Robotica (2002) volume 20, pp. 125-132. © Cambridge University Press

The Weston Wheelchair Mounted Assistive Robot - The Design Story

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ABSTRACT

Robotic technology can be used in several ways to benefit people with disabilities. This paper describes the mounting of a robotic arm to a powered wheelchair to assist disabled users in daily activities. Although there are many potential benefits for the disabled user, there are also very strong requirements and compromises, which must be considered in integrating the robotic arm with the wheelchair. This paper focuses on how these integration issues have been addressed.

INTRODUCTION

Approaches to assistive robotics

At the Bath Institute of Medical Engineering various approaches to assistive robotics have been investigated over several years

Desk based system - "Wolfson" robot.[1]

This approach, while being appropriate for the desk based activities of a person carrying out a job of work, was found to be restricting for use in a domestic environment. A desk-based system restricts the user to a particular room in the home. Most domestic activities take place in different rooms around the home. It is important that the disabled person can take part in these activities with other members of the family.

Trolley mounted system - "Wessex" robot.[2]

This low cost approach to "mobile robotics" requires a carer to move a trolley-based manipulator around from one room to another. This approach seems to work well, though users always want greater functionality from their equipment, and the feed back is often "could it be mounted on my wheelchair" or "could the trolley be powered and moved around under remote control".

Wheelchair mounted system - "Weston" robot

This system is described in greater detail in this paper, particularly the issues involved in integrating the robotic manipulator with the wheelchair. The system shares many common components with the trolley-mounted system - this introduces additional constraints.

Task areas for assistive robotics

Several surveys[3], including our own (unpublished), have identified the following areas as being areas where a robotic device might assist a disabled person.

- Eating & drinking.
- Personal hygiene, including tasks such as washing, shaving, applying make up, or simply scratching an itch.
- Work & leisure, including tasks such as handling papers, books, CD's or videos.
- Mobility. This covers activities associated with mobility and access, such as opening doors, operating light switches or lift buttons.
- General reaching and moving tasks such as reaching down to pick up an item off the floor or reaching up to get an item off of a shelf

For a desktop (or trolley mounted) robotic system, just the first three categories are likely to be relevant. As soon as the system is given extra mobility, by being mounted to a wheelchair, the last two categories of mobility and general reaching and moving become important.

Requirements for wheelchair mounted manipulator

When considering attaching a robotic manipulator to a wheelchair there are different requirements compared to either a desktop or trolley mounted system.

Range of motion

Mounting a robotic manipulator into a desktop provides a "workstation" based approach. All the items to be manipulated are placed within a known area of reach. The trolley-mounted approach is similar since the trolley-mounted manipulator is intended to interact with objects at a number of different workstations. As soon as the manipulator is mounted to a wheelchair the required range of motion is increased. The range of motion in a horizontal plane is increased by moving the wheelchair. The user’s expectations will be for a similarly increased vertical range. It will be necessary to pick up objects from the floor (possibly having been dropped by the manipulator) as well as to extend to head height to reach onto a shelf, or to provide personal hygiene tasks around the user's head.

Must not compromise control of wheelchair

It is vital that the presence of the manipulator does not compromise the safe control of the wheelchair. This requirement covers a number of areas.

- Stability of wheelchair
- Predictable steering
- User control of the wheelchair
- Manoeuvrability of wheelchair
- User's vision

Must not compromise usability of wheelchair

For an electric wheelchair user, their wheelchair is their immediate environment. The presence of the manipulator must not compromise such aspects as seat adjustment, pressure relief and transfer into or out of the wheelchair. In addition, the robotic device must be able to be easily removed when not required.

Visual Impact / Aesthetics

Having a manipulator attached to a wheelchair has a considerable visual impact. This impact should be positive. The user must be the centre of focus to both friends and strangers, rather than being hidden within a forest of technological gadgets. After many years of neglect the aesthetics of wheelchairs are being recognised as important. The presence of the manipulator must aesthetically integrate with the wheelchair both in terms of shape, styling and colour.

