

Design and evaluation of an alternative wheelchair control system for dexterity disabilities

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This work details the design and development of a novel 3D printed, modular alternative wheelchair control system for powered wheelchair users afflicted with dexterity inhibiting disorders, which mechanically interfaces directly with the installed standard joystick. The proposed joystick manipulator utilises an accelerometer for gesture control input processed by the Arduino microprocessor and a mechanical control interface, which sits over a standard installed two-axis proportional joystick, the preferential control system for most powered chair manufacturers. When fitted, this allows powered electric wheelchair users with limited dexterity, independent to navigate their wheelchair unassisted. The mechanical system has been selected so that the joystick manipulator is as universal as possible and can be installed to almost any powered wheelchair that uses a two-axis joystick. The design process and key aspects of the operation of the joystick manipulator are presented as well as field testing on a wheelchair conducted. The test results show that the proposed joystick manipulator is a successful system that can be universally fitted to most powered chairs and offers potentially greater independence for the powered wheelchair user.

1. Introduction: A study based on the provision of powered wheelchair for 544 electric powered indoor outdoor wheelchair users across three NHS Trusts found that 10% of users, often suffering from disabilities such as cerebral palsy (CP) or muscular dystrophy (MD), required the installation of ‘individualised adaptations to their control systems’ [1]. Disabilities, such as CP and MD, can severely affect limb movement and fine dexterity making the two-axis joystick impossible to use. Therefore, many users must resort to an ‘attendant control’ system, which allows someone else to navigate the powered chair on the user’s behalf from a rear mounted proportional two-axis joystick, hindering the independence of the user.

Alternative wheelchair control systems, such as chin control, sip and puff, switch arrays and scanning arrays as shown in Fig. 1, offer some control alternatives for the limited dexterity user [2] but these control solutions can often be cumbersome, difficult and costly to install. Many such systems can often also require a specific ‘range of motion’ and a basic level of proficiency to operate [3]. Recently, a wheelchair system controlled with eye movements and blinks has been proposed that uses deep convolutional neural networks for classification, however, the system has not been implemented on ‘real’ wheelchairs [4]. In [5], face and eye were used to control the wheelchair using a facial recognition algorithm. Limited research has been carried out on tongue controlled wheelchairs. In [6], the authors use radio frequency identification tags mounted in the mouth and controlled by the tongue. The authors of [7, 8] use electroencephalogram signals from the brain connected via electrodes to control a prototype wheelchair. These systems can be intrusive as they require electrodes to be placed on the brain. Software control systems such as fuzzy logic and proportional–integral–derivative (PID) control has been proposed in [9] to improve the accuracy and dynamic performance of wheelchairs. In [10], Lyapunov stability model has been proposed for adaptive control, whereas Tian and Xu [11] propose an adaptive fuzzy PID control for speed control of wheelchairs. Soares dos Santos and Ferreira [12] proposed field programmable gate arrays (FPGAs) with fuzzy logic for position tracking of a wheelchair, however, FPGAs are not suitable for embedded applications and can be expensive. Most of the systems proposed are offering speed or dynamic control of the wheelchair. There has been some

preliminary work on the brain and face control wheelchairs, however, these systems are in a simulation or a specially built prototype and do not offer a modular system.

One of the challenges in the development of an alternative wheelchair control system is to meet the complex needs of the patient as defined by the clinicians. Therefore, to develop a fully customised approach can often be frustratingly hampered by ‘intellectual property issues and incompatibility issues between components’, resulting in the control system components and motor controllers to be often ‘brand locked’ and therefore incompatible with one another [13]. When a two-axis proportional joystick has already been installed to a powered wheelchair base, the motor controllers tend to be inalterable and therefore the purchase of a new controller or even a new powered chair base is required [13]. The purchase of a new chair base is often necessary to permit the development of a bespoke control system.

