Towards Early Mobility Independence: An Intelligent Paediatric Wheelchair with Case Studies

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***Abstract*—Standard powered wheelchairs are still heavily dependent on the cognitive capabilities of users. Unfortunately, this excludes disabled users who lack the required problem-solving and spatial skills, particularly young children. For these children to be denied powered mobility is a crucial set-back; exploration is important for their cognitive, emotional and psychosocial development. In this paper, we present a *safer* paediatric wheelchair: the Assistive Robot Transport for Youngsters (ARTY). The fundamental goal of this research is to provide a key-enabling technology to young children who would otherwise be unable to navigate independently in their environment. In addition to the technical details of our smart wheelchair, we present user-trials with able-bodied individuals as well as one 5-year-old child with special needs. ARTY promises to provide young children with "early access" to the path towards mobility independence.**

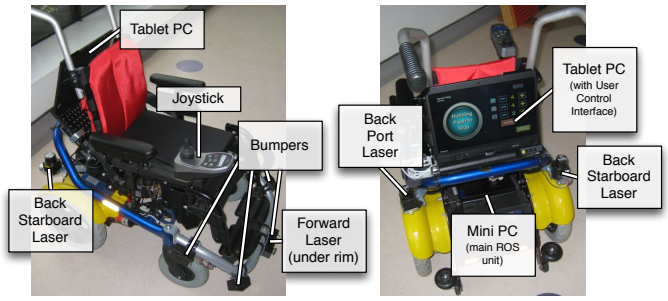


Fig. 1. The Assistive Robotic Transport for Youngsters (ARTY) Smart Wheelchair.

I. Introduction

Nicholson and Bonsalls 2002 survey of 193 wheelchair services [1] showed that 51% of the respondents did not supply wheelchairs to children under 5 years. The top two reasons cited were safety of the child (36%) and safety of others (34%). Although safety is clearly an important factor, for these children to lose independent mobility is a crucial set-back at a critical age. Mobility loss spawns a vicious cycle: the lack of mobility inhibits cognitive, emotional and social development, which in turn further limits personal independence [2], [3], [4]. Ultimately, this results in a severe long-term deterioration in a child's quality of life.

In our research, we aim to break this cycle by providing a key-enabling technology: a *safe*, intelligent paediatric wheelchair. In contrast to traditional assumptions, powered mobility can be made safe, for the child and others. Risks can be mitigated through the use of robotic technology and shared control systems [5], [6], [7], [8], [9]. Safe powered mobility can improve social, emotional and intellectual behaviour [10] and has the potential to drastically change lives.

This paper details our prototype intelligent pediatric wheelchair: the Assistive Robot Transport for Youngsters (ARTY), shown in Fig 1. ARTY promises to provide an independent lifestyle for disabled children, a training implement for therapists and also an experimental platform for scientists. A core aspect of our work is that we seek to bring our prototype wheelchair into the field at an early design stage. In this paper, we describe a case-study involving able-bodied children comparing two different shared control mechanisms. We also present one case study involving a young 5-year boy with special needs, who was considered by healthcare professionals not yet appropriate for a *regular* powered wheelchair.

In the following section, we provide a review of powered mobility for children and research on smart children's wheelchairs. In Section III, we present technical details on our ARTY. Section IV discusses our hybridised shared-control algorithm. This is followed by Sections V and VI which details our experimental findings with child participants. Finally, Section VII presents conclusions and discusses our planned future work.

II. Background

In this section, we review the current state of powered mobility for children and recent research on smart paediatric wheelchairs.

A. Powered Wheelchairs for Young Children

In his 1987 paper, Hays [11] identified four categories of children who could benefit from powered mobility: those who will never walk, those who cannot efficiently move in a walker or manual wheelchair, those who lose their mobility due to traumatic injury or neuromuscular disorder and those who require temporary assistance (such as after surgery). In the UK alone, there are more than 50,000 disabled children who fall under this category and require mobility assistance [12]. Despite the provision difficulties stated in the introduction,

powered mobility advocates consider mobility "an essential component of a child's early intervention program" [13], [14], [15].

