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Development of a Robotic Platform for Upper Limb Rehabilitation

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Development of a robotic platform for upper limb rehabilitation.

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Abstract

The aim of this project is to develop a rehabilitation robot intended for use in a non-specialised or domestic setting. Robots have been shown to have a positive effect on limb rehabilitation and developing rehabilitation robots for use outside of specialist rehabilitation centres could be beneficial in terms of access to, intensity and cost of treatment.

The device is intended for the rehabilitation of the shoulder/elbow region of the upper limbs. The design requirements for such a device mean that it must be low cost, portable, robust and have a detailed focus on safety. Other areas of interest pertaining to rehabilitation robotic devices intended for this purpose are also discussed. One of these areas of interest is robot based patient assessment methods. The current widely accepted assessment scales are manually applied, which is inefficient for rehabilitation on a non-specialised or domestic setting and also leads to issues relating to intra-rater and inter-rater reliability. Another area of interest is high level control strategies that could be potentially suitable for this type of robot.

1 Introduction

Limb impairment can be a serious impediment to a person being able to independently perform the activities of daily living. This can have a negative effect on their quality of life. One of the primary causes of limb impairment is stroke. 'Stroke' is a term used to describe brain injury caused by an abnormality of blood supply to a part of the brain. Cerebral infarction (the death of brain tissue) due to stroke, is the primary cause of post-stroke impairment [1]. This impairment may effect differenct parts of the body and with different severity depending on the type of stroke and what areas of the brain are effected.

Neuroplasticity is the ability of the brain to change, to make new connections, in response to ones experiences, external stimuli or damage [2]. There are practical implications of this regenerative ability for people who are suffering from limb impairment caused by stroke. Areas of the brain that control motor function may be damaged during a stroke. However, the brain has the ability to adapt to this so that these skills are not gone forever but may be relearned over time. It is this potential for recovery that underlies the motivation to develop more effective neurological rehabilitation methods.

Limb rehabilitation tends to be quite repetitive, with the subject repeating the same movements many times. Robots are ideal at performing intensive, repetitive activities, which first led to them being used in rehabilitation research. To date, research has shown that robots have potential in the effective rehabilitation of limb impairment [3, 4]. However, it is still not fully known if some approaches to controlling and administering robot mediated therapy are more effective than others, or, as stated by Lum et. al. [5], if the specific benefits of the many approaches to robot rehabilitation are ultimately relatively insignificant compared to the effects of frequency, duration and intensity of treatment.

Limb rehabilitation can be split into two categories, upper limb rehabilitation and lower limb rehabilitation. Rehabilitation of the upper limb can also be split into different sub-categories i.e. hand, wrist, elbow and shoulder. The focus of the research discussed in this paper is on the shoulder/elbow region of the upper-limb. The shoulder/elbow region is primarily used by people to perform reaching tasks. Reaching tasks are an integral part of many of the movement combinations required to be able to perform common activities of daily living, for example, picking up an object and then putting it down again in another position. Also, the dynamics of these joints is somewhat simpler than for the wrist or hand. This makes any robot platform for administering therapy to the shoulder/elbow region easier to implement mechanically than an equivalent device for the wrist or hand.

Robots for use in a non-specialised or domestic setting have the potential to take the some of the burden off of post-stroke patients in relation to having to travel to and spend time in specialist rehabilitation centres. Therapy intensity is known to positively influence post-stroke rehabilitation outcomes and rehabilitation robots for use in a non-specialised setting potentially allow intensive rehabilitation therapy to be administered to subjects for a longer period. It also potentially allows for a reduction in the costs associated with rehabilitation, for things such as travel and accommodation at rehabilitation centres. In Europe, in particular, the population is ageing such that the ratio of retired people to working people is increasing. This portends to reduced funding per person in the medical system in future necessitating increased efficiency to maintain service levels. Adopting effective rehabilitation robots for local or domestic use could contribute to this. Also, therapists could be largely freed from administering repetitive rehabilitation therapy and could instead concentrate on monitoring patients progress and tailoring therapy to best suit their needs.

