 CONCLUSION

The completed prototype can be seen in figure 4.17. The anti gravity arm is able to support its own weight through the use of tension bands. Adjusting the control arms to a higher position reduces the requirement for tension bands but decreases the linearity of support provided by the arm. This occurs as the length of the tension bands change as the arm is moved about. The closer the control arms are to each other the smaller this change is, but a lower lifting force is applied to the arm. It can therefore be seen that to reduce the magnitude of the change in force the control arms need to be as close as practical to each other while allowing a free range of motion while still being far enough apart so that the tension bands can still provide sufficient force to support the arm.
Movement of the anti gravity arm is smooth and requires very little effort to move through a wide range of motion. The ball bearings mounted at each point of rotation help to eliminate much of the friction.

Bournes 10 turn precision potentiometers are used to measure the motion of each joint. The output from the potentiometers is converted from an analogue voltage signal to a digital signal by five ADC’s on the LPC-MT-2138 micro controller. The micro controller can then process this data and communicate with a PC via an RS-232 port.
5 SOFTWARE DESIGN

Software for the anti gravity arm is written for two separate platforms. Software for the micro controller is written in C. This software controls the micro controller including ADC operation, RS232 operation and the forward kinematics. Software for the PC is written in Visual Basic. This software controls data input and output through the RS232 port and generates the virtual environment that the anti gravity arm exists in.

5.1 CODE FOR THE LPC-MT-2138 IN C

The code for the ARM7 micro controller has been written in C using the IAR ARM Workbench 32Kb limited software, version 4. The software provided by IAR is free so long as the compiled code is limited to 32Kb. This software was chosen due to its ease of use and setup with most of the available C libraries found compiled for use by the IAR compiler. This has reduced the time needed for software development.

Most of the libraries used for software development have been provided by the manufacturer of the micro controller on the CD provided when purchased. An exception being the libraries named adc.c, calibrate.c and delay.c and the main program, main.c, which I have written. Code for these libraries can be found in Appendix B. Figure 5.1 is a flow chart that describes the micro controller program.
5.1.1 MENUS

The menu system for the micro controller is setup with the main menus operating vertically with the sub menus operating horizontally. The menu system includes an initial screen detailing the project name and student name as seen in figure 5.2. This is suggested as being used for all projects so that there is a way to confirm that the correct micro controller is being used. As there are two identical controllers available, there is significant risk that you could cause damage to your device should you connect a micro controller not containing code applicable to your project.

![Micro Controller Initial Screen](image)

**Figure 5-2 - Micro Controller Initial Screen**

After the initial screen there are two help screens detailing the use of the buttons in relation to the project shown in figure 5.3a and 5.3b. Once these screens have been displayed the first menu screen is shown, see figure 5.4. The normal operation screen
SOFTWARE DESIGN

shows the user that they are not in the calibration mode. This menu also acts as the trigger to start running the ADC conversions and as such to start performing the position control calculations.

**Figure 5-3 - (a) Up, Down, Left, Right and (b) Centre Button Menu Instructions**

The second menu option is for calibration of the potentiometers. Included in the code are five tested values for a relative zero position for each of the potentiometers. This menu as shown in figure 5.5 has been developed as there is a chance that these values will change as the device is moved around, or if the potentiometers are replaced. Once this menu has been entered the user then has five horizontal menus to access, one for each of the potentiometers as seen in figure 5.6. As each potentiometer is zeroed and the centre button is pressed, the resultant reading from the potentiometer is displayed on screen and stored as the new potentiometer calibration number.

**Figure 5-4 - Normal Operation Mode**

**Figure 5-5 - Potentiometer Selection Menu**

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As the new variable for potentiometer calibration is lost when the device is turned off, zeroing should be performed upon each start up operation. I have included the on screen display of the potentiometer reading so that during testing it is an easy matter of updating the potentiometer calibration variables the next time that I carry out a compile and re-flash of the micro controller.

5.1.2 ANALOGUE TO DIGITAL CONVERTORS

Five ADC’s are used, one for each potentiometer. The five ADC’s used are ADC0.0, ADC0.1, ADC0.2, ADC0.6 and ADC0.7. Ideally I would have liked to use ADC’s that were in numerical order without number spacing as this would have made the code just that little bit easier. The resultant spacing was unavoidable due to the way that the LPC-MT-2138 output pins are set up.

ADC calculations are performed after every iteration through the main program when the normal operation flag is set and the micro controller is not in calibration mode. To start a conversion the `getAnalogueInput_AD0` operator is used, passing the identification number of the selected ADC. The ADC conversion results in a value from 0 to 1023 for each potentiometer. Each incremental change is equal to approximately 3.6° of rotation. By knowing the potentiometer value for a given zero position and the new position, it is possible to calculate the angle of the potentiometer.

5.1.3 RS232 SERIAL PORT

RS-232 operation has an international standard that applies to the electrical connections and how data is transferred. By using the rs232.c library that was supplied with the micro controller, RS-232 input and output becomes a simple command sequence using operators such as UART0ReadChar and UART0WriteChar.
Within the program it is possible to select the baud rate that the RS-232 port can read and write data at. For high speed transmission a speed of 38400 baud was selected by using the UART0Initialize operator.

Data transmission is performed by passing one character at a time to the UART0WriteChar operator within a loop structure until the transmission is complete. Data receipt is carried out by checking the RS-232 receive buffer using the UART0ReadChar or UART0ReadChar_nostop operators. Use of UART0ReadChar reads a single character if available, UART0ReadChar_nostop reads data until the buffer is empty.

### 5.2 Code for the PC in Visual Basic

Code for the PC has been written in Visual Basic using Microsoft Visual Basic 2008 Express Edition. This is a freely downloadable package available from the Microsoft website. This software was chosen for its ease at creating standard Windows programs that are comfortable for most people to use. The program structure for the PC application is shown in figure 5.7.

![Flowchart Depicting PC Program](image-url)

*Figure 5-7 - Flowchart Depicting PC Program*
5.2.1 MENUS

The menu structure for the PC application includes a standard File and Help drop down menu as well as a Games menu option. The File menu includes the option to save and load previous sessions, print the data from a session, close a session and a secondary menu to control the RS-232 options. The Help menu provides a basic help file as well as program details.

The Games menu allows for selection of one of three different games. “Reach for it!” is a game where the patient must move the end effector of the anti gravity arm around the virtual environment while trying to reach an object. Once successful, the object will move to a new location. “Chase it!” is a game where the patient must try to catch a moving object as it moves through the virtual environment. “Draw it!” is a game where the patient must try and draw a specific shape within the virtual environment using the end effector of the anti gravity arm for a pen.

Upon selection of a game a secondary window will appear prompting the patient to place their arm in a neutral position with adequate movement fore and aft, side to side and up and down. Once in position the program will calibrate the system by taking readings from the micro controller and setting these as the base position on screen. This position is midway for the x-plane (depth) and y-plane (horizontal) and one third along the z-plane (vertical).

5.2.2 INPUT

There are two methods that can be used to control data flow from the micro controller to the PC. One method is call polling, where the micro controller will not output data until it is asked. The other method called streaming is when the micro controller constantly sends data to the receive buffer of the PC’s RS-232 port. The PC only acknowledges this data when required by the program flow. As the RS-232 port is FILO in nature (First In Last Off), the most recent data is the first to be read. All old data is eventually pushed out of the buffer.

The method I trialled was polling. With polling it is very easy to control data flow. The method I used was to allow the micro controller to continuously convert new forward kinematic values with each new kinematic calculation over writing the last. When the
PC application needs new position data, a single character request is sent to the micro controller. Upon receipt of this request, the micro controller would send the latest kinematic calculation to the PC. The timing of the request for new positional data was controlled by a timer with a period of 50ms.

It was found that this method presented problems as the time required to send the data after receiving a request for data would often be greater than the time between data requests. This resulted in moderate lag in the updating of position data. Subsequently the projected movement on screen was not as smooth as I would have liked.

5.2.3 VIRTUAL ENVIRONMENT

The virtual environment presented on screen is established by drawing a three dimensional room within the program window. This illusion is established by drawing lines that create the outline of the floor and three walls. The on screen representation of the patient’s hand is performed by moving a picture of a pointing hand around the virtual room.

To create the illusion of the hand moving away from the patient, the picture of the hand is scaled from its original size. To eliminate pixilation, the original image is scaled to 50% during calibration. As the patient moves their hand away from themselves, the on screen hand reduces in size at a proportional pace. As the patient retracts their hand the image increases in size thus completing the illusion. Two screen shots of the hand moving away from the patient are shown in figures 5.8 and 5.9.

