Collaborative Control in Human Wheelchair Interaction Reduces the Need for Dexterity in Precise Manoeuvres

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ABSTRACT

Distributing control appropriately between man and machine is particularly pertinent to assistive technology. We use shared control techniques to augment wheelchair users' capabilities, enabling them to safely perform precise manoeuvres. In this paper, we investigate the effects of our collaborative controller on the driver, in terms of how their behavioural interaction with the wheelchair changes. We apply a third order analysis to the joystick signals, to gain a better understanding of the user's interaction with our system. Consequently, we demonstrate how precise manoeuvres, such as driving through doorways, can be achieved with a reduced level of dexterity, requiring fewer corrective joystick movements. However, we note that care should be taken when designing and testing robotic assistive devices, so as not to inadvertently cause deterioration of the user's capabilities.

Categories and Subject Descriptors

I.2.8 [**Artificial Intelligence**]: Problem Solving, Control Methods and Search—*control theory, plan execution, formation and generation*; I.2.9 [**Artificial Intelligence**]: Robotics—*operator interfaces, autonomous vehicles*

General Terms

Human Factors

1. INTRODUCTION

Powered wheelchairs are increasingly being presented as a solution to the lack of independence suffered by mobility-impaired individuals. However, a significant proportion of these users find it difficult to operate their chairs reliably; this can be due to a variety of physical, perceptive or cognitive reasons [14]. Although many 'smart' systems are being developed, they have often approached the problem from a traditional mobile robotics point of view, by creating fully autonomous solutions that make optimal decisions based upon criteria such as speed and total distance of the trajectory. Conversely, shared control techniques can be used to gain relatively high-level input from the user (e.g. select the approximate desired direction) whilst using the computer to implement the low level control and maintain safety, as was done in the Wheelesley system [16].

Human robot interaction (HRI) not only refers to the device through which the user communicates with the machine, but more importantly how the system responds to such stimulus. Traditionally, powered wheelchairs have been driven with a joystick, which has proven to be an intuitive solution. Unfortunately — in order to drive both safely and effectively — this requires the user to have good reactions and steady hand-control. Some users are unable to provide this level of sustained control; consequently, alternative methods of interaction are being investigated. Preliminary work has been carried out in the fields of speech [13], gesture [9, 8] and gaze-direction recognition [11] for this application, as well as in more novel fields, such as brain-actuated control [12].

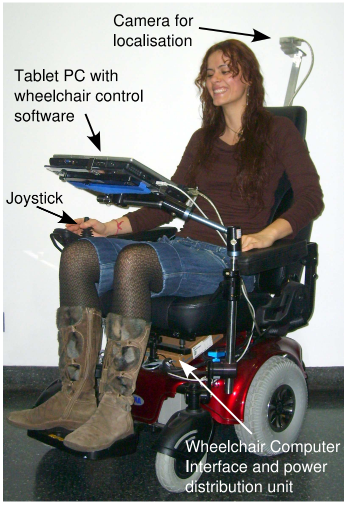


Figure 1: A participant driving our robotic wheelchair. The software on the tablet PC combines the stimulus from the joystick with the localisation data derived from the camera, to collaborate with the user in controlling the wheelchair motion.

We believe that in many cases, a more sophisticated *intelligent* controller could compensate for the lack of steady joystick control and poor reactions, if it were not only aware of its surroundings, but also of the user's higher-level intentions. Although we recognise that the aforementioned multimodal input approaches can be useful in extreme cases, most of our work has been based upon human interaction with a standard wheelchair joystick. This has been for several reasons, not least that people do not want to draw excessive attention to themselves whilst going about their activities of daily living. However, we envisage our *prediction of intent* findings may also be useful in determining the user's

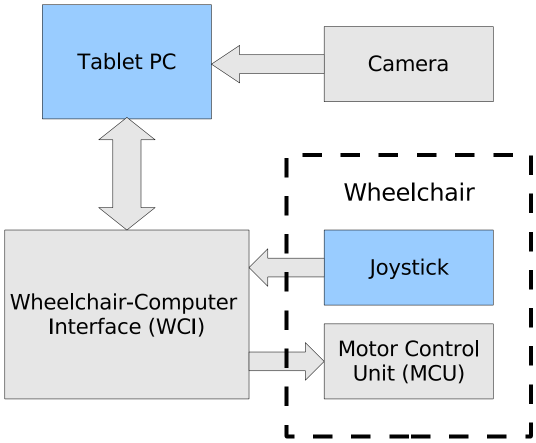


Figure 2: Our system diagram highlights the current methods of user interaction: via the joystick or the tablet PC. Joystick signals are processed before being sent to the wheelchair's MCU.

attention[1] when interacting through other media.

