**PhD Transfer Report**

“The Development and Comparison of Impedance and Admittance Control Strategies for a 2 Degree of Freedom Planar Rehabilitation Robot”

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*May 2019*

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Nomenclature

# Chapter 1: Introduction

## Motivation

The likelihood of having a Stroke increases with age. Statistics show that the population of the UK is aging, due in part to an increase in life expectancy. This means that Stroke is becoming more prevalent in the UK, and this is a trend reflected across much of the Western world. The increase in Stroke prevalence places a large burden on the NHS and rehabilitation services, especially considering that it is understood that effective neural rehabilitation should be intensive and occur early after the onset of Stroke. In order to ease the burden on medical services and provide more access to therapy, research is increasingly focused on the use of robotics.

Rehabilitation robotics for the rehabilitation of neurological injuries such as Stroke are designed to assist the patient with training exercises, and by necessity focus on specific target areas. Gait trainers assist with walking rehabilitation, for example, and upper limb devices assist with reaching exercise training. The benefits of rehabilitation robotics are that repeatable, measurable and consistent training exercises can be provided alongside traditional human-led physiotherapy. This comes at the cost of systems which are expensive and therefore only appropriate to install in community settings such as hospitals, which limits the access to important rehabilitation. Whilst there has been some research into low cost robotic systems, all the commercially available rehabilitation robots cost in excess of $100 000.

## MyPAM

MyPAM (previously known as hCAAR – Home based Computer Assisted Arm Rehabilitation) is a planar 2 Degree of Freedom robot designed for the upper limb rehabilitation of Stroke patients. It is designed to be low cost, such that it may be installed in the homes of patients in order to increase the access to and intensity of rehabilitation.

MyPAM currently consists of 3 of linked elements. The robot itself is a powered joystick that assists the patient to play games which simulate reaching exercises. A computer with a Microsoft Operating System contains the Unity game environment, where 5 games have been developed, and a LabVIEW host program. A National Instruments MyRIO embedded device deals with robot control and the data communication between the computer and the robot. A high-level overview of the data communication and the relationship between these 3 elements is shown by figure 1.2.1:

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|  |
| Figure 1.2.1: A UML diagram showing the relationship and data transfer between the elements of the MyPAM |

# Chapter 2: Literature Review

## Introduction

The likelihood of having a Stroke increases with age. Statistics show that the population of the UK is aging, due in part to an increase in life expectancy. This means that Stroke is becoming more prevalent in the UK. The increase in Stroke prevalence places a large burden on the NHS and rehabilitation services, especially considering that it is understood that effective neural rehabilitation should be intensive and occur early after the onset of Stroke. In order to ease the burden on medical services and provide more access to therapy, research is increasingly focused on the use of robotics.

## Stroke Mechanisms and Effects

Stroke, also known as Cerebrovascular Accident, is the leading cause of disability in the UK according to the Stroke Association (2018). Stroke is classified by 2 mechanisms: Haemorrhagic Stroke and Ischaemic Stroke. Haemorrhagic Stroke occurs when an artery in the brain ruptures, often as a result of high blood pressure. Ischaemic Stroke occurs due to the blockage of an artery in the brain, usually caused by a blood clot or fatty deposits. Both mechanisms lead to cell damage or cell death in the affected region of the brain because of a lack of oxygen (Moskowitz et al, 2010).

The symptoms of Stroke are wide ranging and dependant on which region of the brain has been affected and the severity of the Stroke. Different regions of the brain control different behaviour, as shown by figure 2.2.1:

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|  |
| Figure 2.2.1: Different regions of the brain associated with control of different behaviour (Stroke Association, 2018) |

Common symptoms include motor impairment along one side of the body (known as hemiplegia), impairment to speech, difficulties swallowing and impairment to memory. It was found in a study by Sommerfeld et al (2004) that up to 80% of Stroke patients initially experience motor difficulties. Lawrence et al (2001) performed a community-based study on first-time Stroke patients in which 77.4% of the Stroke patients suffered from upper limb impairment.

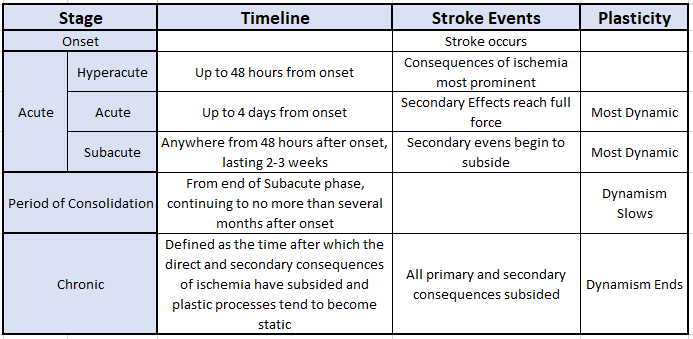
Stroke has a significant negative impact on a patient’s quality of life. Regular activities such as walking, eating, and manipulating objects become difficult or impossible. This often leads to dependency on care and assistance from others. Aside from the personal impact on the patient, Stroke has financial implications for society. Xu et al (2018) estimated the mean cost of health and social care per Stroke patient to be £46039. This figure is in close agreement with the Stroke Association (2017), who estimated that in 2015 the mean cost of health and social care per Stroke patient was £45409.

## Stroke Recovery

### Neural Recovery

Since Stroke is a neurological issue, it follows that Stroke recovery must exploit neurological mechanisms. Cerebral plasticity (otherwise known as neurofunctional plasticity) is the ability of the brain to “reorganise during ontogeny, learning or following damage” (Duffau, 2006). It is this ability of the brain to reorganise that provides the mechanism for Stroke recovery, though this is not yet fully understood according to Kreisel et al (2007).

Without the intervention of rehabilitation, there does remain some natural motor recovery after Stroke. The timeline for natural motor recovery after Stroke is summarised in the table 2.3.1:



It can be seen from table 2.3.1 that the neurofunctional plasticity of the brain is most dynamic after the Hyperacute phase, but then the dynamism slows. Once the patient has reached the Chronic stage, the plastic processes become static and motor deficits remain unchanged after this point (Kreisel et al, 2007).

