Assistive trajectories for human-in-the-loop mobile robotic platforms

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Abstract—autonomous and semi-autonomous smoothly interruptible trajectories are developed which are highly suitable for application in tele-operated mobile robots, operator on-board military mobile ground platforms, and other mobility assistance platforms. These trajectories will allow a navigational system to provide assistance to the operator in the loop, for purpose built robots or remotely operated platforms. This will allow the platform to function well beyond the line-of-sight of the operator, enabling remote operation inside a building, surveillance, or advanced observations whilst keeping the operator in a safe location. In addition, on-board operators can be assisted to navigate without collision when distracted, or under-fire, or when physically disabled by injury.

Keywords—trajectory; assistive; tele-operated; military; robot; wheelchair; navigation; collision avoidance

I.   INTRODUCTION

Whilst existing autonomous robotic systems are suitable for a workshop or factory environment, they prove to have deficiencies when human interaction becomes an integral part of that system. In such scenarios, it is necessary to adapt that system to allow for the additional requirements of the human passenger, both in terms of comfort of motion and additional user interaction governing the behavior of the system. One such human-in-the-loop pilot onboard system is the powered wheelchair (PWC).

According to Pires et al. (1998) [1] the motion of the PWC 'must be coherent and inspire confidence to the user' and yet Garcia et al. in 2013 [2] reported that these problems were still yet to be overcome, they note that current PWC research was applying modern autonomous robotic methods. However earlier research by Madarasz et al. [3] had identified that autonomous operation 'may not ultimately be practical, nor desirable'. Nisbet [4] had also identified that 'the most important design aim should be to develop systems which complement, maximize and augment the pilot's skills, not replace them.' Having identified that the smart PWC was not the same as a robotic system, Yanco et al. [5] went on to state the issue of doorway passing as being a fine navigational requirement, and that mapping would not be required, and that the system should operate without external infrastructure.

Any mobile robotic system with the human-in-the-loop would therefore need to be assistive and include the user in all the decision making and control processes; not autonomous and indiscriminately directive. Powered wheelchair users may find operation in enclosed environments such as buildings difficult, because wheelchairs are not much narrower than the typical doorway or corridors they wish to pass through or down and may well not be much smaller than rooms the user wishes to enter. Therefore correct alignment with doorways and passageways is important if the platform is to pass through collision free.

Remotely operated platforms, such as those used by the military for security purposes, with a human-in-the-loop, have additional problems. Pezzaniti et al. (2009) [6] evaluated various different tasks using a military TALON robotic platform [7]. The research found that the operators of tele-operated robots could better perceive the environment when using 3D displays as opposed to 2D displays and that 'lack of depth perception hinders their task'. However Chen et al. (2012) [8] evaluated operator performance when tele-operating the driving of a military TALON robot by negotiating four cone marked courses, as quickly as possible, with each one taking around one minute to complete. The research reported that although participants generally had fewer collisions and faster course times using 3D displays over 2D displays the difference failed to be statistically significant. The mean total number of cones hit over the four courses was around four for both 2D and 3D displays although the research does not report the total number of cones used on each course.

Undertaking tasks where there are no time constraints, such as when manipulating grippers and cutters on bomb disposal tasks by using visual feedback from different camera angles to overcome short-comings such as the lack of 3D perception [6], can have very different results in comparison with navigating a vehicle in rough hazardous terrain when under the pressure of time; or more importantly when under fire. These situations may well be a reasonable comparison with the difficulties, limitations, and frustrations faced by disabled PWC users whilst negotiating the cluttered public environment, such as shops and public transport.

When we investigate the literature with regard to evaluating these human-in-the-loop systems, there is no standard metric or benchmark; PWC testing usually involves negotiating doorways and corridors [9], and equally the evaluation of tele-operated platforms involves negotiating some type of marked and bounded course [6]. It can be seen from the evaluation of the 2D and 3D tele-operated displays that true performance improvements are difficult to quantify.

Rather than trying to identify improvements using small scale evaluations the problems need to be expressed in global terms and long term assessments need to be undertaken.

