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THE MIDDLESEX UNIVERSITY REHABILITATION ROBOT

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This paper describes the development of an electrically powered wheelchair-mounted manipulator for use by severely disabled persons. A detailed review is given explaining the specification. It describes the construction of the device and its' control architecture. The prototype robot used several gesture recognition and other input systems. The system has been tested on disabled and non-disabled users. They observed that it was easy to use but about 50% slower than comparable systems before design modifications were incorporated.

The robot has a payload of greater than 1 kg with a maximum reach of 0.7-0.9 m

1 Introduction

Rehabilitation Robotics has developed over the past four decades, with many of its original pioneers active in the development of orthotic and prosthetic devices (e.g. the Texas Institute for Rehabilitation and Research, and the VA Palo Alto Research Centre).

Systems have typically been designed to address either vocational tasks or activities of daily living, and have employed industrial robots, educational robots or purpose-built arms. [1, 2, 3, 4, 5, 6 & 7].

The work described here [8-10] was part of a charity funded development of a cheap robotic arm to assist severely disabled wheelchair users, [11]. The work started in 1988 as a result of collaboration with Robin Platts at the Royal National Orthopaedics Hospital at Stanmore Middlesex. Funding was provided by the

Association for Spinal Injury Research, Rehabilitation and Reintegration (ASPIRE) and the National Advisory Body (NAB). Initially the work was directed towards using low cost pneumatic actuators similar to the work of Jim Henniquin and Inventaid Ltd. The initial choice of pneumatic operation was on the grounds of safety with the actuators providing considerable compliance. Although the ease of use and cost was satisfactory the control was difficult due to considerable non-linearity and the precision was poor. Noise was also excessive and disturbed users. Subsequent work used electric actuation illustrated here. Sensors developed for the control of the robot include speech control, head gesture control and the use of biological, EMG & visual signals.

2 Review of Comparable Rehabilitation Robots

2.1 *The Manus Arm*

The Manus arm, initiated in 1984, was developed primarily as a wheelchair-mounted system to assist with daily living tasks. It employs a sophisticated kinematic structure consisting of eight axes. The design employs an articulated arm on a telescoping base with a combined mass of 20 kg, providing a reach of 88 cm and a payload of 1.5 kg. Slip couplings are employed on a number of the joints. Control is via a microprocessor, initially an 80186, with a new control system due to be released shortly, using a keypad, foot switches and a joystick, with feedback being provided by a small LED display. The cost of the basic system is approximately $30,000 [12]. The gripper has a clamping force of 20 N with a maximum spread of 90 mm. Developments in the Manus system are illustrated by the FRIEND system used at the University of Bremen.[13]. They describe the use of visual servoing and data gloves. In visual servoing features of the object are extracted from camera images and the robot is moved by the controller to match the features to the current image seen by the camera on the arm. The Exact Dynamics, manufacturers of the MANUS system, describe head gesture devices; speech recognition as well as sip & puff and keypads. The MANUS system has been used for investigation of collaborative control. Fong [14] describes how the process of active dialogue is used between the user and the robot, “by exchanging information they negotiate the next action.”

2.2 *HANDY-1*

The HANDY-1 system was developed from 1992 by Rehabilitation Robotics Ltd as a dedicated feeding aid, by modifying a low-cost educational robot, the Cyber 310. The Cyber robot is a 5-axis arm, weighing 15 kg, and offering a repeatability of 1.5 mm with a payload of 500 g. The arm is fairly compact at 51cm in height, with a length when fully extended of 90 cm. This 'no frills' approach has resulted in a system cost of £5000, including assessment for suitability, delivery, training, and a one year call-out service contract [15].

2.3 *The Wolfson, Wessex, and Weston systems.*

Bath Institute for Medical Engineering developed initially a commercially available robot employed in a fixed workstation, this was replaced by a purpose-built arm, 0.5 mm resolution, 1 kg payload, and the ability to traverse the workspace in 5 s [2, 7], which was eventually mounted on a mobile platform. [6]

2.4 *The Neil Squire Foundation*

Regenesis (RAA) has 4 rotary and 2 linear axes, a payload of 2.2 kg, and a mass of 8 kg. Potentiometer feedback is used for closed loop PID control, providing a resolution of 0.73 mm for the linear axes, and 0.33º for rotational axes. The motor control system employs a Motorola 6809 CPU, communicating to a PC based user interface. User interaction has been via a standard keyboard, with the assistance of a handstick, mouthstick, or headstick. The cost of the robotic system is $23, 000, but the total cost of the workstation system including a special desk, computer adaptations, and architectural modifications, is $35,000 [16].