DESIGN SOLUTIONS

General Configuration

The starting point for the design was the configuration, and many of the components, of the trolley mounted "Wessex" manipulator. In this "Modified SCARA" configuration most of the joints operate in a horizontal plane, while the vertical movement is achieved by a single vertical actuator. Following on from the "Wessex" robot project, some concept drawings were prepared and a full scale mock up built (Figure 1) to suggest one way in which the same basic components might be mounted on a wheelchair.

The initial aim of the current project was to implement this concept. Discussions with users soon revealed the problems associated with this particular arrangement. In particular forward reach is poor, and the position of the robotic device interferes with a reclining backrest. It also assumed that the ability to reach to the ground was not required. This ability has subsequently been identified as being a necessary requirement.

In spite of these problems, using the "Wessex" manipulator as a starting point has several advantages:

- The configuration is not dissimilar to the action of a human arm making it familiar to users and intuitive to control.
- Since most of the joints operate in a horizontal plane, low powered motors can be used with benefits for safety and power economy.
- It allows both systems to be developed in parallel, with benefits of scale for any subsequent commercialisation.

Fig. 1 Original concept mock up

However the main disadvantage is that all the vertical movement must come from a single vertical actuator. While this is acceptable for the trolley-mounted system with a total vertical range of 0.5m, it presents problems for the wheelchair-mounted system with a total required range of 1.2m.

Other groups have mounted robotic devices onto wheelchairs and have come up with different solutions. None of these other projects take a "Modified SCARA" as their starting point:

- Manus (Exact Dynamics, Netherlands).[4] This system mounts the arm above the front castors of the wheelchair. The arm folds up compactly below the level of the armrest. This system has proved very successful, and is commercially available. It is the standard against which other wheelchair mounted manipulators are judged.
- Inventaid (UK).[5] This pneumatic powered system was mounted across the lower back of the wheelchair, with a linkage reaching forward from this position.
- Raptor (Applied Resources Corp., US). This is a commercial development of the earlier Helping Hand (KRI, US).[6] This system has limited functionality and only 4 degrees of

freedom, but a significantly lower price than the Manus. It is mounted low down at the rear side of the wheelchair.

In order to progress our project and determine the most appropriate configuration several alternative mounting positions were investigated with potential users. Initially a series of sketches were prepared, and the most promising built up into a second non powered mock-up (Figure 2) which could be positioned adjacent to a user's wheelchair. This mock-up allowed users to clearly visualise the system and comment on it without any great investment in developing hardware.

Fig 2. Second mock up

The configuration chosen mounted the hardware at the rear side of the wheelchair. When the user wanted to use the robotic device, a powered link would rotate through 180deg to swing the manipulator to the forward position illustrated. Users noted several shortcomings of this arrangement:

- The height of the vertical actuator was unacceptable, especially in the forward position.
- The use of an extra link presented additional complexity and cost
- Significant clearance was required to the side of the wheelchair to allow the arm to swing from its rear to forward position.
- The arm at the front gave good forward reach, but restricted the ability to manoeuvre the wheelchair under a desk or tabletop.

As a result of these investigations a position near to the shoulder of the user was found to present the best solution (Figure 3). Mounting the manipulator in this position on a fixed mounting point is relatively simple to implement, is not too visually obtrusive and does not block the user's line of vision, while still allowing a reasonable forward reach. The height of the vertical actuator was reduced by the use of a two-stage mechanism

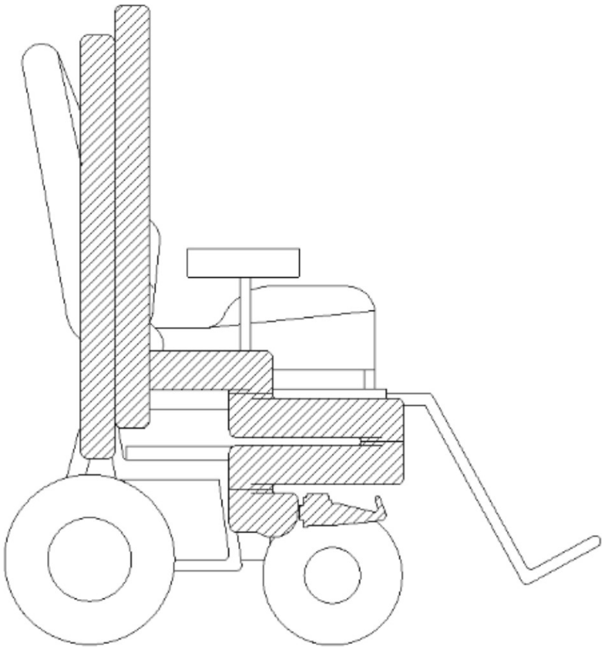

Fig 3. General arrangement of manipulator mounted to wheelchair

Detailed mechanical design.