A survey of 1200 members of the National Association of Paediatric Occupational Therapists (NAPOT) [16] summarised the key features that an ideal young children's wheelchair should possess. For example, the wheelchair should have a "fun" appearance (such that it appears to be a plaything) and the ability to be a training aid in early stages. It should be adaptable so that it could be used by children with different disabilities, i.e, accommodate different seating systems and a wide variety of control options (e.g., joystick, sip and puff). A subsequent survey carried out by the charity Whizz-Kidz concluded that no commercial powered wheelchair met these specifications and significant improvements were necessary before commercial systems meet the needs of many disabled children and their caregivers.

B. Smart Paediatric Wheelchairs

Research on smart wheelchairs has grown over the past two decades, fuelled in part by the recognition that standard powered wheelchairs are lacking in many respects. A recent analysis by Simpson [17] showed that 61-91% of all wheelchair users would benefit from a smart wheelchair (approximately 1.4 to 2.1 million people). Early work in (adult) smart wheelchairs [18] include MITs Wheelesley [19], the TAO wheelchairs [20], Tin Man II [21] and NavChair [22], with more recent prototypes developed by research teams around the world [23], [24], [25], including the Personal Robotics Lab at Imperial College [8], [6]. For a more complete review of adult smart wheelchairs, we refer readers to comprehensive surveys in [26], [9].

Of interest to us are smart *paediatric* wheelchairs, a subtype of intelligent wheelchairs that have garnered far less attention. Early seminal work in the area was performed by the Communication Aids for Language and Learning (CALL) Centre at the University of Edinburgh [4]. They reported that the introduction of twelve smart wheelchairs to three special schools encouraged motivation and developmental improvements in ten disabled participants [27]. In fact, most of the children experienced significant improvements in mobility and psychosocial traits. There currently exist two commercial systems based on the CALL Center Smart Wheelchair: the "Smart Wheelchair" and the "Smart Box" (both distributed by Smile Rehab Ltd.) [9]. However, the Smart Wheelchair is expensive (USD 14,000) and is only capable of rudimentary abilities (bump and stop/backup/turn, line following). The cheaper Smart Box (USD 5,000) was designed to be fitted onto a standard wheelchair to provide similar capabilities to the Smart Wheelchair.

The falling cost of sensors and computational power has resulted in the incorporation of more sophisticated sensing devices and algorithms than the CALL Centre wheelchair (which was equipped with bump and sonar sensors). Recent smart childrens wheelchairs use infra-red (IR) rangers, vision-based methods, shared-control algorithms and obstacle-avoidance algorithms for semi/fully-autonomous navigation [28], [29], [30], [31]. Moreover, researchers have begun incorporating the use of haptic devices to train children, with the goal of supplementing or possibly replacing the hand-over-hand method currently employed in rehabilitation centers. One noteworthy paper by Marchal-Crespo, Furumasu and Reinkensmeyer [28] discussed the use of fading haptic guidance. Their study concluded that their system, RO-bot-assisted Learning for Young drivers (ROLY), improved the steering ability of twenty-two able-bodied children and one disabled child with cerebral palsy.

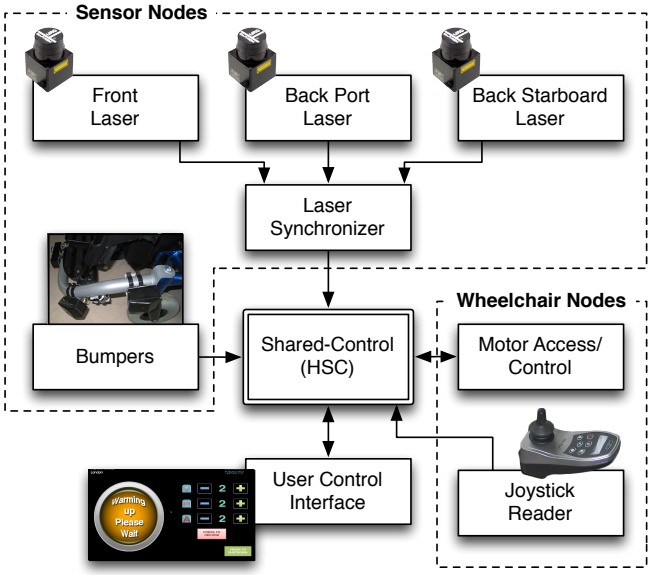


Fig. 2. Schematic of Software Components (ROS Nodes)

Despite remarkable technological progress, we found a lack of structured clinical trials with disabled users. A notable exception is the PALMA project where Ceres *et al.* [29] performed a small-scale clinical study of their robotic wheelchair involving five children with severe mobility impairments and reduced motor control. Experiments with end-users are challenging for many reasons. For example, the CALL Center wheelchair was not a single entity but multiple variants had to be designed (to accommodate different users) [27]. That said, research needs to move beyond laboratory settings with able-bodied children to real-world locations (such as rehabilitation centers) with end-users to be relevant; this is one challenge that requires significant effort, without which, limits smart wheelchairs from gaining widespread acceptance [7].