2.5 *RAID*

RAID (Robot to Assist the Integration of Disabled people) employed the RTX by Universal Machine Intelligence Ltd, UK. RAID has undertaken successful evaluations [17], despite its high cost at $55,000 per workstation.

Kinetic Rehabilitation Instruments in the USA has developed the Helping Hand - a wheelchair-mounted robotic arm significantly cheaper than the MANUS arm at $9,500. The 5 degree of freedom arm has also addressed the size and weight problems of the MANUS arm: at 11 kg the arm adds just 1 inch to the width of the wheelchair. The arm is operated one joint at a time by a joystick. Closed-loop control is not implemented, and Cartesian movement or pre-programmed routines are not available [18].

2.6 KARES

This impressive Korean development described by Bien [19] utilises a 6 DOF arm with all revolute joints unlike most of the other rehabilitation robots presented here. It is designed to have PUMA like Denavit-Hartenberg parameters. The strength of the Korean developments lies not in the manipulator but in the range of input devices used to control the device. The impressive range of developments include: visual servoing; an eye mouse; a haptic suit and EMG based control. One of the areas pioneered by this team is the recognition of facial expressions including whether the user wants to have a drink by recognising an open mouth. [20]

2.7 Raptor

The Raptor is a commercially available arm available for $12500. It has 6 DOF with a simple close/open gripper. The maximum lift capacity is 2.3 kg. The overall mass is 8 kg. Power is 24 V DC and the control interfaces can be joystick, keypads or a puff and sip device. It can be operated in a fast/slow mode, with the slow motion limited to 2 rev/min. Each joint is provided with a slip clutch of maximum force 22 N.

2.8 Flexibot

This robot funded by European Research money and headed by Professor Topping at Staffordshire University is a sophisticated general concept able to be used in many modes. It is a revolute robot with a reach in excess of 1m. It has a mass of 11 kg and a load capacity of 2.8 kg. Control inputs at present are limited to buttons or sip & puff. It is designed to have interchangeable connectors for different end effectors.

2.9 *System performance*

There is no correlation between accuracy and payload and user acceptance. The HANDY 1, with a repeatability of 1.5 mm and a payload of 0.5 kg, provides lower performance than most of the systems, but has achieved considerable success.

3 Robot Specification

For the current application, user tasks were first described informally by considering how an able-bodied person may undertake the task [11], or how similar tasks are achieved with existing rehabilitation robotic systems from video footage of the MANUS, Handy-1 and RAID systems [11], Table 1 shows the importance indicated by users. Some of these tasks, when translated to physical requirements place a severe burden on the robot design. For example filling a kettle requires a lifting capacity for a normal kettle of 2.5 kg and the ability to hold the kettle while operating the water tap (faucet).

The design guidelines were formulated as follows:

- low-cost should be prioritised; (to enable many users to be gained)
- the system should be of general purpose, providing functionality that addresses a range of user needs;
- base-line performance characteristics should be derived from the requirements of the user tasks that are addressed;
- The design should facilitate future modifications to improve system performance and functionality;
- a form of system mobility/portability should be provided;
- operation should be possible with a wide range of user input devices;
- a variety of control modes should be available;
- ease of use should be enhanced by allowing systems to be configured to match individual user needs;
- the system should have an acceptable appearance, and
- the system should allow for safe operation

These requirements were focussed initially around simple feeding tasks to explore the interface design problems and the interaction with speed of operation. The range of tasks reported here were limited to these although tests on other tasks such as picking up objects and opening doors were easily achieved but not systematically investigated.

3.1 *Defining User Requirements*

An analysis of user requirements was performed by Prior [1], [21]. The survey of 50 individuals with various disabilities identified the activities that were either difficult or impossible to perform, and established a number of tasks that people would wish to undertake with a robotic device.

Prior employed a weighted matrix method to order the tasks dependent upon the cost, control complexity, accuracy and payload that they would be likely to require. This was achieved by assigning each of these criteria a weight corresponding to an estimate of its importance relative to the other criteria. The results acted as a prioritised task list, on which the design specification was based. The tasks are listed in table 1 in order of score. Estimates are also shown of the number of degrees of freedom (DOF) the manipulator likely to be required in order to undertake the tasks

3.2 *Design*

Prior noted that the SCARA geometry has been employed by successful rehabilitation robot designs such as the RTX and Wessex systems, outlining a number of the design's advantages, for example, the major joints do not oppose gravitational forces, and can therefore require smaller torque. The arrangement of jointed planar linkages allow the actuators to be either direct-drive, or mounted in-board and driven through belts or chains. This lowers the moment of inertia of the links and the bending moment of the arm about the base joint.