### Physiotherapy for Rehabilitation

The use of physiotherapy is an accepted element for the rehabilitation of Stroke patients. Physiotherapy is applied by trained physiotherapists, though there has been a rise in the use of robots for post-Stroke physiotherapy in recent years. There is little agreement on the effectiveness of different rehabilitation strategies. 2 main rehabilitation strategies are in widespread use according to Morreale et al (2016) and Coleman et al (2017). Proprioceptive Neuromuscular Facilitation (PNF) involves stretching and contracting a targeted muscle group, as shown by figure 2.3.2.1:

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|  |
| Figure 2.3.2.1: Proprioceptive Neuromuscular Facilitation (PNF) (Marek et al, 2005) |

More advanced PNF involves resisting the movement of the patient, although this relies on the patient having enough motor control to move the exercised limb.

Cognitive Therapeutic Exercise (CTE) involves high level cognitive training through task-based activity (Lee et al, 2015). Robotic rehabilitation devices use the CTE strategy due to the ease of integrating tasks using computer game or virtual reality technologies.

Van Peppen et al (2004) performed a systematic review which showed that physical rehabilitation is more effective when performed intensively and early after Stroke. This is corroborated by Morreale et al (2016), who observed that early intervention was a factor on the effectiveness of rehabilitation. Indeed, these findings make sense when considering the neurofunctional plasticity of the brain is most dynamic early after onset, as shown in table 1.3.1. Morreale et al (2016) also stated, however, that “the optimal schedule and content of rehabilitation in the acute phase of care is still undefined”. It is generally agreed that early intervention of physical rehabilitation is important for recovery, but there is little evidence to support the existence of an optimal rehabilitation strategy. Kreisel et al (2007) agree, stating that “mechanisms that support or modulate recovery are not yet fully understood”.

## Stroke Prevalence

A study by O’Mahony et al (1999) found that 1.75% of a sample population of 2000 had suffered from Stroke. Stroke can occur in people of any age, but it has been shown by the Stroke Association (2018) that the likelihood of an individual having a Stroke increases with age. According to the Office of National Statistics (2018) the population of the UK is aging, with 26.5% of the population projected to be aged 65 or older by 2041, as shown by figure 1.4.1:

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| Figure 1.4.1: Aging population in the UK (Office of National Statistics, 2018) |

This ‘greying’ of the population is common across most Western societies due to falling birth-rates and an increased life expectancy, and is expected to become an issue globally. Figure 1.4.2 shows an age group distribution of the population using data gathered from 195 United Nations countries from 1950 onwards and projected to 2050:

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|  |
| Figure 1.4.2: Projected aging of a worldwide population (Lee and Mason, 2011) |

Observing the projected trend, it is reasonable to expect that the total number of Strokes will increase. This will increase the demand and financial costs upon the NHS and rehabilitation services, especially when considering that the research shows that early and intensive physical rehabilitation is an important factor in recovery.

## Using Robots for Rehabilitation of Stroke Patients

In recent years there has been an increase in interest and research into the use of robots for rehabilitation of Stroke patients. This is mainly because of the increased demand upon medical and rehabilitation services due the greying of the population identified in section 1.4. According to Maciejasz et el (2014) and Culmer (2007), rehabilitation robots are categorised by their mechanical structure as either an end-effector based device or an exo-skeleton based device. These can be further categorised as class 1 or class 2 devices, as stated by Sulzer et al (2007) and Sivan et al (2014). Class 1 devices are of high cost and intended for lab use, whereas Class 2 devices are low cost and intended for home use. Most of the research in robotic rehabilitation devices has focused on Class 1 devices, since it was necessary to produce evidence that robotic rehabilitation was a valid rehabilitation strategy. However, Johnson et al (2007) identified a “need to improve the cost-to-benefit ratio of robot-assisted therapy strategies and their effectiveness for stroke therapy in home environments characterized by the low supervision by clinical experts, low extrinsic motivation as well as low cost requirement”, which justifies further work in the area of Class 2 devices.

An established control hierarchy exists for rehabilitation robotics, which is necessary since a high-level rehabilitation strategy must be encoded as low-level strategies according to Marchal-Crespo and Reinkensmeyer (2009). The low-level control strategies usually run in real time, since these control specific implementations of force, position or other types of interaction control. This hierarchy is shown by figure 1.5.1:

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| Figure 1.5.1: Rehabilitation Robotics Control Hierarchy |

### Trajectory Generation

As with any robot designed to move an end-effector from a starting position to a desired position, a trajectory must be generated. A number of approaches exist, the selection of which depends on what the trajectory is required to optimise. The simplest solution is to generate a simple linear trajectory which covers the shortest distance between the current position and the desired position. This method, however, has the potential to generate unacceptable changes in acceleration.

A better solution, implemented by the MIT-MANUS (Hogan et el, 1998), produces a minimum jerk trajectory. A minimum jerk trajectory minimises jerk, which is the 3rd time derivative of position (or 1st time derivative of acceleration), thus a minimum jerk trajectory ensures that there should be no unacceptable changes in acceleration. Minimum jerk trajectories are an example of trajectories based on normative mathematics, which cover the most common trajectories used for rehabilitation robotics according to Marchal-Crespo and Reinkensmeyer (2009), though there is no evidence that normative trajectories maximise motor plasticity. Another common approach is to pre-record a trajectory.

### High Level Control Strategies

All rehabilitation robotic devices must consider and implement both high-level control strategies and low-level control algorithms according to both Maciejasz et al (2014), who performed a systematic review of rehabilitation robotic devices, and Marchal-Crespo and Reinkensmeyer (2009), who performed a systematic review of control strategies for rehabilitation robotic devices. The high-level control strategy describes the movement strategy of the robot designed to promote neurofunctional plasticity of the damaged motor control areas of the brain, whereas the low-level control algorithms describe the specific implementation of position, force, impedance or admittance control. Erol and Sarkar (2007) suggest that the role of the high-level controller is equivalent to the role of the physiotherapist, in that it monitors the status of the task, monitors the safety of the patient and “informs the low-level controller about the task updates”.

High-level control strategies can be broadly split into four categories: 1. Assistive control, 2. Challenge based control, 3. Haptic stimulation, and 4. Non-contacting coaching (Maciejasz et al, 2014) and (Marchal-Crespo and Reinkensmeyer, 2009).

Assistive control is a strategy whereby the patient is aided to complete the task. Usually, measures are put into place to allow the patient to move unrestricted as long as the correct trajectory is being followed. If there is deviation from the desired trajectory a restoring force proportional to the level of deviation is applied, as seen with the MIT-MANUS (Krebs et al, 2004). An Assistive control strategy is commonly implemented with Impedance or Admittance control as the low-level control algorithm.