Vertical Actuator

In order to overcome the excessive overall height, yet provide an improved vertical range of 1.2m, an extending mechanism was used with two parallel vertical tracks driven by a single motor. The rear section is fixed to the wheelchair, while the front section slides on the rear. The upper arm slides on the front section. A toothed belt means that as the front section slides upwards on the rear section, so the upper arm slides upwards on the front section. The photograph (Figure 4) shows the arm towards its upper position, with the shrouds removed. In its parked (lower) position the whole mechanism does not extend above the head height of the user. Integral constant force springs keep the weight of the upper arm counter balanced so that the low power (4W) gearmotor is only driving against the friction of the system and any load carried by the manipulator.

Upper arm

The upper arm structure (Figure 5) consists of three vertical axes (identified as shoulder, elbow and wrist yaw), all to a common design. Since none of these actuators act against gravity, low powered motors can be used (3.5W). Each motor is a 24v Maxon gearmotor with planetary gearhead and optical encoder on the rear of the unit. The motor drives the rotary actuator through a bevel gear stage and toothed pulley belt. The

main arm structure is based around a 38mm x 51mm aluminium extrusion. The gearmotor and bevel gear stage are mounted within the extrusion. The pulley stage as well as motor control electronics are mounted on top of the extrusion, protected by a cosmetic cover.
This arrangement has several beneficial implications:

- Clean aesthetics
- Low power motors are a major safety feature
- Low power drain from wheelchair batteries.

Fig. 4. Vertical actuator arrangement

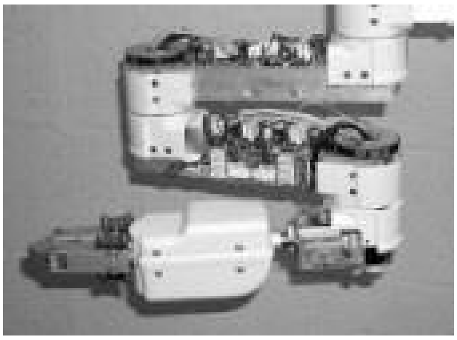

Fig. 5. Upper arm structure

Wrist

At the "wrist" a reverse differential is used, being a very compact arrangement, combining roll and pitch. The ability of the wrist to pitch down is an important part of the overall design as it increases the vertical range.

Gripper

The earlier trolley-mounted manipulator used a prosthetic hand end effector. This never proved totally effective as a robotic gripper. A purpose made gripper has been designed specifically for the current device (Figure 6).

It has the following features:

- Two parallel moving jaws, based on a four bar link mechanism.
- Slim profile to allow good visibility of the item being gripped.
- Compliant elements in the drive train allow variable force gripping.
- Non backdrivable gearing and compliance to maintain grip force when power is removed from the drive motor.

Further development of the gripper is planned.

Fig. 6. Gripper mechanism

Mounting to Wheelchair

Mounting to Home & Away Wheelchair

As an initial arrangement the robotic manipulator was mounted to a Scandinavian Mobility (Part of Invacare, US) "Home & Away" powered wheelchair (Figure 7). A mounting plate was permanently clamped to the wheelchair. The manipulator fixed to the mounting plate using three threaded fasteners. The manipulator increased the width by 120mm with no increase in overall length.