In this paper we briefly describe our system architecture, before giving a more detailed explanation of our approach to creating an effective collaborative controller. In previous work we have shown how the combination of intention prediction and adaptive shared control can help improve the quality of trajectories driven by powered wheelchair users [4]. Now, we take the evaluation of such an architecture a step further by investigating how the user is affected in the short-term by this dynamic assistance mode. We pay particular attention to the user's dexterity by studying the amount of joystick movement required to achieve specific tasks. Furthemore we apply a third order analysis to the joystick control signals, which yields some interesting results regarding the jerk component. We conclude that our collaborative control system drastically reduces the amount of jerk exhibited by the driver's hand; however, we note that care must be taken not to design counter-productive assistive devices. For example, if the user becomes gradually more dependent on the assistance mode, their own capabilities may deteriorate.

2. THE SYSTEM ARCHITECTURE

We have built our system upon a mid-wheel drive EPIOC (electrically powered indoor/outdoor chair), typical of the sort that might be prescribed to a severely mobility impaired patient. A tablet PC has been interfaced with both the joystick and motor control unit, as shown in Figure 1. We intercept the joystick signals and are able to alter them, where necessary, before sending them to the wheelchair's motor control unit (Figure 2). We have also developed a computer vision-based localisation system that works in mapped, indoor environments (with minimal modification of the environment), which is integrated with the collaborative controller.

[1]For example, when the user is talking, are they issuing navigational commands, or simply chatting to a friend in the corridor?

2.1 Self-localisation

To allow the wheelchair to understand what the human intends to do, it must be aware of its own surroundings and know where it is in relation to some sort of *world coordinate system*. Therefore, we will briefly describe our current self-localisation framework.

We assume, for the moment, that the wheelchair will be operating in a known, indoor, mapped environment. This simplifies the complex self-localisation problem. GPS (the Global Positioning System) requires line-of-sight to the satellites, so although it would be the natural choice for an outdoor, mapped environment, it is unsuitable for use indoors [15]. Consequently we decided to use computer vision, along with a series of fixed markers, to determine the chair's location, requiring minimal modification of the environment.

Two-dimensional, rotationally-asymmetric markers (termed fiducial's) were affixed at regular intervals on the ceiling. This prevented them from being obscured by other objects in the scene. The wheelchair was then fitted with a camera, focused directly towards the ceiling, i.e. with its z-axis perpendicular to the plane of the fiducials. The extremes of brightness (caused by the ceiling lights) were overcome by applying an adaptive Gaussian thresholding function to the images. A transformation matrix is then computed — based upon the position, size and orientation of the fiducials that have been detected in the camera's viewport — which determines the camera's position relative to each specific marker. Due to the fact that each fiducial's position is known in the *global coordinate system* and the relative placement of the camera to the wheelchair's centre is also known, we can calculate the location of the chair in the pre-mapped environment. This method was found to be accurate to within 5cm and a 2 degree heading error.

2.2 Trajectory-based Actuation

The wheelchair must know how to actuate its motors in order to reach arbitrary points on a map, if it going to be able to provide any useful navigational assistance. Given the position of the wheelchair (the current state of the system) we use the term *inverse models*, to describe the functions that generate the control commands required to reach another position (the specified target state) [6].

Our architecture consists of two primitive functions: a driving-forward model and a turning left/right model. Each of these models is constructed with a PID controller. Using this method, the control signals produced have components which are proportional to: the error; the integral of the error; and the derivative of the error. The integral (or accumulation of the error signal) increases the final spatial accuracy of the movement, whereas the derivative part provides damping, which in turn prevents oscillatory behaviour. The two error signals we use are the distance and angle to the target position from the current location of the wheelchair. Therefore, to follow a specified path, we feed the inverse models with targets, which are successive points along the desired trajectory.

3. COLLABORATIVE CONTROL

A 'smart' wheelchair must share the control appropriately between the user and the robot. Such a system should be

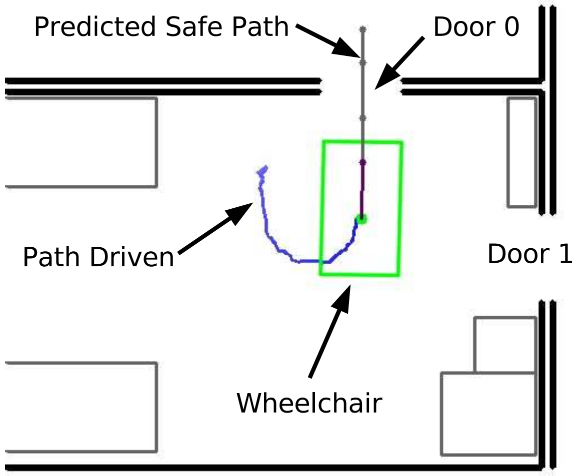


Figure 3: The wheelchair is shown at the point where the 'Door 0' confidence crosses the threshold, as shown in Figure 4. The path along which it has already travelled is plotted, along with four waypoints, which have been generated to form a safe passage through the doorway.

capable of: determining the user's intentions; verifying the desired action is safe to perform; and, where necessary, adjusting the resultant control signals, in order to reach the target position safely. We define an action to be safe, providing it does not result in an impact with another object. Evasive action must be taken if a crash looks likely and many algorithms have been presented in the field of *route planning and collision avoidance* to achieve this [10, 1, 7].

