

Smart Wheelchairs: Using Robotics to Bridge the Gap between Prototypes and Cost-effective Set-ups

Matthew Aquilina^a, Marvin K. Bugeja^b and Simon G. Fabri^c

Department of Systems and Control Engineering, University of Malta, Msida, MSD 2080, Malta

Keywords: Smart Wheelchair, Assistive Technology, ROS, Autonomous Navigation, Mapping, Electronic Hardware Design.

Abstract: Wheelchairs have improved the lives of many people with limited mobility. Yet, to this day, conventional wheelchairs are still not a viable option for mobility independence in cases of people with severe weakness or poor coordination e.g. Amyotrophic Lateral Sclerosis (ALS). Smart wheelchairs (SWs) overcome many of these limitations by adding an extra layer of intelligence to the system. SWs have so far remained mostly inaccessible to the general public, due to a limited market presence and steep costs. This paper thus presents the design and implementation of a novel SW which makes the upgrade of a commercially available motorised wheelchair to a SW a much simpler process. The system is a complete implementation offering low-level hardware control, a specialised ROS architecture and autonomous navigation algorithms allowing shared user control or fully-autonomous movement. Contrary to most other published works, the focus of this paper is to implement a fully-featured working prototype with minimal hardware complexity and an efficient modular software development environment. Initial practical tests in typical use scenarios showcased the successful operation of the complete system. The developed prototype SW has the potential to restore autonomy to people who are unable to use conventional or powered wheelchairs.

1 INTRODUCTION

Wheelchairs have been around since the 17th century. Initially, these models all required the user or a carer to manually propel the wheelchair. Designs for Powered Wheelchairs (PWs) appeared in the early 20th century. PWs allow the user to control movement of the motorised wheelchair through a joystick. PWs and the more conventional manual wheelchairs are the most popular kinds of wheelchairs in use today (Simpson et al., 2008).

Conventional PWs provide mobility to many people with special needs or to those who cannot walk unaided. However, people with severe weakness who cannot direct a joystick (e.g. individuals with ALS) or people with very poor coordination (e.g. Cerebral Palsy) cannot use PWs (Simpson et al., 2008). Persons in such a situation often end up dependent on others to propel their wheelchair.

The concept of a Smart Wheelchair (SW) started

taking shape in the 1980s (Simpson, 2005). A SW is an upgraded form of PW to which a number of sensors and computing units are attached to enable semi-autonomous or autonomous modes of operation (Leaman and La, 2017). The SW operates via navigation algorithms, such as those for path-planning and obstacle avoidance, to achieve autonomous and safe mobility. These systems, coupled with some simple input mechanisms (such as a touchscreen or voice command) can compensate for a user's lack of coordination or weakness. SW technology has progressed greatly worldwide, with designs consisting of multiple sensors and complex algorithms. However, despite many sophisticated models being developed, practically none of them have made it to the commercial market (Leaman and La, 2017).

This paper aims to challenge this state of affairs by presenting a novel and inexpensive design methodology by which a standard commercially available PW could be upgraded to SW level, both in technology and in autonomy. The hardware used is easily accessible, and all software is coded using open-source frameworks. To demonstrate its applicability, a SW platform was designed and retrofitted on top of a sim-

^a <https://orcid.org/0000-0002-4039-1398>

^b <https://orcid.org/0000-0001-6632-2369>

^c <https://orcid.org/0000-0002-6546-4362>

ple and inexpensive PW available on the market, the process of which is detailed in this paper. Both semi-autonomous and fully-autonomous navigation algorithms were deployed successfully on this prototype, demonstrating the capabilities of the build.

The paper is organised in the following manner. Section 2 contains a brief review of related work in the literature. Section 3 details the process followed to upgrade the hardware systems to SW level starting from the standard PW frame. Section 4 builds on Section 3 by going into further detail on the supporting software infrastructure. Section 5 expands on the navigation algorithms, and Section 6 details and discusses the results obtained, followed by conclusions in Section 7.

2 RELATED WORK

Generally, SWs in development fall into one of two categories: navigation aids or fully-autonomous vehicles. Both use similar sensors and hardware to achieve their aims; the difference lies in the software and algorithms they use.