III. ARTY SMART WHEELCHAIR

Our proposed smart paediatric wheelchair, Assistive Robotic Transport for Youngsters (ARTY), was designed to enable more children to benefit from independent mobility. In this section, we detail ARTY's hardware and software components.

A. Base Wheelchair

The base wheelchair is the Skippi, an electronic powered indoor/outdoor chair (EPIOC) designed specifically for children. We chose the Skippi as our base unit because it fulfilled some of the requirements identified by Orpwood's study [16]; in addition to working both indoors and outdoors (maximum speed of 6 km/h and a maximum range of 30 km), the Skippi is colourful, easily transportable, has adjustable seats, is relatively lightweight, has batteries that last for more than a day and was not prohibitively expensive.

An attractive feature was that Skippi uses a controller-area network (CAN) based electronic system. CAN is a message-based protocol originally designed for automotive systems but is now used in a variety of devices from powered wheelchairs to the iCub humanoid robot [32]. All interacting modules (e.g., joystick, motor system) on the wheelchair are identified as CAN nodes and exchange information via messages. Our "smart" components interface with the base-wheelchair via the CAN network.

B. Sensors and Computational Units

To sense its environment, ARTY is equipped with three Hokuyo URG-04LX laser scanners and five bump sensors. These sensors are connected via USB to a mini-PC powered by an Atom processor. This "lower-level" unit is responsible for integrating sensory information. Higher-level path planning and obstacle avoidance is performed by a Tablet PC connected via Ethernet. Splitting the processing tasks allowed us to decrease response time (since the tablet PC had higher computational capability) and to accommodate future expansion. The tablet-PC also presents a more natural touch-interface for users to change the wheelchair's basic settings.

C. Software System

ARTY's software system (high-level schematic shown in Fig. 2) was developed using the Robot Operating System (ROS) [33], an open-source, thin, robotic platform that supports distributed processing.

In our system, each sensor is managed by its own ROS node running on the mini-PC. Since ARTY has three lasers, it was necessary to synchronise them to obtain a coherent obstacle map. Communication with the base wheelchair is the responsibility of two interface nodes: the motor access/control (MAC) node and the joystick reader. Both nodes perform the necessary translations from CAN messages to desired commands velocities and vice-versa. In addition, the MAC node provides odometry information for mapping/localisation. The user interface node on the Tablet PC provides a simple means of turning on/off the wheelchair and changing basic settings such as the maximum translational and rotational velocities.

Finally, a primary component of our system is the shared-control node which modulates the user's control commands to avoid collisions. It provides three basic shared-control levels: basic (no modulation), safeguarding and finally, assisted control. Details on our shared-control method are described in the next section.

IV. Shared-Control

For this work, we used a hybrid shared-control (HSC) method that combines the merits of the Combined Vector Field (CVF) [34] (a variant of the Vector Field Histogram (VFH) [35] for non-point robots) and the Dynamic Window Approach (DWA) [36]. Both algorithms are widely-known in robot navigation and collaborative versions have been used in smart wheelchairs such as Sharioto [37], our adult wheelchair [8] and the Bremen Autonomous Wheelchair Roland III [38]. Both methods are well covered in the literature and we refer readers to [34][36] for details. In this the following subsections, we give an overview of HSC.

A. Obstacle Map

Shared-control methods, including HSC, rely on an obstacle map (OM); a representation of potential obstacles in the environment [39]. Building an OM is equivalent to estimating the posterior probability over possible maps m given the observations z and robot poses x thus far, i.e., $p(m|z_{1:t}, x_{1:t})$.