So that it is suitable for use in a local or domestic setting, the robot platform has a number of features that are not required for robots intended primarily for use in a specialist rehabilitation centre setting. These include low cost, portability, robustness and a strong emphasis on safety. Another area of interest in using a rehabilitation robot in a non-specialised or domestic setting is monitoring patient progress. This allows the effectiveness of therapy to be gauged, which can inform decisions on the selection of the type of exercise, assistance level etc. These variables can be adjusted by a therapist throughout a course of rehabilitation therapy to optimise patient recovery. Also, regular feedback on their progress to the person undergoing rehabilitation can be motivational. To be able to monitor patients effectively it necessary to be able to assess the movement ability of a patient throughout a course of therapy. Human-administered clinical scales are the accepted standard for quantifying the motor performance of people who have had a stroke [6] and are also the standard used to assess patients undergoing robot mediated therapy. The most common in in the literature for rehabilitation robotics is the motor functioning domain of the fugl-meyer assessment. It assesses movement, coordination, and reflex action of the shoulder, elbow, forearm, wrist, hand, hip, knee, and ankle [7]. The person being assessed is given verbal instructions to make specific movements and is then scored based on the assessor's direct observation of their performance. Each individual task that the subject performs is scored on the ability of the subject to complete the task using a three-point scale: cannot perform the task, can partially complete the task or can fully complete the task.

There are issues with these manually applied outcome measures. They are time consuming to apply and subject to problems with inter-rater and intra-rater reliability [6]. Inter-rater reliability refers to the issue of different human assessors assessing the same subject, but obtaining different results. Intra-rater reliability refers to the issue of the same human assessor obtaining different results from doing the same assessment a number of different times. There are also practical issues with using a manually applied scale for assessing the progress of a person undergoing robot mediated therapy in a non-specialised or domestic setting. If the person undergoing rehabilitation therapy was still required to travel to a rehabilitation centre to be assessed on a regular basis it would probably be an inefficient use of the rehabilitation robot.

In contrast, robot-based assessment measures are highly repeatable, have the potential to detect smaller changes than standard manual assessment measures and could potentially reduce the time it takes to administer an assessment [6, 8]. Robot based assessment therefore has the potential to become very useful in the measurement of post-stroke recovery. Robot based assessment can also be potentially performed on the patient in a remote setting, which would make it particularly suitable for use with a rehabilitation robot intended for use in a local clinic or domestic setting. In the case of our robot platform, it is envisaged that a person would partake in a simple assessment exercise. Kinematic metrics would be recorded as the assessment was being performed. These metrics would then be inputted into a mathematical model that would map the subjects movement ability, based on these recorded metrics, to one of the widely accepted manual clinical assessment scales, most likely the fugl-meyer assessment.

To date, robot assessment measures have been devised for different robotic therapy devices. However, the results obtained cannot be reliably compared with the results obtained from other robotic therapy devices due to often significant variations in design and their relationship to clinical scales is mostly unknown [6]. For robotic assessment techniques to become more prominent a detailed, cross platform, widely agreed standard is required [8]. Retaining the use of widely accepted assessment scales and then creating mathematical models to map kinematic metrics onto this could be a successful approach. More precise data on post-stroke recovery could be acquired in a more convenient way. In terms of using rehabilitation robots in a non-specialised or domestic setting, the results from these assessments could possibly be sent via the internet to stroke rehabilitation experts in a distant specialist rehabilitation centre for analysis, in terms that are already familiar to them. Also, adopting an approach like this would mean that, if required, the results obtained from a robot based assessment could be manually verified.

Some work has already been done in this field. Studies by Bosecker et al. [6] and Murphy et al. [9] to estimate clinical scores from kinematic metrics have met with some success however, more work in this area is required.