2.1 Wheelchairs with Navigation Aids

Wheelchairs with navigation aids aim to enhance the user's mobility without completely ignoring the user's input when navigating. One of the oldest and most well-developed examples is the NavChair (Levine et al., 1999). This chair could use its on-board Vector Field Histograms (VFH) (Borenstein and Koren, 1991) and Virtual Force Field (VFF) (Borenstein and Koren, 1989) obstacle avoidance methods to guide the wheelchair in the general direction the user indicates through a joystick. Similarly, Carlson and Demiris (2012) present another study where the wheelchair acts to help a user reach a destination inferred through a joystick. This system uses a camera localisation system, laser rangefinder and ultrasonic sensors, resulting in a much better picture of the environment than that obtained through ultrasonic sensors alone. Many other systems (Nasri et al., 2016; Leaman et al., 2016; Cavanini et al., 2014) have been developed with features designed to complement a user's guiding input. However, all of these studies typically have one or more obstructive hardware limitations, such as dependence on a laptop rather than an embedded PC, a prohibitively expensive sensor suite or the requirement of a specific wheelchair brand for the software to operate.

2.2 Autonomous Wheelchairs

Fully-autonomous SWs depend almost completely on their software and sensory systems for navigation. Some SWs, such as in Echegu et al. (2017), plan paths in advance on a map using planners such as the A* (Hart et al., 1968) or D*Lite (Koenig and Likhachev, 2002) algorithms. With the plan complete, the wheelchair is guided through the path, using a local obstacle avoidance algorithm (such as VFH (Borenstein and Koren, 1991) or Dynamic Window Approach (DWA) (Fox et al., 1995)) to navigate obstacles unmarked on the map. Others, such as Kinpara et al. (2011), navigate by following a designated carer or group of carers. This is made possible through a complicated system of laser rangefinders and a camera acting as people/group detectors. Additionally, fully-autonomous modes can be used to enhance maps with more in-detail features. Hemachandra et al. (2011) achieve this through a SW which follows a tour guide and draws up a map using laser rangefinders, whilst also tagging different rooms with information it infers through listening to the tour guide. Generally, such advanced features require a larger sensor suite, resulting in a more complicated or expensive design.

In this project, both navigation aid and autonomous functionalities were implemented onto the wheelchair. A combination of the VFH+ (Ulrich and Borenstein, 1998) and A* (Hart et al., 1968) path planners were utilised to achieve these functions. A laser rangefinder was used as the primary method of obstacle detection, complemented by a set of ultrasonic sensors. Navigation was managed through wheel encoders for both localisation and closed-loop speed control. By keeping the sensor suite small, the developed SW retains a similar footprint to its original PW design, whilst providing enough information about the environment to navigate safely. The developed software is implemented using an ROS (ROS, nd) backbone, keeping the system lean, modular and efficient whilst providing an easy-to-use Python development environment.

3 TECHNICAL HARDWARE DESIGN

One of the main hindrances to SW adoption is the difficulty of mounting the required technology onto a standard powered wheelchair frame. This section provides an overview of the procedure adopted to efficiently upgrade our PW to a SW.

3.1 Powered Wheelchair Upgrade

The Surace 715 Magic (Figure 1) was selected as the PW base (Surace, nd). This wheelchair came with two 24V geared DC motors along with a battery pack, motors driver and a joystick. The controller electronics were closed-source and had to be removed completely, leaving only the motors and battery to be used by the SW. This situation also applies to the vast majority of standard PWs that are available commercially.

3.2 System Architecture

The architecture of the new system installed on the wheelchair is shown in the block diagram of Figure 2.

3.2.1 Computer and Motor Controller System

A computer was placed on board the wheelchair, in order to act as the central communication point whilst executing algorithms. A compromise needed to be achieved between size and processing capability/speed. The Intel NUC mini PC (Intel, nd) offered the best balance. These PCs are available with a range of options, allowing one to either prioritise on extra capability or a lower budget.

Communicating data to and from the computer was facilitated through the use of USB ports. Thus, the motor controller selected for the SW needed to have some way to transfer and receive data via USB. Rather than introducing a converter or microprocessor unit to achieve USB communication, the USB-compatible MCP233 Advanced Motor Controller (BasicMicro, nd) was selected instead. This controller offered the capability of driving both motors simultaneously, in-built Proportional Integral Derivative (PID) code and several mixed functionality pins for sensor interfacing, brake driving etc.



Figure 1: The standard powered wheelchair (Surace, nd).

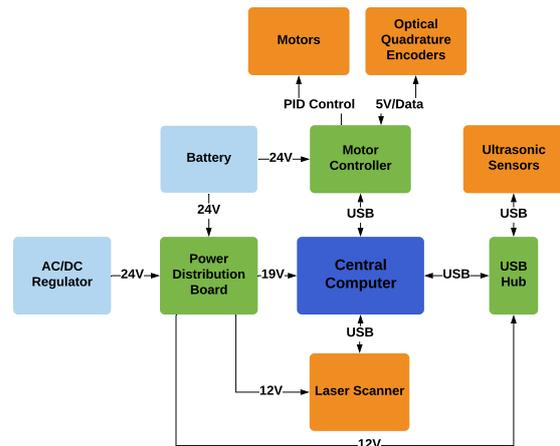


Figure 2: Hardware system block diagram.