Another type of Assistive control uses a counterbalance to make a task easier for the patient, the Wilmington Robotic Exoskeleton (WREX) (Sanchez et al, 2005) being a good example. A further method of implementing Assistive control is to use Surface Electromyography (sEMG) sensors to measure signals in the nerves, which is used to trigger assistance according to the patient’s movement intention. This is difficult, however, since the noise to signal ratio is very high.

Challenge based control methods are designed to make the task more difficult for the patient, and are categorised as resistive, error amplifying or constraint induced. Resistive strategies resist the movement of the patient, simulating the more advanced techniques of Proprioceptive Neuromuscular Facilitation (PNF). Error amplifying strategies amplify movement errors rather than decrease them, according to (Marchal-Crespo and Reinkensmeyer, 2009). Error amplification strategies have been shown to increase motor learning compared with assistive strategies according to Patton et al (2006), who tested 18 hemiparetic Stroke patients.

Constraint induced strategies involve constraining the unimpaired limb, so that the impaired limb must perform the task. This particular strategy is particularly suited to exercises involving 2 limbs, for example reaching for a sizable object. Constraint induced strategies are not relevant, however, for end effector type devices such as the MIT-MANUS or hCAAR. In general, challenge based control methods are not useful for severely impaired patients with little or no motor control, since the patient does not have sufficient control to begin the required movement.

Haptic strategies involve the use of Virtual Reality (VR) or Altered Reality (AR), where the user must where a headpiece which provides visual feedback in a 3-Dimensional environment. This was implemented by Montagne et el (2007), who found that the use of an engaging VR environment for visual feedback coupled with an exoskeleton robotic rehabilitation device significantly increased patient motivation. A clinical trial of this device showed increased motor control after 6 weeks of use, though only 3 chronic patients were tested and there is no evidence to show that the implementation of VR provides a greater clinical benefit than simply displaying visual feedback via a computer screen, as implemented by many other robotic rehabilitation devices.  
 Non-contact coaching devices do not interact with the patient, and simply provide instructions to the patient, according to both Maciejasz et al (2014) and Marchal-Crespo and Reinkensmeyer (2009). This may be useful for patients with high amounts of motor control but is not useful for patients with higher levels of disability who require assistance to complete exercises.

### Accounting for Interaction Forces

The case of a robotic physiotherapy device interacting with a human patient should be considered as a coupled mechanical system (Maciejasz et al, 2014). This means that the use of a force control strategy or a position control strategy alone is insufficient, since interaction forces with the patient are not accounted for and are thus inherently unsafe. Further to this, failure to account for interaction forces raises the possibility of controller instability. Hogan and Buerger (2004) demonstrated this instability by showing that the Rough-Hurwitz stability criterion were met when considering an example system in isolation but were not met when considering the same system in a coupled mechanism.

In order to account for interaction forces, the majority of rehabilitation robotic devices use Impedance Control or Admittance Control as the low-level control strategy. Impedance Control and Admittance Control involve modulating the dynamic behaviour of the robot alongside position or force control, according to Hogan (1984), by specifying the robot’s position and force relationship using virtual mass, spring and damping characteristics which are heuristically determined (Richardson, 2001). Richardson (2001) explains this using figure 1.5.3.1:

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| Figure 1.5.3.1: The external force changing the desired position (Richardson, 2001) |

Essentially, the desired position changes due to the application of an external force in a predictable manner defined by the mass, spring and damping characteristics.

A physical system which accepts force inputs and produces position outputs is defined as an admittance. A physical system which accepts position inputs and produces force outputs is defined as an impedance (Ott et al, 2010) (Hogan,1984). The end effector of a mechanically coupled robot is subject to physical constraints, so it acts as either an admittance or an impedance. If the environment acts as an admittance, the end effector must act as an impedance according to Hogan (1984). Conversely, if the environment acts as an impedance, the end effector must act as an admittance.

### Admittance Control

Admittance control is a strategy whereby the force exerted on the end effector is measured, and the robot provides the corresponding displacement (Maciejasz et el, 2014). This means that the controller is acting as an admittance and the environment is acting as an impedance. As such, an Admittance control strategy is based around an inner loop position controller, as shown by the block diagram in figure 1.5.4.1:

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| Figure 1.5.4.1: A block diagram for a generic Admittance Controller (Richardson, 2001) |

According to Culmer et al (2010), the control signal can be simply defined as shown by equation 1.5.4.1:

|  |  |
| --- | --- |
|  | Eqn 1.5.4.1 |

Where:

### Impedance Control

Impedance control is a strategy whereby the motion of the end effector is measured, and the robot provides the corresponding force-feedback (Maciejasz et el, 2014). This means that the controller is acting as an impedance and the environment is acting as an admittance. An Impedance control strategy is based around an inner loop force controller, as shown by the block diagram in figure 1.5.5.1:

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| --- |
|  |
| Figure 1.5.5.1: A block diagram for a generic Impedance Controller (Richardson, 2001) |

According to Culmer et al (2010), the control signal can be simply defined as shown by equation 1.5.5.1:

|  |  |
| --- | --- |
|  | Eqn 1.5.5.1 |

Where:

### Selecting Impedance Control or Admittance Control

It is agreed by Ott et al (2010) and Maciejasz et el (2014) that the advantages and disadvantages of Impedance and Admittance control systems are opposite, which makes sense considering that the definition of a mechanical Impedance is inverse, dual (Culmer, 2007), to the definition of a mechanical Admittance. Devices using Impedance control are stable in stiff environments but can be inaccurate in free environments due to unmodelled dynamics such as friction (Ott et al, 2010). Conversely, devices using Admittance control provide “high level of accuracy in non-contact tasks but can result in instability during dynamic interaction with stiff environments”.

Anderson and Spong (1988) state the duality theory, which is that “the manipulator should be controlled to respond as the dual of the environment”. Simply put, this means that inertial environments, which act as an Impedance, require position based low-level control and the optimal interaction control strategy is Admittance control. In contrast, environments characterised by a mass, spring and damper relationship, which act as an Admittance, require force based low-level control and the optimal interaction control strategy is Impedance control.