The contribution of this Letter is to present the design, development, and testing of a novel modular, alternative powered wheelchair control system, which interfaces with the user through a limb mounted accelerometer. The device is mountable over the user’s standard proportional two-axis joystick, controlling the powered chair through mechanical manipulation. A mechanical interface system has been chosen over an electrical, hard-wired approach as it allows for easy installation and relative universality, with mounting on almost all standard joysticks possible due to the modular system, easily alterable through the use of filament deposition machining (FDM) manufacturing for all key components.

2. Joystick manipulator design: The main motivation of the joystick manipulator design was to offer better universality, resilience, and accessibility to all users. In addition, the joystick manipulator is highly adaptable and open source, enabling a personalised control solution to be developed to better enable independence for the user, a key aspect of the design. The detailed design considerations for the joystick manipulator are as follows:

Universality: Compatibility with a wide range of different proportional two-axis joysticks, with little to no design change required for each type. This should be achieved through a modular-based design.



Fig. 1 Alternative types of powered chair control systems; sip and puff (left), head switch array (middle) and chin control (right) [2]

Ease of installation: Mechanical interaction with the already installed joystick, without the need for any modifications to existing wheelchair hardware. The system must emulate the only universal protocol for a powered chair, the human hand [14].

Reversibility: Installable with only temporary fastenings, requiring no permanent adaptations to be made. When removed, the device should be entirely removable from the powered chair and not integrated structurally.

Adaptive input system: The developed accelerometer-based gesture control system must have the ability to be calibrated to users chosen operating position. The accelerometer should be usable when mounted on the palm of the hand or the wrist, but other positions on the body should also be considered (e.g. the head). The sensor must be as unobtrusive to the user as possible, achieved through small dimensions and minimum wired connections as possible.

Open source: Wherever possible, the system should use open source or easily accessible components (servo motors and micro-processor) so that further improvements and developments can be made to the joystick manipulator in the future.

Resilience: All components must be manufactured in a manner that is hard wearing and modular so that replacement is possible if required.

Accessibility: The cost must be kept to a minimum wherever possible and utilise non-traditional manufacturing techniques, such as FDM 3D printing, allowing for low cost, low volume production.

Enhance independence: The main purpose of the joystick manipulator is to enhance the independence of a powered chair user, offering greater degrees of control to the user at the lowest possible point of invasiveness to the person or powered chair. The joystick manipulator must offer a significant improvement of user experience in comparison with the installed proportional two-axis joystick.

3. Methodology: The joystick manipulator is a novel alternative control system for powered wheelchairs, which utilises a body mounted accelerometer, used for gesture control through motion detection. The detected movements made by the user are then processed by the Arduino microprocessor mounted in the control unit of the joystick. The joystick control unit then mechanically manipulates the powered wheelchairs installed two-axis proportional joystick with two servo motors, manoeuvring the powered chair in the desired direction. Developments of the joystick manipulator have focused around a mechanical design solution because, as highlighted from prior projects, mechanical systems can easily be installed and removed, and require no permanent alteration to the installed hardware of a powered wheelchair. The use of a mechanical approach in the design of the joystick manipulator has also ensured that alternative control system technologies can be applied to a powered wheelchair that previously would have been too expensive or impractical to adapt in the past.

The joystick manipulator can be divided into two main assemblies:

- (i) *The joystick control unit:* an FDM manufactured modular system featuring two servos, mechanically interacting with the wheelchair joystick, controlled by an Arduino Nano.

- (ii) *Gesture control human interface (the 'hand band'):* A palm mounted three-axis accelerometer used to detect motion for gesture control.

(i) *The joystick control unit:* The joystick control unit shown in Fig. 2 is the main operational assembly of the joystick manipulator. It is responsible for converting the motion inputs from the accelerometer sensors into a usable mechanical output, where the servos move the two-axis joystick incrementally in the desired direction of travel. This gives the user directional as well as incremental speed control.