3.2.2 Sensors

The sensors chosen for the system included a Hokuyo 240° laser rangefinder (Hokuyo, nd), a set of ultrasonic sensors (Maxbotix, nd) and 1024 ppr optical quadrature wheel encoders (Hengstler, nd). The laser rangefinder was mounted at the front of the wheelchair on an extended arm in order to keep its line-of-sight clear of obstructions. The ultrasonic sensors were mounted in a ring around the wheelchair, attached directly to the chassis. The wheel encoders were attached directly to each motor shaft by extending the shafts through the motor caps. The resulting setup had an effective angular resolution of 0.00275°. Given the large number of sensors (and other devices requiring USB ports), two USB hubs were used to expand the ports available; one unpowered and one powered (through a 12V power supply).

3.2.3 Power Distribution System

With all devices accounted for, the different voltages required for the system were: 19V for the computer, 12V for the USB hub and laser rangefinder, 5V for the encoders and 24V for the motors. A simple regulatory circuit was custom-built to provide all the required regulated voltages from the unregulated 24V wheelchair battery. Additionally, a switchover system was designed and implemented to allow all electronics (except the motors and controller) to be powered via an external AC wall plug. This allowed the developer to continue using the computer and sensors, even while the battery was charging. The motors themselves were powered solely from the MCP233 controller. The controller was connected to the battery through a custom-designed protection system incorporating in-rush current prevention, fuses and a reverse energy recovery diode.

3.3 Final Implementation

Three methods of user-input were made available on the wheelchair. A fixed joystick (USB) was mounted next to the wheelchair’s arm rest, along with a wireless remote control which emulated the fixed joystick’s functionality at a distance. This remote control was attached to the system via the mini PC’s in-built Bluetooth module. Additionally, a touchscreen monitor was mounted at the front of the chair, which allowed the user to directly interface with the computer operating system, navigation controls and system diagnostics.

All electronics were housed within a two-level PVC compartment mounted at the bottom of the chair. The bottom level was dedicated completely to the power and motor controller units, while the top level was occupied by the computer and USB hubs. Due to the large number of high power components, various space optimisations were introduced such as fixing components to the ceiling of the compartment or connecting cables to busbars. The complete SW is shown in Figure 3. By opting for USB connectivity, and by designing custom-made power solutions, the price of the upgrade was kept to a minimum.

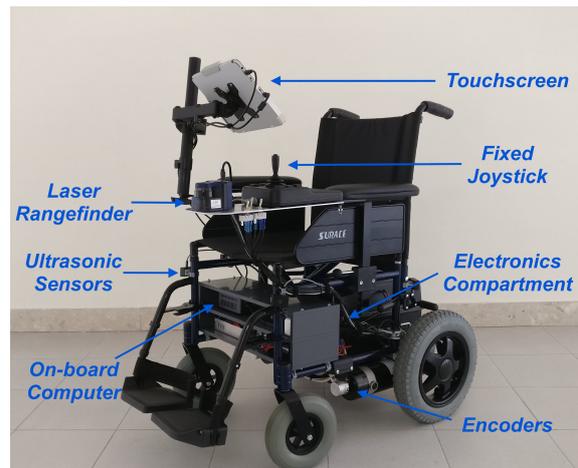


Figure 3: The complete Smart Wheelchair.

4 SOFTWARE INFRASTRUCTURE

With the hardware shell complete, the software driver systems had to be built before any navigation algorithms could be employed.

4.1 Software Platform

4.1.1 ROS

The primary decisions were to select which software platform, framework and language to use for the system. The ideal solution for the wheelchair was found in Robot Operating System (ROS) (ROS, nd) (specifically version Lunar Loggerhead). ROS provides many tools and services which allow one to build a whole web of interconnected programs working in a parallel manner whilst sharing data between them.

The parallelised system, along with a host of well-built and open-source libraries and development tools, made ROS ideal to act as the software base architecture for the wheelchair. Simulations of the algorithms used on the SW were carried out directly in ROS, following which they were imported to the system on-board the wheelchair PC.

4.1.2 Platform and Language

Ubuntu Linux (specifically version 16.04 LTS) (Ubuntu, nd) was selected as the operating system for the wheelchair, being one of the most popular and user-friendly Linux distributions available. The whole system was coded in Python 2.7, due to its extensive ROS support and availability of open-source mathematical, graphing and multithreading libraries.