An alternative design solution was suggested, combining one or more of the basic kinematic arrangements. Combining the advantages of the SCARA configuration with the vertically articulated arm seemed to give an optimum solution to the twin problems of reach and suitable workspace.

3.2.1 The Scariculated Arm Design

The design solution proposed by Prior [1] combined the advantage of large vertical stroke from the vertically articulated geometry with the advantage of large horizontal stroke from the SCARA geometry. This was achieved by inserting the 0° ± 90° joint at the beginning of the first link of a standard SCARA design. The arm is thus enabled to reach to the floor (-90° position) in the vertically articulated mode and up to a high reach (+90° position) also in the vertically articulated mode by the use of this extra joint; with the 0° position being the normal SCARA mode. The design consists of seven joints and the end effector grasp (five rotary and two linear). The kinematic arrangement selected for the prototype design is therefore a hybrid combination of the SCARA geometry and the vertically articulated geometry, and is referred to as the SCARICULATED arm geometry, illustrated in figure 1.

3.3 *The Middlesex Manipulator Prototype*

An early prototype of the Middlesex Manipulator employed pneumatic 'flexator' actuators. [1] Research in the application of these actuators to the field of rehabilitation robotics was motivated by the safety offered by their natural compliance, their low-cost, and their favourable power to weight ratio. As anticipated, the actuators presented a more challenging control problem than DC motors, partly due to friction and hysteresis.

The Middlesex robot in its' tested version is shown in figures 2 & 3. The five axes shown include two prismatic axes (base and forearm), and three rotational axes (elbow, and two degrees of freedom at the shoulder). The Upper arm is 360 mm in length, and the forearm is 330 mm, extendible to 530 mm. The overall height of the manipulator varies from 620 mm to 900 mm. The shoulder joint can rotate through 200° in the horizontal plane, and 360° in the vertical plane. The elbow joint can rotate through 315°.

To reduce weight, holes have been machined in non-critical areas. Lightweight plastics are employed for the cover, and where possible for gears, and plastic linear bearings for the prismatic joints. The resulting overall weight is 7 kg (excluding end effector).

Although the initial design specified lifetime this has not been possible to ascertain at this time.

An end-effector with two detachable compliant fingers is shown with the manipulator on a temporary trolley mounting in figure 2. The end effector has wrist bending and rotation degrees of freedom. The actuators are dc servos. The maximum opening of the fingers is 35 mm and the speed of opening is 5 mm/s. The simple gripper was designed to enable cups of liquid of mass 450 gms to be lifted without slipping. Plates with food of mass 980 gms without spilling could also be lifted to wheelchair height. The maximum force applied was 15 N. More complex grippers were not used since the complexity of their operation would hinder observations of the overall arm/interface performance. A much more sophisticated three fingered proportional gripper was built by undergraduates and is the subject of further user tests.

3.4 *User Interface and Control System Overview*

The task analysis used identified the following possible modes of control:

- positional (movement to a pre-taught position)
- joint (movement of a specific joint)
- Cartesian (movement of the end-effector in space)
- routine (performing a pre-taught trajectory relative to current position)
- task (executing a pre-taught task that accesses pre-taught absolute positions)
- speed (setting manipulator speed levels)

Further modes are required to allow the teaching of positions, routines or tasks:

- teach position (record the current position of the end-effector as a pre-taught position).
- teach routine (record a trajectory)
- teach task (record a task).

The User Interface system communicates with a separate motor control system implemented on dedicated embedded micro-controllers. A dedicated embedded control system with built-in redundancy increases system safety, and reduces the performance requirements of the PC. Drive circuitry for the DC servomotors is purpose built, implementing closed-loop position control, and open-loop speed control. Input and feedback devices may be purpose-built and/or commercial dependent on system configuration.