However, this is too computationally expensive to execute in real-time and as such, the problem is usually simplified in three ways. First, the problem is reduced from three-dimensions to two (so, we have a slice instead of a volume). Second, each cell of the map, m_i, is considered as independent and as such, $p(m|z_{1:t}, x_{1:t}) = \prod p(m_i|z_{1:t}, x_{1:t})$. Finally, instead of using a true probabilistic model of the sensor sensor data, we resort to a simple binary model; $p(m_i|z_{1:t}, x_{1:t}) = 1$ if the sensor reports a hit at m_i and clear, $p(m_i|z_{1:t}, x_{1:t}) = 0$, if no hit is reported or the cell is in the sensor's line of sight between the robot and a detected obstacle.

In our work, instead of resorting to a grid of cells representation, we used a KD-tree which conferred quick rectangular range searches (on the order of $O(\sqrt{n} + m)$ where n is the number of obstacles in the tree and m is the number of reported points). This also permitted us to store obstacle locations with greater precision compared to the cell-grid (which requires a pre-set resolution).

B. Hybrid Shared Control

In initial versions of ARTY, we have used either VFH *or* DWA. Both presented problems. VFH is computationally low-cost but unfortunately, difficult to tune (particularly since our wheelchair is rectangular and non-holonomic). Furthermore, the relationship between VFH parameters and behaviour was not always obvious, making it difficult to assure ourselves that the method would work in non-tested situations.

On the other hand, DWA, which incorporates the wheelchair's shape and dynamics, was easier to tune and provided greater assurance, but required far greater computation time; the projections and obstacle collision prevention for non-circular robots requires many point-in-polygon checks.

To overcome these limitations, our hybrid approach (HSC) uses CVF to provide an approximate solution, which is refined

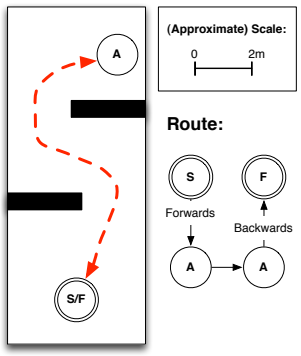
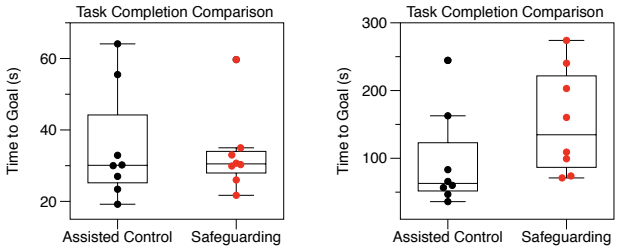


Fig. 3. Obstacle Course for Forwards and Backwards Driving Task (with able-bodied children).



(a) Forwards Driving Task (b) Backwards Driving Task

Fig. 4. Task-completion times for the forwards and backwards driving portion of the task.

using (limited) DWA. The idea is straight-forward: we first project forwards in time using the robot's dynamics (using motion equations) and check for future collisions. If there are none, the user's command velocity is left unchanged. However, if a future collision is predicted, we use CVF to generate the principal steering direction, which is then converted into a control velocity. Instead of sending this directly to the motors, we further refine this control by considering *scaled* command velocities. In this work, we generated 11 commands where the scale α was varied from 0 to 1 (inclusive) with 0.1 step size. DWA was then used to search through this space for the optimal solution (and provide assurance that command velocity did not result in a collision). Note that if all the command velocities result in a collision, the default command is zero.

There are three shared-control modes: basic, safeguarding and assisted. For the assisted control mode, HSC is applied. For the safeguarding mode, CVF is not used; instead, the scaled command velocities are generated directly from the user's control velocities. Early tests showed us that HSC achieves a fast response time (15Hz-20Hz) on our hardware while still providing a smooth driving experience for the user.