4.2 Low-level Setup

Some low-level configurations and tuning needed to be applied before integrating the ROS node system. The encoders were connected directly to the motor controller which read the encoder pulses for closed-loop speed control. Additionally, the controller sent the raw encoder counts to the computer via USB, where standard dead-reckoning calculations were performed to turn this data into a source of odometry.

The controller’s internal PID system needed to be tuned with appropriate gain values. The PID control was set to reach the targeted velocity value as quickly as possible. Instant acceleration, however, was not the desired behaviour on the wheelchair; this would have led to a very uncomfortable ride for the user. Thus, acceleration was regulated by another P controller programmed into ROS. This controller took in the desired target velocity and limited the change from the current velocity within reasonable limits, before sending this adapted velocity to the motor controller. In this way, the acceleration was made smoother, and abrupt starts or stops were kept to a minimum. Additionally, immediate control of the motor speeds was still available in emergencies, thanks to the rapid response of the hardware PID system. The velocity control procedure is presented graphically in Figure 4.

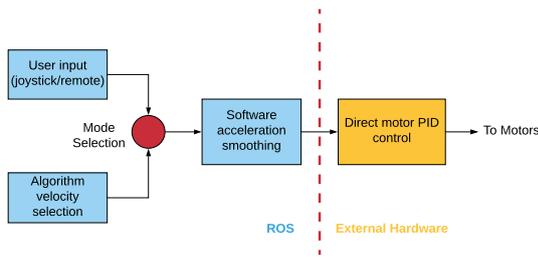


Figure 4: Velocity Smoothing Procedure.

4.3 Node Setup and Integration

All sensor and input streams were separated into different ROS nodes, resulting in the structure shown in Figure 5.

4.3.1 Mapping and Costmapping

When using the SW in an indoor environment, maps can help in localisation and allow the SW to pre-plan paths through its environment. Mapping in this system was facilitated through the use of the ROS Gmapping package (ROS, ndc). This uses a Rao-Blackwellised particle filter (openSLAM, nd) to fuse laser and odometry data together to form a well-dimensioned map. To build this map, the wheelchair was slowly driven around the selected area, while data from the laser rangefinder and encoders was gathered. These were then fed to the Gmapping package, which translated them into an occupancy grid map. An example of such a map is provided in Figure 10. Before being able to produce accurate maps, a lengthy procedure of manual parameter tuning (number of particles, linear/angular update intervals and range) had to

be followed to correctly fit the Gmapping system to the SW hardware. The Costmap_2D (ROS, ndb) ROS package was used to inflate obstacles on the map with the wheelchair’s radius.

4.3.2 TF

The TF package from ROS (ROS, ndf) was used to keep track of the many coordinate systems present on the wheelchair. The hierarchical structure in Figure 6 was built through this package. The bottom relation in this structure was the positioning of each sensor with respect to the wheelchair centre (Base_Link in Figure 6). These relations were fixed (i.e. the laser rangefinder was always at a fixed distance away from the centre of the wheelchair). This information was used when determining the wheelchair navigational paths (to be described in Section 5).

Along with these hardware levels, TF also managed the link between a map, the odometry system and the wheelchair position. Odometry was taken care of entirely by the wheel encoders, which referenced the distance travelled from a fixed point. When using a map, the system needed to define where the wheelchair was, relative to the map. To handle this, the Adaptive Monte Carlo Localisation (AMCL) (ROS, nda) package (unmodified) from ROS was used. This package handled publishing the transform between the Odom and Map transforms (Figure 6) and hence took care of positioning the wheelchair on the map. This package does not only rely on encoder readings to position the wheelchair on the map due to their inherent drift issues. Instead, AMCL uses a particle filter to stochastically fuse laser scans and encoder readings and compare these readings with the

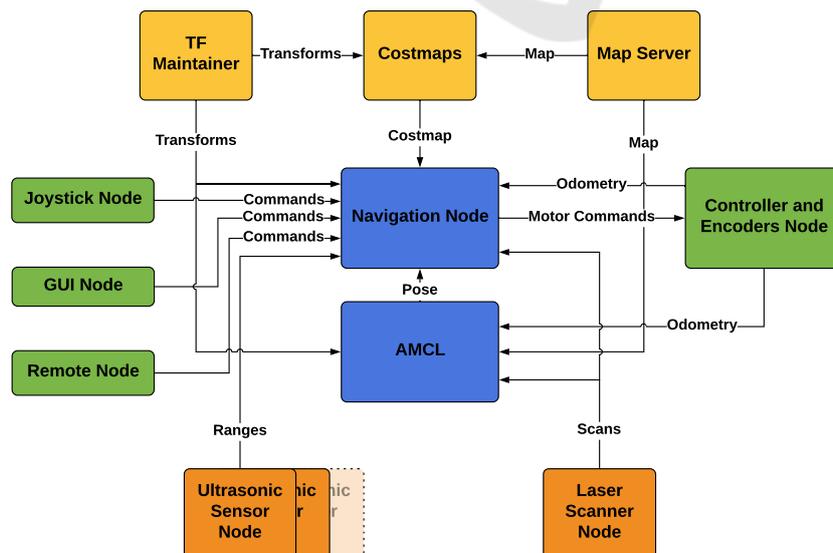


Figure 5: ROS system node diagram.

current map. This helped the SW localise with the map as a reference point, thus mitigating considerably the errors introduced by encoder dead-reckoning.