For the moment, we will explain our collaborative architecture using a cut-down example scenario, which will be expanded to a larger obstacle course in our evaluation. Initially, the user is in an uncluttered office and has the option of driving around the office, or through one of two narrow doorways; *Door 0* links to the adjoining office and *Door 1* goes into the corridor (as shown in Figure 3). The wheelchair must determine whether or not the user intends to drive through either of these doorways, and if so, guide them through the desired one, safely and efficiently. We will therefore explain how we predict the user's intentions, before investigating how best to assist them in performing the identified manoeuvre.

3.1 Prediction of Intent

Solutions to the problems of intention prediction and plan recognition are proposed in many different ways, as described in [5, 2]. The area of plan recognition can be split into two categories: *intended recognition* and *keyhole recognition*. When the user actively wants the system to understand their intentions, we use the term *intended recognition*, whereas the latter is when the system unobtrusively observes the user and tried to help accordingly. We should treat the plan inference of a 'smart' wheelchair system as *keyhole recognition*, since although the driver is actively communicating with the system — in terms of moving the chair in the desired direction — they are not trying to explain their overall goal. Applying this notion, the user is allowed to drive naturally, without the additional cognitive load of worrying whether the wheelchair understands their intentions or not.

In such an architecture, the user's actions are represented by many different inverse models, at various levels of abstraction. Between them, they predict, in parallel, the signals a human would give to perform a number of different tasks. By comparing someone's actual commands with each of the predictions, it is possible to gain a measure of confidence as to which task the person is trying to perform. These models can be arranged hierarchically, such that local predictions (for example, movement within a room) can be extrapolated towards longer term goals (for example, movement throughout the entire floor of a building).

Going back to our example scenario, the driver is able to drive through one of two doorways, or remain in the current room. Therefore, we designed a local model that represented the action *moving towards a doorway*. In this model, we defined a confidence function (Equation 1), which only increases when moving towards a target. This function is the product of two parts: the first (Equation 2) is computed using the Euclidean distance from the current wheelchair position (x, y) to the target (x_t, y_t), the second (Equation 4) is based upon the heading of the chair θ, compared with the angle to the target ϕ (Equation 3). The scaling factor of k in Equation 4 determines the sensitivity towards the angular error and in our case was set to 2.

$$C = C_d C_\theta \tag{1}$$

$$C_d = \exp\left\{-\sqrt{\{(x - x_t)^2 + (y - y_t)^2\}}\right\} \tag{2}$$

$$\phi = \tan^{-1}\left(\frac{x - x_t}{y - y_t}\right) \tag{3}$$

$$C_\theta = \exp\left\{\frac{k(\pi - |\theta - \phi|)}{\pi} - k\right\} \tag{4}$$

Exponentials were chosen as the basis functions for our confidence value, since they fall off steeply when spatial or angular errors are introduced. They also have the desirable property that the output will fall in the interval (0, 1]. The confidence values can be much more effectively compared if they are known to fall on the same interval, which is useful, since the values of each inverse model will be competing. Similarly, the winner-takes-all notion [6] can be extended by introducing an arbitrary threshold; the system will not be confident that the user is performing any of the known tasks, until this threshold has been breached. Beyond this point, we predict that the user is performing the task which exhibits the highest confidence.

The coordinates of interesting targets (in our example, the two doorways) can be stored to quickly generate several models. We experimentally set the confidence threshold C_{thresh} to be 0.2, which prevented false positives and allowed for a substantial margin of error. The clear separation between confidence values is shown in Figure 4 as the wheelchair performs the manoeuvre illustrated in Figure 3.

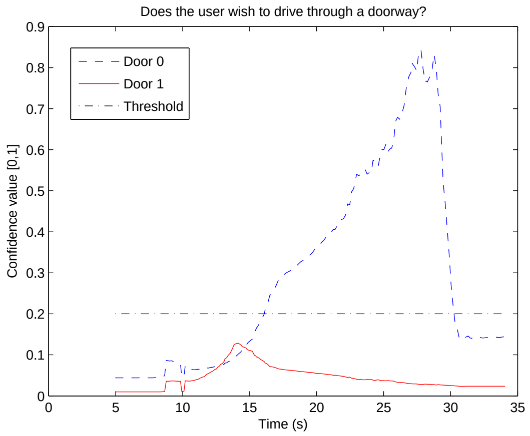


Figure 4: The confidence functions evaluated as the user drives towards, through and away from Door 0. Note the steep drop-off due to the C_θ component, once the wheelchair has passed through the door.