However, these criteria are not the sole determining factor on the most appropriate low-level control strategy. For example, whilst a robot actuated by direct drive electric motor systems may lend itself to force control (and thus Impedance control as an interaction control strategy), in reality this relies on an accurate dynamic model which can be difficult to obtain. Further to this, the robot would require force sensors at each joint, whereas a robot using Admittance control would require a force sensor only at the end effector, thus proving to be a more cost-effective solution. A comparison of Admittance control and Impedance control are summarised in table 1.5.6.1:

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| Table 1.5.6.1: Comparison of Interaction Control Techniques (Richardson, 2003) |

## Rehabilitation Robots

Over the last 30 years, much work has been done in the area of rehabilitation robotics. In this section of the Literature Review there follows a brief overview of a selection of devices designed for upper limb rehabilitation of Stroke patients.

### MIT-MANUS

MIT-MANUS was the first robotic device designed for the rehabilitation of upper limbs of Stroke patients. The device consists of a direct-drive five bar-linkage SCARA (Selective Compliance Assembly Robot Arm) which provides 2 DoF movement for the elbow and forearm in the horizontal plane (Krebs et al, 2004). MIT-MANUS guides the patient’s arm through a series of predetermined exercises, with visual feedback provided on a computer screen according to Hogan et al (1995).

A series of extension devices were designed to aid in rehabilitation, since trials of MIT-MANUS found that positive motor learning effects on the exercised muscle groups did not have any effect on unexercised muscle groups. The first module extends the operating range of the MIT-MANUS by adding a third degree of freedom, which allow exercises to be performed in 3D space (Krebs et al, 2004). The second module was designed to rehabilitate the muscle groups in the hand. The MIT-MANUS and the hand module were successful enough that commercial products were released as the InMOTION Arm™ and the InMOTION Hand™. Figure 1.6.1.1 shows the InMOTION Arm™:

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| Figure 1.6.1.1: The InMOTION Arm™ |

According to Krebs et al (2004), one of the driving design features for the MIT-MANUS is that it is “configured for safe, stable, and compliant operation in close physical contact with humans”. This was achieved using Impedance Control as the low-level control strategy and ensuring that the hardware was backdrivable enough that frail patients could easily move the device. The Control hierarchy, which is similar that that seen across all robotic rehabilitation devices and defined in section 1.5, is shown by figure 1.6.1.2:

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| Figure 1.6.1.2: The Control hierarchy for MIT-MANUS (Hogan et el, 1998) |

The hierarchy in figure 1.6.1.2 shows the following process:

1. A high-level controller sets the sequence of targets for the therapy session.
2. The Task encoder translates the sequence of targets into sets of minimum-jerk trajectories.
3. The low-level controller is an impedance control strategy which uses the trajectories to provide varying assistance levels to the patient and control the interaction forces.
4. Force and position feedback from the hardware and environment are used as feedback parameters.

MIT-MANUS is the most extensively tested device for upper limb rehabilitation of Stroke patients. An initial pilot study was performed in which half of a cohort of 20 patients, as the control group, received only physiotherapist guided therapy and the second half of the cohort, as the experimental group, received physiotherapist guided therapy alongside robot guided therapy. The results of the pilot trial showed that the patients who received robot led therapy alongside physiotherapist led therapy gained significant motor control in the targeted muscle groups (Krebs et al, 1998). Importantly, it was also found that patients in the experimental group improved “further and faster” than those in the control group (Krebs et al, 1998). A further study retested a subset of the patients 3 years after the initial therapy, and it was found that the experimental group “showed further significant decreases in impairment measures of the affected limb” (Volpe et al, 1999).

### MEMOS

The Mechatronic System for Motor Recovery After Stroke (MEMOS) is a 2DoF planar robotic rehabilitation system designed to be as low cost as possible. This was achieved by building the device using as many ‘off the shelf’ parts as possible and ensuring that any part which could not be simply bought was able to be manufactured as simply as possible (Micera et al, 2005). Much like the MIT-MANUS, the MEMOS system guides the patient’s arm through a series of exercises with visual feedback provided on a computer screen.

The result of these cost saving measures is that the device costs only 4450 Euros. This is considerably more cost effective compared with the estimated $110 000 for the InMOTION Arm™, which is also a 2DoF planar robot. The MEMOS system consists of a handle connected to a trolley which runs on rails in a cartesian configuration, shown by figure 1.6.2.1:

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| --- |
| C:\Users\adamg\AppData\Local\Microsoft\Windows\INetCache\Content.MSO\632B11EB.tmp |
| Figure 1.6.2.1: The MEMOS system (Micera et al, 2005) |

The MEMOS system defines 3 High-level control strategies: Completely assisted movement where the patient provides no input, assisted movement where the patient provides some input, and unassisted movement where the patient provides total input. If the patient fails to produce a minimum force after a certain amount of time, the robot moves the handle to the target with a predefined velocity. This is clearly seen in the control signal shown by equation number (Micera et al, 2005):

|  |  |
| --- | --- |
|  | Eqn number |

Where:

It can be seen from the control signal that the low-level control strategy implemented is Admittance Control, although this choice is not explained.

MEMOS was subjected to a preliminary clinical trial containing 8 patients suffering from chronic hemiparesis after Stroke. The subjects’ hemiparesis in all 8 subjects was considered to be only slightly to moderately impairing. The testing consisted of a 40-minute session with the device twice a day for 3 weeks, where the exercises consisted of reaching tasks (Micera et al, 2005). The results showed that 7 of the 8 subjects improved in motor control of the targeted muscles groups. Importantly, the results of the clinical trial showed that it is possible for rehabilitation to have an effect even in the chronic phase, although it should be noted that none of the tested subjects had severe impairment, so it is not possible to extrapolate the findings to severely disable chronic Stroke patients.

### The Mirror Image Motor Enabler (MIME) System

After an initial 2-DoF prototype was built, the second iteration of the Mirror Image Motor Enabler (MIME) system used an industrial PUMA 6-DoF robot to move the impaired limb of a Stroke patient. The MIME device moved the patient’s arm in a planar motion, with the weight of the arm borne by a separate support which contained position sensors. The unaffected arm was connected to a separate support, also containing position sensors. A third iteration of the device used a larger PUMA 6 DoF robot which could support the full weight of the impaired limb and allow the separate support to be removed. The benefit of this was that a 3D workspace could be utilised. This arrangement is shown by figure 1.6.3.1:

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| Figure 1.6.3.1: The 3rd iteration of the MIME system (Burgar et al, 2000). |

The MIME system had 4 high-level control strategies. The first was a completely assisted mode (in the literature called ‘passive-guided mode’), where the robot moved the impaired limb along a predefined trajectory and the patient was required to input no effort. The second was an assisted mode, where the patient initiated movement of the impaired limb and the MIME robot provided assistance to complete the exercise. The third was a resistive mode, where the patient moved the impaired limb and the MIME robot resisted the motion. The fourth was a novel bilateral mode, where the robot could move the impaired limb as a mirror image to the movement of the unimpaired arm, in a master/slave relationship (Lum et al, 2006).