Figure 5.8 illustrates the patient’s hand directly after calibration. The image of the hand is at 50% of its original size. As the anti gravity arm is moved forwards, or directly away from the body, the image of the hand is scaled down. This scaling can be seen in figure 5.9. The scaling of the hand when seen as a fluid change in size is seen as the hand moving ‘into’ the virtual environment. The illusion, while hard to recreate on paper works well in operation.
5.3 CONCLUSION

The software for the anti gravity arm has been developed on two separate platforms. The software for the micro controller is written in C. The C programming language was
used as it is the standard for programming ARM7 micro controllers. Many libraries are available to complete common tasks such as LCD control and RS-232 operation. The C language allows for complete control of the micro controller with short, concise code.

The micro controller controls the conversion of analogue data from the potentiometers into digital data that can be processed. The micro controller processes positional information by converting the potentiometer data and performing the forward kinematics while in the normal operation mode. The micro controller can perform a calibration of the potentiometer readings to establish a zero position for forward kinematic calculations. The micro controller will only send position data to the PC upon receipt of a request from the PC.

The software for the PC is written in Visual Basic. Visual Basic is used as it is an easy language with which to develop standard windows programs. The PC software establishes a virtual environment that the patient can move a representation of their hand around in. This is accomplished by the software requesting new position data every 50ms and updating the position of the virtual hand within the virtual environment. Problems were found with this method as lag appeared in the movement of the virtual hand.

The movement of the patient’s hand is depicted by a virtual hand moving about a virtual room. The virtual hand can move left and right, up and down and in and out of the room. The third dimension of moving in and out of the room is performed by scaling the image of the virtual hand proportionally to the movement required.
6 KINEMATICS OF ARM

Movement of the anti gravity arm is measured through five precision potentiometers whose output voltage is converted into a digital signal twenty times per second. To translate this digital output into three dimensional movements, a method needs to be used that can relate each individual movement of a potentiometer into the position of the end of the arm in the same reference plane as the base. This method is called the forward kinematics. There are various methods to determine the forward kinematics of a robot. For the anti gravity arm kinematics, the Denavit-Hartenberg method was used.

6.1 DENAVIT-HARTENBERG CONVENSION

Each rotational joint in the anti gravity arm is represented by the Denavit-Hartenberg convention as a link whose frame of reference is dependant on the previous link. In this way it is possible to relate the rotation and translation of each section of the anti gravity arm resulting in the position and orientation of the end effector in the same frame of reference as the base.

In establishing the forward kinematics using the Denavit-Hartenberg convention, an initial frame of reference is selected with the z-plane along the axis of rotation of the first joint. Each subsequent frame of reference is established using the right hand rule, with the x-plane along the common normal between $z_{n-1}$ and $z_n$. A table of link parameters can now be set up. The four parameters used are link length ($a_n$), link twist ($\alpha_n$), link offset ($d_n$) and joint angle ($\theta_n$) (Spong, Hutchinson & Vidyasagar 2006).

A transformation matrix that can represent each link is then established by multiplying four, four by four matrices representing the rotation along the z-plane, translation along the z-plane, translation along the x-plane and rotation along the x-plane. These matrices are shown in equation 6.1. The final forward kinematic matrix can be established by
multiplying each transformation matrix in the form \( T^0_n = A_1 \ldots A_n \). The (x, y, z) position of the end effector can be given as \( \left( T^0_n(4,1), T^0_n(4,2), T^0_n(4,3) \right) \).

\[
A_n = \text{Rot}(z_{n-1}, \theta_n) \text{Trans}(z_{n-1}, d_n) \text{Trans}(x_n, a_n) \text{Rot}(x_n, \alpha_n)
\]

\[
= \begin{bmatrix}
  c(\theta_n) & -s(\theta_n) & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
  s(\theta_n) & c(\theta_n) & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
  0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
= \begin{bmatrix}
  c(\theta_n) & -s(\theta_n) c(\alpha_n) & s(\theta_n) s(\alpha_n) & c(\theta_n) a_n \\
  s(\theta_n) & c(\theta_n) c(\alpha_n) & -c(\theta_n) s(\alpha_n) & s(\theta_n) a_n \\
  0 & s(\alpha_n) & c(\alpha_n) & d_n \\
  0 & 0 & 0 & 1
\end{bmatrix}
\]

Equation 6.1 - Denavit-Hartenberg Transformation Matrices

6.2 ANTI GRAVITY ARM FORWARD KINEMATICS

The forward kinematics of the anti gravity arm can be developed using the Denavit-Hartenberg convention. The first step in determining the forward kinematics is to establish an initial frame of reference. In the case of the anti gravity arm this is the rotating joint of the stand shaft and clavicle. The z-plane will follow the line of the stand shaft with the x-plane following the line of the clavicle. This is shown in figure 6.1.

It is now possible to establish the rest of the planes for the anti gravity arm.

- The z-plane for shoulder yaw is the same as for the base plane. The x-plane will follow the path of the shoulder.
- The z-plane for shoulder pitch will follow the line of the sensor shaft that connects the shoulder to the control arms. The x-plane will follow the line of the control arms.
- There is now a mirrored plane that will keep the shoulder and elbow parallel.
The z-plane for elbow pitch follows the line of the elbow shaft with the x-plane following the line of the lower elbow.

Finally the z-plane for pseudo elbow yaw follows the line of the sensor shaft connecting the upper elbow to the control arm, with the x-plane following the line of the control arm.

The mirrored plane is a requirement due to the dual control arms used between the shoulder and elbow. This arrangement keeps the shoulder and elbow parallel throughout their range of motion. If the mirrored plane was not included in the analysis, then the position of the end effector of the anti gravity arm would not be correctly calculated by the forward kinematics. An example of why this mirrored plane is important is when the patient raises their arm by shoulder pitch. The elbow will rise as well, but the fore arm will stay horizontal. Without the mirrored plane, the forward kinematics will see the fore arm rise in the same plane as the upper arm. This would result in a miscalculation of the position of the end effector.

The planes for the rest of the anti gravity arm are shown in figure 6.2. These planes are developed by following the Denavit-Hartenberg convention with the z-plane along the path of rotation and the x-plane along the common normal between z-planes. The
planes are numbered from zero, with the zero plane being the initial plane of reference. The kinematic links start with link number one and are described as the connection between plane n and n-1.

Figure 6-2 - Planes for the Anti Gravity Arm Forward Kinematics

It is now possible to develop the table of kinematic links that describes the relationships between the links. The table 6.1 details the link length \( a_n \), link twist \( \alpha_n \), link offset \( d_n \) and joint angle \( \theta_n \).
Using the table of link parameters and the transformation matrix shown in chapter 6.1, it is now possible to develop the transformation matrices for each link. The six matrices are detailed below.

\[
A_1 = \begin{bmatrix}
\cos(\theta_1) & -\sin(\theta_1) & 0 & 110\cos(\theta_1) \\
\sin(\theta_1) & \cos(\theta_1) & 0 & 110\sin(\theta_1) \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
A_2 = \begin{bmatrix}
\cos(\theta_2) & 0 & \sin(\theta_2) & 25\cos(\theta_2) \\
\sin(\theta_2) & 0 & \cos(\theta_2) & 25\sin(\theta_2) \\
0 & 1 & 0 & -225 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
A_3 = \begin{bmatrix}
\cos(\theta_3) & -\sin(\theta_3) & 0 & 300\cos(\theta_3) \\
\sin(\theta_3) & \cos(\theta_3) & 0 & 300\sin(\theta_3) \\
0 & 0 & 1 & 115 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
The final transformation matrix can now be formed. Due to the complexity and shear size of the calculations, it is not feasible to present the final transformation matrix here. It can be developed by $T_6^0 = A_1A_2A_3A_4A_5A_6$.

### 6.3 APPLYING DENAVIT-HARTENBERG IN C

When calculating the forward kinematics of the anti gravity arm, it is apparent that there is no need to know the pan, tilt or rotation of the end effector, only the location of the end effector relative to the starting position. By establishing this it is possible to greatly simplify the calculations.

The final transformation matrix includes all the calculations required to find the pan, tilt, rotation and position of the end effector. By ignoring the pan, tilt and rotation calculations, what is left is the position of the end effector. Cell (4,1) of the matrix provides for position in the x-plane, cell (4,2) the y-plane and cell (4,3) the z-plane.

The resulting calculations are very long with more than 60 separate cosine and sine calculations for the x-plane alone. In an effort to speed up the process it is possible to
perform the cosine and sine calculation for each potentiometer reading beforehand and use these variables in the calculation of the x, y and z position.