4 Control Hardware design

4.1 *System overview*

The following section provides an overview of the motor control system for closed-loop positional control and open-loop speed control. The decision was taken to implement the motor control system using embedded micro-controllers. The option was available to implement a motor control module containing an 8051 for each of the Manipulator's axes. However, the cheaper option was selected, of having a single micro-controller for all axes. It was estimated that an 8032 chip operating at 12 MHz with an appropriate selection of peripheral components would provide adequate processing power to achieve the moderate performance required. This could be achieved through the use of programmable timer ICs generating Pulse Width Modulated (PWM) drive signals. A second embedded micro-controller could be included in a separate and simpler module, to provide system redundancy and enhance system safety.

Suitable low-cost motor drive ICs were used, capable of accepting PWM control signals. These also contained a system-brake input that could be triggered by a motor-current sense facility as a safety option. The brake input also allows for power consumption reduction when the Manipulator is not in motion.

Evaluations of rehabilitation robotic systems have highlighted the need for carers to be able to control or move the manipulator. As carers can not always use the input devices provided, systems such as the MANUS and Helping Hand employ slip clutches that allow the arm to simply be pushed out of the way.
However, the current design of the Middlesex Manipulator employs self-locking joints that are cheaper to manufacture, and offer safety when the power to the system is cut. The design option was therefore taken to include a manual control system that

can override the embedded micro-controller, operated by pressing buttons mounted on each of the Manipulator's axes. A power supply module is included; to generate the various voltage levels required from a 12V battery. Power for the motor drive modules, is provided by a 24 V supply, electrically isolated from the remainder of the system. Figure 4 illustrates the interconnection of these system components.

4.1.1 The embedded microcontroller module

Peripheral components were address-mapped, and these include:

- 8254 programmable timer ICs for PWM signal generation.
- An 8255 programmable peripheral interface IC for general purpose IO.
- A 12 bit A/D converter, the HI 5812, allows for conversion of the positional feedback signals.
- An analogue multiplexer, the MAX 378, allows the processor to select 1 of 8 analogue input channels.
- An RS 232 line driver, the MAX- 202, allows for serial communication with the PC-based user interface system.

Shaft encoders were made providing a resolution for control of each of the prismatic joints of $\pm$0.5 mm.

4.2 *Micro-controller software development*

The micro-controller is responsible for lower-level control concepts, such as setting a speed, or moving a joint to a specific position. The algorithms for higher-level control, such as task execution, are implemented on the PC-based User Interface System (UIS). For the development model only proportional control was implemented, to be replaced with PID control on the production model, with a 50% increase in speed of response.

A protocol was developed to allow this communication between the micro-controller and the UIS. This is referred to Juvo Motor Control Language (JMCL). A set of the Juvo instructions is shown in Table 2. Initial code tests indicated that a sampling rate of 30 ms could be guaranteed with the validated code written in C.

4.3 *Performance characteristics*

This section summarises measurements of the manipulator's performance characteristics, achieved with the control system described above. The arm reached its' desired speed in less than 0.3 s in all axes when loaded. Table 3 summarises the speed and repeatability in each axis.

4.3.1 Velocity and Noise limitations

Ideally, the operating speeds of each of the manipulator's axes would be set to allow a velocity at the manipulator's end-effector corresponding to that detailed in the design specification, i.e. a maximum operating speed of 200 mm s^{-1}, with fine-control of 50 mm s^{-1}. However, initial tests indicated that aspects of the manipulator's construction meant that the required speed levels would not be achievable. For the linear axes, speeds were limited principally by the unacceptable levels of acoustic noise generated by friction between the plastic strips used as linear bearings, and the manipulator's casing (the hollow casing acting as an acoustic amplifier).

Noise levels of around 65 dB(A) were measured at angular speeds of around 1500 rev/min for axis 1, and 1800 rev/min for axis 4. One approach would have been to reduce axis speeds until levels below 40 dB(A) were generated. However, the user evaluation reported below, highlighted the fact that the type of noise being generated was also a significant factor. In particular, variation in pitch and amplitude with the manipulator in motion was reported to have a significantly negative effect on the user's impression of the system. Consequently, a more subjective approach was taken to establishing the maximum speed of each axis: speed levels were reduced until noise levels were deemed acceptable by the user (and designer). This limited the angular velocities of axes 1 and 5 to 750 rev/min. and 900 rev/min respectively.
Selecting appropriate speed levels involved a trade-off between speed and repeatability for axes 2, 3, and 4, and speed and noise for axes 1 and 5. Thus improving the manipulator's speed performance would also require mechanical modifications. The maximum speed attainable for the user trials was less than that required, this is particularly evident for Cartesian control with around 40 mms^{-1} possible through the horizontal plane, and 25 mms^{-1} through the vertical plane.