The casing of the joystick manipulator acts as the chassis for all the control components. The joystick manipulator is mounted directly over the powered wheelchair's joystick as shown in Fig. 3 and is fastened into position using '3M double sided foam tape'. This was selected as it holds the joystick manipulator in place so that the servos could act against the joystick, it is weather resistant, and easily removable if required satisfying the reversibility aspect of the design requirements.

The joystick control unit casing has been designed with a series of slots in the base, which is used to locate the modular components such as servo mounts and stem boss. These slots not only allow for easy removal and replacement of key components but also ensure that the modular components are correctly located and centred, utilising 'poke-yoke' principles. This, in turn, guarantees that after installation, the servos and interface plates correctly align with the joystick ensuring correct and accurate directional control.

To enable universality and ease of installation, a modular design approach has been adapted for all key components of the joystick control unit and utilised across the joystick manipulator system.

The interface paddle shown in Fig. 4a forms the principle mechanical contact surface between the joystick control unit and two-axis proportional joystick. It is connected to the servo armature as shown in Fig. 5 and directs the servo's rotational movement to the joystick. It features a step in the design, ensuring that maximum movement can be achieved. The bevelled slot allows for lateral movement of the joystick stem and the width can



Fig. 2 Joystick control unit



Fig. 3 Joystick control unit mounted on the test joystick jig



Fig. 4 The interface paddle and the main hole for the joystick control unit
a Interface paddle – the primary mechanical contact between the joystick control unit and two-axis proportional joystick
b Stem boss – centres the device over the powered chair joystick, ensuring accurate positioning

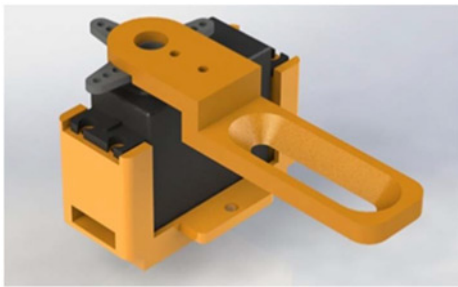


Fig. 5 Servo mount with interface paddle in position

easily be altered for differing joystick types. The stem boss shown in Fig. 4*b* forms the main hole that centres the joystick control unit over the joystick for ease of installation. The stem boss is a modular component so that the diameter can easily be changed for different joystick dimensions, allowing for greater universality.

The servo mounts shown in Fig. 5 have been manufactured to fit into the slots of the joystick control unit casing, ensuring that the servos are correctly located for correct and calibrated operation. The servo mounts are made to be easily removable from the joystick control unit so that servos can easily be replaced. Although designed to take parallax standard servos, the design can easily be altered if another component was selected.

The hand band was used in this research as the primary gesture control input device for the joystick manipulator system. The human interface or ‘hand band’ presented in Fig. 6 is an initial design for a palm mounted accelerometer. The hand band utilises an ‘Adafruit’ accelerometer, which communicates with the control unit of the joystick over an I2C serial protocol. However, because of the implementation of the I2C protocol, more improved and



Fig. 6 Hand band as installed on the user

personalised sensors can be developed for the joystick manipulator for future applications.

(ii) *Gesture control human interface (the ‘hand band’)*: The hand band is designed to house an Adafruit 3-axis accelerometer. The unit casing consists of two main components; the base, which is in contact with the user and acts as the main mount for the accelerometer, and the lid, which protects the accelerometer and attaches to the strap used to hold the hand band in position. The hand band acts as a primary test platform for the user interface system, allowing for possible alternate design developments in the future.

Fig. 7 shows that the joystick control unit and hand band form an integral part of the overall system operation feedback loop. The user moves the hand band in the desired direction of travel, causing the accelerometer to detect a change in positional state. This signal is then processed by the Arduino Nano microprocessor mounted in the control unit of the joystick housing, which then translates the accelerometer input into a usable output position for the servos. The servos are programmed to have three discrete positions in each direction (i.e. three forward positions, three backward positions etc.) allowing for proportional speed control for the user.

