Tackling the duality of obstacles and targets in shared control systems: a smart wheelchair table-docking example

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***Abstract*— Many studies have shown that a smart wheelchair could improve the quality of life of people with restricted mobility by providing them with more freedom in the daily activities they can undertake independently. In addition to enhancing independent mobility, it is important to ensure safety for wheelchair users and those around them. To date, previous studies have mostly focused on (semi-)autonomous navigation or obstacle avoidance. By contrast, in this study, we tackle the challenging, but important problem of safely docking to tables. We propose a robotic navigation assistance, applied to electric powered wheelchairs using Time-of-Flight (ToF) sensors to facilitate table-docking for users. To meet this objective, we designed a low-cost sensor system that was integrated into our smart wheelchair prototype, which can detect a table and accurately estimate its height. We then developed a robust algorithm to deliver the manoeuvring assistance. First, we simulated the smart wheelchair system within Unity3D to find the best positions for the ToF sensors and evaluate the accuracy of the docking system, employing different table styles. Then, we experimentally validate the system on our physical wheelchair, using varying angles of approach, which demonstrate its feasibility.**

I. INTRODUCTION

Assistive technologies facilitate the participation of people with disabilities into day-to-day life activities [1]. The World Health Organization (WHO) reported that 75 million people need a wheelchair globally [2]. More specifically powered wheelchairs are tools that provide independent mobility and greater freedom for people with severe mobility restrictions, including those with wide range of motor and sensory diseases from e.g. spinal cord injury (SCI) to motor neurone disease (MND) and amyotrophic lateral sclerosis (ALS), to name but a few. According to the National Health Service (NHS), there are 1.2 million wheelchair users in the UK, of which two thirds of them are over the age of 60 [3]. Furthermore, the number of wheelchair users is projected to rise in the near future as a consequence of longer life expectancy [4], [5].

A wheelchair plays a substantial role in facilitating social participation (e.g. meeting with a friend in a restaurant) and improving life activities (e.g. going to school or work) [6], [7]. The main eligibility criteria of the Electrically Powered Indoor Outdoor Wheelchair (EPIOC) in the UK on behalf of NHS is to control the wheelchair independently and safely [8]. A study by Chen et al. (2011), in which 95 active manual or powered wheelchair users participated, reported that 54.7% of the wheelchair users experienced at least one wheelchair-related accident, while 16.8% had two or more accidents within three years [9]. Also, the study indicated that 87.8% of all those accidents were related to tips and falls, while specifically for powered wheelchair users 33% of the accidents were associated with accidental contact and dangerous operation. Thus, the key characteristic of the wheelchair should be not only to maximise the mobility for users with severe mobility restrictions but also to decrease the risk of the accidents. Breakthroughs in collision-avoidance technology [10] and implementation of this technology into powered wheelchairs, such as the Drive-Safe System [11], paved the way for developing safer smart wheelchair systems and reducing those recorded accidents. The Drive-Safe System [11] is based on obstacle detection, such that the wheelchair gradually decelerate and stop in the presence of an obstacle.

The main priority for smart wheelchair systems is to make the driving experiences safer and more comfortable, whilst providing more independent navigation. Independent safe navigation would decrease the need for human assistance in desired activities such as in work or social engagement, which would enable the wheelchair users to socialise more easily and increase their quality of life [12]. To date, different control modes have been tested for navigation support, ranging from autonomous [13]–[16] to shared control (semi-autonomous) [17]–[19]. As opposed to the normal assumption that a fully-autonomous solution would be best, several studies have shown that wheelchair users prefer a shared control system to provide them with assistance, whilst maintaining their own control authority [12], [20]. The notion of shared control has been used in many domains of human-machine systems and refers to when "*human(s) and robot(s) are interacting congruently in a perception-action cycle to perform a dynamic task, that either the human or the robot could execute individually under ideal circumstances*" [21].

Most research has tended to focus on the level of control offered to the driver (e.g., shared or fully-autonomous) [12]–[20], [22] or obstacle avoidance [15], [16], [22]–[25]. However, the current state-of-the-art technology that has focused on obstacle avoidance often actually prevents wheelchair users from being able to easily communicate with others and socialise. For example, consider the scenario of sharing a lunch with other people in the office, or meeting up with a friend for a cup of tea in a cafe. Then imagine the

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challenge if your wheelchair tries to avoid the table to which you are trying to dock, or is not able to detect the table (because it is not a solid object all the way to the floor) and instead attempts to drive straight through it! A previous study based on wheelchair users' experiences reported that a desired feature for a smart wheelchair would be to assist the user specifically when docking at a table [12]. However, to our knowledge, there has been little progress reported in this direction and especially not for docking to a desk in an office environment. Therefore, we propose a low-cost sensor system integrated into our previous smart wheelchair prototype [18] to overcome the specific problem of docking to tables.