The target repeatability given by the requirements specification is 10 mm. The principal factor determining the magnitude of repeatability was mechanical, namely the backlash that exists in the gear mechanisms. As would be expected, repeatability is improved if a target position is always approached from the same direction.

Thus estimates of ‘single-approach’ repeatability for axes 2 and 3 are 5mm and 4 mm respectively.

Future developments of the prototype will address the degree of backlash within the gear mechanisms; however, it was considered reasonable to expect that the current levels of repeatability would suffice for initial evaluations. This approach may be justified considering that the estimates are ‘worst-case’ in that they presume the arm to be fully extended, thus for much of the working envelope, repeatability will be better than the estimates.

5 Development of the User Interface

The system allows for multiple interface components, dispatching an input command to a mode of control module, and displaying the current set of possible input commands. This issue was enabled by introducing an additional module referred to as the Dialogue Manager, which activates a control module, in response to a series of input commands.

A PC was selected as the platform for the user interface system on a cost basis. This allowed for the development of Windows applications that can run in a multi-tasking environment.

The task analysis described in [11] identified appropriate modes of control, and provided an outline of the structure of each mode, defined in the user command language, JUCL (Juvo User Command Language). Two methods for presenting the JUCL commands to the user were employed. The first was used during initial development and evaluation of the Middlesex Manipulator, and involved presenting the JUCL commands in the form of a flat menu system (figure 5). The Windows display is used here to simulate the commands as would be presented on a custom feedback device such as an LCD display unit. The second form of interface employed the Microsoft Windows (figure 6) dialog based graphical user interface. This allowed all control options to be presented simultaneously, allowing for faster task completion. However the interface required the user to be fairly competent when using a mouse or trackball. This requirement led to the development of a 'Head Mouse' as described below.

For initial system evaluation a number of input device modules including Trackball, standard mouse input, Voice Recognition and Electrolytic Tilt Sensors were developed to allow comparison of various input devices.

5.1 Gesture Encoding with Tilt-Sensors

Most physically disabled people are able to partially control at least one part of their body, and the encoding of simple gestures allows for potentially greater signal bandwidth than is achievable with simple switches. A significant amount of research has addressed the use of gestures as a means of communication for assistive technology, for example [12, 13, 14 & 21]. However, the sensors are designed for fairly slow moving bodies, having a time constant just below one second (slow enough to allow the electrolytic fluid to settle). For encoding head gestures, the sensors were mounted on a baseball. However initial indications were that the sensors could be used as simple switches, or applied to a pattern classification system as described below.

5.2 Pattern Classification

Dynamic Programming and artificial neural network (NN) approaches to pattern classification were investigated. Performance of the NN proved superior to the DPA. Tests were then undertaken to compare the more popular multi-layer perceptron artificial neural network (MLP) with the single layer perceptron (SLP). Finally, a Radial Basis Function training algorithm (RBF) was employed.

Once trained, both networks proved capable of successfully classifying all eight gestures. Initial tests produced classification rates of 84% for the SLP and 91% for the MLP (an average from three subjects attempting to perform a total of 90 gestures).

An RBF was implemented with the structure employed for the MLP described above, i.e. 40 inputs, 18 neurons in the first layer, and 8 neurons in the output layer. As was anticipated, the training times for the RBF were lower than the MLP at approximately 2 minutes. However, the classification performance was far poorer at 52%.

Speech recognition and trackerball with gesture recognition were used in the robot trials. Both able bodied and disabled users used the recognition devices with fairly equal facility. Six people of mixed capabilities were eventually trained to use the robot via these interfaces.

5.3 Configuring the Tilt-Sensor for use with the UIS

Initial results indicated that the sensor would not be appropriate for use in a direct-menu selection system. The slow time response of the sensors resulted in gesture lengths of up to 2 seconds. This length of time was required to ensure that each gesture in a set of 8 was adequately different from the remaining gestures. The result of this would be that a system employing direct-menu selection would provide slower user interaction than a scanning system, and since the cognitive demands of direct-menu selection are greater, the scanning system would appear to be the preferable style of interaction if tilt sensors are employed.