V. Case Study with Able-bodied Participants

In this case-study, we sought to compare the safeguarding and assisted control modes described in the previous section. Recall that the assisted mode is more intrusive, modulating the user's control to avoid obstacles, and not merely prevent

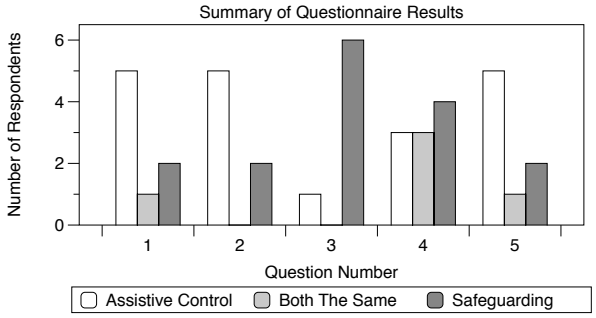


Fig. 5. Summary of Post-trial Questionnaire Results. The bars indicate how many of the respondents indicated higher agreement for each of the modes. Overall, responses for the assisted control was more positive compared to safeguarding.

collisions (which safeguarding accomplishes by reducing the scale of the user's command). Previous studies have performed similar comparisons with adults but our experiment was conducted with child participants.

A. Experimental Setup

We set up the obstacle course shown in Fig. 3 where the task was to drive through the course as quickly as possible — straightforward but with one small complication. Because early trials indicated that forwards driving is relatively easy for able-bodied children, we instructed the participants to drive normally from the start position (S) to the half-way point (A) but *backwards* from A to the finish point (F).

Each child drove through the obstacle course twice, i.e., two *runs* (one for each mode). The mode order was randomised and the participants were not told which mode came first. After each run, they were given a questionnaire (under supervision) asking them how much they agreed with each of the following statements on a five point Likert scale (1 = strongly disagree, 5 = strongly agree):

1) The wheelchair was easy to manoeuvre.
2) The wheelchair behaved as I expected.
3) I had to concentrate hard to drive the wheelchair.
4) It felt natural driving the wheelchair.
5) The obstacle course was easy.

Additionally, after completing both runs, they were asked which run they preferred overall.

B. Results and Discussion

Eight children (aged 11 years) participated in our experiment. As Fig. 4 shows, the children completed the first portion of the task (forwards from S to A) significantly faster than the second portion (backwards from A to F). When using safeguarding, they took an average of 4.3 times longer to complete the backwards segment compared to 2.1 times when using assisted control.

Assisted control did not have a measurable positive effect over safeguarding on the simpler forwards driving portion, but it reduced the time needed to complete the backwards driving segment by an average of 62.9 seconds. This difference

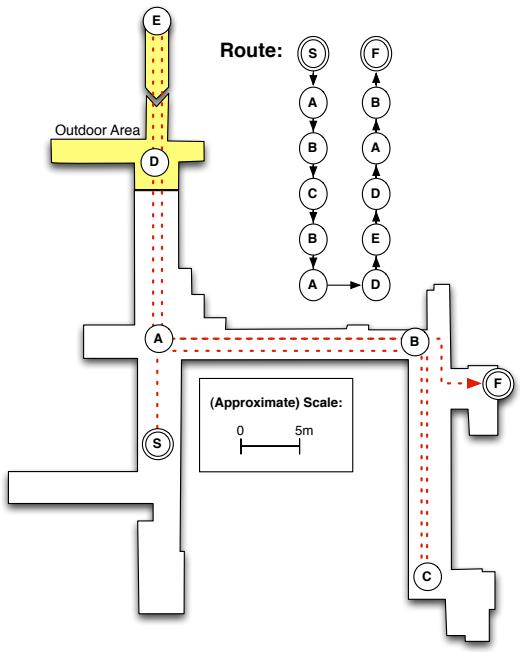
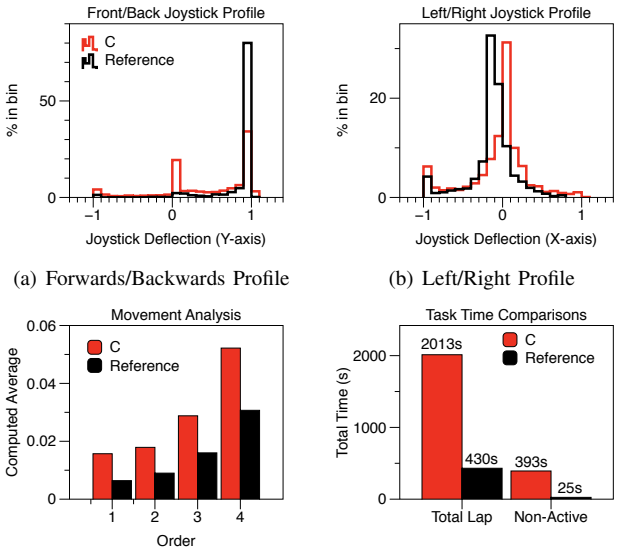


Fig. 6. Experimental Area and C's Driving Route.