In this paper, we present a complementary approach to provide assistance to wheelchair users specifically when docking at a table to offer a safer assistance. First, we describe the design of the sensor system by providing simulations in Unity3D to find the best orientations for the integrated sensors, and then we show the experimental evaluation of the integrated system. The paper is organized as follows: Section II gives a detailed description of the virtual environment setup for the initial developments and the real wheelchair platform including Time of Flight (ToF) sensors for the physical evaluation [26]. Section III describes the simulation results from the virtual environment and the experimental results on the real smart wheelchair platform. These results are then discussed in section IV. Finally, the paper concludes that our shared control system improves table-docking performance, which could improve social inclusion in a working environment.

II. METHODS

The main aim of this study is to build a working prototype of a table-docking system that detects the table's overhanging ledge and calculates its height using the Time of Flight (ToF) sensors [26]. Therefore, in this section, we present an overview of the virtual environment in Unity3D to develop the system, before describing its integration into the physical ADAPT[1] wheelchair [18]. We then explain the control algorithm, and experimental protocol.

A. Virtual Environment Setup

The virtual environment (Fig.1) enabled us to rapidly develop, test and iteratively improve both the sensor positioning and orientation, as well as the navigational assistance. It allowed us to optimise orientation of the ToF sensors and to explore the environmental considerations that the system could accommodate, considering the minimum table width or the maximum distance at which the table can be detected.

The ToF sensors were modelled with Particle Systems in Unity3D, acting as an emitting particles signal, which allowed us to detect the underside of the table surface and measure its distance from the chair, as well as estimate its height from the ground plane. The overall aim was to dock

[1]The UCL Aspire Create team developed a prototype smart wheelchair as part of the ADAPT project: `http://adapt-project.com` [18]

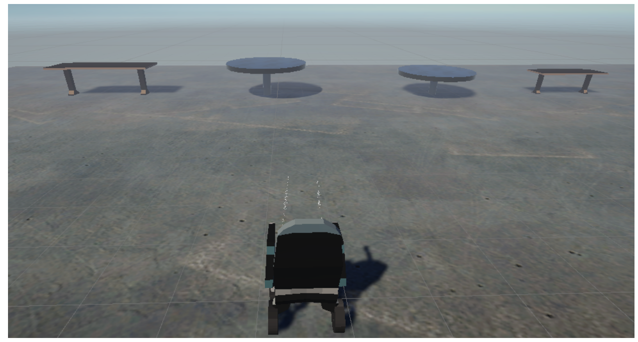

Fig. 1: Virtual Environment designed in Unity3D

perpendicularly to the table, so that the measured error would be the angular difference of the chair from the perpendicular. Once an optimised sensor orientation (resulting in minimum angular error) for the docking system was found, we used it as a design parameter in our 3D printed sensor support component for our physical smart wheelchair.

B. Real World Wheelchair Platform

Based on the virtual environment configuration, the working prototype of a table-docking system (Fig. 2) was implemented by mounting one ToF distance sensor (STMicroelectronics VL53L1X [27]) onto each of the two forward ultrasonic sensor clusters of the ADAPT wheelchair [18]. The ToF system micro-controller was installed under the chair's seat as shown in Fig. 2. Ubuntu terminal was used to send the sensor data to the Raspberry Pi, through a robotic operating system (ROS) publication, across the wheelchair's local network *chairnet*. Kinematic analysis of the wheelchair was performed using UCL's HaMMoC system. HaMMoC is the Human and Machine Motion Capture platform which is a bespoke build, based on the OptiTrack motion capture system using 25 *PrimeX 13* cameras, which is linked to Motive and Unity3D. The wheelchair's trajectory was captured to measure the ground-truth angular error of the docking system relative to the target tables.