The x, y and z-plane calculations are shown below. To simplify the equations, c(n) and s(n) represent cosine and sine respectively and a(n) and d(n) represent translation along the x-plane and z-plane respectively.

\[
\begin{align*}
 x &= ((c[0]*c[1]+s[0]*s[1])*c[2]*s[3]-(c[0]*s[1]-s[0]*c[1])*c[3])*a[4]*c[4]-
 (c[0]*c[1]+s[0]*s[1])*a[4]*s[4]-10*(c[0]*c[1]+s[0]*s[1])*c[2]*s[3]+10
 *(c[0]*s[1]-s[0]*c[1])*c[3]+(c[0]*c[1]+s[0]*s[1])*c[2]*a[3]*c[3]+(c[0]*s[1]-
 s[0]*c[1])*a[3]*s[3]+(c[0]*c[1]+s[0]*s[1])*c[2]*a[2]+(-c[0]*s[1]+s[0]*c[1])
 *d[2]+c[0]*a[1]*c[1]+s[0]*a[1]*s[1]+a[0]*c[0] \\
 y &= ((-c[0]*s[1]+s[0]*c[1])*c[2]*s[3]-(c[0]*s[1]-s[0]*c[1])*c[3])*a[4]*c[4]-
 (-c[0]*s[1]+s[0]*c[1])*a[4]*s[4]-10*(-c[0]*s[1]+s[0]*c[1])*c[2]*s[3]+10
 *(c[0]*c[1]+s[0]*s[1])*c[3]+(-c[0]*s[1]+s[0]*c[1])*c[2]*a[3]*c[3]+(c[0]*c[1]
 +s[0]*s[1])*a[3]*s[3]+(-c[0]*s[1]+s[0]*c[1])*c[2]*a[2]+(-s[0]*s[1]-c[0]*c[1])
 *d[2]+s[0]*a[1]*c[1]-c[0]*a[1]*s[1]+a[0]*s[0] \\
 d[1]
\end{align*}
\]

6.4 RELATING THE REAL WORLD TO THE VIRTUAL WORLD

With values for position, it is now possible to develop a model that can move a representation of the patient’s hand within a virtual three dimensional world. To do this it is necessary to correlate the x, y and z movements developed from the forward kinematics to their equivalent movements on screen. Movement of the patient’s arm is expressed in millimetres whereas the movement on screen will be expressed in pixels.

Movement in the x-plane of the anti gravity arm corresponds to the scaling of the hand on screen. Movement in the y-plane of the anti gravity arm corresponds to the x-plane on screen or along the width of the screen. Movement in the z-plane of the anti gravity arm corresponds to the y-plane on screen or along the height of the screen.
The model for movement is developed in three stages. The first stage is retrieving the new position value and transforming this value into an absolute movement based on the neutral position established during pre game calibration. By subtracting the calibrated neutral position from the new position value it becomes a simple matter to calculate the new position relative to the original starting position.

The second stage is to smooth the effect of this change in value. To smooth the movement of the hand on screen it is necessary to ignore changes in position that are less than three millimetres. A change in value less than 3mm results in constant hand movements all around the screen while the anti gravity arm is for all intents and purposes stationary.

The third stage is to update the position of the hand on screen. At any given time the position of the hand in the z and y-planes is determined as the pixel count measured from the top of the screen to the top of the picture and the pixel count from the left of the screen to the left side of the picture. It is therefore necessary to take the height and width of the picture of the hand into consideration when calculating the new position.

To determine the scaling factor of the picture to represent movement away from the patient in the x-plane, the width and height of the picture must be scaled in relation to their original values. Simply rescaling the already scaled picture will result in the picture reducing in size to nothing or expanding to an enormous size as the rounding errors add up.

6.5 CONCLUSION

To be able to represent the movement of the patient’s arm in a virtual environment, it is necessary to know where the end effector of the anti gravity arm is at any time. A method to calculate this position is the Denavit-Hartenberg convention. This convention sets out specific rules, that when followed allow for the relatively simple calculation of the position of the end effector relative to the initial reference plane.

For the anti gravity arm, the initial reference plane is the rotational joint of the stand shaft and the clavicle. By developing the other planes, forming the kinematic link
parameters table and calculating the transformation matrix by following the Denavit-Hartenberg convention, it is possible to find three equations that describe the x, y and z position of the end effector.

Using the equations developed by the Denavit-Hartenberg convention, it is possible to use the angular measurements from potentiometers to find the position of the end effector in real space. This can then be represented on screen by relating measurements in millimetres to on screen pixels.

Representing movement on screen is simple for horizontal and vertical motions. A change in position in the horizontal or vertical planes in the real world can be represented by a horizontal or vertical movement in the virtual world. The representation of movement forwards and backwards requires the use of scaling to provide the illusion of moving into or out of the screen. The down scaling of the image of the virtual hand while keeping the horizontal and vertical positions stable results in the illusion of the hand moving into the screen. Similarly up scaling the image results in the illusion of the virtual hand retracting and moving out of the screen.
7 TESTING

Testing of the anti gravity arm was conducted by quantifying the amount of effort required to move the anti gravity arm in an unsupported and supported state, the smoothness of movement afforded by the anti gravity arm and the ability to represent three dimensional real world movement into a three dimensional virtual world. The first test can be measured. The second test is speculative as it can not be directly measured and can only be based on my opinion of what would be acceptable. The third test can be defined as the ability for the hardware and software to correctly translate the movement of the anti gravity arm into movement within a virtual world.

7.1 TESTING OF MOVEMENT

To determine the support provided by the anti gravity arm, the amount of effort required to support the end effector was measured at maximum horizontal and vertical extension. The measurement was conducted when supported by tension bands and when not supported by tension bands. The ratio of these efforts can be used to determine the ratio of support offered by the device. When not supported by tension bands the force required to support the end effector was equivalent to supporting a mass of 3kg. When tension bands were applied to provide the anti gravity effect, this equivalent mass was reduced to 0.3kg. The ratio of support is therefore in the region of 10:1 which means that the patient would be required to supply only 10% of their normal muscular activity to produce movement.

It is acknowledged that this is not a finite result and that the result may vary when the anti gravity arm is supporting the weight of a patient’s arm. It may also be suggested that the ratio of support may be dependant upon the angle of the arm. It was noted that during testing the effort required to move the arm in the initial stages was significantly less than that required at full extension. This is a result of the small changes in length of the tension bands as the anti gravity arm is moved. As the arm is raised, the tension bands contract, thus losing some of their tension. Similarly as the arm is lowered the tension bands stretch, thus increasing the tension and therefore making it more difficult to move.
The movement of the anti gravity arm is smooth with no binding or notching of movement. This is a direct result of the bearings mounted at each point of rotation. The movement is smooth enough that slight tilting of the device allows the joints to move. This does cause some concern when moving the anti gravity arm from one location to another and it is suggested that some form of locking mechanism be devised to keep the arm stable during transport and while not in use.

Testing of the anti gravity arm has shown that it is possible to translate five degrees of freedom of the arm of a stroke patient into three dimensional movement represented in a simple virtual world on an PC screen. Movement of the arm forwards is translated into a representation of forward movement on screen. Moving the arm back towards the shoulder is represented as a rearward movement on screen. Similarly moving left and right, up and down are correctly represented on screen.

The movement of the device in the virtual world is not as smooth as it should be. There could be many reasons for this and some of these reasons are explored. The current method of data polling could be causing a bottleneck. As the PC requests new data, the time taken to receive the request and then send the data may be longer than the 50ms allowed between polling. A solution to this would be data streaming where the data is sent constantly from the micro controller and the PC takes the most current data available on the receive buffer when required.

The method used on the micro controller to respond to data requests from the PC is a function called UART0ReadChar_nostop. This function reads a continuous stream of characters until the receive buffer is empty and updates a flag upon receipt of data. This method may be halting all other instructions while in use. A better function may be UART0ReadChar which reads a single character at a time.

It could be a simple matter of inefficient code that may be causing bottlenecks in the use of memory or incurring un-necessary processor use. This is hard to define as I am not an experienced programmer. The only solution to this is to examine likely areas of intensive processor operation and examine them for errors or for the possibility of optimisation.
7.2 CONCLUSION

Testing of the anti gravity arm has been positive. The device manages to perform the tasks required, but there are areas for improvement. The device can provide a ratio of assistance in the order of 10:1. This means that the patient would be required to supply one tenth of the effort normally required to move their arm.

Representation of the anti gravity arm in a virtual environment works as expected. There is lag in the systems as the software updates the position of the virtual hand inside the virtual room. The source of this lag is not yet defined but it is suggested that this lag stems from either data polling, the methods used by the micro controller to respond to polling requests or inefficient code.
8 CONCLUSIONS

The goal of this project was to show that it was possible to develop a low cost anti gravity arm that would reduce the amount of effort required for a stroke patient to move their arm through a range of exercises and have these exercises depicted within a three dimensional virtual environment.