4.3.3 Input/Output Device Interfacing

Each sensor and input device in the system was assigned a dedicated node (except the encoders, which were bundled with the motor controller). These nodes managed the basic processing required to translate data in and out of the system. The laser rangefinder was taken care of by the ROS ‘urg_node’ (ROS, ndg) package which translated laser scans into fixed arrays of distance measurements and angles. The ultrasonic sensors were handled through custom-made serial nodes, which picked up range readings from the sensors at fixed rates. The joystick/remote returned deviations from their centre when actuated. These were translated to angular/magnitude changes and sent to the navigation system for processing. For the touchscreen, a Graphical User Interface (GUI) was constructed using Kivy (Kivy, nd), an open-source GUI Python library. The GUI was populated with diagnostics and tools, allowing a user to control the navigation system (Section 5) and tweak its parameters. Additionally, the touchscreen allowed a user to switch navigation modes and view the wheelchair position on the map. A typical view of the GUI is shown in Figure 7.

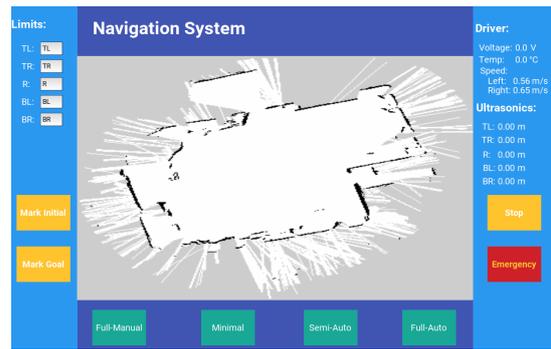


Figure 7: Custom-made GUI showing mode selection, on-line information and laser-generated map.

5.1 Semi-autonomous Navigation Mode

This mode was named ‘semi-autonomous’ due to its reliance on both a user’s input to provide the target directions, as well as on its sensor-based algorithm utilising VFH (Borenstein and Koren, 1991) to guide the wheelchair through a safe path. Essentially, the user directs the wheelchair towards a target goal (with no regard to the obstacles that might lie between them) using the joystick/remote, while the wheelchair attempts to follow this target in as safe a manner as possible by avoiding any obstacles it encounters en route.

5.1.1 VFH+

The approach used for navigation was adapted from VFH+ (Ulrich and Borenstein, 1998); one of the enhanced versions of the base VFH. Originally, this algorithm was intended for robots containing a large number of ultrasonic sensors. Thus, the algorithm had to be modified to work with the laser scanner, and interact with its data structure correctly. The algorithm looped through the cycle shown in Figure 8.

5 NAVIGATION ALGORITHMS

With both the software and hardware infrastructures complete, the actual intelligent navigation algorithms were developed and implemented on the system (as the Navigation Node of Figure 5).

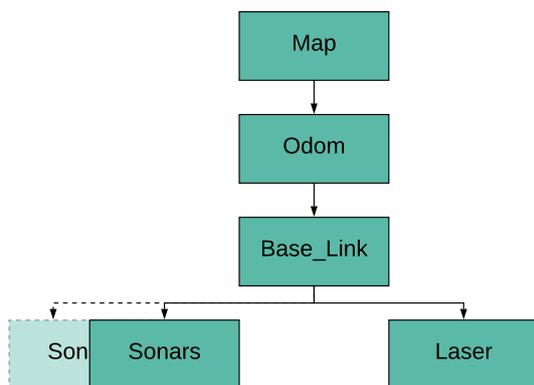


Figure 6: Transformation tree.

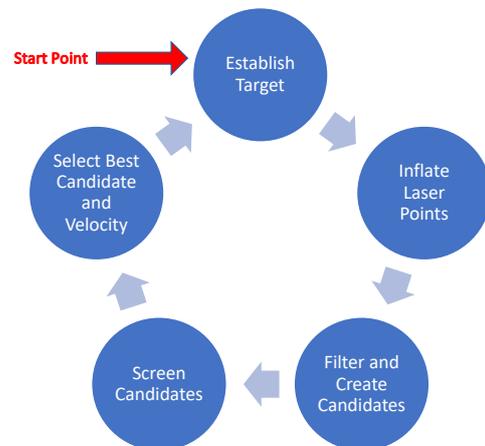


Figure 8: VFH algorithm loop.