(a) Forwards/Backwards Profile (b) Left/Right Profile

(c) Movement Analysis (d) Task Time Analysis

Fig. 7. Analysis of the data collected during C's session.

is statistically significant ($p \approx 0.02$). When asked, seven of the eight children preferred assisted control. This choice is supported by the individual questionnaire results (Fig. 5); the five of the eight participants found ARTY under assisted control to be easier to manoeuvre and behaved more as they expected.

However, it should be noted that not all the participants appreciated the extra assistance. Turning our attention to the one child who preferred safeguarding over assisted control, we postulate that the assisted control caused him confusion when the algorithm changed his control "too much". When the wheelchair swerved to avoid an obstacle, he stopped completely or issued fast "corrective" movements. One research topic of interest for us is detecting and providing the *appropriate* level of assisted control to accommodate such users [3].

Notwithstanding the fact that more confirmatory studies are needed, these results suggest that assisted control is preferable to safeguarding for most children. Based on this conclusion, we used assisted control in the following case study involving a young child with special needs.

VI. Case Study: C, a 5-year old boy with special needs

In this section, we report on a trial-run with C, a five-year old boy with both physical and cognitive disabilities[1]. Because of his age and condition (reduced inhibition and increased impulsiveness), C was considered by his occupational therapist (OT) to be *not yet ready* for a *regular* powered wheelchair. It was his OT's hope that ARTY would allow C to increase the amount of sensory feedback he would gain with movement while remaining safe and calm.

The experiment took place at the rehabilitation center where C is currently a patient (map shown in Fig. 6). Before the start of the trial, C's OT gave him a short introduction to ARTY and told about how it worked. Since this was his first try, the wheelchair was set to a relatively low maximum velocity (0.4m/s translational and 0.4rads/s rotational). Assisted control was used throughout (except in special cases detailed below). Throughout the session, C was allowed the opportunity to freely explore while his OTs provided directional cues and supervision. Data (including sensor readings, joystick movements and assisted controls) was logged at 20Hz. After C's session, an expert driver drove the wheelchair along a similar route to provide a *reference dataset* for comparison.

A. Results and Discussion

In general, we observed that C remained calm and interested while driving ARTY. The driving portion of the session lasted 33.4 minutes and the route taken consisted of both indoor and outdoor areas, as shown in Fig. 6.

To travel the same approximate route took the expert driver 7 minutes. This difference is large but not surprising; the goal of this session was to explore rather to race. Along the route, C interacted with objects and engaged with his friends. Comparing the actual distance travelled (reported by ARTY's odometry), C drove 213m; 44m (20%) more than the reference. In addition, his *non-active* driving time (defined as any contiguous time segment with no joystick input exceeding 5 seconds) was 20% of his total time (See Fig. 7(d)), larger than the expert's 6% (25s)[2]. For the following analyses, the non-active segments were removed to avoid non-informative zero-centred peaks in the obtained distributions.

[1]Informed consent was obtained from C's mother before the session.

[2]The expert driver had to stop and wait at times for passer-bys to cross.

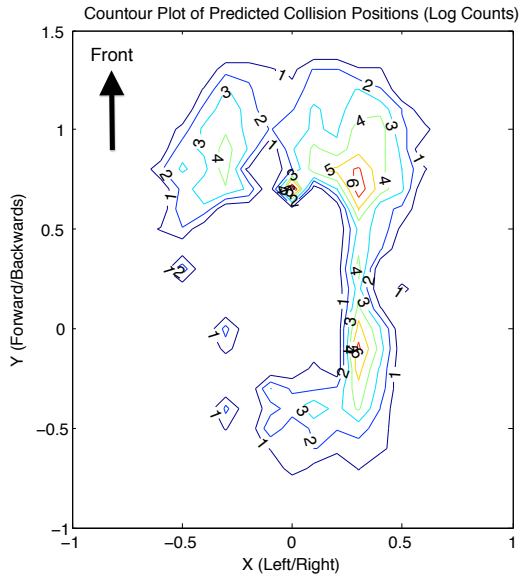
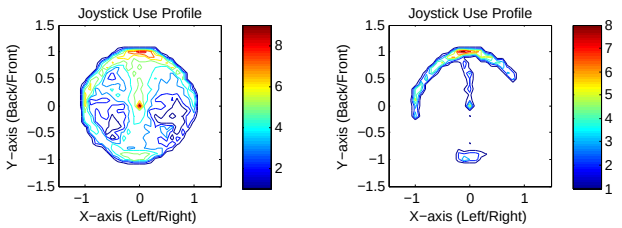