While it is anticipated that much of the future work on this project will centre of robot based assessment methods, this paper focuses on the design of a robotic rehabilitation platform that is suitable from use in a local clinic or possibly even a domestic setting. To that end, an overview of the design will be presented, which includes details of significant design requirements. Then, the construction and operation of the platform will be discussed in terms of its mechanical, electronic and software aspects.

2 Design Overview

The aim of this project is to develop a robotic platform for upper-limb rehabilitation suitable for use in a non-specialised or domestic setting. To do so it is necessary to incorporate into the robot platform a number of features that are typically common to all rehabilitation robots and a number of features that are specific requirements for a robot intended for this purpose. These requirements are all considered essential for a successful design. Some of the features that can be considered to be common to all rehabilitation robots are as follows:-

- Safety: Safety is important for all robotic rehabilitation devices. However, it is especially critical for a robotic device intended for use in a local clinic or domestic setting, where the personnel operating the device may not have received a high level of training. Post stroke patients may be very weak and in a vulnerable position, both physically and emotionally. It is therefore of the utmost importance that the robotic rehabilitation device interacts with people in a very gentle manner so that it cannot hurt a patient and is comfortable for them to use. Therefore, the robot must always operate in a safe, predictable manner. In the event that a sub-system fails, this failure must be handled in a controlled way so that the person using the device cannot be injured by excessive force being applied to their arm. It is preferable that the device does not operate rather than operate in a manner that could potentially injure a patient.

- Low Level Control Strategy: Low level control strategies are concerned with how the robot moves. This is in contrast to a high level control strategy, which is not concerned with how the robot moves but with where it moves, with what velocity and what forces it applies to the subject. A low level control strategy must be developed such that the robot does not impede the movement of a person using it. To achieve this, the effects of friction and interia in the system must be compensated for.

- Interactive Game: Attention and motivation are considered to be key factors influencing motor re-learning following stroke [3, 10, 11]. A study by Loureiro et. al. has shown that subjects were motivated to exercise for longer periods of time when they were using a mixture of haptic and virtual reality systems [12]. Most rehabilitation robots achieves this through a visual display that the subject watches as they use the robot. This allows the subject to play games or to use the robot to interact with a virtual environment as they carry out exercises.

- Flexibility: It was required that the software can readily accommodate different games and robot control modes.

- Minimise Torso Movement: This negates the subject's tendency to try and partially compensate for a deficiency in the motor function of their arm through moving their upper torso.

- Astethics: On a more subjective front, it is important that the robotic device is accepted by the patient. The visual impact of the device may be significant to this.

Some of the features that are specific requirements for a robot intended for use in a local clinic or domestic setting are as follows:-

- Minimise Development Costs: For a rehabilitation robot to be suitable for use in a local clinic or the home it must be affordable. Therefore, development costs for the robotic device have to be kept within a budget of 5,000 Euro. To facilitate this, Commercially Available Off The Shelf (COTS) components and open source hardware and software have been used where possible.

- Portability: For a rehabilitation robot to be suitable for home use it must be easy to transport and set up. Therefore, it must be relatively compact, light enough for two people to carry and easy to assemble/disassemble.

- Robustness: The robot must also be robust enough to survive transport and moderate abuse in the non-specialised setting it is intended to be used in.

- Easy to use: When being used in a domestic or local clinical setting there may not be a technician or any other highly trained person available to help set up the device before use. For the purpose of this robot it is being assumed that the person using the device will be assisted by a family member or local doctor/physiotherapist who has only received a small amount of training on the operation of the device. Therefore, it is essential that it is relatively easy to set up the patient in the device.