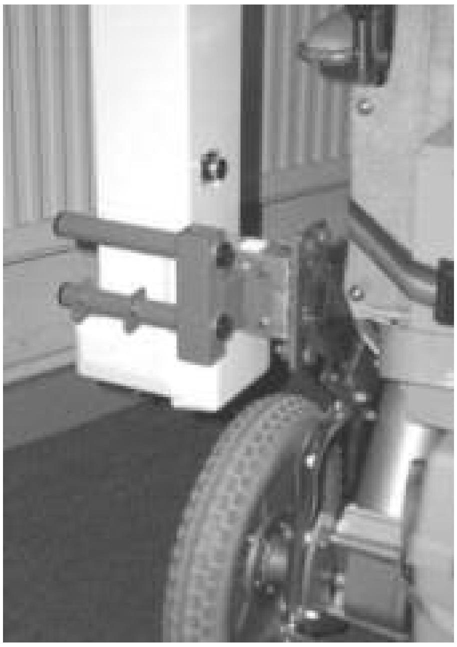

Fig. 7. Manipulator attached to Home and Away wheelchair.

Trolley mounting

Several volunteers were identified to use the system but it was not feasible at this stage to arrange a custom mounting for their own wheelchairs. Equally it was not appropriate or possible to ask volunteers to transfer into the Home & Away chair. The manipulator was therefore mounted on a trolley, designed so that it could be wheeled close to the wheelchair to simulate the position the manipulator would be in, if mounted to the wheelchair (Figure 8).

Fig. 8. Manipulator mounted on trolley

Mounting to Storm Wheelchair

Fig. 9. Manipulator attached to Storm wheelchair

Although positioning the manipulator on a trolley adjacent to the user's wheelchair provided valuable information it would never represent the flexibility (or potential problems) of mounting the manipulator to the wheelchair. A local volunteer was identified who was willing to evaluate the system. He uses an Invacare (US) "Storm" wheelchair, and so it was necessary to make up a custom mounting system for that chair. While the Home and Away chair is of a traditional tubular steel framed design, the Storm is totally different. This particular wheelchair is also fitted with a large reclining seat, with substantial armrests. The manipulator mounted to the Storm wheelchair is illustrated in Figure 9.

The main structural member of the Storm wheelchair is an "H" shaped chassis. The most rigid point is the cross member of the "H" (running across the wheelchair at low level underneath the user's legs), and so the manipulator mounting was cantilevered off this cross member. For easy removal the mounting point is a single vertical peg on the wheelchair and a matching hole on the manipulator structure.

Discussions with users led to the realisation that the manipulator needed to be easily demountable from the wheelchair. This must be achieved without risk of back injuries to carers, or the need to undo engineering fasteners. A wheeled trolley is therefore provided which can be wheeled up adjacent to the wheelchair. A simple jack fitted to the trolley lifts the manipulator off the wheelchair onto a second mounting peg on the trolley. The trolley holds a pair of batteries allowing the manipulator to be used when on the trolley, as well as acting as a balance weight.

Electronics Design

The electronics design (Figure 10) is very similar to that used in the trolley mounted system. The main differences are that the processor has been upgraded from a 6502 card to an 80186 equivalent PC card (GCAT board, DSP Design, Chesterfield, UK) and that the power supply is 24v (taken from the powered wheelchair's batteries) rather than 12v.

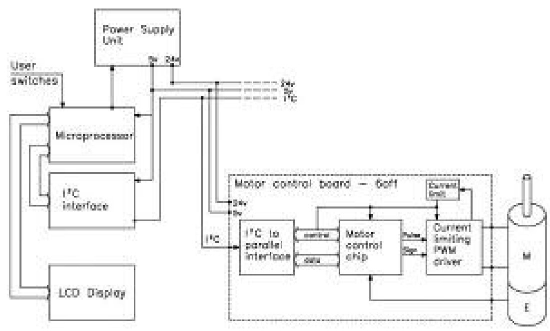

Fig. 10. Electronics block diagram.

The motor control boards are mounted on the arm. The three main cables through the arm comprise the I^2C serial communications bus, a 24v motor power supply and a 5v logic power supply. This arrangement allows for simplified construction and, if necessary, disassembly of the arm. Short ribbon cable links then run to the adjacent motor units. Commands from the processor, mounted within the trolley, are communicated along the I^2C bus to the individual motor control boards. The I^2C (Inter-Integrated Circuit Bus) is a proprietary system developed by Philips Semiconductors.