C. Control Algorithm

The algorithm is implemented in ROS and based on specific subscribers: namely the Joy (joystick) and the two LaserScan (ToF sensors) employed for the navigation aid. The other sensors present on our ADAPT wheelchair are not currently integrated into the docking system algorithm. Instead, in this paper we initially test the docking algorithm in isolation, with a view to integrating into the full shared control system in the future, once validated. The TOF sensors are placed on the left and right sides of the chair, as shown in Figure 2. Every callback made by the subscribers gives the slant distance measured by the ToF sensors. The horizontal distance from the table is then calculated:

$$tableDistance = cos(\theta) * D,$$

where θ represents the angle formed by the ToF sensors and the horizontal vector in radians and D is the slant distance measured by the sensor.

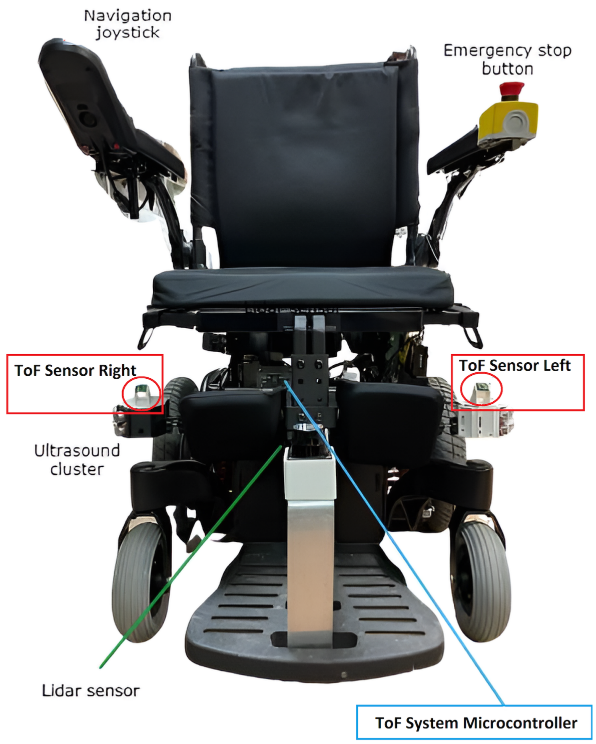

Fig. 2: Real wheelchair platform; including two Time of Flight sensors integrated onto two forward ultrasonic sensor cluster

If the calculated horizontal distance to the edge of the table is less than 2m, the recovered values are used to estimate the height of the table, to check if the chair would fit beneath it. The overall height ψ is calculated as:

$$\psi = sin(\theta) * D + \phi,$$

where ϕ is the height at which the TOF sensors are set, and D the measured slant distance.

If the table height does not not allow sufficient clearance of the chair, the controller will initiate a gentle autonomous "bounce" backward movement to give the user natural feedback. However, if the table's height does allow sufficient clearance, the chair rotates to minimize the difference between both sensor distances and ensure that the chair is correctly aligned, perpendicular to the table. The rotation occurs while the difference between both ToF distances, Δ, is greater than 0.5:

$$\Delta = \sqrt{(D_1 - D_2)^2}$$

The user always has ultimate authority, since they can stop the motion at any point by letting go of the joystick, or they can greatly oppose the motion to overrule the controller.

D. Ethics

This study was approved by the University College London Ethics Committee (ref. 6860/011), to allow us to perform experiments on these novel controllers with healthy able-bodied participants in both the virtual environment and on our physical prototype smart wheelchair, prior to working with patients.

E. Experimental Protocol

We operated a virtual smart wheelchair equipped with virtual ToF sensors within Unity3D to modify and test various conditions (Fig.1). First, the ToF sensors were systematically set at a range of different orientations and the wheelchair was driven to towards a table from several different angles of approach (Fig. 4). This allowed us to determine the best sensor orientation, before tests were undertaken in the virtual environment to evaluate the accuracy of our docking system with a variety of different table formats. Most indoor docking structures have either a rounded or rectangular shape [28], so we tested our docking system using both rectangular and rounded tables. The rectangular tables in real life were based on specific dimensions related to a standard office environment, with a height of 85 cm and a width of 1 m. Tables with different heights, from 65 cm to 80 cm, were used to validate the accuracy of the height detection. This process was important as different responses from the wheelchair are expected depending on the table height. For instance, the wheelchair should only approach and dock to tables higher than 80 cm, to prevent collisions between the user's knees and the tabletop (Fig. 3). We also analysed the difference between the user input and the chair's movement while docking. In the Unity3D environment, an external Arduino potentiometer sensor was used to simulate the user input (joystick angle) while the angle of rotation of the chair was analysed separately.