A scanning system requires a minimum of one gesture for operation, and can therefore be operated with the tilt sensor acting as a switch - tending to suggest that a pattern classification algorithm is not required. However, the use of such an algorithm has potential for recognising involuntary movement, and can allow for added functionality. For example, one gesture may be used to select the current option, another to return to the previous stage of interaction, another to cancel dialogue and stop any movement of the arm. Consequently, increasing the bandwidth of an input device being used with a scanning system reduces the number of options that the scanning system needs to manage, and therefore can allow for more rapid user interaction. This latter approach was adopted for the development of a scanning system.

5.4 Gesture Encoding with a Trackball

Trackballs have been used successfully as input devices for rehabilitation systems for those who have partial hand movement [11]. A program was therefore developed to allow the application of an artificial neural network to the encoding of hand gestures issued by a trackball. As shown below, this form of input does not suffer from the poor time response exhibited by the tilt sensors. This would allow for larger vocabularies of gestures to be more easily generated and hence direct menu selection to be a feasible form of interaction.

A Windows application to generate ‘mouse move’ messages when an input device is being moved was developed to allow for the encoding of gestures in 2 dimensions.

Initial tests of the performance of the MLP were undertaken, classifying sampled gestures against a training set containing eight gesture classes. Additionally, unlike the gestures encoded with tilt sensors, the gestures can be performed in less than 1 s. An experiment was designed to determine usability levels offered by an interface employing gesture recognition. Subjects included able-bodied and physically disabled people, allowing for the implications of the diversity of controlling ability within the subject group.

6 User evaluation overview

This section summarises the results of a user evaluation undertaken by an individual with spinal-cord injury within a laboratory environment. At the time of the evaluation the manipulator employed a temporary single-axis gripper, in place of the final three-axis end-effector. Consequently, the user evaluation was not designed as a product acceptance exercise, but as part of the design process. An individual was identified with a C4 incomplete spinal-cord injury. The evaluator had wide exposure to disability issues through employment as a counsellor, and an appreciation of technical design issues through pre-accident employment and education. The objectives of the evaluation were to test the unit in a feeding situation.

Stage 1 - Familiarisation.

The evaluator was provided with background information regarding the Middlesex manipulator, outlining the project's objectives and status. A description of the field of Rehabilitation Robotics was also provided, including videos of the MANUS and HANDY-1 systems. A demonstration of the interface system was given, during which the evaluator navigated the menu system using a trackball as an input device. The manipulator system was then connected to the interface, allowing the user to experiment with the system's basic operation (joint and pre-taught position modes). The voice and gesture recognition systems were introduced, and user data was recorded, allowing for the recognition systems to be configured for use during subsequent stages.

Stage 2 - The Feeding task

The feeding task was selected from the prioritised task list for the next stage of evaluation, as the complexity of control demanded of the user is fairly low. A semi-structured environment was created, containing pre-taught positions around the food

and user areas. The evaluator was required to retrieve food by accessing the pre-taught positions, and if
necessary, utilising joint control. The task was demonstrated using the voice, trackball and head-gesture input devices. The voice and trackball employed direct menu selection, whereas head-gestures were used with a scanning system. A video recording was made of the evaluator undertaking tasks with each of these input modes, providing comments on performance and usability as appropriate.

Stage 3 - Drinking/Pick & Place tasks

The next stage of the evaluation combined the slightly more complex Drinking and Pick & Place tasks. The user was required to:

Pick up a plastic straw, and place the straw in a cup. Turn a tap on and off, filling the cup. Pick up the cup, and carry it to an accessible position. Finally, replace the cup on the adjacent surface.

The task objects existed in an environment modified to allow ease of manipulation, however pre-taught positions were not provided. A video recording of the session was made for data analysis.

Stage 4 - Interview

Although feedback from the evaluator had been elicited throughout the evaluation, the final stage used a semi-structured interview to allow a more formal recording of user impressions. Questionnaires are of limited value for single-user studies; however, the approach provided structure to the interview, ensuring that issues addressed by similar studies were included. The approach would also facilitate the development of an appropriate interview or questionnaire format for use in subsequent product-acceptance evaluations.

The overall task completion time for the feeding task undertaken as stage 2 of the evaluation is difficult to quantify, as there is no clear end-point for the task (the plate was never completely cleared). Additionally, the time required to complete a feeding task would be strongly dependent upon the type and amount of food used, food preparation, whether an appropriately adapted plate and spoon were available, and the positioning of the plate with respect to the user. Consequently, the analysis focused on the time required retrieving a single spoonful of food from the plate.