Figure 1 shows a picture of the prototype rehabilitation robot platform currently under development. It operates on the horizontal plane and the end-effector is able to move in a 500 mm x 500 mm envelope. For portability, all of the components labelled in Figure 1 can be easily separated from

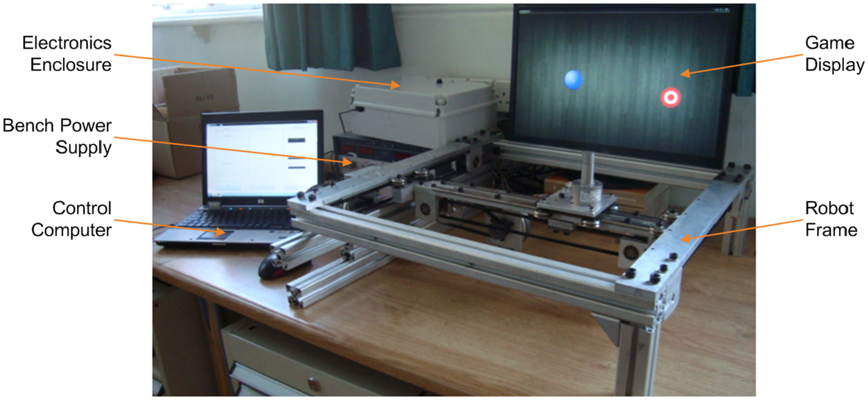

Figure 1: A photo of the current robot workstation setup with major components labelled.

one another. The mass and dimension of each of these individual components is such that they can all be relatively easily separately carried by a single person.

A multi-disciplinary approach to the design of the robot platform was taken. As such, the device contains mechanical, electronics and software elements integrated into a working prototype. These are discussed in turn in the following sections.

2.1 Mechanical Design

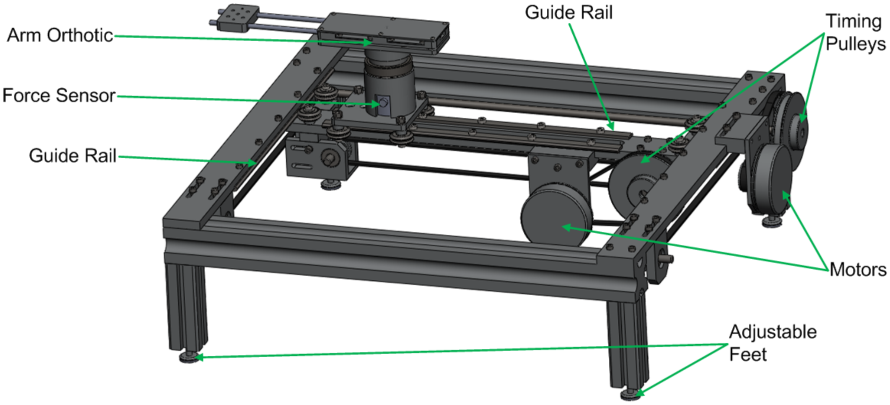

Figure 2: Solid model of the robot assembly with major components labelled.

A solid model of the robot assembly with the main components labelled is shown in Figure 2. It is a relatively simple construction, which is beneficial for reducing manufacturing costs. For a robust design and to minimise mass, extruded aluminium section has been used for the frame and legs. Also, where possible, alumium has been used to manufacture all of the other parts in the assembly. Adjustable feet with rubber pads are attached to the bottom of each leg. These are used to keep the robot platform level and prevent sliding across the table during use. A track and wheel system allows the arm orthotic to move along both the X and Y axes. This track and wheel system allows for smooth movement and has the ability to withstand high loads and moments, which is again essential for a robust design. Any friction in the system compensated for in the software. Separate motors are used to actuate each axis. These are coupled with the arm orthotic through a series of timing pulleys that introduce a 3:1 gear ratio.