To start the loop, the target heading was extrapolated from the user joystick/remote input. The user only needed to indicate the direction once; the system made sure to track this target through the use of the wheel encoders. From here, all obstacles detected by the laser rangefinder were enlarged by the wheelchair's radius (inflated). This inflation process allowed one to consider the wheelchair as a point object. With all objects inflated, candidate directions were selected by finding the gaps between objects that were less than a specific cut-off radius (Figure 9). The best candidate was then selected by prioritising the candidate both closest to the target direction and which kept the wheelchair on the smoothest path; by minimising the following cost function:

$$\text{cost} = \mu_1 \Delta\{c_i, t\} + \mu_2 \Delta\{c_i, c_{i-1}\} + \mu_3 \Delta\{c_i, \theta_i\} \quad (1)$$

where $\Delta\{\}$ is an angular difference measurement function, c_i, c_{i-1} stand for the current and previous candidate respectively, t stands for the current target direction, θ_i stands for the current forward wheelchair orientation and μ_1, μ_2, μ_3 are constant parameters.

The last two terms of the cost function are a measure of how smooth the trajectory of the wheelchair is. Thus, by varying the ratios of μ_1, μ_2 and μ_3 , one can select how much weighting the algorithm should give to the goal or towards a non-oscillatory path. In most instances, it has been found that selecting a μ_1 slightly higher than $\mu_2 + \mu_3$ results in goal-oriented behaviour, with very little oscillatory motion. Once a candidate is selected, the wheelchair is assigned a velocity based on the position of obstacles around its path.

5.2 Fully-autonomous Navigation Mode

For fully-autonomous navigation, the system was placed in complete control of the SW's trajectory.

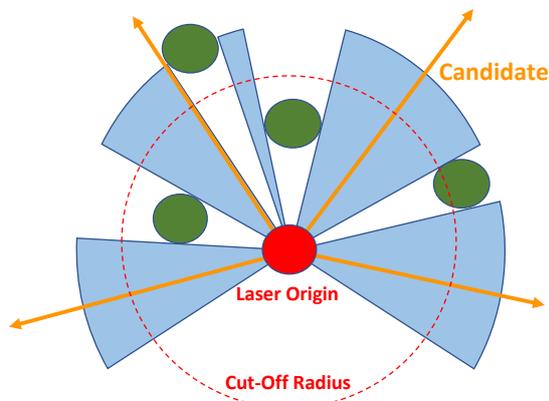


Figure 9: Candidate proposals.

The user only interacted with the system by selecting the desired final destination of the wheelchair on the previously-acquired map using the touchscreen. With a goal and start position defined, a full path between the two was always generated before wheelchair movement, using the A* algorithm (Hart et al., 1968). This algorithm works by generating a path which minimises both the distance from the start as well as the distance to the goal along each node selected. The A* planning process has been built into a customised ROS node, since the official A* path-planning nodes on ROS all require the ROS navigation stack (ROS, ndd) to function.

Once this path was established, the system plotted a set of waypoints along the path and targeted the wheelchair to reach each waypoint sequentially. The VFH algorithm was placed in control of this movement, avoiding all obstacles (mapped and unmapped) while following each waypoint.

5.3 Manual Modes

Additionally, two other fully user-controlled modes were implemented. One was completely manual (joystick/remote controlled), while the other simply prevented collisions by halting the SW before it struck an obstacle. This mode used the ultrasonic ring to detect obstacles in close proximity.

6 RESULTS

6.1 Sensor and Mapping Accuracy

Before building any maps, the encoders were tested for their accuracy in localisation, by checking both their speed and position measurements. To assess speed accuracy, the motors were given a fixed value and the resulting reading compared with that of a laser tachometer. To assess accurate positioning, the SW was set to traverse a known distance, and the reported encoder readings were compared with this value. For speed, the encoder readings were found to be within 0.005m/s of the tachometer and the position readings at a percentage error of around 2.5%, both of which were satisfactory results. To test the laser rangefinder and mapping functionalities, a number of maps were built for different indoor areas. Figure 10(a) shows the map built for a laboratory inside the department.

Whilst this map came out dimensionally accurate and well-defined, others, such as the one shown in Figure 10(b), were less so. While still dimensionally accurate, many fringe error readings were also obtained. This was due to the presence of reflective ma-

terials in the area being mapped. However, even with these errors, these issues would not have affected navigation since they would still be eliminated through the costmapping system.