These global problems with human-in-the-loop and on-board systems can be put into perspective when we review the statistics: Krahl et al. (2010) [10] systematically reviewed US military vehicle accidents; they concluded that there had been few studies on service personnel injury rates, severity, type, and risk factors undertaken, which they postulate would lead to better policy for injury and damage mitigation. They quote that during Operation Iraqi Freedom and Operation Enduring Freedom (2003-2006) that 1024 collisions relating to military vehicles involved 4536 service personnel, of which 15% of those vehicles were combat types. Soudry et al. (1984) [11] compared the incidence of vehicle accidents which involved Israeli Defence Force personnel to those involving Israeli civilians between 1978 and 1981. The findings were that military vehicle accidents were higher for all crash types. More significantly, when no other vehicle was involved in the accident the military to civilian crash rate ratio was 13.6:1 implying possibly that a sense of invincibility existed when using military hardware. The causes for all of these statistics could be split into various classes and a solution sought for each one; however the underlying hypothesis must be that at some time some trajectory misjudgement was made.

In the case of the remote or tele-operated human-in-the-loop system the control problems, according to Melchiorri (2014) [12], are the problems which are caused by platform environmental interactions, and the inherent communication time-delays. These delays can be significant and depend upon the distance between operator and platform. Stating that these need to be properly considered and solved, Melchiorri (2014) [12] then goes on to say there are three possible levels of bilateral control schemes for tele-operation:

- Direct tele-operation: the operator directly controls the motion of the platform and receives feedback in real time; this method can only tolerate negligible time-delays.

- Coordinated tele-operation: whilst the operator remains in the control loop the directed commands are undertaken by a localized low-level feedback control of the actuators. This ensures that time-delays which are varying or are longer than can be tolerated with direct tele-operation.

- Supervisory tele-operation: becomes necessary when the time delay is too great and/or feedback quality is low or suffers intermittent interference. The platform functions locally by taking high-level remote commands and then, using local environmental information from sensor feedback, operates semi-autonomously to carry out those commands whilst still providing supervisory visual feedback to the operator.

Combining the concept of a miss-judged trajectory, the inherent time delays, and intermittent loss of communication, it can be said that a solution to all problems can be expressed as the need to provide a short trajectory which is compatible with one a human would themselves generate. This would enable the platform to remain on a collision free course when the human-in-the-loop is distracted or prevented from applying the correction to the trajectory.

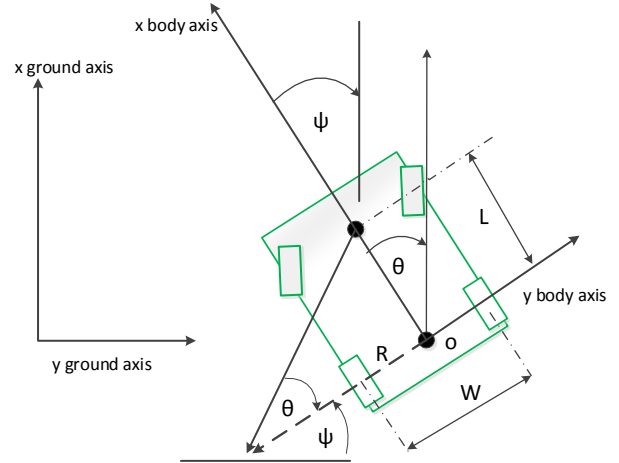## II. KINEMATIC CONSTRAINT ON THE TRAJECTORY

Fig. 1. Robotic platform frame of reference and kinematic

Human transport is largely based upon car-like vehicles, which can all be thought of as acting in a manner whose kinematic modelling can be described as a bicycle model [13]. Another alternative form of transport commonly used is the tank style, or differential drive wheels on the same axle, such as used on PWCs and the TALON; this kinematic model can be thought of as a unicycle [14]. Both the unicycle and bicycle models can be expressed as follows [15]:

$$v_{body} = \frac{v_{right} + v_{left}}{2} \tag{1}$$

$$\dot{x} = v_{rear} \tag{2}$$

$$\omega_{body} = \dot{\theta} = \frac{v_{right} - v_{left}}{W} \tag{3}$$

$$\dot{\varphi} = \frac{v_{rear}}{W} \tan\psi \tag{4}$$

Where:

$v_{body} =$ The tank-like platform x body axis origin 'o' ground velocity

$\dot{x} =$ The car-like platform x body axis origin 'o' ground velocity

$\omega_{body} =$ The tank-like platform body rotation rate about z body axis

$W =$ The distance between the two rear drive wheels

$v_{right,left} =$ The ground velocity of the tank-like platform rear drive wheels

$v_{rear} =$ The sum of the ground velocity of the rear drive wheels

$\dot{\varphi} =$ The car-like platform rotation rate about the z body axis

$\psi =$ The steering angle for car-like platforms

$\theta =$ The steering angle for tank-like platforms

An assumption can be made that, for any practical assistive trajectory, the differential drive wheel steered platform heading angle θ and the car-like single drive motor mechanically steered platform heading angle ψ are bound by $\pi/4 > \psi > -\pi/4$ such that the velocity of all wheels with a magnitude >0 or <0 have the same sign in the ground reference frame. This means that for all cases ψ = θ and therefore both platforms can use the same trajectory.

The path that the two types of platform follow can be said to be a function of the wheelbase length L and width W shown in Fig 1 which gives a curve transcribed by the origin 'o' of the platform coordinates according to the radius R at some time. Therefore, taking our boundary conditions as the minimum turning radius of the platform, and considering that platform kinematic is described by:

$$\tan\psi = \frac{L}{R} \qquad (5)$$

R can be used to generate a curved trajectory for the platform to follow.

III. MODELLING THE NON-HOLONOMIC PROBLEM

Despite previous research in mobile robotics, it could be argued that curved trajectories [16, 17] do not represent intuitive and smooth human like trajectories. Using the PWC as a test vehicle, we have investigated the trajectories undertaken by human drivers. Significant observations were made using this robotic platform, with both aforementioned kinematic constraints, manoeuvring into and out of boxed parking spaces and around closely spaced obstacles such that clearances between vehicle and box were minimized. It was observed that all manoeuvres could be described by a combination of two geometrically shaped trajectories; that of the slalom, and that of the curve.
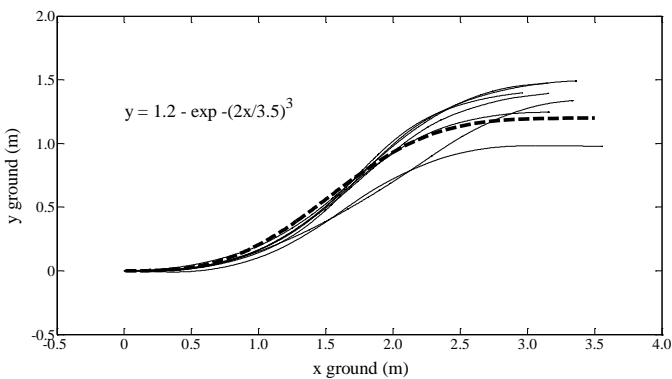

Fig. 2. Exponential sigmoid compared with human trajectories

The slalom, or lane change, was investigated first. A PWC fitted with wheel encoders, to measure the positional change of the platform, was employed to examine the typical human trajectory and Fig 2 shows seven of those human slalom trajectories (solid lines). The PWC platform started at the same position each time, close to the wall, and was driven along a 2.5m wide straight corridor with the user moving out to pass around a 1m wide x 1m deep x 2m high pile of

cardboard boxes located on the right side of the platform adjacent and perpendicular to the wall.
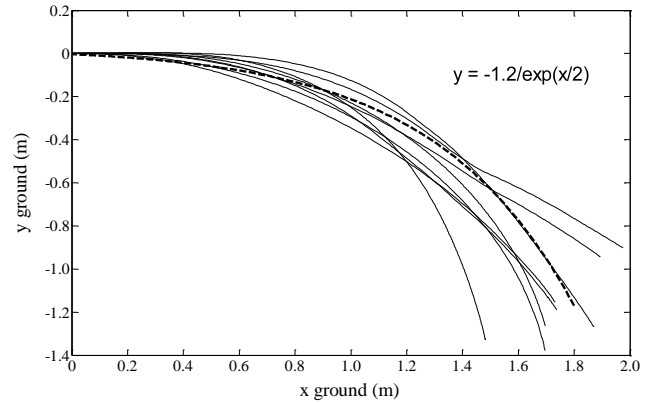