During the feeding task, the plate was placed approximately 1 m away from the evaluator, and the manipulator's speed was set at medium. After an initial familiarisation period of approximately half an hour, the time required to retrieve a spoon of food by the evaluator was measured as 81 seconds (taken as an average of 10 runs). For comparison, the typical time required to retrieve food by the HANDY 1 feeding aid is around 8 seconds (measured from a promotional video: Handy 1 an aid to feeding, Rehab Robotics). Although there are a number of differences between the tasks undertaken by the two systems, an analysis of the evaluation video highlights a number of factors that contribute to the slower performance of the Middlesex manipulator. Firstly, the HANDY 1 is designed to undertake feeding by performing a pre-programmed task or routine. Consequently, considerably fewer commands are required to be issued by the user than is the case with alternative modes of control. The Middlesex manipulator allows for pre-programmed routines to be executed, but for the purpose of the current evaluation, this feature was not exploited.

The feeding task may be decomposed into four components: approaching the plate, scooping food, approaching the user, and stationary (waiting for next command to be completed). The results of the Heuristic evaluation, suggested a number of improvements to the interface, including the use of an 'AND' option that would allow a command to be issued before a previously issued command was completed

Within the feeding task, this allowed the evaluator to begin a dialogue to move to a pre-taught position before the previously selected position had been reached. This feature was implemented towards the end of stage 2 of the evaluation.

The time required to retrieve food reduced from 81 s to 65 s, with the time that the manipulator is stationary reduced to 8% of the total. A considerable proportion of the task is spent scooping food from the plate. The principal axis being operated to perform this action is the linear axis, axis 5. As described in section 4.1, the maximum speed of axis 5 was limited to 30 mm s^{-1}. Consequently, a medium speed had been set at around 24 mm s^{-1}. An alternative design decision would have been to provide one speed setting for the linear axes at 30 mm s^{-1}. This reduces the task duration by approximately 7 s. However, movement of the linear axis would still account for 41% of the total duration, suggesting that more significant design changes would be required to improve performance.

Task completion times for the drinking task were measured after a familiarisation period of approximately half an hour, at which point a time of 7 minutes and 18 seconds was achieved. For the purpose of the following comparison, this is regarded as being representative of a novice user. Task completion times were also measured for an experienced or ‘expert user’ (the authors), with the fastest run recorded as 4 minutes and 55 seconds.

Both the experimenters, students and the subject reported that the Middlesex robot was easy to use with a variety of input devices but was very slow in operation, being more than 50% slower than the Handy robot in a similar situation. It was certainly precise enough for the users to complete the feeding tasks.
Later modifications increased the speed of operation to an acceptable level. All the data input methods used; keyboards, joystick and gesture recognition sensors were quite effective.

6 Comparison with Current designs

Table 4 gives a summary of the features of current rehabilitation projects with the quoted costs. For the Middlesex robot it is a production estimate from a small local company not including VAT, profit and inputs other than a keypad, based on sales of 100 units. The head mouse for example could be supplied at cost for £80. User training would also have to be funded.
The Middlesex robot has a number of features that compare well with competitive designs. The reach is comparable with the MANUS arm, but smaller than the others quoted. It has more degrees of freedom and should be more capable with a better gripper. The weight of the complete system is comparable with the Raptor and less than the other arms. However the payload is less than all, except the HANDY. The interface is as good as the majority, without the more sophisticated visual servoing systems and facial recognition systems of the FRIEND and KARES II. However judging from video clips of the other machines that are available, the Middlesex machine is slower. The flexibility of the software is less than that for the MANUS or KARES II but they have had considerably more development effort, but is better than the RAPTOR, HANDY, Inventaid and the Weston machines in that pre-programmed tasks may be completed. The KARES and Flexibot have much more complex construction, in fact more like industrial robots with implications for cost and maintenance.

7 Discussion

Of all the very tough requirements specified, all but the speed criteria were met by the design. The noise developed at the designed operating speed was not expected and can be reduced substantially at lower speed with a consequent slower operation or by soundproofing. The lower speed operation would not be acceptable to an experienced user who would get frustrated by the slow operation.

It is interesting that the manipulator can be used very effectively despite relatively poor repeatability. This is probably because the operator can efficiently exercise supervisory control with limited input channels.

A comparison with other manipulators is revealing. It has the poorest stated repeatability (as tested; now much improved). It weighs less than the others listed in section2 but it is cheaper than most of the others, although not the production model. It has greater reach and payload compared to the Handy-1 of similar price. The Handy cannot be mounted on a wheelchair in its' present form. It is also smaller than the MANUS device.