3.2 Adaptive Assistance

Once the system becomes very confident that a user is aiming for a specific goal, some assistance may be required, if their input begins to deviate from that prediction. However, they may have just changed their plans, in which case they may not require any further assistance; hence the need for an adaptive response rather than rigid control.

Our controller will generate a safe mini-trajectory to reach the predicted target safely, once the confidence threshold has been breached. The wheelchair is then guided gently towards the first waypoint of the *safe* path. However, we allow them to deviate from the target, if they create large joystick signals that oppose this gentle attraction. The confidence value will then fall accordingly; thus allowing them to regain full control if necessary. Conversely, we will prevent them from deviating from the safe path, once they have reached the first waypoint. However, the speed of the manoeuvre is always controlled by the user, in a manner similar to that of Zeng et al. [17], (it is proportional to the amplitude of the joystick value), whilst the direction is determined by the intelligent controller (such that the chair follows the *safe* path through the doorway). This continues until the corresponding confidence value has dropped below C_{thresh}, which happens once the chair has safely passed through the doorway. We also allow the user to reverse backwards along the safe path at any time, until the confidence value drops below C_{thresh}, at which point they revert to *normal* control. This strategy strives to make the user feel much more in control than using a rigid method, which forces you to stay on a computer-controlled path at all times.

The shared controller, which provides the adaptive assistance, uses information from the *safe mini-trajectory* generator along with the intention predictor to decide exactly how to adapt the joystick signals. An overview of the realisation of this collaborative control architecture is detailed Figure 5. It shows how the shared controller fits inbetween the joystick and the MCU (motor control unit), intercepting the user's input signals, before selecting the final target

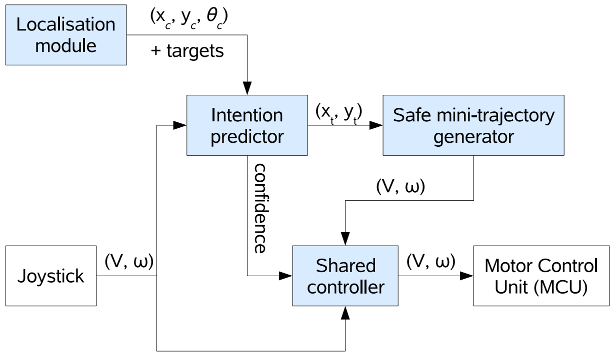


Figure 5: A diagram showing how the shared controller fits into the system. (x_c, y_c, θ_c) and (x_t, y_t) describe the wheelchair's current and target positions respectively. (V, ω) represent the target translational and rotational velocity tuple to be sent to the motor control unit.

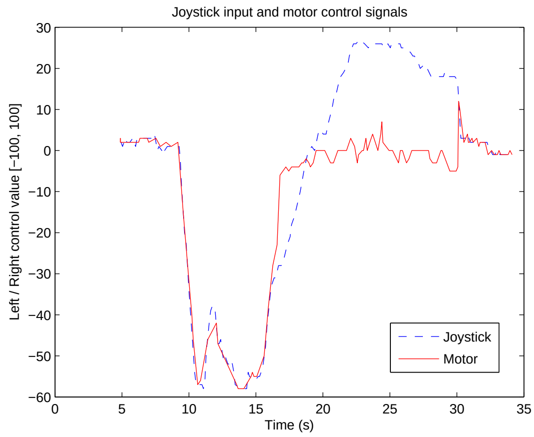


Figure 6: The steering signals sent to the motor unit are modified by the computer between 16 and 30 seconds to prevent the wheelchair from crashing into the doorframe.

velocities.

The *safe* path was defined to be a straight line, perpendicular to and equidistant from each doorframe, that extended 60cm in both directions. Figure 6 depicts typical ammendments that we have seen applied to the steering control signals. Normally, the driving signals sent to the MCU closely follow those of the joystick, as one would expect. However, when the confidence value rises above C_{thresh} in Figure 4 — the period between 16 and 30 seconds — the assisted control mode is active. This can result in significantly different target velocity signals compared with the input we obtain from the joystick. A safety limit has been imposed on the control signals sent to the MCU, which prevents the chair from accelerating rapidly and limits it's maximum speed.