Fig. 3. Exponential curve compared with human turn trajectories

The next test examined the nature of a human right turn; eight examples are shown in Fig 3 (solid lines): a typical 2.5m wide corridor right handed corner was used with the users approaching the turn from middle of the corridor. The slalom and turn experiments were undertaken by a non-disabled experienced operator of a PWC. Platform operators will have some individual bias to their driving trajectory as will each trajectory collected from the same person differ slightly, furthermore clutter and platform dimensions will alter the shape of the trajectory; therefore obtaining data of the average human trajectory would require extensive and exhaustive sampling. The example trajectories shown in Figs 2 and 3 have been assumed to be a reasonable representation for the purpose of this research.
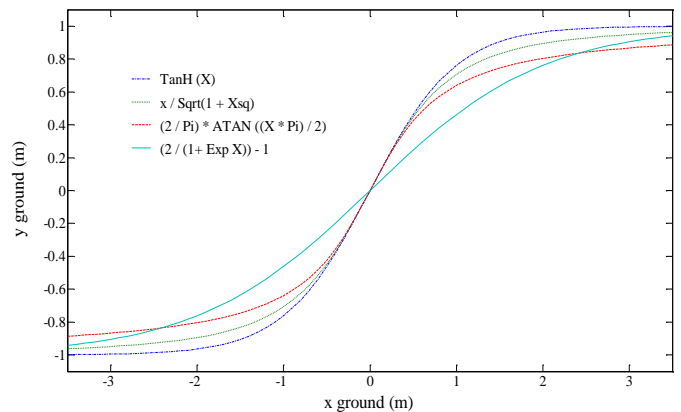

Fig. 4. Human turn PWC trajectories Several types of sigmoid functions

To provide an intuitive human-like assistive trajectory, a mathematical function needs to be developed; one which closely represents that of the human PWC trajectory. After simulating several functions which resemble a slalom trajectory (shown in Fig 4) and then comparing these to the human slalom trajectories (solid lines in Fig 2), it was determined that a best fit would be an exponential function which is shown in Fig 2 as the thick dashed line. This function has adjustable parameters which can be used to change the shape of the trajectory.

From the earlier observations it was realized that a human turn was not necessarily an orthogonal one. An exponential function, shown as a dashed thick black line in Fig. 3, with adjustable properties was also developed and compared with actual human trajectories also shown in Fig. 3. Having determined from previous research that harmonic functions can provide smooth interruptions to trajectories [18-20] the natural exponential function was deemed to be a good starting point for the development of assistive trajectories, which would be highly compatible with an exponential repulsive potential field based real-time collision avoidance.

The next step was to determine the exact exponential functions that could be used and how they could be made adjustable to negotiate specific turns and slaloms. Starting with the basic exponential equations a series of simulations were run, each with different configurations, in order to develop the most suitable adjustable equations which best fit the human trajectories given in Figs. 1 and 2, as follows:

$$f_y = y_d \left(1 - \exp - \left(2 x_t / x_d \right)^3 \right) \qquad (6)$$

$$f_y = y_d - \left(\frac{y_d}{\exp\left(\pi x_t / x_d \right)} \right) \qquad (7)$$

Where (6) represents a slalom manoeuvre, (7) a turn and:

f_y is the y ground displacement in the body reference frame at some time

y_d is the required y ground displacement distance

x_d is the required ground displacement distance

x_t is the x ground displacement in the body reference frame at some time

The turn exponential trajectory similarity to the human trajectory is limited to angles of ψ between:

$$\frac{\pi}{9} < \psi < \frac{2\pi}{5}$$

$$-\frac{\pi}{9} > \psi > -\frac{2\pi}{5} \qquad (12)$$

which are within the platform kinematic constraints.