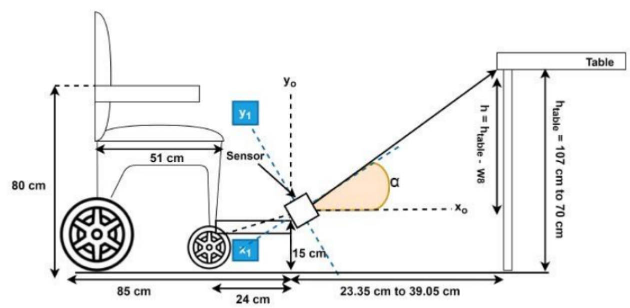

Fig. 3: Diagram representing the real wheelchair profile view with ToF sensors placed at an angle of α

In the real world physical experiments, the data was collected using two different systems. The ground truth wheelchair velocity was determined from the OptiTrack system. We also recorded the wheelchair joystick data, its (x, y) axis values based on the Joy node ROS subscriber. All statistical analyses were performed by using MATLAB. The Shapiro-Wilk test was used to determine whether the samples were normally distributed before the analysis and the significance level was set to 5%.

III. RESULTS

We first present the results from the experiments made in the virtual environment, and then look at the results when

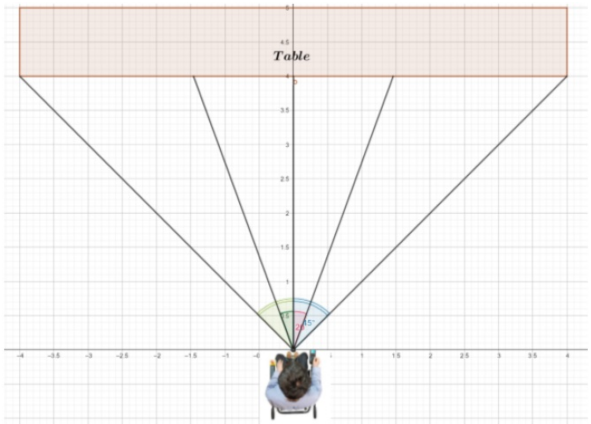

Fig. 4: Different tested wheelchair angle approaches with the start and desired goal pose of the wheelchair for the experiments [not to scale] - designed in GeoGebra.

employing the physical smart wheelchair platform in the real world, to better understand the Human-Machine Systems.

A. Virtual Environment in Unity

The relationship between the sensor angle (elevation angle from horizontal) and the docking angle error (from the wheelchair finishing perpendicular to the table) was found to be well represented by a hyperbolic function as can be seen in Fig. 5. Herein, the data was evaluated using the performance metrics of Root Mean Square Error (RMSE=0.094) and R-square scores (R^2=0.97). Docking angle error had the lowest value (2.59±1.5°) for the docking system when setting the sensor angle at 45° elevation to the horizontal (parameter α in Fig. 3). Therefore, the Time of Flight (ToF) sensors were set at an angle of 45°. Angle errors could arise if the sensor's emitted signals pass beyond the table's depth. To avoid these marginal errors, the minimum table depth for a sensor set at an angle of 25° is 125 cm, quite restrictive in the context of an office environment, whereas a sensor set at an angle of 45° works with a minimum depth of 75 cm. Furthermore, at a 45° angle, the maximum distance at which the table can be detected is 190 cm, compared to only 120 cm for a sensor set at 70°.

Regarding the docking system with a rectangular or rounded table, the data was normally distributed, so a paired-sample t-test was applied to evaluate the accuracy (Fig. 6). We found a significant difference in the docking angle error for rounded vs. rectangular tables ($p<0.05$) at an approach angle of 45°. Although the average docking angle errors for both experiments are relatively small (3-12°), there is still a 10° difference between both tables at an approach angle of 20°, over 20 trials. Indeed, the rounding of the table seems to make the wheelchair's rotation more error-prone, as during the rotation one of the sensors could go past the table while the other would just be underneath it, causing multiple rotational corrections, leading to more angle errors. However, in practice, the differences in accuracy for the same table at different angles can be neglected, as the largest average difference is 5°, which is probably acceptable in a real world context.