The servos then manipulate the two-axis proportional joystick in the desired direction of travel, in turn, moving the powered chair. The hand band and joystick control unit alone form an open feedback control system. However, as seen in Fig. 7, the integration of the powered chair user, who perceives the speed and direction and reacts accordingly forms the feedback element of the control system loop. Overall, therefore, with the human element, the joystick manipulator system can be characterised as a closed feedback loop control system.

The programme to operate the joystick manipulator utilised the Arduino integrated development environment (IDE), which acts both as a programming platform and compiler for uploading the code directly to the Arduino Nano over a USB connection. The Arduino IDE was also used so that the open source servo and accelerometer source driver codes could be used, ensuring compatibility for all components across the joystick manipulator system. The flowchart of the joystick manipulator Arduino programme is shown in Fig. 8.

The programme in Fig. 8 is composed such that the position of the accelerometer is read first. After the push of the calibrate button, the (0, 0) or neutral position for the hand band is established. After the calibration step has occurred, if the hand band is moved forward, then a forward command is sent by the Arduino Nano to the servos.

The Arduino tracks the position of the hand band and assigns a discrete number depending on its position, between -3 and 3 . If the hand band is fully forwarded then a value of $+3$ is assigned, and -3 , if the hand band is in the fully backward position. This range value is used to tell the servo motors how far to move

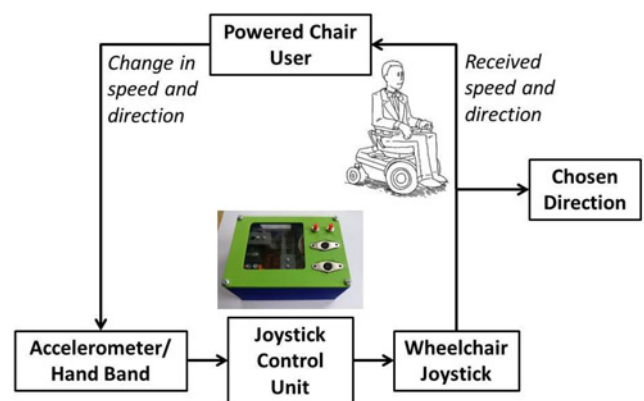


Fig. 7 Operational feedback loop of the joystick manipulator system

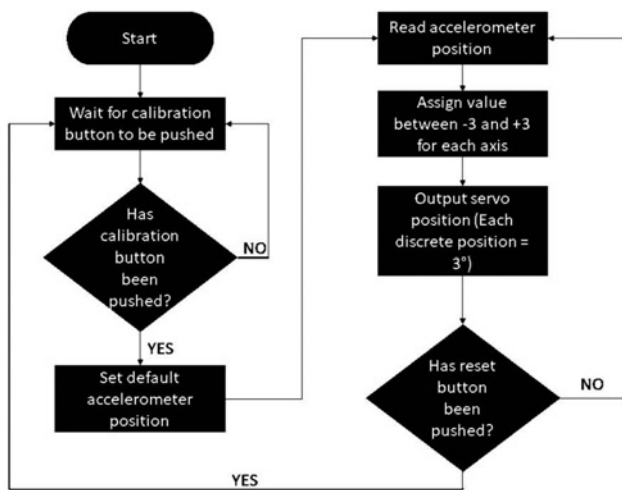


Fig. 8 Flowchart of the joystick manipulator Arduino programme

forward or back in its movement range. Discrete positions were used to prevent the servos from hunting to find the exact positional value, conserving power and reducing mechanical wear. Although only three discrete positions have been used in the code, this provided more than adequate speed control for the user during testing.

As a safety feature, if communication or power is lost to the joystick manipulator, then the servos will automatically return to the neutral position, halting the wheelchair and preventing uncontrolled movement. ‘Soft stops’ or limits of movement ($\pm 18^\circ$ from neutral) for the servos have been defined in the programme to ensure that the interface paddles do not collide during the operation.