6.2 Navigation

To assess the semi-autonomous navigation mode, a number of cluttered environments were set up. One such test result is shown in Figure 11. Here, the SW was directed into the obstacle course, and its path through it was tracked with the encoders. As shown by the red arrows (the route followed by the SW) in Figure 11, VFH+ was able to select the best path through the obstacles, without collisions or sudden movements/path decisions.

The fully-autonomous system was tested by commanding the wheelchair to navigate from one side of the hall to the other, by selecting the destination on the map using the touchscreen. After plotting the path shown in Figure 10(b), the wheelchair was able to follow each waypoint to the goal. Even when additional unseen obstacles were added to the map, the SW was able to navigate through safely until it reached the goal destination, using its VFH system.

Velocity updates were made to reach the motors in less than 0.2s; making the SW capable of reacting almost instantaneously in emergencies. Further efficiency improvements could be possible by using C++ rather than Python, but the current implementation was more than capable of handling the computational load within the selected update interval.

7 CONCLUSIONS

In this paper, a complete SW design process has been detailed. A standard commercially available PW was converted into a SW through the introduction of a novel modular hardware and software system. Several autonomous capabilities were designed and implemented into the architecture. All algorithms and systems were tested in practical environments,

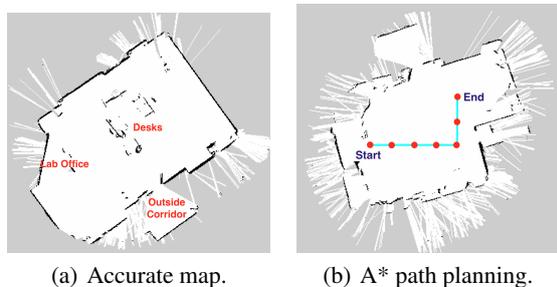


Figure 10: Different maps obtained through SW mapping.

and their robustness verified using thorough experiments.

This whole process was designed to fit onto any standard PW, using its own motors and battery. The whole system can be taken as is, and attached to another wheelchair. The costs for the whole prototype (excluding the wheelchair frame) have been kept to below €5000, with potential savings of more than €1000 if certain prototyping functionalities are removed. An integrated modular ROS system has been built which can accommodate additional sensors and computation nodes, whilst also speeding up further development through the use of Python and its many libraries.

This work has proven that a SW can economically be built on any existing PW frame with excellent results. However, other factors such as practicality, comfort and safety can be improved. Apart from algorithmic enhancements, the system needs to be trialled and thoroughly validated on actual patients. Using their feedback, additional features can be tailor-made to the wishes of the target population or hardware components can be modified to prioritize functionality and comfort. Furthermore, protocols need to be put in place to guard against accidents (such as sensor failure or flat tyres), providing safety cases for both hardware and software breakdowns. This will require significant changes to the navigation system to allow the current algorithms to tackle uncertain situations, whilst keeping the safety of the user paramount to any other task.

ACKNOWLEDGEMENTS

This work has been supported by the Research, Innovation and Development Trust (RIDT) of the University of Malta along with APS Bank.

Special thanks goes to Mr. Noel Agius and the University of Malta Workshop for their aid in assembling the system hardware.



Figure 11: VFH+ avoiding obstacles in tight spaces.