4. SYSTEM EVALUATION

In our previous experiments, we have shown our collaborative control system to improve the quality of the trajectory driven by the user, in terms of reducing the deviation from the *safest*[2] path [4]. This is a vital measure, since safety is of upmost importance. However, we now investigate how the user's behaviour is affected by the shared control system. In this paper, we define the user's behaviour in terms of the way in which they interact with the joystick, to complete a specified task.

We set up a short obstacle course, which represented two adjoining rooms and a corridor alongside them (Figure 7). Each participant was asked to drive from the start, sequentially through each of the doorways (i.e. 1 and 2, then 3) to reach the finish position. To eliminate biases, the odd-numbered participants first drove the course without any assistance and then repeated the experiment with the collaborative controller active. Conversely, the even-numbered participants first drove with the help of the collaborative controller, then performed the manoeuvre unaided, using the traditional wheelchair interface.

The experimental data was obtained from a sample size of 20 participants. All were able-bodied, with an age range of 23 to 56, a mean of 33.4 and standard deviation 12.0. The majority of participants were naïve to the experiment, except for subjects four, five, nine and seventeen, who had some previous experience of driving the wheelchair around the office environment. However, none of the participants were aware of the aims of the experiment before undertaking the trials. Instead, they were instructed to perform the manoeuvre in a way that felt most comfortable and natural for them.

5. EXPERIMENTAL RESULTS

We measured the amount of joystick movement during critical manoeuvres (in this case, whilst approaching and driving through the doorways[3]). However, we were also interested in the amount of corrective movements a user had to make in order to prevent collisions. We found that these corrective movements could be characterised by the jerk component present in the joystick signals, as will be discussed in Section 5.2.

First we analyse the joystick movement, comparing the average amount required to drive through different doorways, with that used in open spaces. We will then look more specifically at how we can measure the jerk components of the joystick signals using a third order analysis of our results and interpret what this data means.

5.1 Joystick Movement Analysis

The movement is measured as the average physical speed of the joystick during the manoeuvre, in terms of a percentage of its maximum deflection range per second. Figure 8 shows the average joystick movement each test subject required in order to safely pass through each doorway. It is easier to see the patterns in Figure 9, where the mean and

[2]We define the safest path to be that which maximises the clearance between the doorframes

[3]The critical manoeuvres were identified as the cases when the confidence value for one of the aforementioned prediction models was greater than the corresponding confidence threshold

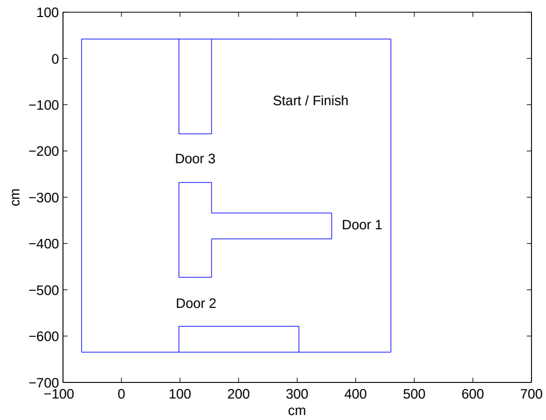


Figure 7: The obstacle course. In the experiment, the participant was asked to drive from the start, through doors 1,2 and 3 (in order) to reach the finish position.

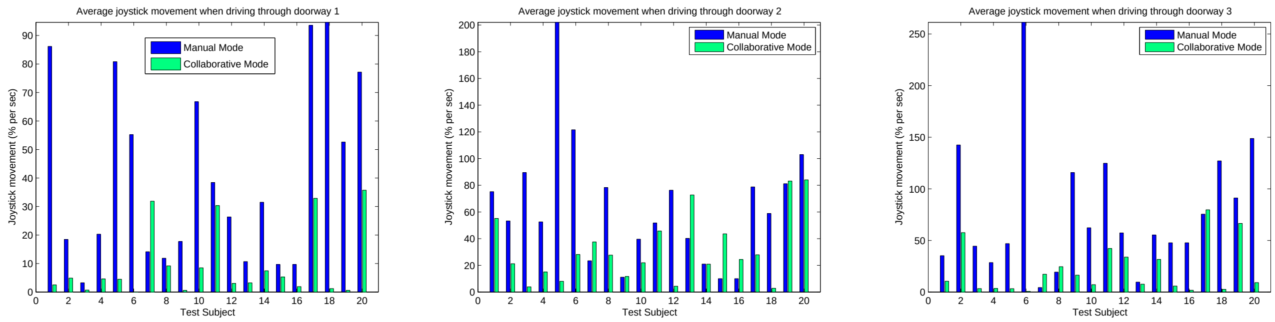
standard deviation of all trials are plotted alongside the average joystick movement exhibited elsewhere in the obstacle course (column E of Figure 9). The significance of the results was tested using a paired one-tailed t test. It is important to note that the collaborative system has no significant effect on the joystick movement elsewhere around the obstacle course, only whilst driving through the three doorways (bars 1, 2 and 3 in Figure 9, with ($p < 0.001$), ($p < 0.015$) and ($p < 0.001$) respectively).