8.1 DISCUSSION

The chosen design for the anti gravity arm was of the passive natural movement type. This type of design is best suited to the low cost design approach as there are no added control systems or actuators required to control the movement of the arm. The forces supplied to the anti gravity arm are passive, as the forces can not be changed once the device has been configured for use.

A natural movement device allows for the widest range of motion but concessions have been made to help reduce the complexity of the design by eliminating the movement associate with the wrist. The elimination of wrist movement does not unduly restrict the exercises available to the patient but does significantly reduce the complexity of the design by eliminating three additional degrees of freedom being rotation, pitch and yaw about the wrist.

Aside from the construction of the anti gravity arm, the largest cost is in the sensors and data acquisition micro controller. The use of precision potentiometers rather than encoders has reduced the cost ten fold, but has the possibility of reducing the accuracy of the anti gravity arm. This has been seen in the selection of potentiometers. The ten turn potentiometers used do not provide the accuracy desired due to the low voltages and small movements of the device. This can be rectified by using three turn potentiometers in future version of the anti gravity arm.

The micro controller used is an LPC-MT-2138 which uses an ARM7 micro controller. The ARM7 series of micro controllers offer high speed with a good assortment of components. The anti gravity arm currently uses five of the sixteen available ADC’s,
the RS-232 communication port, the LCD and five control buttons. With the remaining ADC’s and six Pulse Width Modulators, there is much room for expansion.

The anti gravity arm uses tension bands to supply the force required to lift the upper arm and fore arm to produce the anti gravity feel of the device. In testing, the tension bands were able to reduce the effort required to support the device by a ratio of 10:1. This is an excellent outcome which translates into the patient needing to supply only one tenth of the effort normally required to move their arm.

Translation of movement in the real world to movement in a virtual world has been managed successfully. Horizontal and vertical movement of the anti gravity arm is translated into horizontal and vertical movement on screen. Moving the anti gravity arm away from the patient and retracting the arm back towards the patient results in the illusion of the virtual hand moving into and out of the screen. This is accomplished by down scaling the virtual hand to represent movements into the screen and up scaling the virtual hand to represent movements out of the screen.

The movement works well although there is lag in the system. The exact cause of the lag is unknown at this time, but possible causes have been identified for investigation. The method of data polling on the PC may be causing lag, as is the method of waiting for data requests by the micro controller. Inefficiencies in code can not be eliminated as a reason for the lag, so further investigation into best practice methodologies for intensive processes is needed.

The Denavit-Hartenberg convention has been used to relate the movements of the joints to an initial frame of reference. By using the Denavit-Hartenberg convention it is possible to simplify the calculations for position control into three equations, one for each plane of motion. The three equations are exceptionally long and require methods to reduce the time taken to compute the results. The chosen method is to calculate the cosine and sine for each potentiometer value then simply apply these values to the pre-determined position equations.
8.2 FUTURE WORK

Testing of the anti gravity arm has revealed areas that are suitable for future work. The mechanical design of the anti gravity arm itself is quite satisfactory for a prototype. For the device to be used within a hospital or physiotherapy practice it would be beneficial to redesign the device to be more aesthetically pleasing. One of the biggest steps in getting the device to be used would be patient acceptance. A big part of patient acceptance is the visual aesthetics so that the device looks like a medical device and not an industrial robot.

Eliminating the lag apparent in the system is a major requirement of future use. Along with the elimination of lag, it may be beneficial to change the potentiometers to a lower turn variety. By changing the potentiometers to three turns, there would be an immediate increase in the resolution of the device.

Upgrading the PC virtual environment would entail changing to a game engine as the method for drawing the virtual world. The change to a game engine would increase the speed of the software as well as adding the ability to develop more appealing environments for the patient to experience.

The upgrade from tension bands to air muscles is seen as the next major step in development of the device. The addition of air muscles would enable the user to setup the anti gravity arm at the touch of a button by applying air pressure to the air muscles until the potentiometers reach a pre determined point. With air muscles it becomes a simple matter to adjust the amount of assistance offered by the anti gravity arm. It may be possible to have pre set limits so that the physiotherapist can adjust the amount of assistance at the touch of a button.

8.3 SUMMARY

The anti gravity arm meets the design goals set out for the project. The project has shown that it is possible to build a low cost anti gravity arm. Testing of the device has shown that the anti gravity arm correctly relates real world movement to that in a virtual world although there is lag in the movement of the virtual hand. Areas for investigation into the cause of this lag have been identified.
Future work is expected to take the form of updating the aesthetics of the anti gravity arm, eliminating lag from the position control, upgrading the potentiometers, enhancing the virtual environment by using a game engine and the updating of the force generation from tension bands to air muscles. The work described would be sufficient for two projects.

The work I have performed in the design and development of an anti gravity arm to assist in the rehabilitation of stroke patients is a significant milestone in the production of a device that is ready for rehabilitation therapy. I have designed and built a device that can provide for a 10:1 reduction in the effort required by a patient suffering hemiparesis to move their affected arm. I have developed a software package that can correctly interpret the movement of the patient’s arm and display this as three dimensional movement within a virtual environment. With the few modifications detailed, the device would be ready for preliminary trials within a rehabilitation environment.
REFERENCES


REFERENCES


REFERENCES


University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: SCOTT CARDEN

TOPIC: DESIGN AND BUILD AND “ANTI GRAVITY” ARM SUPPORT FOR USE IN STROKE REHABILITATION.

SUPERVISOR: Selvan Pather

PROJECT AIM: The project seeks to develop a system that would support the patients arm in a “weightless” state, so that the patient may concentrate in the movement of the arm without the need for strength.


1. Research relevant background information regarding effects of stroke, current rehabilitation practices and the effects of assisted exercises.

2. Evaluate T-WREX design.

3. Design an “anti gravity” arm to be manufactured in the USQ workshop.

4. Write software to analyse the motion data from the “anti gravity” arm.

5. Critically analyse the results, suggest improvements and future direction in an academic dissertation.

As time permits:

6. Write a basic exercise program for a stroke patient.

7. Change weightlessness mechanism from bands to air muscles to allow automatic setup.

AGREED

Date: 26/03/2008 (Student)

Date: 26/03/2008 (Supervisor)
APPENDIX B

B.1 MICRO CONTROLLER CODE

B.1.1 MAIN.C

//**************************************************************
 Header Files
***************************************************************/

#include "system.h"
#include "buttons.h"
#include "lcd.h"
#include "delay.h"
#include "adc.h"
#include "rs232.h"
#include "calibrate.h"
#include "stdio.h"
#include "string.h"
#include "math.h"

/*************************************************************************
 MAIN
*************************************************************************/

int main(void){

    //Initialise Variables
    short int vMenu=0, vUpdate=0, hMenu=0, hUpdate=0, enter=0;
    short int i=0, j=0, normal=0;
    //Initial calibration values dated 9th Sept 2008
    int potcal[5];
    int pota[5], potb[5], potc[5], potd[5], pote[5], potf[5];
    float potavg[5], c[5], s[5];
    //Values to help simplify the affine transformation calculations
    float a[5]={110, 25, 300, 140, 310};
    float d[5]={0, 225, 125, 0, 0};
    float x, y, z;
    char dimension=0x0, xStr[4], yStr[4], zStr[4];
    const float PI=3.14159;
    char test[4];

    //Frequency Initialisation
    FrecInit();
    //Initialise the buttons
    InitButtons();
    //Initialise the adc
    adcInit();
    // UART initialization
    UART0Initialize(38400);
    //Initialise the LCD
    LCDInit();
    //Turn the LCD on
    LCDSendCommand(DISP_ON);
    //Turn the LCD light on
    Light(1);
/Write splash screen to LCD - 40 chars per line/16 viewable
LCDSendTxt("Anti Gravity Arm                        Scott Carden");
//Pause for ~5sec to let user read info
Delay(5000000);
//Display instructions
LCDSendTxt(" Up/Dwn-Program                         Lft/Rght-Options");
//Pause for ~5sec to let user read info
Delay(5000000);
//More instructions
LCDSendTxt(" Centre Button                              is Enter");
//Pause for ~5sec to let user read info
Delay(5000000);