REFERENCES

- BasicMicro (n.d.). *MCP233*. <https://goo.gl/oogiQE>. Retrieved February 20, 2019.
- Borenstein, J. and Koren, Y. (1989). Real-Time Obstacle Avoidance for Fast Mobile Robots. *IEEE Transactions on Systems, Man, and Cybernetics*, 19(5):1179–1187.
- Borenstein, J. and Koren, Y. (1991). The Vector Field Histogram-Fast Obstacle Avoidance for Mobile Robots. *IEEE Transactions on Robotics and Automation*, 7(3):278–288.
- Carlson, T. and Demiris, Y. (2012). Collaborative Control for a Robotic Wheelchair: Evaluation of Performance, Attention, and Workload. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 42(3):876–888.
- Cavanini, L., Benetazzo, F., Freddi, A., Longhi, S., and Monteriù, A. (2014). SLAM-based autonomous wheelchair navigation system for AAL scenarios. In *2014 IEEE/ASME 10th International Conference on Mechatronic and Embedded Systems and Applications (MESA)*, pages 1–5.
- Echefu, S., Lauzon, J., Bag, S., Kangutkar, R., Bhatt, A., and Ptucha, R. (2017). Milpet – The Self-Driving Wheelchair. In *Electronic Imaging*, volume 2017, pages 41–49.
- Fox, D., Burgard, W., and Thrun, S. (1995). The Dynamic Window Approach to Collision Avoidance. Technical report.
- Hart, P. E., Nilsson, N. J., and Raphael, B. (1968). A Formal Basis for the Heuristic Determination of Minimum Cost Paths. *IEEE Transactions on Systems Science and Cybernetics*, 4(2):100–107.
- Hemachandra, S., Kollar, T., Roy, N., and Teller, S. (2011). Following and Interpreting Narrated Guided Tours. In *2011 IEEE International Conference on Robotics and Automation*, pages 2574–2579.
- Hengstler (n.d.). *Icuro RI36 Encoders*. <https://goo.gl/hWDLmh>. Retrieved February 20, 2019.
- Hokuyo (n.d.). *UBG-04LX-F01*. <https://goo.gl/TzfEvh>. Retrieved February 20, 2019.
- Intel (n.d.). *NUC7I7BNH*. <https://goo.gl/ZqkN6v>. Retrieved February 20, 2019.
- Kinpara, Y., Takano, E., Kobayashi, Y., and Kuno, Y. (2011). Situation-Driven Control of a Robotic Wheelchair to Follow a Caregiver. In *2011 17th Korea-Japan Joint Workshop on Frontiers of Computer Vision (FCV)*, pages 1–6.
- Kivy (n.d.). *Kivy Homepage*. <https://kivy.org/>. Retrieved February 20, 2019.
- Koenig, S. and Likhachev, M. (2002). D*Lite. In *Eighth National Conference on Artificial Intelligence*, pages 476–483, Menlo Park, CA, USA. American Association for Artificial Intelligence.
- Leaman, J. and La, H. M. (2017). A Comprehensive Review of Smart Wheelchairs: Past, Present, and Future. *IEEE Transactions on Human-Machine Systems*, 47(4):486–499.
- Leaman, J., La, H. M., and Nguyen, L. (2016). Development of a smart wheelchair for people with disabilities. In *2016 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI)*, pages 279–284.
- Levine, S. P., Bell, D. A., Jaros, L. A., Simpson, R. C., Koren, Y., and Borenstein, J. (1999). The NavChair Assistive Wheelchair Navigation System. *IEEE Transactions on Rehabilitation Engineering*, 7(4):443–451.
- Maxbotix (n.d.). *MB1413 USB Ultrasonic Sensors*. <https://goo.gl/Lh9W2d>. Retrieved February 20, 2019.
- Nasri, Y., Vauchey, V., Khemmar, R., Ragot, N., Sirlantzis, K., and Ertaud, J.-Y. (2016). ROS-based Autonomous Navigation Wheelchair using Omnidirectional Sensor. *International Journal of Computer Applications*, 133(6):12–17. Published by Foundation of Computer Science (FCS), NY, USA.
- openSLAM (n.d.). *Gmapping*. <http://openslam.org/gmapping.html>. Retrieved February 20, 2019.
- ROS (n.d.a). *AMCL Package*. <http://wiki.ros.org/amcl>. Retrieved February 20, 2019.
- ROS (n.d.b). *Costmaps Package*. http://wiki.ros.org/costmap_2d. Retrieved February 20, 2019.
- ROS (n.d.c). *Gmapping Package*. <http://wiki.ros.org/gmapping>. Retrieved February 20, 2019.
- ROS (n.d.d). *Navigation Stack*. <http://wiki.ros.org/navigation>. Retrieved February 20, 2019.
- ROS (n.d.e). *ROS Main Page*. <http://www.ros.org>. Retrieved February 20, 2019.
- ROS (n.d.f). *TF Package*. <http://wiki.ros.org/tf>. Retrieved February 20, 2019.
- ROS (n.d.g). *Urg Node*. http://wiki.ros.org/urg_node. Retrieved February 20, 2019.
- Simpson, R. (2005). Smart wheelchairs: A Literature Review. In *Journal of rehabilitation research and development*, volume 42, pages 423–438.
- Simpson, R., Lopresti, E., and A Cooper, R. (2008). How Many People Would Benefit from a Smart Wheelchair? In *Journal of rehabilitation research and development*, volume 45, pages 53–71.
- Surace (n.d.). *715 Magic Power Wheelchair*. <https://goo.gl/gDK53W>. Retrieved February 20, 2019.
- Ubuntu (n.d.). *Ubuntu Main Page*. <https://www.ubuntu.com>. Retrieved February 20, 2019.
- Ulrich, I. and Borenstein, J. (1998). VFH+: Reliable Obstacle Avoidance for Fast Mobile Robots. In *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146)*, volume 2, pages 1572–1577 vol.2.