IV. KEEPING THE HUMAN IN THE CONTROL LOOP

The purpose for the generation of the human-like trajectory is for the system to plan in real-time short trajectories ahead of the platform. The trajectories previously developed can be combined and adjusted to form a safe passage around obstacles and through narrow passages, doorways, and other waypoints. Having generated these short trajectories, should communication become poor and intermittent on tele-operated platforms then the system will use sensors to determine an obstacle free path and generate a safe short trajectory. Where the pilot is on-board then the system can be used to warn the operator that the current

trajectory deviates from a safe one, perhaps displayed on the windscreen.

Using the developed trajectories, steering assistance can be provided which keeps the operator in as much of full control of the platform as is possible. The relationship between the steering angle, platform velocity, and geometry and the resulting rate of turn is given by:

$$\omega_{body} = \frac{v_{body}}{L} \tan \psi \qquad (13)$$

Having defined our trajectory as an exponential then the gradient of that function at some time is the height of the function. If we also obtain the actual platform heading angle from inertial sensors, or through the direct use of wheel drive-shaft encoders, then an assistive control function can be developed to determine the body rotation rate at some time according to the desired velocity input, such that when the steering input from the joystick is lost then the system uses the generated trajectory heading; that function is defined as:

$$\omega_{body} = k \frac{v_{joystick}}{L} \sin\left(\psi_{trajectory} - \psi_{actual} \right) \qquad (14)$$

The value k is some constant, which is used to proportionally adjust the turn rate with respect to the operator forward velocity input according to the actual platform dynamic behaviour, the value of which can be obtained from practical observation of the platform performance.

The operator of the remote platform provides the joystick input which is transmitted wirelessly to the system. The system continuously uses on-board sensors to monitor obstacles in front of the platform. For example the type of indoor waypoint can then be determined [21, 22] and a safe trajectory generated; this will equally apply in the outdoor arena. The system generated trajectory can then be constantly applied with visual feedback to the operator or set to only function when communication is poor or lost; in this case the platform could be set to follow the trajectory until communication is restored. If after some set distance communication has not been restored, the platform would have been pre-programmed to return to the last location of good communication. Whilst consideration has been given to generating a set trajectory there remains the issue of the need for the assisted trajectories to be able to be dynamically interrupted should a previously undetected obstacle arise, or should the need to correct small positional errors occur.

V. INTERACTIVE COLLISION AVOIDANCE

The dynamic localized adjustable force field method (DLAFF) [23] is a dynamic elliptical window approach which travels with the platform. The inner ellipse better represents the physical boundary of the platform and the outer ellipse is shaped to keep motion within the kinematic constraints of that platform. One of the foci of each: the inner ellipse, and outer ellipse, which are shown in Fig. 5, is located at the body coordinate origin marked 'o'; the other foci of both ellipses are located along the x body axis. The inner ellipse's second focus coincides with the front axle, the ellipse having A and B

dimensions such that the ellipse covers the entire platform shape. The outer ellipse is free to move outward from the inner foci location according to the required adjustments.
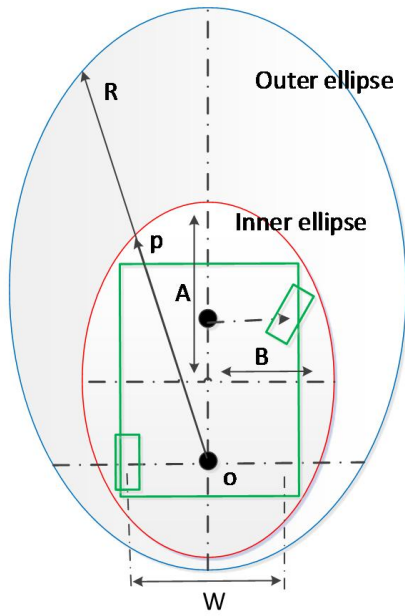

Fig. 5. Elliptical obstacle avoidance model

The damping terms given in Eqns. 15 and 16 act along the region between the inner ellipse and outer ellipse, radiating out from 'o' along the line 'r' to 'P' to provide a non-linear repulsive turn on the platform, thus preventing the platform from colliding with obstacles. The function is exponential and therefore forms localized repulsion acting upon the nearest obstacle on each side of the platform; this combined with the elliptical shape allows the platform to manoeuvre smoothly close to and around obstacles. This can then be combined in real time with the generated trajectory to provide a robust real-time navigation for tele-operated mobile robots.

$$F_r = 1 - \frac{1}{\exp^{((R-p)/k_r)}} \tag{15}$$

Where: $\theta \geq 0$ and $\theta \leq \alpha_{max}$

$$F_l = 1 - \frac{1}{\exp^{((R-p)/k_l)}} \tag{16}$$

Where: $\theta < 0$ and $\theta \geq -\alpha_{max}$

The angle α relates to the maximum steering angle of the car-like platform whilst in forward motion, the term k allows the potential field slope to be empirically tuned.