There is no explicit description of the low-level control system, but the literature states that both joint position and patient-handle interaction force were measured (Lum et al, 2005), which suggests the use of an Admittance control scheme.

The MIME system has undergone extensive clinical trials. In an initial trial of the 3rd iteration of the device 11 chronic subjects were exposed to robot training therapy as the test group and 10 chronic subjects received traditional physiotherapy as the control group. Therapy sessions lasted for 1 hour, and this occurred for 24 sessions over a 2-month period (Burgar et al, 2000). It was found that the robot test group experienced increased motor control in the targeted muscles groups to a greater extent than the control group, though at a 6 month follow up it was found that the gains were equivalent in both the test group and the control group.

In a further study subacute subjects were split into 4 test groups. The first of the groups were exposed to robot therapy that started as completely assisted and progressed resistive therapy. The second of the groups were exposed to bilateral robot therapy. The third of the groups were exposed to robot therapy that was split between bilateral training and unilateral training. The fourth group was the test group who were exposed to no robot therapy, but instead received an equal amount of traditional physiotherapy (Lum et al, 2005). The therapy sessions lasted for 1 hour, and this occurred 15 times over a 4-week period. The robot test groups demonstrated significantly increased motor control in the targeted muscle groups at the end of the testing, to a much greater extent than the test group. This is consistent with the previous study. However, at a 6 month follow up it was found that “gains in robot

and control groups were equivalent” (Lum et al, 2005), similar to the chronic test group from the previous study.

In a follow up Lum et al (2006) suggest that from a pragmatic point of view, robotic therapy is useful for patient motivation when access to a physiotherapist may be limited, even if the long-term gains from robotic therapy are equivalent to that of traditional physiotherapy. To this end, it is suggested that research efforts should be directed towards producing low-cost versions of clinically tested robots.

### The Assisted Rehabilitation and Measurement) ARM Guide

The Assisted Rehabilitation and Measurement (ARM) Guide is a 2 DoF device designed to rehabilitate and measure upper limb reaching movements of Stroke patients. The device is mechanically simple and consists of a splint connected to a linear slide rail. The splint is driven along the rail using an electric motor. The slide mechanism can be adjusted in the horizontal and vertical planes, allowing a variety of reaching exercises to be performed (Reinkensmeyer, 2001). The interaction force between the patient and the ARM Guide is measured using a 6 DoF force sensor. The ARM Guide is shown by figure 1.6.4.1:

|  |
| --- |
|  |
| Figure 1.6.4.1: The ARM Guide system (Reinkensmeyer et al, 2001). |

The ARM Guide system uses 2 distinct high-level control strategies. Due to the linear mechanical design of the ARM Guide system, all exercise trajectories are linear. The first high-level strategy is termed ‘Counterpoise Assistance’, which is based on traditional physiotherapy techniques. Counterpoise Assistance provides enough assistance to overcome passive forces resisting the desired motion, such as gravity and arm tone according to Reinkensmeyer et al (2001). The low-level control scheme which is implemented to achieve this involves measuring the resistive forces and counteracting them by applying an opposite force with the motor.

The second high-level strategy is Triggered Assistance, where full assistance is given to complete the reaching exercises as soon as the patient initiates the movement. The low-level control scheme uses a PD position control loop (Reinkensmeyer et al, 2001).

The ARM Guide was subjected to trials containing 19 Chronic Stroke patients suffering from hemiparesis, who were split randomly into 2 groups. The test group engaged in robot assisted reaching exercises and the control group engaged in unconstrained and unassisted reaching exercises. The study consisted of 24 separate sessions lasting 45 minutes over a period of 8 weeks. It was found that both groups had significantly improved range of movement and velocity control at the end of the study, and that the robot assisted test group did not experience statistically significant detectable improvements in motor control beyond that experienced by the unassisted control group (Kahn et al, 2006).

### The End Effector Upper Limb Rehabilitation Robot EEULRebot System

The End Effector Upper Limb Rehabilitation Robot (EEULRebot) is a planar system designed to assist in the rehabilitation of Stroke patients with upper limb motor control deficiencies. The planar workspace is adjustable in the vertical (z) direction by adjusting the inclination angle, making the device quasi-3 DoF. The 2 joints are powered using Maxon motors. The end effector contains a force sensor to measure the interaction force between the patient and the EEULRebot device. A SolidWorks model of this arrangement is shown by figure 1.6.5.1:

|  |
| --- |
|  |
| Figure 1.6.5.1: A SolidWorks model of EEULRebot System (Liu et al, 2017) |

The EEULRebot System has 3 distinct high-level control strategies (Liu et al, 2017). Similar to the MIME System in section 1.6.3, The first is a completely assisted mode (in the literature called ‘passive-guided mode’), where the robot moves the impaired limb along a predefined trajectory and the patient is required to input no effort. The second is an Assistive mode (in the literature called ‘Active-Constrained mode’) where the robot provides assistance to complete the exercise, and in particular provides a restoring force to ensure that any deviation from the desired trajectory is corrected. The third is a Resistive mode (in the literature called Active Assistant or Resistant Mode’) where the robot resists the movement of the end effector if the user exceeds a velocity threshold in the direction of the desired trajectory, thus making the exercise more difficult.

Impedance control was used as the low-level control strategy, with a restoring force normal to the trajectory designed to align the current position with the current point on the desired trajectory (Liu et al, 2017). A force parallel to the direction of the desired trajectory was also defined. In the assistive mode this force was positive, helping the patient to move the impaired limb along the desired trajectory. In the resistive mode this force was negative, making it more difficult to complete the exercise.

The EEULRebot device underwent trials with 11 healthy subjects and 3 hemiplegic subjects who had suffered from a Stroke. The healthy subjects tested all 3 of the high-level control strategies, but only 1 of the hemiplegic subjects was able to do so. The other 2 hemiplegic patients had insufficient motor control to test the Assistive mode or the Resistive mode, and so only tested the Passive-guided mode. The trial was designed to test the robustness of the device rather than to validate it in as a useful clinical tool. The trials demonstrated that the EEULRebot was robust in that the control strategies worked as intended, though it was noted that further extensive trials were required with a greater number of impaired test subjects (Liu et al, 2017).