Fig. 8. Predicted Crash Positions. Note that the wheelchair is centred at (0,0) and most of the predicted crash positions occurred in the front area of the wheelchair and on the right-hand side. This was consistent with our observations during the session.



(a) C (b) Reference

Fig. 9. Joystick Profiles for C and the expert driver. The contours indicate log frequencies of the joystick positions during the driving sessions. Best viewed in colour.

During the session, we observed C had a right-side bias when operating the joystick; this is clear when comparing C's x-axis joystick distribution against the reference (Fig. 7(b)). Furthermore, a majority of the predicted (and avoided) collisions were on the right-side of the wheelchair (Fig. 8).

This right-side bias would also often lead C very close to walls and into situations where he would get stuck in a corner. In these cases, after giving C an opportunity to manoeuvre his way out, his OT provided assistance. However, because of the position C would get stuck in, we noted that it was difficult for the OT to control the wheelchair (since she had to stand on the left side of the wheelchair while the wall and joystick were on the right) and we had to disable shared-control briefly using the tablet PC. To avoid similar difficulties in future sessions, we plan to provide the OT with a simple hand-held remote control to toggle shared-control.

Taking a closer look at C's joystick use, we observed his joystick position distribution (Fig. 9), to be broader compared to the expert. A possible reason was that C, being unfamiliar with driving wheelchairs, more actively explored the joystick space. Another contributing factor was that whenever C got stuck, he would engage in random joystick motions in an attempt to "get free". We also noted that during 180 degree turns, he would always turn counter-clockwise, leading to the higher frequency on the far-left side of the distribution (Fig. 7(b)).

To better understand C's control capabilities, we computed the average first through fourth difference orders on the joystick movement data. This is akin to the velocity, acceleration, jerk and snap of the motion (but without the division by time). As Fig. 7(c) shows, movements were more rapid and jerky compared to the expert; for adults, quick motions are an indication of inexperience with the joystick since rapid movements typically indicate quick corrective movements [8].

Overall, his OTs considered C's session with ARTY to be a success; C drove safely around his environment (both indoors and outdoors). Moreover, C's experience with ARTY was his *first* experience driving a powered wheelchair. Under normal circumstances, he would not have been allowed to drive a wheelchair until he was older. ARTY provided him with early access to the path towards mobility independence and it is expected that C will participate in future sessions.

VII. Conclusions and Future Work

In this paper, we reviewed the current state of research on smart paediatric wheelchairs and presented ARTY, our contribution to the field. In addition, we provided two case studies; the first involving eight able-bodied children who demonstrated the benefits of our shared-control method. The second involved C, a five-year old boy with both physical and cognitive disabilities. Although it was C's first time in a powered wheelchair, he drove ARTY for more than 30 minutes and engaged with objects and people in his environment.

Moving forward, we plan to continue to work closely with our healthcare colleagues at the children's rehabilitation center to provide C with more sessions with ARTY in order to improve his well-being in the process. As we begin to conduct more studies with children with disabilities, we believe it is necessary to further develop smart wheelchair interaction/experimental methodologies as well as analytical tools. We are currently working on metrics to provide occupational therapists with quantitative measures of wheelchair driving performance.

Finally, we consider our case-study with C to be an important milestone: a proof-of-concept demonstrating the feasibility of using smart wheelchairs in rehabilitation centres to provide young children with early access to independent mobility.

Acknowledgement

The authors thank Raquel Ros Espinoza, Yan Wu, Arturo Ribes, Miguel Sarabia, Kyu Hwa Lee, Carolyn Dunford, Claire Hall and Michelle Holmes for their assistance in conducting the experiments. Harold Soh is supported by a Khazanah Global Scholarship. This work has been partially funded by the EU FP7 ALIZ-E project (grant 248116).

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