Doors 2 and 3 required significantly more joystick movement compared with the rest of the course, when driving without any assistance. This is probably due to the users having to set up a suitable approach angle and think about how they wish to depart from the doorway. However, when the collaborative system is employed — along with its intention prediction module — the user moves the joystick significantly less to achieve the same tasks, therefore requiring less effort.

Due to the large variance in driving styles, it is important to check how often the system did reduce the required movement. From all the trials shown in Figure 8, we can deduce that this metric was improved in 81.7% of cases. The few cases where the movement actually increased under the influence of the collaborative system were most likely due to the chair taking too much control too soon. Therefore the user performed additional *corrective* movements, when the wheelchair did not respond as they expected. However, it can be seen that in the majority of cases, the collaborative system requires significantly less movement than the traditional method, to perform the same critical tasks.

5.2 Third Order Jerk Analysis

We define jerk, in line with control engineers, as the third derivative of position, i.e. the rate of change of acceleration. This is another particularly interesting phenomenon to observe, since it characterises the *smoothness* of the user's hand movements. The jerk increases with sudden corrective movements, if we can reduce the errors in the first place,



(a) (b) (c)

Figure 8: Charts (a), (b) and (c) show the average joystick movement for each test subject when driving through doors 1, 2 and 3 respectively. The movement is measured as the average physical speed of the joystick during the manoeuvre, in terms of a percentage of its maximum deflection range per second. It can be seen that in the majority of cases, the collaborative system (the second bar in each pair) exhibits much less movement than the traditional method.

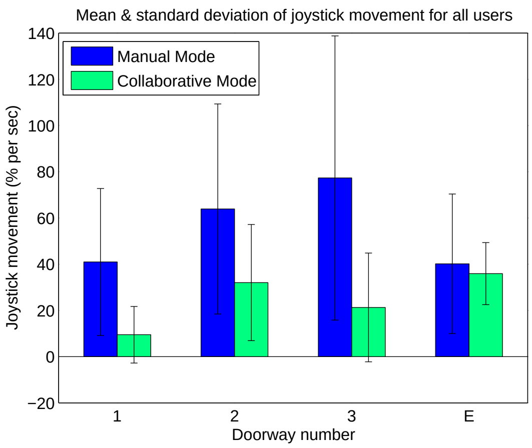


Figure 9: The average joystick movement of all the trials when driving through doors 1, 2 and 3. Column E shows the average joystick movement everywhere else in the experiment. The movement is measured as the average physical speed of the joystick during the manoeuvre, in terms of a percentage of its maximum deflection range per second.

there will be little need for the user to make such sudden movements.

Significant joystick jerk was a behaviour that was exhibited by several users — which was easily observed during the trials — when the subjects were operating the joystick like a discrete switch, rather than an analogue input device. This resulted in the chair being driven inefficiently, with the user providing large, rapidly changing target velocity signals. We hypothesise that this behaviour occurred due to the participant's incorrect perceptions of the wheelchair's forward model, as will be discussed. However, this characteristic input behaviour could be typical of users with uncontrollable spasms or limited dexterity.

Particularly important cases to note are the performance of subjects five and six in Figure 10. Subject five was a 25 year old male who regularly used a joystick to drive radio controlled cars and play video games. Similarly, subject six was a 28 year old female who considered herself experienced in joystick use for playing computer games. In both of these cases, the subjects had a pre-conceived model of how the wheelchair would behave when they moved the joystick (as they drew analogies with their previous experiences). However, the dynamics of a heavy wheelchair are much more complex and encompass relatively large delays in reaching the target velocity, compared with video games and radio controlled cars. This led the users to over-exaggerate their movements (look at the large values in Figure 8) and consequently have to make sudden corrective signals, resulting in the excessive jerk, which can be seen in Figure 10.