### The intelligent Pneumatic Arm Movement (iPAM) System

The intelligent Pneumatic Arm Movement (iPAM) is a cooperative dual robot system designed for upper limb rehabilitation of Stroke patients. Each of the dual iPAM robots uses pneumatic actuators to power the movement of its 3 joints (Culmer et al, 2005). Similar to other rehabilitation robotic devices, iPAM guides the patient’s arm through a series of exercises with visual feedback provided on a computer screen. The iPAM dual robot system is shown by figure 1.6.6.1:

|  |
| --- |
|  |
| Figure 1.6.6.1: The iPAM system (Jackson et al, 2007) |

The iPAM uses Assistive control as the high-level control strategy, and so it assists the patient to complete the exercises. The iPAM can be adjusted to provide increased or decreased assistance. The input trajectory fed to the low-level control scheme is based on the kinematics of the arm. This procedure is consistent with the control hierarchy defined in section 1.5.

The iPAM uses Admittance control for the low-level control strategy. The control scheme is cooperative, since both robots must act in unison (Culmer et al, 2006). Admittance control was chosen because it favours pneumatic actuation, as agreed by Culmer (2010) and Richardson (2001). This is because it is difficult to model the non-linear dynamic effects, such as stiction, of pneumatic actuators accurately enough to ensure an accurate force control inner loop, which is required for impedance control. The level of assistance provided to the patient is changed by altering the stiffness coefficient in the admittance filter.

Initial trials demonstrate that the iPAM is capable of providing assistance to the upper limb with similar trajectories and patterns of movement to a subject’s unconstrained motion (Jackson et al, 2007). This was considered important because the system was designed not to exert unwanted and uncontrolled forces on the limb, which would encourage unnatural motions. It was noted, however, that the device was unsuitable for use with patients who had “little to no voluntary movement” (Jackson et al, 2007), since it was necessary for the patient to have some amount of motor control because the device was not capable of providing total assistance.

### hCAAR (home-based Computer Aided Arm Rehabilitation) System

The hCAAR (home-based Computer Aided Arm Rehabilitation) system is a 2DoF planar device developed to be installed in the houses of Stroke patients for upper limb rehabilitation. This would increase patient therapy hours, since literature suggests that the more access to therapy a patient has, the greater the potential for motor recovery. The hCAAR system guides the patient’s arm through a series of games, with visual feedback provided on a computer screen, as shown by figure 1.6.7.1:

|  |
| --- |
|  |
| Figure 1.6.7.1: The hCAAR system (Sivan et al, 2014) |

Since the hCAAR was intended for home use, it was designed to be as cost effective as possible. To this end, the first iteration of hCAAR used only position control so as to limit the use of expensive sensors. The second iteration of the hCAAR system uses a novel form of Impedance Control as the low-level control strategy whereby the motor current draw at each joint motor are estimated from a system model, allowing an inner loop which controls motor current draw rather than directly controlling torque, according to Firouzy (2011). This means that expensive torque sensors are not required for the force feedback necessary for an inner force control loop. The downside to this is that current measurements are noisy and thus the reliability of the control system is questionable. The block diagram for this arrangement is shown by figure 1.6.7.2:

|  |
| --- |
|  |
| Figure 1.6.7.2: The hCAAR system block diagram (Firouzy, 2011). |

The hCAAR has 2 distinct operation modes, which can be considered as the high-level control strategies. The first mode is assistive where a level of assistance, which can be varied, aids the patient to complete the tasks. The second mode is passive where no assistance is provided, which is used to collect data about patient progress.

The first iteration of the hCAAR system, which used position control only, was subjected to clinical trials with 19 patients, 17 of which completed the trial. Each patient had a hCAAR device installed in their home for a period of 8 weeks in order to undertake home exercises alongside their usual rehabilitation. A baseline assessment was carried out just before home installation, an assessment was carried out after the 8-week trial period and a further assessment was carried out after another 4 weeks (at the 12-week period). According to Sivan et al (2014), “statistically significant improvements were observed”, though it was noted that a study “comparing the combination of conventional therapy and hCAAR with conventional therapy alone needs to be explored”. It should be noted also that with position control only there is no mechanism for measuring or controlling the interaction forces with the patient, and thus potentially dangerous torques or forces could occur.

### RUPERT (Robotic assisted Upper Extremity Repetitive Therapy) System

The Robotic assisted Upper Extremity Repetitive Therapy (RUPERT) device is an exoskeleton robot designed to rehabilitate Stroke patients suffering from upper limb mobility problems. The RUPERT device is aimed specifically at training 3DoF reaching tasks critical for daily living (Sugar et al, 2007). Assistance is provided to the patient through the use of pneumatic ‘air muscles’, much like the iPAM in section 1.6.6. The RUPERT system is shown in figure 1.6.8.1:

|  |
| --- |
|  |
| Figure 1.6.8.1: The RUPERT system (Sugar et al, 2007). |

Common to many robotic rehabilitation devices, RUPERT uses Assistive control as the high-level control strategy. The patient is requested to make a movement. If after a certain amount of time the patient has been unable to do so, RUPERT provides assistance. Interestingly, the low-level control of the RUPERT device relies is open loop feedforward position control. This means that the physiotherapist must set and monitor speed and position parameters in order to ensure patient safety, along with a set limit on the maximum angular speed of the joints. Sugar et al (2007) acknowledge the limitations of this low-level control algorithm, stating that closed loop control would be required when dealing with more severely impaired patients.

The second iteration of the RUPERT device was subjected to limited clinical trials containing 10 Stroke patients who had moderate or mild upper limb motor control difficulties. The test ran for 3 weeks, with a modified Wolf Motor Test. Though the testing description is limited, 6 of the 10 test subjects completed the trials and 5 of these showed improvements in motor control in the targeted muscle groups.

## Summary of the Literature

There has been much development in the use of robotics to provide rehabilitation for Stroke patients in recent years, which has been prompted by the financial and social implications of an aging population where Stroke is becoming increasingly prevalent. The area of robotic rehabilitation is dominated by 2 main classes of devices. The first is exoskeleton-based robotics, and the second is end-effector based devices. These can be further split into Class 1 devices, intended for clinical and lab use, and Class 2 devices, intended to be low cost and installed for home use.