The construction of the motor control board uses surface mount techniques with a small number of multifunctional integrated circuits. This allows a very small board 50mm x 50mm size. The motor control boards are based around the Hewlett Packard HCTL 1100 motor controller. This allows the motor to be controlled in various modes - holding a set position, moving at a regulated velocity, or using a trapezoidal velocity profile to move to a particular position. The Pulse Width Modulated output from the controller is taken to a current limiting amplifier to drive the motor. Current feedback trips the controller to idle mode when an over current condition occurs for more than a few seconds. The motor control board also has two serial to parallel interface integrated circuits for the I^2C bus.

In the current implementation a development configuration of the processor system is used, incorporating a floppy disk drive and comprehensive input and output facilities. Eventually the target system will use a combination of on board flash and EPROM memory and PCMCIA card, with custom input and output facilities.

Software Design

The software is programmed in the “C” Language using a Borland Compiler, compiling off line on a PC and transferred as an executable file by floppy disk to the target system. In the long term the software will be downloaded onto EPROM and/or flash memory on the processor card.

At the top level the software implements the user interface menu system, calling on functions for controlling the robotic system. At a lower level there are software modules to handle arm movements, cartesian position calculations, motor control board calls and I^2C communication.

The straight-line movement of the arm uses a simple algorithm developed in earlier phases of the robot project. The algorithm makes two significant, but acceptable compromises. Firstly, it operates purely in the horizontal plane and tracks the position of the manipulator wrist, whilst keeping the gripper at a constant orientation in space. Secondly, it doesn't attempt to provide constant spatial velocity of the gripper end point. Rather it optimises the angular velocities of the upper arm rotary joints. It has proved to be efficient in software and hardware and intuitive for the user.

User Interface

The user interface assumes that the user will be able to use a two dimensional input, such as a joystick, as commonly used for electric wheelchair control. Using the joystick, the user controls a cursor to make selections from a menu screen. Figure 11 illustrates the menu layout for controlling the main directions of movement of the manipulator. A similar menu allows control of the wrist and gripper movements. The menu is displayed on a monochrome LCD display (320 x 200 pixels) with backlighting. The size of the screen is 190mm x 100mm in a 270mm x 200mm plastic enclosure.

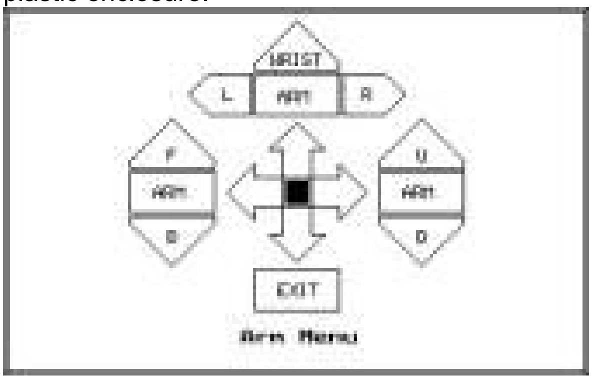

Fig. 11. User interface display

The main emphasis has been on the direct control of the manipulator in real time, by the selection from the menu of different movement directions. There are currently limited facilities for the use of pre-programmed routines. As reported later in the paper this has been found to be very valuable by users and so more comprehensive facilities are planned.

Currently the manipulator has a user interface system completely independent of the wheelchair control system. In the longer term the two systems need to be integrated. Many wheelchairs use a control system such as the Dynamics (New Zealand) DX bus, and it should be possible to control both the manipulator and the wheelchair through a common input device and display using this system.

EVALUATION

A fuller report on the evaluations is planned for a separate publication

Trolley mounted

The manipulator was positioned on a trolley adjacent to the wheelchairs of five volunteer users. This allowed evaluation of the general positioning and control of the manipulator, although without some of the flexibility or potential compromises of the full wheelchair mounted system.

The shoulder-mounted position was well accepted, although forward reach was restricted. The likely increase of width of 120mm was discussed with volunteers. In a number of cases this would be a major problem.

The aesthetics were considered to be very good. However the current white/grey colour scheme was considered too clinical and a darker colour might be preferable.