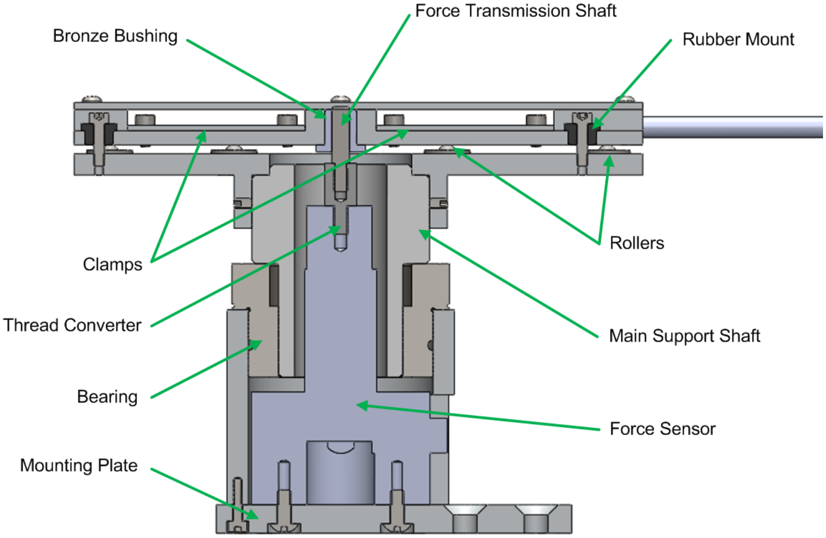

Figure 3: A section view of the arm orthotic and force sensor.

In normal use, it is intended that a persons arm are would be connected to the arm orthotic using simple velcro straps. The arm orthotic is free to rotate around an axis through the centre of the force sensor. A section view of the arm orthotic and force sensor is shown in Figure 3. The rollers in the upper part of the arm orthotic ensure that when a person applies a force, the components of that force along the X and Y axis are transmitted to the force sensor. However, components of that force applied along the Z axis and moments applied to the arm orthotic are instead transmitted to the frame of the robot.

To date, the robot has always operated in a horizontal plane, however, with minor modifications it could not be also used in a vertical or angled plane. Extra supports could be easily attached and the effects of gravity could be compensated for in the software. This feature greatly enhances the flexibility of the robot platform.

2.2 Electronic Design

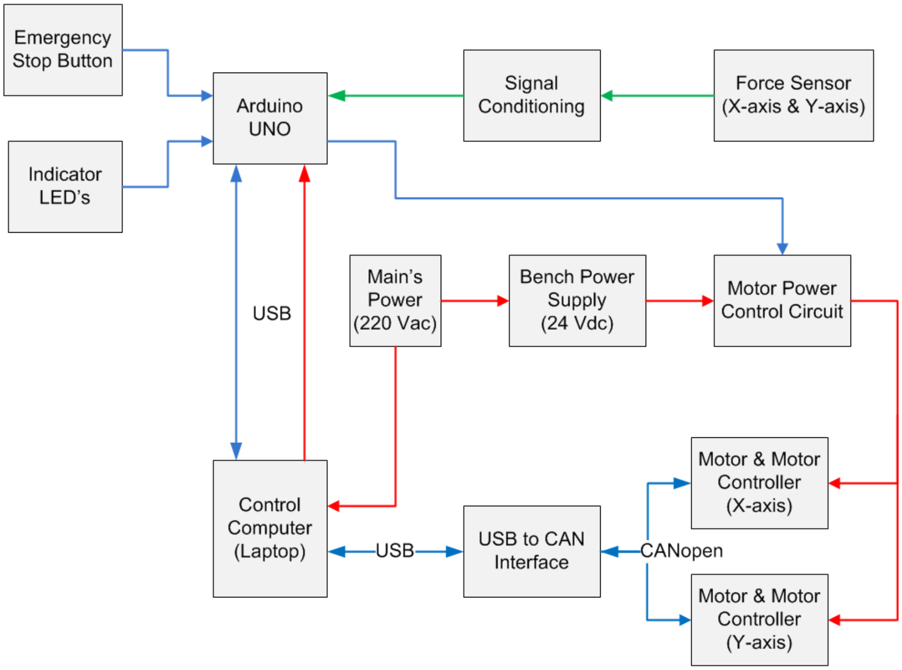

Figure 4: A block diagram of the prototype robots electronic systems. Red arrows indicate power, blue arrows represent digital signals and green arrows represent analogue signals.