Rehabilitation robotics devices follow an established control strategy. The high-level control strategy is designed to follow principles of established physiotherapy principles which attempt to promote neurofunctional plasticity, though this area is not well understood. A trajectory is generated, and the low-level control strategy describes the specific implementation of position, force, impedance or admittance control.

Many of the devices utilise some form of interaction control for the low-level control strategy. Interaction control was heavily developed by Hogan and can take the form of Admittance control or Impedance control, though some rehabilitation robotics devices use a hybrid form of the two. The MIT-MANUS, for example, uses Impedance control and the iPAM uses Admittance control.

A review literature has identified research gaps. Johnson et al (2007) identified a requirement to develop low cost solutions for rehabilitation robotics, which is significant because the leading commercial solution, the InMOTION Arm™, costs in excess of $100 000. Marchal-Crespo and Reinkensmeyer (2009) suggest that future research efforts should focus on a “rigorous comparison of control algorithms” to determine whether there is any clinical benefit to the selection of one over another. There is evidence that the use of rehabilitation robotics can positively affect motor control of targeted muscle groups, but consistent with traditional physiotherapy, there is no consensus on an optimal high-level strategy, low-level strategy or rehabilitation schedule. This is because “mechanisms that support or modulate recovery are not yet fully understood” (Kreisel et al, 2007) .

# Trajectory Generation

## The Current System

In the current MyPAM system the game (running at 30Hz) is responsible for generating the trajectory for each reaching movement. The game creates the final target position and generates equidistant intermediate positions as a linear path, as shown by figure 3.1.1:

|  |
| --- |
|  |
| Figure 3.1.1: An example of a linear trajectory generated by the game. |

These intermediate positions are passed 1 at a time to the controller. The controller (running at 500Hz) is only aware of the current position and the next intermediate position. Using position PID, the controller generates motor demands. A number of problems arise as a result of this current division of responsibilities and method:

1. A linear trajectory of this nature is not reflective of natural human motion.
2. The game does operate at 30 Hz reliably as a result of being dependant of the non-deterministic operating system on Windows. There may be instances where the game rate will drop, resulting in inaccurate intermediate position data being sent to the controller.
3. There are occasions where no intermediate points are generated and the final target position is sent to the controller, for example during some game types and during transitions between different games. This leads to a large difference between the current position and the target position, and large motor demands are generated. This leads to aggressive accelerations and potentially dangerous interaction forces between the patient and the robot.

Trajectory Generation

A smooth trajectory is desirable in order to mimic natural human motion when assisting the user to reach a target. Mathematically, a smooth trajectory translates to minimising the rate of change of an input, where the input corresponds to the order of the system. For example, a 1st order system corresponds to a kinematic model where velocities may be arbitrarily specified. This is summarised in the table x below:

|  |  |
| --- | --- |
| **Order of the system** | **Input to the system** |
| 1st | Velocity, |
| 2nd | Acceleration, |
| 3rd | Jerk, |
| 4th | Snap, |
| 5th | Crackle, |
| 6th | Pop, |

The function for the trajectory may be found using Calculus of Variations, using the general equation shown by Equation x.1:

|  |  |
| --- | --- |
|  | Eqn x.1 |

Where .

Alternatively, the trajectory may be found by satisfying the Euler-Lagrange equation shown by Equation x.2:

|  |  |
| --- | --- |
|  | Eqn x.2 |

For example, the shortest distance between 2 points may be found using Equation x.3 or x.4:

|  |  |
| --- | --- |
|  | Eqn x.3 |
|  | Eqn x.4 |

Calculating the Minimum Jerk Trajectory using the Euler-Lagrange formulation

For a Minimum Jerk Trajectory, , since a minimum jerk trajectory is based on minimising the sum of squared jerk across the trajectory.

Forming the Euler-Lagrange formulation as shown by Equation x.2:

|  |  |
| --- | --- |
|  | Eqn x.5 |
|  |  |
|  |  |
|  | Eqn x.6 |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |
|  | Eqn x.7 |

Substituting boundary conditions as shown by table x:

|  |  |  |  |
| --- | --- | --- | --- |
|  | Position | Velocity | Acceleration |
| t = 0 | a | 0 | 0 |
| T = tf | b | 0 | 0 |

As shown by Equation x.7:

|  |  |
| --- | --- |
|  | Eqn x.7 |

Thus:

|  |  |
| --- | --- |
|  | Eqn x.8 |
|  | Eqn x.9 |

Substituting boundary conditions:

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |

Solving for the coefficients:

|  |  |
| --- | --- |
|  |  |
|  |  |

Giving:

|  |  |
| --- | --- |
|  | Eqn x.10 |
|  | Eqn x.11 |

Where:

Justifying the use of a Minimum Jerk Trajectory

A Minimum Jerk Trajectory produces a smooth trajectory, but so too do other trajectories based on minimising the squared sum of derivatives of position. Figure number shows position and velocity graphs for the Minimum Acceleration, Minimum Jerk, Minimum Snap, Minimum Crackle and Minimum Pop trajectories to displace x from 0-100mm in 2 seconds. It may be observed that as the order of the system increases the position curve approaches a step function and the peak acceleration increases.

|  |
| --- |
|  |
| Figure Number: Position and Velocity Graphs showing a displacement of 100mm in 2 seconds using Minimum Acceleration, Minimum Jerk, Minimum Snap, Minimum Crackle and Minimum Pop trajectories. |

For assistive rehabilitation technology, it would be advantageous to generate a trajectory which mimics human movement. According to Richardson and Flash (2002), one measure of human reaching motion is the ratio of peak velocity to average velocity across the movement. Flash and Hogan (1985) found that the ratio of peak velocity to average velocity, R, across a reaching movement is around 1.8. The ratio for Minimum Acceleration, Minimum Jerk, Minimum Snap, Minimum Crackle and Minimum Pop trajectories is shown by table x:

|  |  |
| --- | --- |
| **Trajectory Type** | **R = Peak Velocity/Average Velocity** |
| Minimum Acceleration | 1.50 |
| Minimum Jerk | 1.88 |
| Minimum Snap | 2.19 |
| Minimum Crackle | 2.46 |
| Minimum Pop | 2.71 |

Thus, it is clear that by this measure the Minimum Jerk trajectory most closely resembles natural human motion and is therefore the most appropriate trajectory for the MyPAM.