The user interface was considered to be very good and intuitive to operate, The quality of the back lit LCD was excellent, but the bulk of the display was too big, causing problems in positioning it appropriately.

Evaluation of useful reach

The arm has a theoretical area that it can reach into, defined by its geometry and the end stops on the various actuators. However when using the manipulator it is clear that this is not always useful area. Since the directions of motion are defined in a cartesian fashion it is the largest rectangle which can be placed within the envelope of reach which is important. The outer limit of reach is a circle of radius 0.8 m. However the largest useful rectangle is only about 0.3 m x 0.4 m. This means that the user has to carefully consider the best strategy to manipulate an object, say, on a tray in front.

Stability tests

The stability of the manipulator mounted to the Home & Away wheelchair was evaluated in a number of ways.

- Dynamic stability - running the wheelchair at various speeds, around various radii tracks and with the manipulator in various configurations around a large hall.
- Dynamic stability on a slope - stopping and starting facing up and down a fixed slope.
- Static stability on an adjustable ramp with the manipulator in various configurations with the wheelchair facing in different directions.

In general the conclusion was that there was no serious effect on stability. However there was some concern relating to:

a) Cornering at speed with the arm extended to maximum vertical height.
b) The use of the manipulator when the wheelchair is on a significant slope.

Although these are extreme conditions, they should be avoided by limiting certain combinations of wheelchair speed, inclination and manipulator configuration. These limits should be enforced by hardware/software limits as well as in the instructions for use for the system.

Wheelchair mounted

The robotic system was tested by a volunteer, mounted to his Invacare Storm Wheelchair. The volunteer is male, aged 36, with a spinal cord injury at level C4 (complete)

This particular user uses a chin-mounted joystick. The wheelchair control system uses the Dynamics DX bus. Ideally the manipulator should be controllable through the wheelchair joystick. However although this is possible using the "DX" bus system it is not a trivial exercise and in the short term the manipulator joystick is mounted adjacent to the wheelchair joystick in front of the user. He is able to control both joysticks, but at the expense of visual clutter. The LCD display is mounted above his lap and line of sight is slightly obscured by the joystick. For chin operation a small display adjacent to the joystick would be preferable to the larger display at a distance. A similar arrangement might be investigated for users of a hand-operated joystick.

He used the system over a period of 3 weeks. He found the system easy to use, but slow. He felt its usefulness would be improved if it were faster to control, perhaps by the greater use of pre-programmed routines as well as the use of voice activation. In many respects he felt that the manipulator integrated well with his wheelchair, although the extra width was a problem in his small living room. The ease of mounting and dismounting the robot from the wheelchair was identified as a critical issue, particular where there are different carers attending the user. He felt that in some instances it would be more appropriate to use the robot in a trolley mounted configuration rather than mounted to the wheelchair.

Further evaluations are planned, mounting the manipulator to the wheelchairs of other users, and also in trolley mounted form.

CONCLUSIONS

There are many compromises that must be considered in mounting a robotic manipulator to a powered wheelchair. In the current project a number of integration issues have been successfully addressed, and a working system built and briefly evaluated. The following areas need further work.

1. <u>General fitting</u>. The manipulator has been fitted to two different wheelchairs. Considerable work was necessary to change the mounting arrangement. In the longer term it will be necessary to develop a range of kits to allow a standard manipulator configuration to fit to various wheelchairs. Ease of mounting and dismounting from the wheelchair needs further work. The flexibility of using the robot either on the wheelchair or on the trolley needs to be considered.

2. Width. The excess width of the manipulator remains a major obstacle to the use of our robotic system by a number of potential users.
3. User control interface. The robotic control system needs to be integrated with standard wheelchair bus systems such as the DX system. The appropriate size and placement of the LCD display needs further work. Greater use of pre-programmed routines will be incorporated to make user control of the device faster and simpler.
4. Stability. In most situations the manipulator presents no stability problems. There are however certain extreme configurations which could cause problems. The system must ensure that these configurations do not occur.
5. Gripper. The current gripper provides a simple gripping device with parallel jaws. Further development is needed, particularly in the area of intelligent gripping.

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