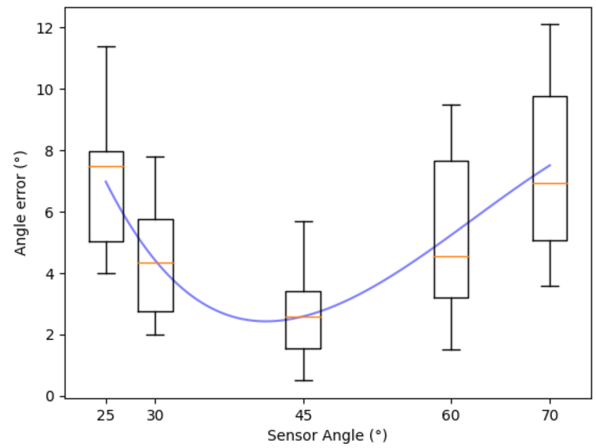

Fig. 5: Simulated docking at a standard table; final docking angle error when the ToF sensors are positioned at a variety of angles to the horizontal; 25°, 30°, 45°, 60° and 70°; hyperbolic function with R^2=0.97 and RMSE=0.094, which indicates a good fit with our results.

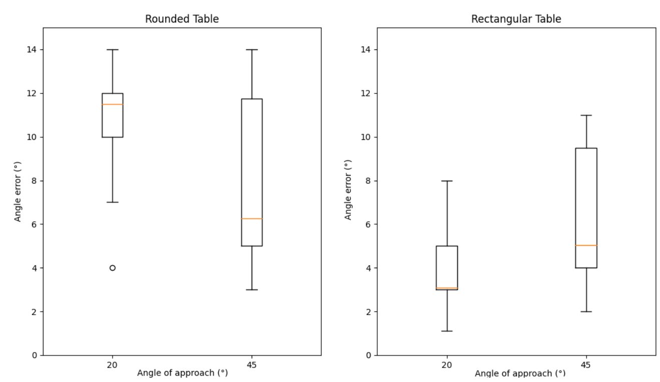

Fig. 6: Docking angle error for different angles of approach to a rounded and rectangular table (significant difference between the rectangular and rounded tables at an approach angle of 45° with a $p<0.05$).

B. The Real World Wheelchair

In the real world, the same sensor orientation (45° to the horizontal), was used to validate the behaviour of the docking system, with 20 trials from left and right hand side approaches at a shallow (20°) and a large (45°) angle of approach to the edge of the table. When changing the approach from the right and left hand side, the results do not show any significant difference (Fig. 7).

Qualitatively, the value of the joystick input is more noisy than in the virtual environment, which leads to more variations, partly due to the physical motion of the wheelchair. However, it remains fairly stable around a target angle value of 0° (i.e. user input indicates drive straight forwards, as observed from the OptiTrack motion capture analysis). For example, as the wheelchair approaches the table, it is

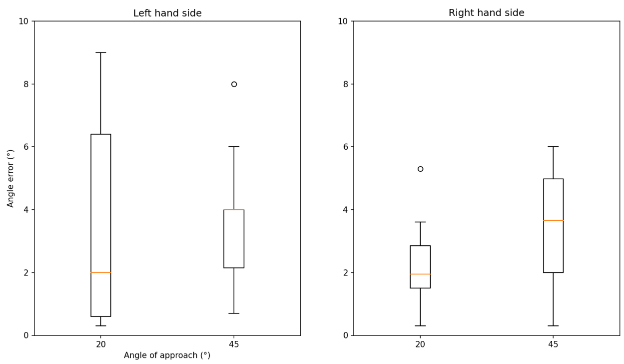

Fig. 7: Docking system angle of approach error analysis on the smart wheelchair in the real world

successfully detected (approximately 9 s into the example trial shown in Fig. 8). At this point, the wheelchair performs a 35° rotation, due to the semi-autonomous assistance. The wheelchair's final pose is perpendicular to the table at approximately a 0° angle.

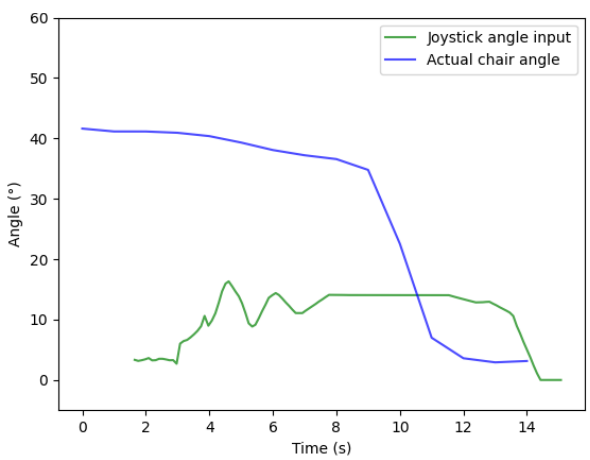

Fig. 8: An example from one of the experiments, showing the rotation of the wheelchair's docking system for a 40° angle of approach to the table.