/******************START OF MENU SYSTEM*******************/
//select first menu to display
vMenu = 1;
vUpdate = 1;
//Endless loop to check for button input to select 'program'
while(1){
    //Programs Normal running and Calibration
    /*        B1                Up
              B2  B3  B4      Left  Enter  Right
              B5                Down              */
    //Which button was pressed and what does it do
    //If Button 1 pressed
    if(!BUT1_PRESSED){
        vMenu--; vUpdate++;
        if (vMenu < 1){ //Control scrolling back past menu 1
            vMenu = 2;
        }
    }
    //If Button 2 pressed
    if(!BUT2_PRESSED){
        hMenu--; hUpdate++;
        if (hMenu < 1){ //Control scrolling back past option 1
            hMenu = 5;
        }
    }
    //If Button 3 pressed
    if(!BUT3_PRESSED){
        hUpdate++;
        vUpdate++;
        enter++;
    }
    //If Button 4 pressed
    if(!BUT4_PRESSED){
        hMenu++; hUpdate++;
        if (hMenu == 6){ //Control scrolling past option 5
            hMenu = 1;
        }
    }
    //If Button 5 pressed
    if(!BUT5_PRESSED){
        vMenu++;
        vUpdate++;
        if (vMenu == 3){ //Control scrolling past menu 2
            vMenu = 1;
        }
    }
}
if(vUpdate!=0){  //Check if need to change screen
    //Update LCD to selection and run function
    switch(vMenu){
        case 1:
            LCDSendTxt("Normal Operation Processing");
            //Normal Operation.
            normal = 1;
            break;
        case 2:
            LCDSendTxt("Pot. Calibration Please Select");
            //Calibrate Pots.
            //Turn off normal operations
            normal = 0;
            break;
        default:
            break;
    } //End of switch
    //Reset vUpdate
    vUpdate = 0;
} //End of if

//Update screen for calibrating Pots
if(vMenu == 2){
    if(hUpdate!=0){  //Check if need to change screen
        switch(hMenu){
            case 1:
                LCDSendTxt("  Centre Pot0 Press Enter");
                //Calibrate Pot0
                if (enter!=0)
                    potcal[0] = calibrate(7);
                sprintf( test, "%d", potcal[0] );
                LCDSendTxt(test);
                break;
            case 2:
                LCDSendTxt("  Centre Pot1 Press Enter");
                //Calibrate Pot1
                if (enter!=0)
                    potcal[1] = calibrate(6);
                sprintf( test, "%d", potcal[1] );
                LCDSendTxt(test);
                break;
            case 3:
                LCDSendTxt("  Centre Pot2 Press Enter");
                //Calibrate Pot2
                if (enter!=0)
                    potcal[2] = calibrate(2);
                sprintf( test, "%d", potcal[2] );
                LCDSendTxt(test);
                break;
            case 4:
                LCDSendTxt("  Centre Pot3 Press Enter");
                //Calibrate Pot6
                if (enter!=0)
                    potcal[3] = calibrate(1);
                sprintf( test, "%d", potcal[3] );
                LCDSendTxt(test);
                break;
            case 5:
LCDSendTxt("Centre Pot4 Press Enter");

//Calibrate Pot7
if (enter!=0){
    potcal[4] = calibrate(0);
    sprintf(test, ",%d", potcal[4] );
    LCDSendTxt(test);
}
break;
default:
break;
};//End of switch
};//End of if
//Reset hUpdate
hUpdate = 0;
};//End of if
else{
//Reset hMenu
hMenu = 0;
//Reset hUpdate
hUpdate = 0;
}//End of else
//Need ~0.2sec delay as system too fast
//Delay(200000);
//Reset enter
enter = 0;

/* END OF MENU SYSTEM */

//START OF POSITION SYSTEM

//Still in the endless While loop
if (normal==1){//Get ADC results if normal operation selected
j=8;
i=0;
while (j!=0){ // Skip ADC channels that are not being used
    j=3; //Need this roundabout method as it would not accept otherwise??!!  
}
    potf[i] = pote[i];
    pote[i] = potd[i];
    potd[i] = potc[i];
    potc[i] = potb[i];
    potb[i] = pota[i];
    pota[i] = getAnalogueInput_AD0(j-1);
    potavg[i] = (pota[i] + potb[i] + potc[i] + potd[i] + pote[i] + potf[i])/6;
i++;
});//End of while

/* MATHS BEHIND POSITION CONTROL */

//Reset x, y and z for new calculations
x = 0; y = 0; z = 0;
//Calculate cos and sin of each angle
  c[0] = cos(((potavg[0] - 490) * 3.515625) * PI / 180);
s[0] = sin(((potavg[0] - 490) * 3.515625) * PI / 180);
c[3] = cos(((518-potavg[3]) * 3.515625) * PI / 180);
s[3] = sin(((518-potavg[3]) * 3.515625) * PI / 180);
c[4] = cos(((483-potavg[4]) * 3.515625) * PI / 180);
s[4] = sin(((483-potavg[4]) * 3.515625) * PI / 180);
// Affine calculation - ignoring rotations
x = ((c[0]*c[1]+s[0]*s[1])*c[2]*s[3]-c[0]*s[1]-s[0]*c[1])*c[3])*a[4]*c[4]-
(c[0]*c[1]+s[0]*s[1])*s[2]*a[4]*s[4]-10*(c[0]*c[1]+s[0]*s[1])*c[2]*s[3]+10*(c[0]*s[1]-
s[0]*c[1])*c[3]+(c[0]*s[1]+s[0]*c[1])*c[2]*a[2]*a[4]-
c[0]*s[1]+s[0]*c[1])*d[2]+c[0]*a[1]*c[1]+s[0]*a[1]*s[1]+a[0]*c[0];
y = ((-c[0]*s[1]+s[0]*c[1])*c[2]*s[3]-c[0]*c[1]+s[0]*s[1])*c[3])*a[4]*c[4]-
c[0]*s[1]+s[0]*c[1])*s[2]*a[4]*s[4]-10*(-
c[0]*s[1]+s[0]*c[1])*c[2]*s[3]+10*(c[0]*c[1]+s[0]*s[1])*c[3]+(-
c[0]*s[1]+s[0]*c[1])*c[2]*a[3]+(c[0]*s[1]+s[0]*s[1])*a[3]*s[3]+(-
c[0]*s[1]+s[0]*c[1])*c[2]*a[2]+s[0]*a[1]*c[1]-c[0]*a[1]*s[1]+a[0]*s[0];

//********************************UART control***************************//
// Write result to UART0 when command received from PC

i = 0; // Reset loop flag

switch (dimension) {
  case 'x':
    // Convert int xStr into char array to send over UART0
    sprintf( xStr, "%f", x );
    while (xStr[i]){
      UART0WriteChar(xStr[i]);
      i++;
    } // end of while
    //UART0WriteChar('*');
    break;
  case 'y':
    // Convert int yStr into char array to send over UART0
    sprintf( yStr, "%f", y );
    while (yStr[i]){
      UART0WriteChar(yStr[i]);
      i++;
    } // end of while
    //UART0WriteChar('*');
    break;
  case 'z':
    // Convert int zStr into char array to send over UART0
    sprintf( zStr, "%f", z );
    while (zStr[i]){
      UART0WriteChar(zStr[i]);
      i++;
    } // end of while
    //UART0WriteChar('*');
    break;
  default:
    default;
    break;
} // End of switch
} // End of if

//******************************************************************************END OF POSITION SYSTEM******************************************************************************//

} // End of while

} // End of main

******************************************************************************End of Program******************************************************************************//
B.1.2 ADC.C

#include "adc.h"
#include "delay.h"
#include "iolpc2138.h"

// Available Pins on Ext output are /*
   External Header
Ground        20 19 3.3V
Out           18 17 P1_16 FREE
P1_25 FREE    16 15 P1_24 FREE
P0_29 AD0.2   14 13 P0_28 AD0.1
P0_27 AD0.0   12 11 P0_26 AD0.5
P0_19 FREE    10 9  P0_18 FREE
P0_17 FREE    8  7 P0_13 AD1.4
P0_12 AD1.3   6  5 P0_8 AD1.1
P0_7 FREE     4  3 P0_6 AD1.0
P0_5 AD0.7    2  1 P0_4 AD0.6
*/

void adcInit()
{
    // Set 5 pins to input for ADC *Still to do
    PINSEL0 = 0x0000FF00; // Selects ADC's 0.6, 0.7
    PINSEL1 = 0x05400000; // Selects ADC's 0.0, 0.1, 0.2

}

//-------------------------- getAnalogueInput_AD0 function ---------------------/
unsigned short int getAnalogueInput_AD0(unsigned char channel)
{
    unsigned short int val;

    //AD0CR = 0x00200600; // enable ADC, 11 clocks/10 bits, ADC clock = 4.286 MHz

    // start conversion (for selected channel)
    AD0CR = 0x00200400 | (1 << channel);
    AD0CR |= 0x01000000;

    // wait until done
    while((AD0DR & 0x80000000) == 0);

    // get ADC data
    val = ((AD0DR & 0x0000FFC0)) >> 6;

    // Reset ADC
    AD0CR = 0x00000001;

    return(val);
}

B.1.3 BUTTONS.C

//buttons.c
#include <iolpc2138.h>
#include "buttons.h"