The relatively poor repeatability would be improved in a production version by using PID controllers and better gears.

7 Conclusions

- A novel scariculated wheelchair mounted manipulator has been developed for disabled users.
- An embedded micro-controller-based motor control system has been implemented. Up to eight DC servomotors may be driven using PWM closed-loop position and open-loop speed control. A modular approach to system design has been taken, to allow for ease of maintenance through the replacement or servicing of system modules. A communication protocol has been defined (JMCL), allowing full functionality of the system to be controlled via a serial interface.
- User inputs can be made with mouse, speech recognition, head mouse and trackerball.
- Two separate HCI formats were devised based on windows.
- The total estimated production cost of the robot would be less than £5000 without non-standard command inputs

- The robot has a payload of greater than 1 kg with a maximum reach of 0.7-0.9 m
- Although the current version has low repeatability, users found it easy but slow to conduct a simple feeding task

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TABLES

Task	Score	D.O.F.
Pouring liquid	0.285	4
Painting	0.285	5
Drinking	0.275	4
Posting a lette	0.270	4
Combing hair	0.270	5
Gardening	0.250	5
Shaving/makeup	0.250	5
Eating/feeding	0.240	5
Reach & grip.	0.225	6
Re-arranging clothes	0.220	6
Pick from floor	0.215	5
Open/close windows	0.210	5
Playing pool/snooker	0.210	4
Pick & place objects	0.200	5
Filing documents	0.200	5
Cooking	0.195	5
Filling the kettle	0.195	5
Pick & throw objects	0.175	6

Table 1 Weighted Matrix Results

BRK -	sets motor brake for all axes
ERM -	indicates motor brake set
ACK -	acknowledge
CAN -	cancel dialogue
ERT -	error in transmission
HLT -	stop all axes
Hn -	stop axis n
Sk -	set max speed for axis k
Vn -	set speed of axis n to value passed in next byte
Mnd -	move axis n in direction d
Pn -	move axis n to absolute position specified by next 2 bytes
WIn -	transmit 2 bytes containing position of axis n
RST -	reset motor brakes
NXT -	request next byte
Lnd -	limit of axis n in direction d encountered.

Table 2 Part of the JMCL instruction set

Axis	Velocity/ ms^{-1}	Repeatability/ Mm
1	0.25	2
2	0.38	5
3	0.83	6
4	0.97	4
5	0.3	2

Table 3 Prototype Maximum Velocity and Repeatability

Parsons, B., White, A.S., Prior, S.D. and Warner, P.; 2005; The Middlesex University Rehabilitation Robot; Journal of Medical Engineering & Technology; (ISSN 0309-1902); Vol. 29; No.4; July/August; pp.151-162.

Project	Date(s)	Units Sold	Price (£)	Speed	Tasks	Power	DoF	Safety	Interface	Arm Size/mm	Mass/kg	Payload/ kg	Autonomy
Manus	1985 - Date	150	25,000	250 mm/s	ADL	24 VDC	6 + 2	Slip Couplings + Software	Multiple	850	~20	2	Semi-Autonomous
Handy	1987-Date	250	5,000	Slow	Hygiene, Makeup & Feeding	Mains	5 + grip	Slow	Single switch (scanning lights)	Cyber 310 Industrial Robot		<1	Direct Control
Inventaid	1988-1991	3	5,000	Slow	ADL	24 VDC	6 + grip	Pneumatic Actuators	Multiple	1000	25	3	Direct Control
Weston	1995-2001	0	10-15,000	N/a	ADL	24 VDC	6 + grip	Software	Joystick + Menu	1000	21	2	Direct Control
Raptor	1998 - Date	N/a	8,000	Fast/Slow (2 rev/min)	ADL	24 VDC	4 + grip	SlipClutch (23 N)	RX200 Multiple	1220	8	2.3	Direct Control
Flexibot	2001 - Date	0	N/a	N/a	ADL	Docking Station	5	Hardware Locks	N/a	1300 x ϕ110	11	2.8	Autonomous
KARES	1998 - Date	N/a	N/a	150°/s	ADL	24 VDC	6 + grip	compliant	Multiple	750?	N/A	2?	Autonomous
Middlesex	1988-2001	0	5,000	50-100 mm/s	ADL	24 VDC	7 + grip	Hardware + Software	Multiple	900	8	1.5	Semi-Autonomous

Table 4 Comparison of Various Rehabilitation Robots