Figure 4 shows the main electronic components of the robot and how they interface with one another. The control computer is a Hewlett Packard laptop, running 64 bit Windows 7. It was chosen primarily because of it's portability.

A bi-axial force sensor is used to measure the force applied by the user to the robots arm orthotic. The force sensor is a strain gauge type and force is measured separately along the X and Y axes. First order low pass filters are used to reduce noise. Two instrumentational amplifiers then amplify the output signals before they are digitised.

Two Maxon Electronically Commutated (EC) motors are used on the robot platform, one for actuating each axis. Each motor has built in hall sensors for measuring the angular position of the motor shaft. Each of the motors is controlled by a dedicated Maxon Motors EPOS24/5 motor controller. These are currently powered by the 24 V, 10 A bench power supply. These motor controllers are capable of being used in a number of different modes including current control, velocity control and position control mode. PID control is used throughout. The motor controllers communicate with each other and with the control computer through a CANopen network, typically used for automotive applications. The control computer does not have a native CAN port so a USB to CAN interface is used.

An open-source Arduino Uno microcontroller prototyping board is used to acquire the data from the force sensors through two analogue ports at a resolution of 10 bits. The Arduino includes an Atmel ATmega328 microcontroller and electronic components to facilitate simpler prototyping, on a single printed circuit board. An emergency stop button, a circuit that can switch off power to the motor controllers and a set of four LED's are also connected to the Arduino through it's digital IO ports. Finally the Arduino is connected to the control computer through a USB connection. This provides power and facilitates serial communication between the Arduino and the control computer. A free Integrated Development Environment (IDE) for developing software for the Arduino is available. During normal use it monitors the emergency stop button and reads force data from the force sensor. This force data is then sent to the control computer through the serial interface. However, if this force data exceeds a certain threshold or communication with the control computer is lost, the Arduino switches off power to the motor controllers, bringing the robot to an immediate stop. This is one of the critical safety features built into the robot.

The Arduino, its associated circuits and the motor controllers are all mounted inside the same electronics enclosure. This is done both for their protection and portability.

2.3 Software

The software running on the main computer has been written in Python. Python is an open-source, general purpose, object orientated computer language, whose design philosophy emphasises code readability. A large number of third party modules are available for python and many of these have been used as part of this project. These include modules that facilitate multi-threaded programing, creating sub-processes, serial communication and the creation of games and GUI's. While Python is not a compiled language, its execution speed and performance when communicating with peripherals were deemed to be sufficient for this application. Moreover, Python's relatively simple, but still powerful, syntax potentially allows a substantial reduction in software development time to be achieved over using other languages.

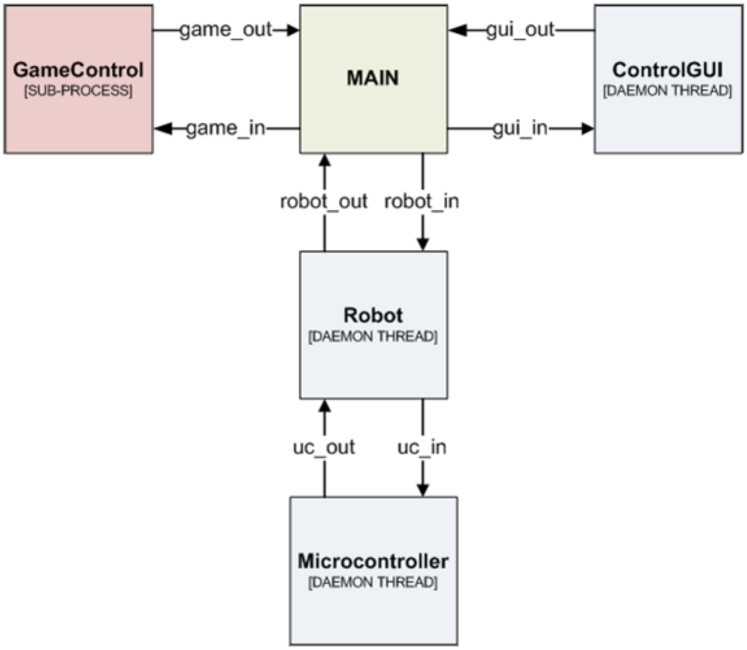

Figure 5: The threads and sub-processes that form part of the robot software. The arrows each represent a queue. Queues are used to send instructions and data between the different parts of the software.