4. Experimental setup: This section outlines the experimental procedures that were followed to establish the performance capabilities of the finished joystick manipulator prototype developed. The experiments conducted can be categorised as follows:

- (i) *Laboratory tests:* These tests were conducted in a controlled environment setting, with the joystick manipulator mounted on a bespoke joystick jig. These experiments were used to establish how reliable the joystick manipulator was as a system.
- (ii) *Field tests:* The joystick manipulator system was attached to a wheelchair and tested for usability and intuitiveness for the user. The field tests were used as a comparison with a standard joystick to better understand how the joystick manipulator compares in terms of controllability and therefore independence for the user.

(i) *Laboratory test:* For the laboratory test, the control unit of the joystick was mounted on a specially made joystick jig presented in Fig. 3 earlier that utilised an ‘Invacare Shark 2’ control module, deemed as an industry standard unit. The test conducted was to ensure that the joystick manipulator was a reliable system in a static, controlled environment.

To ensure success, 100 cycle tests were conducted in rapid succession, where the hand band was moved to the maximum forward position, maximum aft position, maximum left position and maximum right position in a ‘figure of eight’ style motion. The servos and joystick were then monitored to ensure that the correct movement range had been achieved. This test ensured that both the maximum ranges and degrees of the movement were tested. Videos of the laboratory tests are available. [YouTube links for JCD Field Test Videos: Branch Test at <https://www.youtube.com/watch?v=iRIDyGGDMRw>.

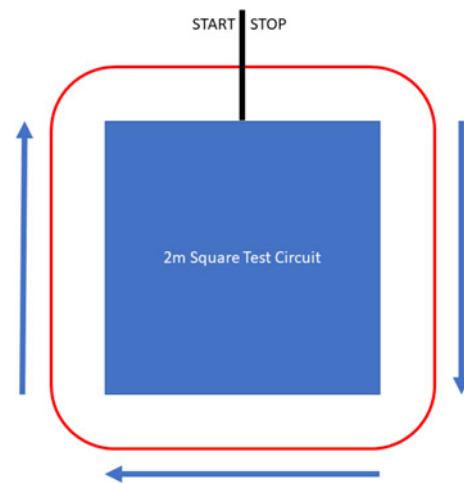


Fig. 9 Test circuit used to time the speed of each test run

[youtube.com/watch?v=iRIDyGGDMRw](https://www.youtube.com/watch?v=iRIDyGGDMRw). Initial bench test of the JCD system, with the JCU mounted on a jig to simulate a fitted two-axis joystick (field test 1, palm mounted – initial field test with the JCD fitted to an Invacare Shark 2 joystick. The hand band is mounted in the palm of the left hand) at <https://www.youtube.com/watch?v=bDwq9Bjq4rl>. (Field test 2, arm in contracture – JCD with hand band sensor located again on the hand, but with the arm in a ‘contracture’-like state to simulate a user with CP) at <https://www.youtube.com/watch?v=7sLY-RKmCBM> (field test 3, head mounted - hand band sensor mounted on the side of the head, allowing for ‘nod’ style gesture control, where the powered chair is controlled by the movement of the head) at <https://www.youtube.com/watch?v=VSz3rgDkoT8>].

(ii) *Field test:* The field tests were based upon the test method presented in ‘alternative wheelchair control’ [15]. The joystick manipulator was attached to the joystick of a powered wheelchair and operated by the hand band, mounted on the palm of the test operator’s hand. The powered chair was directed around a 2-m² course shown in Fig. 9 and the time to complete one circuit was recorded. The same circuit was then completed again, with the test operator using the standard installed ‘Invacare Shark 2’ joystick, so that a control comparison could be made.

Where possible, alternate mounting positions for the hand band, such as an arm in contracture (useful for users suffering from CP), and around the head (useful for a quadriplegic or partial upper body paralysis users), were also tested and timed around the circuit.