// init buttons port
void InitButtons(void) {
    IO0DIR_bit.P0_15 = 0;    //set port0.15 as input (button 1)
    IO0DIR_bit.P0_16 = 0;    //set port0.16 as input (button 2)
    IO0DIR_bit.P0_20 = 0;    //set port0.20 as input (button 3)
    IO0DIR_bit.P0_30 = 0;    //set port0.30 as input (button 4)
    IO0DIR_bit.P0_9 = 0;     //set port0.9 as input (button 5)
}

B.1.4 CALIBRATE.C

#include "adc.h"
#include "iolpc2138.h"

short int calibrate(short int pot){
    short int calValue;

    //Get ADC result to calibrate Pot
    calValue = getAnalogueInput_AD0(pot);

    //return calibrated value
    return calValue;
}

B.1.5 DELAY.C

//A simple delay
void Delay (unsigned long a) {
    while (--a!=0);
}

B.1.6 GPIO.C

#include "gpio.h"
#include "delay.h"
#include "iolpc2138.h"

// Available Pins on Ext output are
/*
   External Header
   Ground    20 19  3.3V
   Out       18 17 P1_16 FREE
   P1_25 FREE 16 15 P1_24 FREE
   P0_29 AD0.2 14 13 P0_28 AD0.1
   P0_27 AD0.0 12 11 P0_26 AD0.5
   P0_19 FREE 10 9  P0_18 FREE
   P0_17 FREE  8 7  P0_13 AD1.4
   P0_12 AD1.3 6  5  P0_8 AD1.1
   P0_7  FREE  4 3  P0_6 AD1.0
   P0_5 AD0.7  2 1  P0_4 AD0.6
*/

void gpioInit()
{
    //Set 5 pins to input for ADC *Still to do
PINSEL0 = 0x00000F00; //Selects ADC's 0.6, 0.7
PINSEL1 = 0x05400000; //Selects ADC's 0.0, 0.1, 0.2

AD0CR = 0x00200604; // enable ADC, 11 clocks/10 bits, ADC clock = 4.286 MHz

B.1.7 LCD.C

//lcd.c
#include <string.h>
#include "delay.h"
#include "lcd.h"

unsigned long data;

void E_Pulse()
{
  IO1SET_bit.P0_18 = 1; //set E to high
  //Delay(10);
  Delay(100);
  IO1CLR_bit.P0_18 = 1; //set E to low
}

void LCDInit()
{
  //first set D4, D5, D6, D7, RS, RW, E to output ports
  IO1DIR_bit.P0_17 = 1;
  IO1DIR_bit.P0_18 = 1;
  IO1DIR_bit.P0_19 = 1;
  IO1DIR_bit.P0_20 = 1;
  IO1DIR_bit.P0_21 = 1;
  IO1DIR_bit.P0_22 = 1;
  IO1DIR_bit.P0_23 = 1;

  //LCD initialization
  //step by step (from Gosho) - from DATASHEET
  IO1CLR_bit.P0_17 = 1; //set RS port to 0
  IO1CLR_bit.P0_19 = 1; //set R/W port to 0

  unsigned short int getAnalogueInput_AD0(unsigned char channel)
  {
    unsigned short int val;

    //start conversion (for selected channel)
    AD0CR = (AD0CR & 0xFFFFFF00) | (1 << channel) | (1 << 24);

    //wait until done
    while((AD0GDR & 0x80000000) == 0)
    {
    }

    // get ADC data
    val = ((AD0GDR & 0x0000FFC0)) >> 6;
    return(val);
  }
IO1CLR_bit.P0_18 = 1; //set E port to 0
Delay(110000);       //delay ~110ms
//Delay(1100000);      //delay ~110ms

IO1SET_bit.P0_20 = 1; //set D4 port to 1
IO1SET_bit.P0_21 = 1; //set D5 port to 1
E_Pulse();           //high->low to E port (pulse)
Delay(10000);        //delay ~10ms
//Delay(100000);       //delay ~10ms

IO1SET_bit.P0_20 = 1; //set D4 port to 1
IO1SET_bit.P0_21 = 1; //set D5 port to 1
E_Pulse();           //high->low to E port (pulse)
Delay(100000);       //delay ~10ms
//Delay(1000000);      //delay ~10ms

IO1SET_bit.P0_20 = 1; //set D4 port to 1
IO1SET_bit.P0_21 = 1; //set D5 port to 1
E_Pulse();           //high->low to E port (pulse)
Delay(1000000);      //delay ~10ms
//Delay(10000000);     //delay ~10ms

IO1SET_bit.P0_20 = 1; //set D4 port to 1
IO1CLR_bit.P0_21 = 1; //set D5 port to 1
E_Pulse();           //high->low to E port (pulse)

}

void LCDSendCommand(unsigned long a)
{
    IO1CLR_bit.P0_19 = 1; //set RW port to 0
    //Delay(2000);             //delay for LCD char ~2ms
    Delay(20000);            //delay for LCD char ~2ms
data = 0x0;

    data = 0xffffff0f | a; //get high 4 bits
    IO1CLR |= 0x00f00000;   //clear D4-D7
data = data << 16;

    IO1SET = (IO1SET | 0x00f00000) & data; //set D4-D7
    IO1CLR_bit.P0_17 = 1;    //set RS port to 0 -> display set to command mode
    E_Pulse();              //pulse to set d4-d7 bits

    //data = (a << 4) & 0x000000f0;   //get low 4 bits
    //IO1CLR |= 0x000000f0;       //clear D4-D7
    //data = data <<4;
data = 0x0;
a = a<<4;

    data = 0xffffff0f | a; //get high 4 bits
    IO1CLR |= 0x00f00000;   //clear D4-D7
data = data << 16;
    IO1SET = (IO1SET | 0x00f00000) & data; //set D4-D7
    IO1CLR_bit.P0_17 = 1;    //set RS port to 0 - display set to command mode
    E_Pulse();              //pulse to set d4-d7 bits

}
void LCDSendChar(unsigned long a)
{
    IO1CLR_bit.P0_19 = 1; //set RW port to 0
    Delay(2000); //delay for LCD char ~2ms
    //Delay(20000); //delay for LCD char ~2ms
    data = 0x0;

    data = 0xffffffff | a; //get high 4 bits
    IO1CLR |= 0x00000000; //clear D4-D7
    data = data << 16;
    IO1SET = (IO1SET | 0x00000000) & data; //set D4-D7
    IO1SET_bit.P0_17 = 1; //set RS port to 0 -> display set to command mode
    E_Pulse(); //pulse to set d4-d7 bits

    //data = (a << 4) & 0x000000f0; //get low 4 bits
    //IO1CLR |= 0x000000f0; //clear D4-D7
    //data = data <<4; data = 0x0; a = a<<4;

    data = 0xffffffff | a; //get high 4 bits
    IO1CLR |= 0x00000000; //clear D4-D7
    data = data << 16;
    IO1SET = (IO1SET | 0x00000000) & data; //set D4-D7
    IO1SET_bit.P0_17 = 1; //set RS port to 0 -> display set to command mode
    E_Pulse(); //pulse to set d4-d7 bits

    /*
    IO1CLR_bit.P0_19 = 1; //set RW port to 0
    Delay(2000); //delay for LCD char ~2ms
    //data = 0xffffffff | a; //get high 4 bits
    //IO1CLR |= 0x00000000; //clear D4-D7
    data = 0xffffffff | a; //get high 4 bits
    IO1CLR |= 0x00000000; //clear D4-D7
    IO1SET = (IO1SET | 0x00000000) & data; //set D4-D7
    IO1SET_bit.P0_17 = 1; //set RS port to 0 -> display set to command mode
    E_Pulse(); //pulse to set d4-d7 bits

    //data = (a << 4) & 0x000000f0; //get low 4 bits
    //IO1CLR |= 0x000000f0; //clear D4-D7
    data = (a << 4) & 0x00f00000; //get low 4 bits
    IO1CLR |= 0x00f00000; //clear D4-D7
    IO1SET = (IO1SET & 0xff0fffff) | data; //set D4-D7 (only PORTC4-PORPC7)
    IO1SET_bit.P0_17 = 1; //set RS port to 1 -> display set to data mode
    E_Pulse(); //pulse to set d4-d7 bits
    */
}

void LCDSendTxt(char* a)
{
    LCDSendCommand(CLR_DISP);
    LCDSendCommand(DD_RAM_ADDR);
    for(int i=0; i<strlen(a); i++)
    {
        LCDSendChar((unsigned long)a[i]);
    }
}
void LCDSendInt(int a)
{
    LCDSendCommand(CLR_DISP);
    LCDSendCommand(DD_RAM_ADDR);
    int h = 0;
    int l = 0;

    l = a%10;
    h = a/10;