Figure 5 shows the basic structure of the custom software that has been developed. Queues are used to facilitate communication between the sub-process, all of the threads and MAIN. The following is a brief description of the function of each of the parts of the code:-

- MAIN: This is the top level scope in which the program executes. The code here is implemented as a variation on a finite state machine. This state machine starts and stops all of the other threads and sub-processes. The logging of all robot kinematic and operational data is also handled here.
- GameControl sub-process: This controls the game that is displayed on the second large mon-

itor. The position of a cursor on the monitor is controlled by the movement of the robot arm orthotic. Running the game is relatively processor intensive so having it as a sub-process allows it to be run on the second processor core in the laptop, in parallel with the rest of the software. The GameControl sub-process has also been structured in such a way that addiditonal games can be readily incorporated into the code.

- ControlGUI thread: This displays a Graphical User Interface (GUI) on the monitor of the control computer. The GUI displays information to the user on the status of the robot software and allows the control mode of the robot and the game that is to be played to be selected by the user. There are also buttons on the GUI that the user can click to start and stop the robot.
- Robot thread: The code for controlling the movement of the robot is executed here. The thread has been designed in such a way that additional control modes for the robot can be easily integrated into the existing code as required. This thread also handles communication between the control computer and the motor controllers. Overall, it is able to write approximately 450 command sets per second to the motor controllers.
- Microcontroller thread: This thread handles communication between the control computer and the Arduino, via a serial interface. Force data is acquired from the Arduino and a check sum is used to ensure it has not been corrupted. A handshake protocol is used for the serial communication. This ensures that a data packet from the Arduino is only sent when the control computer is ready to receive it. This prevents data from building up in the control computers serial input buffer, which would lead to undesirable system lags. Implementing communication with the Arduino in a separate thread allows it to run in parallel with motor controller communication. This leads to an overall reduction in the overall time it takes to communicate with peripheral devices which results in better software performance.

2.4 Operation

The robot platform has been designed to accommodate many different games and robot control modes. In the following sections the initial game developed for robot testing purposes and the robot control mode currently implemented will be briefly discussed.

2.4.1 Games

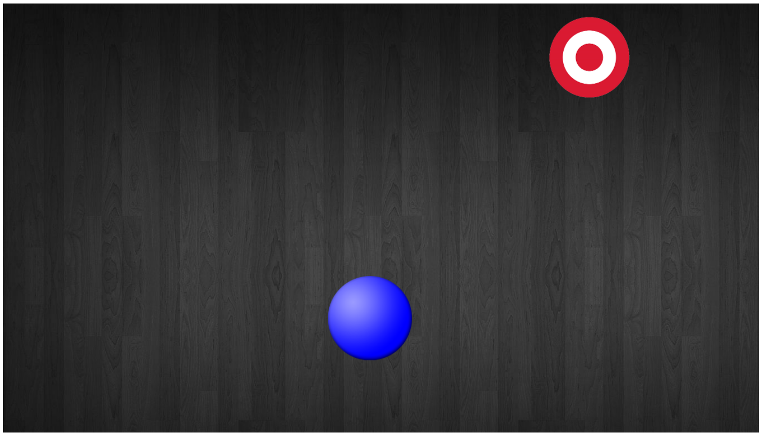

Figure 6: A screen shot of the first test game developed. The blue circle represents the position of the robot end-effector. The red and white circle is the target.

To date, a game has been developed for test purposes only. However, the structure of the robot software is such that it is relatively easy to incorporate different games into the code. Figure 6 shows a screen shot of the current game. The blue circle represents the position of the robot arm orthotic and the red and white circle represents the target. When the robot arm orthotic is moved to the position of the target the target explodes and then appears again at a new randomised position.