VI. EXPERIMENTAL RESULTS

The first experiment was to determine if the function in Eqn. 14 would be suitable for following the generated trajectory. The system was programmed to calculate a trajectory, by using data from sensors to determine the centre point of a doorway, when the platform was placed offset from the doorway centre. The operator then moved the joystick forward, as the platform moved forward the controller turned the platform to follow the generated trajectory shown in Fig 6 following the trajectory smoothly and closely.
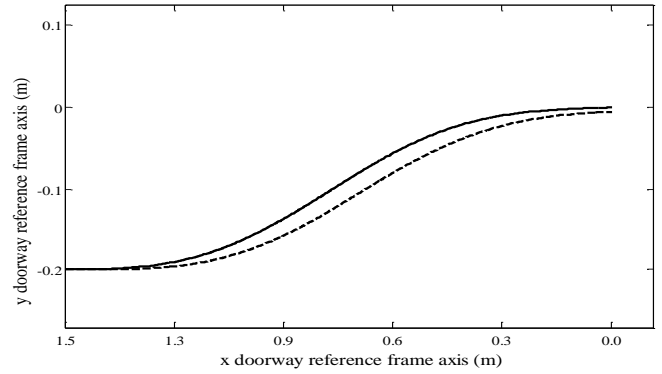

Fig. 6. System generated trajectory and actual path platform took with the operator-in-the-loop
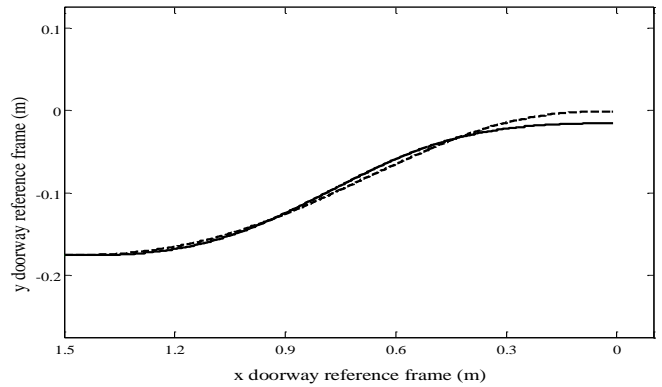

Fig. 7. Generated trajectory with DLAFF collision avoidance with the operator-in-the-loop
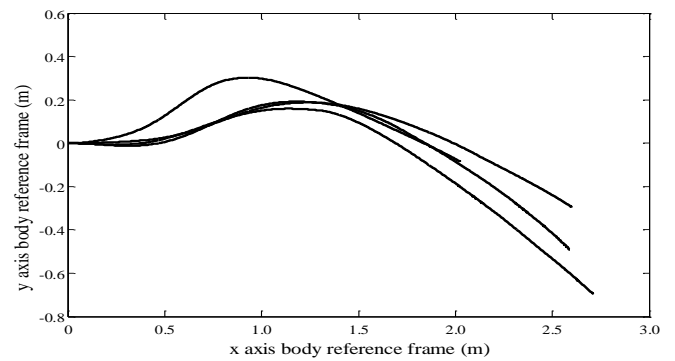

Fig. 8. Generated trajectory combined with DLAFF collision avoidance in an autonomous mode

The next experiment repeated the first only this time the platform was also turned about the body axis so as to be an angular and translational offset from the doorway. In addition, the real-time DLAFF collision avoidance was added to correct

for small alignment errors and any real-time obstacle adjustment. The operator performed the same task, this time the platform was heading for the narrow opening with an incorrect angular alignment. Fig 7 shows the additional smooth correction provided by the real-time intervention of the collision avoidance.