    LCDSendChar(h+48);
    LCDSendChar(l+48);
}

void SmartUp(void)
{
    for(int i=0; i<40; i++) LCDSendCommand(CUR_RIGHT);
}

void SmartDown(void)
{
    for(int i=0; i<40; i++) LCDSendCommand(CUR_LEFT);
}

void Light(short a)
{
    if(a == 1)
    {
        IO0SET_bit.P0_21 = 1;
        IO0DIR_bit.P0_21 = 1;

        IO0SET_bit.P0_25 = 1;
        IO0DIR_bit.P0_25 = 1;
    }
    if(a == 0)
    {
        IO0SET_bit.P0_21 = 0;
        IO0DIR_bit.P0_21 = 0;

        IO0SET_bit.P0_25 = 0;
        IO0DIR_bit.P0_25 = 0;
    }
}

B.1.8 RS232.C

//rs232.c
#include "rs232.h"

unsigned int processorClockFrequency(void)
{
    //return real processor clock speed
    return OSCILLATOR_CLOCK_FREQUENCY * (PLLCON & 1 ? (PLLCFG & 0xF) + 1 : 1);
}

unsigned int peripheralClockFrequency(void)
APPENDIX B

 APPENDIX B

{ //VPBDIV - determines the relationship between the processor clock (cclk)
  //and the clock used by peripheral devices (pclk).
  unsigned int divider;
  switch (VPBDIV & 3)
  {
    case 0: divider = 4;  break;
    case 1: divider = 1;  break;
    case 2: divider = 2;  break;
  }
  return processorClockFrequency() / divider;
}

/**** UART0 ****/
void UART0Initialize(unsigned int baud)
{
  unsigned int divisor = peripheralClockFrequency() / (16 * baud);

  //set Line Control Register (8 bit, 1 stop bit, no parity, enable DLAB)
  U0LCR_bit.WLS   = 0x3;    //8 bit
  U0LCR_bit.SBS   = 0x0;    //1 stop bit
  U0LCR_bit.PE    = 0x0;    //no parity
  U0LCR_bit.DLAB  = 0x1;    //enable DLAB
  //with one row
  //  U0LCR = 0x83;

  //divisor
  U0DLL = divisor & 0xFF;
  U0DLM = (divisor >> 8) & 0xFF;
  U0LCR &= ~0x80;

  //set functionalite to pins: port0.0 -> TX0, port0.1 -> RXD0
  PINSEL0_bit.P0_0 = 0x1;
  PINSEL0_bit.P0_1 = 0x1;
  //with one row
  //  PINSEL0 = PINSEL0 & ~0xF | 0x5;
}

void UART0WriteChar(unsigned char ch0)
{
  //when U0LSR_bit.THRE is 0 - U0THR contains valid data.
  while (U0LSR_bit.THRE == 0);
  U0THR = ch0;
}

unsigned char UART0ReadChar(void)
{
  //when U0LSR_bit.DR is 1 - U0RBR contains valid data
  while (U0LSR_bit.DR == 0);
  return U0RBR;
}

unsigned char UART0ReadChar_nostop(void)
{
  //when U0LSR_bit.DR is 1 - U0RBR contains valid data
  if(U0LSR_bit.DR == 1) return U0RBR;
  else return 0;
}

void UART0WriteChar_nostop(unsigned char ch0)
{
**** UART1 ****

void UART1Initialize(unsigned int baud)
{
    unsigned int divisor = peripheralClockFrequency() / (16 * baud);

    // set Line Control Register (8 bit, 1 stop bit, no parity, enable DLAB)
    U1LCR_bit.WLS = 0x3;  // 8 bit
    U1LCR_bit.SBS = 0x0;  // 1 stop bit
    U1LCR_bit.PE = 0x0;   // no parity
    U1LCR_bit.DLAB = 0x1; // enable DLAB
    // with one row
    // U0LCR = 0x83;

    // divisor
    U1DLM = divisor & 0xFF;
    U1DLL = (divisor >> 8) & 0xFF;
    U1LCR &= ~0x80;

    // set functionality to pins: port0.8 -> TX1, port0.9 -> RXD1
    PINSEL0_bit.P0_8 = 0x1;
    PINSEL0_bit.P0_9 = 0x1;
    // with one row
    // PINSEL0 = PINSEL0 & ~0xF | 0x5;
}

void UART1WriteChar(unsigned char ch0)
{
    // when U0LSR_bit.THRE is 0 - U0THR contains valid data.
    while (U1LSR_bit.THRE == 0);
    U1THR = ch0;
}

unsigned char UART1ReadChar(void)
{
    // when U0LSR_bit.DR is 1 - U0RBR contains valid data
    while (U1LSR_bit.DR == 0);
    return U1RBR;
}

unsigned char UART1ReadChar_nostop(void)
{
    // when U0LSR_bit.DR is 1 - U0RBR contains valid data
    if(U1LSR_bit.DR == 1) return U1RBR;
    else return 0;
}

void UART1WriteChar_nostop(unsigned char ch0)
{
    // when U0LSR_bit.THRE is 0 - U0THR contains valid data.
    if(U1LSR_bit.THRE == 1) U1THR = ch0;
}
B.1.9 SYSTEM.C

//system.c
#include <iolpc2138.h>
#include "system.h"

#define VIC_TIMER0_bit (1 << VIC_TIMER0)

//oscillator frequency
//IMPORTANT - if you use oscillator with different frequency,
//please change this value, because timer not work correctly
#define OSCILLATOR_CLOCK_FREQUENCY 14745600 //in MHz

unsigned int GetCclk(void)
{
    //return real processor clock speed
    return OSCILLATOR_CLOCK_FREQUENCY * (PLLCON & 1 ? (PLLCFG & 0xF) + 1 : 1);
}

unsigned int GetPclk(void)
{
    //VPBDIV - determines the relationship between the processor clock (cclk)
    //and the clock used by peripheral devices (pclk).
    unsigned int divider;
    switch (VPBDIV & 3)
    {
        case 0: divider = 4; break;
        case 1: divider = 1; break;
        case 2: divider = 2; break;
    }
    return GetCclk() / divider;
}

void FrecInit(void)
{
    //devides or multiplier
    //here is calculate frecuence
    PLLCFG_bit.MSEL = 0x3; //M - multiplier
    PLLCFG_bit.PSEL = 0x1; //P - divider
    //set changes (require from architecture)
    PLLFEED_bit.FEED = 0xAA;
    PLLFEED_bit.FEED = 0x55;
    //enable or connect PLL
    //enable PLL
    PLLCON_bit.PLLC = 1;
    //set changes (require from architecture)
    PLLFEED_bit.FEED = 0xAA;
    PLLFEED_bit.FEED = 0x55;
    //wait for PLOK (correct freq)
    while(PLLSTAT_bit.PLOCK == 0);
    //connect PLL
    PLLCON_bit.PLLC = 1;
    //set changes (require from architecture)
    PLLFEED_bit.FEED = 0xAA;
    PLLFEED_bit.FEED = 0x55;
}
B.2 PC CODE

B.2.1 APPLICATION.VB

Imports Microsoft.VisualBasic.PowerPacks
Public Class MainPage

    Dim WithEvents serialPort As New IO.Ports.SerialPort ' Serial Port usage
    Dim newX, oldX, newY, oldY, newZ, oldZ, originalX, originalY, originalZ
    Dim screenSize As Size
    Dim valUpdate = 0 ' Flag
    Dim calUpdate = 0 ' Flag
    Dim newValue
    Dim canvas As New ShapeContainer
    Dim vLine1, vLine2, vLine3, vLine4, vLine5, hLine1, hLine2 As New LineShape
    Dim lWindow, rWindow, tWindow, bWindow As New LineShape

    Private Sub MainPage_Load(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles MyBase.Load
        ' Open COM Port with default values
        If serialPort.IsOpen Then
            serialPort.Close()
        End If
        Try
            With serialPort
                .PortName = "COM1"
                .BaudRate = 38400
                .Parity = IO.Ports.Parity.None
                .DataBits = 8
                .StopBits = IO.Ports.StopBits.One
                .ReadTimeout = 10
            End With
            serialPort.Open()
        Catch ex As Exception
            MsgBox(ex.ToString)
        End Try
        ' Draw room
        screenSize = Me.Size
        ' Set the form as the parent of the ShapeContainer.
        canvas.Parent = Me
        ' Set the ShapeContainer as the parent of the LineShape.
        vLine1.Parent = canvas
        vLine2.Parent = canvas
        vLine3.Parent = canvas
        vLine4.Parent = canvas
        vLine5.Parent = canvas
        hLine1.Parent = canvas
        hLine2.Parent = canvas
        ' Floor
        vLine1.StartPoint = New System.Drawing.Point(0, screenSize.Height)
        vLine1.EndPoint = New System.Drawing.Point((0.2 * screenSize.Width), (screenSize.Height - (0.4 * screenSize.Height)))
vLine2.EndPoint = New System.Drawing.Point(screenSize.Width -
(0.2 * screenSize.Width), screenSize.Height - (0.4 *
screenSize.Height))
hLine1.StartPoint = New System.Drawing.Point((0.2 *
screenSize.Width), screenSize.Height - (0.4 * screenSize.Height))
hLine1.EndPoint = New System.Drawing.Point(screenSize.Width -
(0.2 * screenSize.Width), screenSize.Height - (0.4 *
screenSize.Height))
' Rear Wall
vLine3.StartPoint = New System.Drawing.Point((0.2 *
screenSize.Width), screenSize.Height - (0.4 * screenSize.Height))
vLine3.EndPoint = New System.Drawing.Point((0.2 *
screenSize.Width), 0)
vLine4.StartPoint = New System.Drawing.Point(screenSize.Width -
(0.2 * screenSize.Width), screenSize.Height - (0.4 *
screenSize.Height))
vLine4.EndPoint = New System.Drawing.Point(screenSize.Width -
(0.2 * screenSize.Width), 0)
WindowPic.Visible = True
WindowPic.SendToBack()
WindowPic.Left = 0.25 * screenSize.Width
WindowPic.Top = 0.1 * screenSize.Height
End Sub