2.4.2 Robot Control Modes

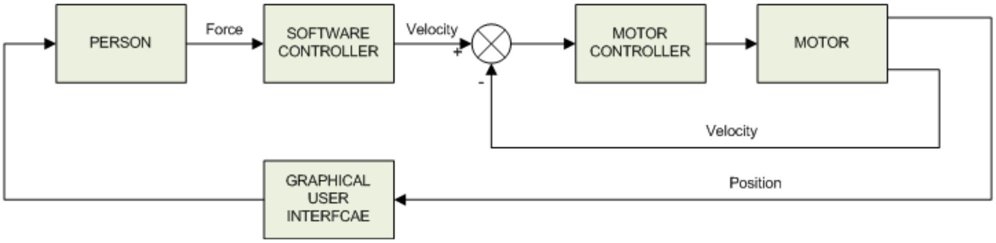

Figure 7: A block diagram of the robot control system when the motor controllers are being used in velocity control mode.

For the first iteration of the robot controller the velocity control function of the motor controllers has been used to create an admittance control system. A block diagram of the overall robot control system when used in this mode is shown in Figure 7. Essentially the motor controllers control the velocity of the robots motors such that it is proportional to the force applied by the person using the robot to the arm orthotic. The factor that relates these two values can be adjusted on the GUI, thereby adjusting the ‘feel‘ of the robot. The robot controller shown in Figure 7 implements a low level control strategy. Low level control strategies are concerned with how the robot moves and for this application the most important feature of the low level robot controller is to ensure the arm movements of the person using the robot are not impeded in any way. On the other hand, high level strategies are not concerned with how the robot moves but with where it moves, with what velocity and what forces it applies to the subject to assist or resist their movement. It is the high level controller that determines how therapy is performed on the subject by assisting or resisting their arm movements to help them complete the designated task. Different approaches to high level control have been taken by different researchers, however, for a rehabilitation robot primarily intended for use in a non-specialised or domestic setting an iterative learning control strategy may have potential. Such a strategy could allow the robot control system to self adjust in response to changes in the subjects movement ability. An examination into these strategies is ongoing.

3 Conclusion

This paper has described a robotic rehabilitation platform intended for use in a non-specialised or domestic setting. This is a multi-disciplinary project with significant mechanical, electronic and software elements. The most significant aspects of the robot platform described are: safety, an interactive game, a low cost design, portability, robustness and flexibility. Safety is the most critical aspect of any robotic device meant for interaction with humans. If the device cannot operate in an inherently safe manner then it is not fit for purpose. The robot platform has also been shown to be of a low cost design, portable and robust. These are all essential features for a device intended for use in a non-specialised or domestic setting. A simple interactive game to provide patient feedback and to act as a tool to maximise the motivation of the subject to fully interact with the robot has also been described. Finally, the robot platform has been shown to be flexible in that it can accommodate many different games and robot control modes. Also, with minor modifications, it should be possible to use this robotic device in a vertical or angled plane, as well as in the horizontal plane used to date.

Testing of this prototype device is ongoing. This is an iterative process and as more feedback is received on the performance and acceptability of the device then further modifications may be made to the design.

One area of interest that merits further investigation is the use of robot based assessment methods. A possible direction to move forward with this would be in the development of a mathematical model that could be used to map kinematic metrics recorded from the robot onto the results obtained from administering the widely accepted fugl-meyer assessment. Another area that is of interest is the particular benefits of using iterative learning control as the basis for the high level control strategy in this type of device. Both of these avenues of investigation are complimentary to a robotic device primarily intended for use in a local clinic or domestic setting.

Finally, the robot platform described has largely been presented in terms of the rehabilitation of post-stroke impairment. However, its application is not strictly confined to this area. Future consideration could also be given to applying this robot platform to other rehabilitation tasks, for example sports injury rehabilitation.

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