This jerk component was drastically reduced in 75% of the cases (Figure 10) to insignificant values when the collaborative system was used to assist the user. Once the system was aware of the user's intentions to drive out of the room, it would plot a safe mini-trajectory [3] through the appropriate doorway. The over-exaggerated user input would then be reduced by the system in an attempt to follow the safe mini-trajectory. Since this was the user's original intention, they would no longer have to provide rapid (over-)corrective movements. Therefore, a significantly smoother trajectory

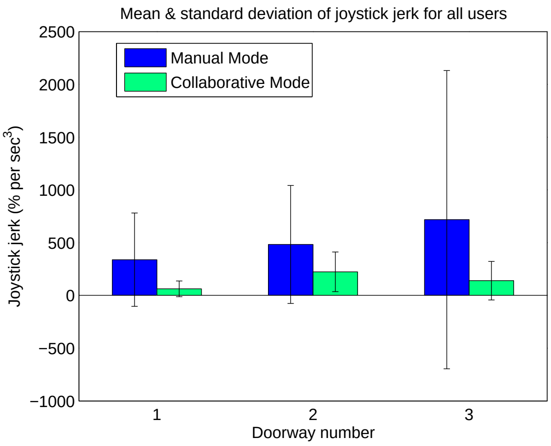


Figure 11: The average joystick jerk of all the trials when driving through doors 1, 2 and 3. The jerk is measured as the average physical rate of change of acceleration of the joystick during the manoeuvre, in terms of a percentage of its maximum deflection range per second-cubed.

resulted, requiring much less effort from the user.

There are a few occasions where the observed joystick jerk components are larger compared with the same subject's performance when using the traditional manual control (e.g. trials 13—16 through doorway 2, Figure 10(b)). After receiving feedback from the participants, we understand that this occurred when the user stopped the wheelchair because they felt they were too close to the doorway. In fact, the collaborative system *knew* there was sufficient clearance, but should perhaps be more aware of the driver's *feelings*. However, in the most part, the collaborative system reduced the wildly-varying, significant jerk experienced throughout the trials to a much more acceptable level, as can be seen in Figure 11.

6. CONCLUSIONS

This study has been concerned with wheelchair drivers' reactions to an adaptive system that attempts to assist them in performing difficult manoeuvres. Therefore, all the results that have been presented evaluate the 'performance' of the user — in terms of their dextrous movements — when using the collaborative system, compared with traditional control.

Many participants in our experiments have exhibited rapid corrective movements of the joystick, whilst attempting to perform critical manoeuvres, such as driving through doorways, or other narrow spaces. This type of behaviour is undesirable for two reasons. First, these rapid movements result in a large jerk component in the control signals, which can potentially cause harmful oscillatory behaviour in the wheelchair's trajectory. Second, the corrective nature of the movements require fast reactions from the user to prevent collisions, which demands a high level of concentration.

Instead, we attempt to prevent the wheelchair from making such mistakes in the first place. This is achieved by using a collaborative system, which predicts the user's intentions and accordingly alters the signals sent to the motor control unit where necessary. In this manner, the wheelchair assists the user to safely achieve their desired goals. As a result, the driver no longer needs to make rapid corrective joystick movements, so the trajectory the wheelchair follows becomes accordingly smoother and safer.

7. FUTURE WORK

Our platform aims to empower a person to achieve independence, enabling them to freely perform activities of daily living, thus increasing their quality of life. To date, our experiments have been carried out with able-bodied participants. Therefore, we are planning a further series of experiments, which will be undertaken by participants with neuromotor disorders. These subjects would typically be unable to use a joystick to manoeuvre safely and effectively through narrow doorways and cluttered spaces by themselves. We believe the feedback from these trials will provide the most meaningful evaluation of the system yet. Not only would we be able to record quantitative technical data, but we would also make use of the valuable qualitative feedback that such users can give.

It is important that longer term studies are carried out to ensure that our system (and indeed any other research in the field) augments the user's capacity, without undermining their capabilities. That is to say, that although the reduction in joystick movement and jerk initially seem positive factors, could this cause longer-term negative effects? Perhaps this could result in the deterioration of the user's ability to perform dextrous movements, gradually becoming more reliant on the assistive technology. In our research, we aim to avoid such deterioration of the user's inherent capabilities, by making sure maximum control is returned to them when they are not performing *safety-critical* manoeuvres, e.g. whilst they are driving in uncluttered spaces. In summary, care must be taken not to design counter-productive assistive devices.

8. ACKNOWLEDGEMENTS

The authors are extremely grateful to all those who participated in our experiments. We would also like to thank the members of the BioART team — Simon Butler, Anthony Dearden, Murilo Fernandes Martins, Matthew Johnson, Bálint Takács and Paschalis Veskos — for their helpful comments and continued support.