VALIDATION FOR FUTURE WORK

Integrating a controller generated trajectory into the architecture

The blah blah blah integration required

This process is shown by figure number:

|  |
| --- |
|  |
| Figure number: A flowchart showing the Minimum Jerk Trajectory integration into the MyPAM |

PIGGYBACK ONTO PPI THING WITH QUESTIONAIIRS

# End Effector Force Sensing

## Introduction

A necessary component for the Admittance or Impedance control schemes planned for comparison on the MyPAM is the ability to measure the interaction force between the patient and the end effector. The majority of rehabilitation robots which require a force sensor use off the shelf force sensors. For example, the iPAM used a 6-axis ATI Mini40 (Culmer, 2007), with a cost of around $5500. Since the MyPAM is designed to be a low-cost device it is necessary to develop an economically viable force sensor.

## Force Sensing

Force sensing basics.

RR thesis.

Mag1 – Pete’s research group.

## Silicone thing

Four test pieces were manufactured. Test piece 1 contained a solid inner core manufactured from EcoFlex™ 0010. Test piece 2 contained a solid inner core manufactured from EcoFlex™ 0050. Test piece 3 contained a split inner core manufactured from EcoFlex™ 0010. Test piece 4 contained a solid inner core manufactured from EcoFlex™ 0050. A section view of the test pieces is shown by figure 3.x:

|  |
| --- |
|  |
| Figure 3.x: A section view of the four test pieces. |

Test piece 3, consisting of a split inner core manufactured from EcoFlex™ 0010 was found to transfer displacement most the best, so a Finite Element Analysis was performed in ANSYS to establish the relationship between force and displacement.

FEA Analysis.

In order to perform the FEA it was necessary to establish the material properties for EcoFlex™ 0010, which are not well published.

The FEA Analysis is shown by figure 3.x:

|  |
| --- |
|  |
| Figure 3.x: An FEA Analysis |

A 6.5mm diameter cylindrical neodymium magnet was selected, since the Finite Element Analysis and manual testing showed that the maximum displacement in one direction was less than 3mm. This means that even at maximum displacement in one direction (for example the x-direction) the distance between the magnets and the hall effect sensors in the y direction, y1 and y2, remain unchanged, as shown by figure 3.x:

|  |
| --- |
|  |
| Figure 3.x: The y-distance remains unchanged when the force is only applied in the x-direction. |

This means that no matter the direction the force is applied in, it will be automatically resolved into x-y components, since any displacement caused by a force in the x-direction should change the output voltages of the hall effects sensors only in the x-direction BLAH BLAH BLAH FINISH THIS.

Estimate stiffness from FEA blah blah blah

This means that the magnitude of each component of force is found by Equation 3.x:

|  |  |
| --- | --- |
|  | Eqn 3.x |

The direction of each component of force is given by the following rule shown in Equation 3.x:

|  |  |
| --- | --- |
|  | Eqn 3.x |

In order to obtain the displacement at each Hall Effects Sensor, the relationship between the magnetic field and distance must be understood. This is shown by equation 3.x (Wang et al, 2016):

|  |  |
| --- | --- |
|  | Eqn 3.x |

Where:

The Magnetism of the magnet, M, is not listed as a material property for the magnet chosen. Instead the flux density, Br, is given. The relationship between the two properties is given by equation 3.x:

|  |  |
| --- | --- |
|  | Eqn 3.x |

This allows the substitution:

|  |  |
| --- | --- |
|  | Eqn 3.x |

Solving for z:

|  |  |
| --- | --- |
|  | Eqn 3.x |

# Admittance Control

As discussed in section 2.x, an Admittance controller is effectively a position controller where the desired position is modified by the interaction forces. As with any position control scheme it is necessary to perform forward kinematics to transform the joint positions into global frame cartesian positions, and to perform inverse kinematics to transform a desired end-effector global frame cartesian positions into desired joint positions.

## Forward Kinematics

|  |
| --- |
|  |
| Figure 5.1.1: Forward Kinematics for the MyPAM |

The End Effector (Hand) position is given by Equation 5.1.1:

|  |  |
| --- | --- |
|  | Eqn 5.1.1 |

The Elbow position is given by Equation 5.1.2:

|  |  |
| --- | --- |
|  | Eqn 5.1.2 |

The Shoulder (origin) position is given by Equation 5.1.3:

|  |  |
| --- | --- |
|  | Eqn 5.1.2 |

## Inverse Kinematics

|  |
| --- |
|  |
| Figure 5.2.1: Inverse Kinematics for MyPAM |

|  |  |
| --- | --- |
|  | Eqn 5.2.1 |

Solving for θ0 By the Cosine rule:

|  |  |
| --- | --- |
|  | Eqn 5.2.2 |
|  | Eqn 5.2.3 |
|  | Eqn 5.2.4 |
|  | Eqn 5.2.5 |

|  |
| --- |
|  |
| Figure 2.2: Inverse Kinematics for MyPAM |

Solving for θ1 by the Cosine rule:

|  |  |
| --- | --- |
|  | Eqn 5.2.6 |
|  | Eqn 5.2.7 |
|  | Eqn 5.2.8 |

# Future Work

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* Placeholder

# Appendices

Calculating the Minimum Jerk Trajectory using Calculus of Variations

For a Minimum Jerk Trajectory, . Using Equation x.1:

|  |  |
| --- | --- |
|  | Eqn x.1 |
|  |  |

Multiplying through by ½ tidies up the maths later on.

Introducing a small variation, , which has the following properties:

|  |  |
| --- | --- |
|  |  |

To minimise , add as a variation:

|  |  |
| --- | --- |
|  |  |
|  |  |

Differentiating with respect to :

|  |  |
| --- | --- |
|  |  |
|  |  |

Integrating by parts:

|  |  |
| --- | --- |
|  |  |

Where:

|  |  |
| --- | --- |
|  |  |

Thus:

|  |  |
| --- | --- |
|  |  |

Integrating by parts again:

|  |  |
| --- | --- |
|  |  |

Where:

|  |  |
| --- | --- |
|  |  |

Thus:

|  |  |
| --- | --- |
|  |  |

Integrating by parts a final time:

|  |  |
| --- | --- |
|  |  |

Where:

|  |  |
| --- | --- |
|  |  |

Thus:

|  |  |
| --- | --- |
|  |  |

Finally producing:

|  |  |
| --- | --- |
|  |  |

Since this must hold true for any function of which has the properties specified above, this means that Equation x.12 must be true:

|  |  |
| --- | --- |
|  | Eqn x.12 |

Which can then be solved for as shown in section 3.x