It is important to mention that a sudden and extreme change of speed for the user could be uncomfortable or even dangerous. Based on the previous result obtained from the HaMMoC system, we examined the 3D positional mapping of the chair and looked at an example of its translational velocity while testing the table-docking system; with and without the assistance of our docking system. As can be seen in Fig. 9, after 7 s, there is the decelerating phase followed by an abrupt change of speed, which is 4 times steeper without the assistance. When employing our docking system, the velocity decreased much more gradually, which is safer and more comfortable.

IV. DISCUSSION

The purpose of this study was to add important new functionality to the ADAPT smart wheelchair [18], so it

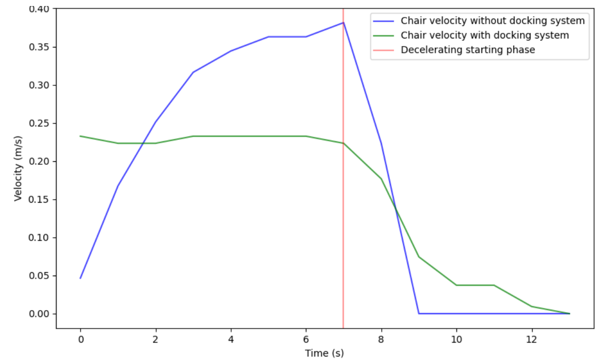

Fig. 9: Translational velocity of the chair with and without the docking assistance

could detect a variety of tables and estimate their heights in order to dock safely or to avoid them. The table height detection was implemented with a low-cost sensor system including ToF sensors. It is important to note that following our simulations, the choice of mounting the sensors at 45° to the horizontal worked well with the ToF sensors in the real world despite the inevitable slight variations between measured and ground truth values. As described in the sensor's data sheet, different lighting of the ToF sensor does affect the accuracy, which could explain some of the negligible variations in the measured signal [27].

In future work, variation in the lighting of the testing environment should be taken into account as this could be a significant factor found in a real office and home environments. In addition, the calculated distance could have also been subject to variation by the microcontroller's baud rate settings. These settings affected the distance change process up to the corrective approach phase. As with Fitt's Law, this caused a speed–accuracy trade–off: the greater the approach velocity, the higher the docking angle error will be.

Despite these limitations, we have shown that the integrated low-cost ToF sensor system is feasible. The placement of the sensor on the wheelchair has been shown to work well as it is rarely obstructed by the user's legs and has reliably detected a range of tables in our experiments. The long-term goal would be to fine tune the ToF-based detection and for it to work better at higher velocities as well as validating in a wider range of more complex scenarios (including different lighting conditions). Nonetheless, the table-docking system worked well overall and especially for rectangular tables. Although the performance was degraded (and less symmetrical) when approaching a rounded table, the median docking angle error was still below 10°. Thus, the current table-docking system would be most suitable for office-like environments, employing mostly rectangular tables and may need further refinement if end-users require higher precision docking to rounded tables (e.g. in café-like environments).

Since any type of object passing in front of the chair could be considered a table, we have also begun developing a multimodal system that incorporates a computer vision system to improve robustness. We have trained the Yolov5 algorithm on a custom dataset of table edge and surface images, which has resulted in an 82% accuracy. The dataset itself consists of 500 images, composed of 20% rounded tables and 80% rectangular tables (generally more frequent in an office environment), with some brightness modifications (-25%/+25%), horizontal flip, and noise added to render a more robust trained algorithm. In practice, a camera could be mounted at the arm level of the wheelchair or higher, to detect the table edges or surface. This could be complementary to our ToF detection and render a more accurate understanding of the environment. Therefore, in future work we intend to integrate the Yolov5 table edge detection with the ToF sensors to improve accuracy and robustness of the table detection.

V. CONCLUSION

The overarching goal of this study remains to help people with severe mobility restrictions to improve their quality of life by maximising their independence and increasing safety when using powered wheelchairs. Much of the focus on smart wheelchairs has been to avoid obstacles. By contrast, we have developed a low-cost table-docking system, based on ToF sensors, that adds functionality to our existing smart wheelchair. We have found that it is important not only to prevent collisions with tables, but also to adjust the wheelchair's pose while approaching the table, to yield a safe, practical and comfortable trajectory. Our initial findings have confirmed the system is feasible, but further work is required to investigate particular lighting conditions and improve performance for higher velocity approaches.

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