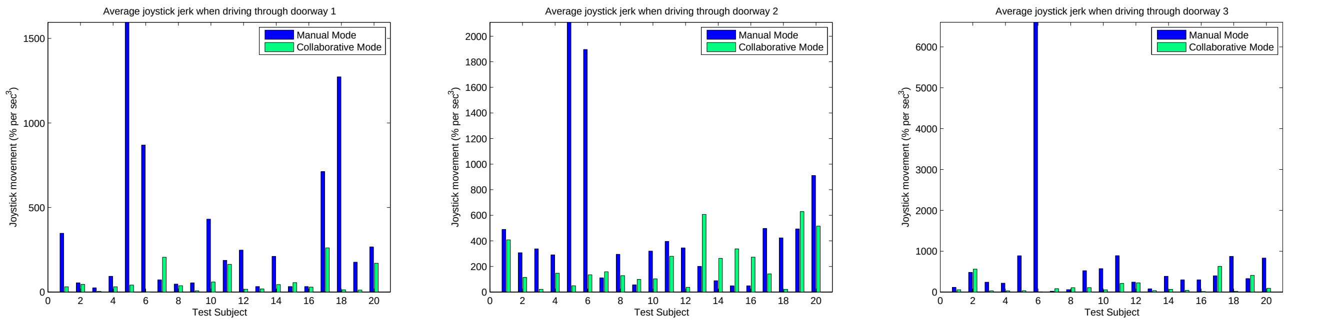
9. REFERENCES

[1] J. Borenstein and Y. Koren. The vector field histogram - fast obstacle avoidance for mobile robots. *IEEE Transactions on Robotics and Automation*, 7(3):278–288, 1991.

[2] S. Carberry. Techniques for plan recognition. *User Modeling and User-Adapted Interaction: The Journal of Personalization Research*, 11(1-2):31–48, 2001.

[3] T. Carlson and Y. Demiris. Evidence of shared control improving accuracy in human-wheelchair interaction. In *Proc. The MAIA Project Workshop 2007*, K.U. Leuven, Belgium, Nov 2007.

[4] T. Carlson and Y. Demiris. Human-wheelchair collaboration through prediction of intention and adaptive assistance. In *Proc. of IEEE International*



(a) (b) (c)

Figure 10: Charts (a), (b) and (c) show the average joystick jerk for each test subject when driving through doors 1, 2 and 3 respectively. The jerk is measured as the average physical rate of change of acceleration of the joystick during the manoeuvre, in terms of a percentage of its maximum deflection range per second-cubed.

Conference on Robotics and Automation, page (to appear), Pasadena, CA, 2008.

[5] Y. Demiris. Prediction of intent in robotics and multi-agent systems. *Cognitive Processing*, 8(3), September 2007.

[6] Y. Demiris and B. Khadhouri. Hierarchical attentive multiple models for execution and recognition of actions. *Robotics and Autonomous Systems*, 54:361–369, 2006.

[7] S. Dubowsky, F. Genot, S. Godding, H. Kozono, A. Skwersky, H. Yu, and L. Yu. Pamm - a robotic aid to the elderly for mobility assistance and monitoring. In *IEEE International Conference on Robotics and Automation*, pages 570–576, San Francisco, 2000.

[8] P. Jia, H. H. Hu, T. Lu, and K. Yuan. Head gesture recognition for hands-free control of an intelligent wheelchair. *Industrial Robot: An International Journal*, 34(1):60–68, 2007.

[9] S. Keates and P. Robinson. Gestures and multimodal input. *Behaviour and Information Technology*, 18(1):36–44, 1999.

[10] S. Levine, D. Bell, L. Jaros, R. Simpson, Y. Koren, and J. Borenstein. The navchair assistive wheelchair navigation system. *IEEE Transactions on Rehabilitation Engineering*, 7(6), 1999.

[11] Y. Matsumoto, T. Ino, and T. Ogasawara. Development of intelligent wheelchair system with face and gaze based interface. In *Proc. of 10th IEEE Int. Workshop on Robot and Human Communication (ROMAN 2001)*, pages 262–267, 2001.

[12] J. Millán, F. Renkens, J. Mouriño, and W. Gerstner. Noninvasive brain-actuated control of a mobile robot by human eeg. *IEEE Trans Biomed Eng*, 51(6):1026–1033, June 2004.

[13] R. Simpson and S. Levine. Adaptive shared control of a smart wheelchair operated by voice control. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems 2*, pages 622–626, Grenoble, France, September 1997.

[14] R. Simpson, D. Poirot, and F. Baxter. The hephaestus smart wheelchair system. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 10(2):118–122, June 2002.

[15] A. Smith, H. Balakrishnan, M. Goraczko, and N. B. Priyantha. Tracking moving devices with the cricket location system. In *2nd International Conference on Mobile Systems, Applications and Services (Mobisys 2004)*, Boston, MA, June 2004.

[16] H. A. Yanco. *Shared User-Computer Control of a Robotic Wheelchair System*. PhD thesis, Massachusetts Institute of Technology, 2000.

[17] Q. Zeng, E. Burdet, B. Rebsamen, and C. L. Teo. Evaluation of the collaborative wheelchair assistant system. In *IEEE Conference on Rehabilitation Robotics*, The Netherlands, June 2007.