Private Sub ExitToolStripMenuItem_Click(ByVal sender As Object,
ByVal e As System.EventArgs) Handles ExitToolStripMenuItem.Click

' Close COM Port
Try
    serialPort.Close()
Catch ex As Exception
    MsgBox(ex.ToString)
End Try

' Close Program
End
End Sub

Private Sub AboutToolStripMenuItem_Click(ByVal sender As Object,
ByVal e As System.EventArgs) Handles AboutToolStripMenuItem.Click

' Show the about box
AboutBox1.Show()
End Sub

Private Sub ReachForItToolStripMenuItem_Click(ByVal sender As Object,
ByVal e As System.EventArgs) Handles ReachForItToolStripMenuItem.Click

' Stop timer running (ie: when selecting new game)
DataTimer.Enabled = False
' Reset calibration flag (ie: when selecting new game)
calUpdate = 0
' Show the calibration instruction text box
Calibrate.ShowDialog()
' Show the hand representation picture
HandPic.Visible = True
' Start the timer to initiate reading position info
DataTimer.Enabled = True
End Sub

Private Sub DrawItToolStripMenuItem_Click(ByVal sender As Object, ByVal e As System.EventArgs) Handles DrawItToolStripMenuItem.Click
    ' Stop timer running (ie: when selecting new game)
    DataTimer.Enabled = False
    ' Reset calibration flag (ie: when selecting new game)
    calUpdate = 0
    ' Show the calibration instruction text box
    Calibrate.ShowDialog()
    ' Show the hand representation picture
    With HandPic
        Visible = True
    End With

    ' Start the timer to initiate reading position info
    DataTimer.Enabled = True
End Sub

Private Sub ChaseItToolStripMenuItem_Click(ByVal sender As Object, ByVal e As System.EventArgs) Handles ChaseItToolStripMenuItem.Click
    ' Stop timer running (ie: when selecting new game)
    DataTimer.Enabled = False
    ' Reset calibration flag (ie: when selecting new game)
    calUpdate = 0
    ' Show the calibration instruction text box
    Calibrate.ShowDialog()
    ' Show the hand representation picture
    With HandPic
        Visible = True
    End With

    ' Start the timer to initiate reading position info
    DataTimer.Enabled = True
End Sub

Private Sub Timer1_Tick(ByVal sender As Object, ByVal e As System.EventArgs) Handles DataTimer.Tick
    ' Send "x" to initiate data transfer for x co-ordinate
    Try
        serialPort.Write("x")
    Catch ex As Exception
        MsgBox(ex.ToString)
    End Try
    ' Wait while the ARM micro responds
    While valUpdate = 0
        ' Wait
        End While
    ' New value received
    oldX = newX
    newX = newValue - 300
    If newX < oldX + 3 And newX > oldX - 3 Then
        newX = oldX
    End If
    If newX > oldX + 3 Then
        newX = oldX + Math.Sqrt(newX - oldX)
End If
If newX < oldX - 3 Then
    newX = oldX - Math.Sqrt(oldX - newX)
End If

' With xBox
'.Text = newValue
' End With

' Record original value if calibration flag is not set
If calUpdate = 0 Then
    originalX = newValue
End If

' Reset wait flag
valUpdate = 0

' Send "y" to initiate data transfer for y co-ordinate
Try
    serialPort.Write("y")
Catch ex As Exception
    MsgBox(ex.ToString)
End Try

' Wait while the ARM micro responds
While valUpdate = 0
    ' Wait
End While

oldY = newY
newY = newValue * -1
If newY < oldY + 3 And newY > oldY - 3 Then
    newY = oldY
End If
If newY > oldY + 3 Then
    newY = oldY + Math.Sqrt(newY - oldY)
End If
If newY < oldY - 3 Then
    newY = oldY - Math.Sqrt(oldY - newY)
End If

' With yBox
'.Text = newValue
' End With

' Record original value if calibration flag is not set
If calUpdate = 0 Then
    originalY = newValue
End If

' Reset wait flag
valUpdate = 0

' Send "z" to initiate data transfer for z co-ordinate
Try
    serialPort.Write("z")
Catch ex As Exception
    MsgBox(ex.ToString)
End Try

' Wait while the ARM micro responds
While valUpdate = 0
    ' Wait
End While

oldZ = newZ
newZ = newValue + 270
If newZ < oldZ + 3 And newZ > oldZ - 3 Then
    newZ = oldZ
End If
If newZ > oldZ + 3 Then
    newZ = oldZ + Math.Sqrt(newZ - oldZ)
End If
If newZ < oldZ - 3 Then
newZ = oldZ - Math.Sqrt(oldZ - newZ)
End If
'With zBox
'.Text = newValue
'End With
' Record original value if calibration flag is not set
If calUpdate = 0 Then
    originalZ = newValue
End If
'Reset wait flag
valUpdate = 0

'Set calibration flag once all original values have been set
calUpdate = 1

'Move the hand
HandPic.Location = New Point(0.5 * screenSize.Width + newY, 0.5 * screenSize.Height - newZ)
HandPic.Width = 150 * (100 / (100 + 0.5 * newX))
HandPic.Height = 123 * (100 / (100 + 0.5 * newX))
'newX = oldX
End Sub

Private Sub serialPort_DataReceived(ByVal sender As Object, ByVal e As System.IO.Ports.SerialDataReceivedEventArgs) Handles serialPort.DataReceived
    newValue = serialPort.ReadExisting
    'Set the wait flag
    valUpdate = 1
End Sub
End Class

B.2.2 CALIBRATE.VB

Imports System.Windows.Forms

Public Class Calibrate

    Private Sub OK_Button_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles OK_Button.Click
        Me.Close()
    End Sub

End Class
APPENDIX C

C.1 DESIGN DRAWINGS

Appendix C includes the design drawings for the anti gravity arm that were used by the USQ workshop for production of the device. Supplied are the original drawings that may have been modified by the workshop to suit common sizes of the materials used. An example of this would be the use of 20mm aluminium bar by the workshop where 25mm may have been requested in the detail drawings.

The detail drawings presented are not their original size. They have been reduced from A3 sheet to fit within the borders of the dissertation.
C1.1 UPPER SHOULDER BLOCK
C1.2 LOWER SHOULD BLOCK

[Diagram of a lower shoulder block with dimensions and notes]
C1.3 UPPER ELBOW BLOCK
C1.4 LOWER ELBOW BLOCK
C1.5 SHAFT HEAD
C1.6 ARM SHAFT SENSOR

[Diagram of ARM SHAFT SENSOR with dimensions and notes]
C1.7 ELBOW SHAFT SENSOR
C1.8 STAND SHAFT
C1.9 UPPER SHOULDER SHAFT

Scale 1:10
All Dimensions in mm

Upper Shoulder Shaft

Anti Gravity Arm

22-02-2008
Rev. 1

Plus Locknuts and Washers to suit M10x1 threads
C1.10 TENSION SHAFT

[Diagram of Tension Shaft with dimensions and notes]

Manufacture 3 of
Scaler 21
All Dimensions in mm

Tension Shaft

Anti Gravity Arm

07-03-2008
Rev. 3

Plus Locknut and Washer to suit M8x1 and M10x1
C1.11 SHORT TENSION SHAFT

[Diagram of Short Tension Shaft]

Plus Locknut and washer to suit M10x1

Scale: 4:1
All Dimensions in mm

Short Tension Shaft
Anti Gravity Arm
06-03-2008
Rev. 1
C1.12 CONNECTION SHAFT
C1.13 SHAFT END
C1.15 SENSOR L MOUNT