5. Results and discussions: *Laboratory test:* As specified in Section 4, the joystick control unit was mounted on the joystick rig shown in Fig. 3 earlier and was subjected to 100 operational cycles. A serial link between the Arduino Nano and a laptop running the Arduino IDE was used to observe both the input values from the hand band and the output values from the Arduino Nano to the servo motors. The serial link proved that on all counts, the values inputted by the hand band and outputted to the servos were within an expected range, and therefore, reliable. Visual observations of the joystick as it was moved by the servos also demonstrated that on all occasions, the joystick was being moved in the correct desired direction and to the desired magnitude. The laboratory test can be characterised as a success and, in this early stage of design, the joystick manipulator system can be described as 100% reliable in the test environment.

Field tests: The joystick control unit was mounted to the joystick of an operational powered wheelchair as shown in Fig. 10. The hand band was tested in multiple different body positions; on the palm of the hand, on arm in a ‘contracture’ position (to simulate



Fig. 10 Joystick manipulator (circled red) mounted on a powered wheelchair for final field testing, with the hand band mounted on the palm (circled green)

Table 1 Results of joystick manipulator field tests

Input type	Recorded time (seconds)
Invacare Shark 2 joystick (control value)	19
joystick control unit & hand band – palm mounted	32
joystick control unit & hand band – arm in contracture (CP simulation)	38
joystick control unit & hand band – head mounted	41

a user with CP), and on the side of the head. The time was then recorded for each control method used to navigate the powered wheelchair around a 2 m² as shown in Fig. 9. and compared against the initial control value. The results are shown in Table 1.

As can be seen from Table 1, although all times recorded with the joystick manipulator system are at least 13 s slower than the control value, the spread of data was only 9 s. This shows that wherever the accelerometer was mounted when combined with the joystick control unit, it provided an effective control system. The reason for the 13 s increase in the time could have been due to confidence and competence of the test operator and, with practice, if times were recorded for the joystick manipulator system again they could be significantly closer to that of the control value. All videos of the tests are available.

The joystick manipulator system described in this Letter has only been manufactured as a singular prototype and tested in controlled conditions. For a more meaningful investigation into the capabilities of such a device, and to further establish the full capabilities and validity of the joystick manipulator system, longer ‘real world’ trials would have to be conducted with users suffering from dexterity inhibiting disorders.

6. Conclusions: This Letter describes the design development and testing of a novel modular, 3D printed alternate wheelchair control system, the joystick manipulator control system via Arduino Nano with accelerometers. The results demonstrate that the joystick manipulator system is successfully capable of using gesture control technology to navigate a powered electric wheelchair. In bench tests, the joystick manipulator was successful in completing 100 operational cycles, demonstrating that it is a reliable system, suitable for real world applications. Primarily, however, the field tests demonstrated that the hand band gesture control module was capable of detecting gestures and movements from a variety of

body positions. The joystick control unit was capable of correctly operating the installed joystick, offering an accurate degree of both directional and speed control, demonstrating that it could potentially increase the independence of the user. In all aspects, as an initial prototype system, the design of the joystick manipulator can appropriately be characterised as meeting the key aspects of the design specification

By meeting the key aspects of the design specification, it becomes apparent that there is an appropriate place for relatively inexpensive, modular powered wheelchair control systems. This Letter demonstrates that through the use of rapid prototyping technologies and a modular design approach, a relatively universal control system can be created that overcomes the issues of ‘brand locking’. The utilisation of commercially available components such as the servos, and commonly available control circuits (the Arduino Nano) allows for clinicians the possibility to create bespoke solutions for powered control systems, based on the express needs of the patient. Such previous experimental systems arguable have not been able to achieve this.

Future work will focus on modifying the code to offer more discrete speed positions so that more control of speed can be offered to the user. The calibrate and reset buttons on the casing of the joystick control unit presently require pushing by an attendant, but future designs could feature more appropriate switches for limited dexterity users so that total independence can be guaranteed. Consideration to make a wireless hand band would help to reduce invasiveness to the user.

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