An additional experiment was conducted to examine the performance of the combined DLAFF collision avoidance and the human-like generated trajectory, without the operator being involved in the control loop, replicating a short autonomous trajectory such as would be required if communication was temporarily lost and the platform needed to continue a short distance to re-connect with the operator. The results in Fig 8 show smooth corrections to the generated doorway passing trajectories with the result that the platform passed through the narrow opening correctly aligned on each occasion; four examples are plotted.

VII. Conclusions

A novel pair of adjustable trajectories for assisting tele-operated and pilot on-board robotic mobile ground platforms has been developed and shown to be suitable for developing into a human-in-the-loop assistive system to aid safe navigation in an uncertain environment. A method of controlling the platform to follow along that trajectory has also been proposed.

The result of combining the trajectory and collision avoidance has been shown to provide a robust method of providing a precise alignment with a doorway such that a non-holonomic robotic platform can pass through with a very narrow safety gap, either with a human in the control loop or autonomously.

These trajectories have been shown to be compatible with collision avoidance in real time providing a complimentary safe navigation through a narrow doorway. Further work will be required to determine the operating boundaries and the trajectory adjustment range required for different platforms and scenarios across a range of platform velocities.

Users will undertake personal preference based actions when navigating the environment; therefore the adjustable trajectory equations will need to be personalized using some form of learned training for the assistive system when initializing the platform for each particular user.

VIII. Acknowledgments

IX. References

[1] G. Pires, R. Araujo, U. Nunes and A. De Almeida, "RobChair-a powered wheelchair using a behaviour-based navigation," in Advanced Motion Control, 1998. AMC'98-Coimbra, 1998 5th International Workshop on, 1998, pp. 536-541.

[2] J. C. Garcia, M. Marron, J. Ureña and D. Gualda, "Intelligent Wheelchairs: Filling the Gap between Labs and People," Assistive Technology: From Research to Practice: AAATE 2013, vol. 33, pp. 202, 2013.

[3] R. Madarasz, L. Heiny, R. Cromp and N. Mazur, "The design of an autonomous vehicle for the disabled," Robotics and Automation, IEEE Journal of, vol. 2, pp. 117-126, 1986.

[4] P. Nisbet, "Who's intelligent? wheelchair, driver or both?" in Proceedings of the 2002 IEEE International Conference on Control Applications, Glasgow, Scotland, 2002.

[5] H. A. Yanco, A. Hazel, A. Peacock, S. Smith and H. Wintermute, "Initial report on wheelesley: A robotic wheelchair system," in Proceedings of the Workshop on Developing AI Applications for the Disabled, 1995.

[6] J. L. Pezzaniti, R. Edmondson, J. Vaden, B. Hyatt, D. B. Chenault, D. Kingston, V. Geulen, S. Newell and B. Pettijohn, "3D vision system assessment," in IS&T/SPIE Electronic Imaging, 2009, pp. 723705-723705-13.

[7] P. Wells and D. Deguire, "TALON: A universal unmanned ground vehicle platform, enabling the mission to be the focus," in Defense and Security, 2005, pp. 747-757.

[8] J. Y. Chen, R. V. Oden and J. O. Merritt, "Utility of stereoscopic displays for indirect-vision driving and robot teleoperation," Ergonomics, vol. 57, pp. 12-22, 2014.

[9] H. Yanco, "Evaluating the performance of assistive robotic systems," NIST SPECIAL PUBLICATION SP, pp. 21-25, 2002.

[10] P. L. Krahl, C. J. Jankosky, R. J. Thomas and T. I. Hooper, "Systematic review of military motor vehicle crash–related injuries," Am. J. Prev. Med., vol. 38, pp. S189-S196, 2010.

[11] A. Soudry, P. E. Slater and E. D. Richter, "Military police traffic surveillance activity and occurrence of accidents in Israel," Mil. Med., vol. 149, pp. 321-323, Jun, 1984.

[12] C. Melchiorri, Robot Teleoperation. London: Springer, 2014.

[13] A. De Luca, G. Oriolo and C. Samson, "Feedback control of a non-holonomic car-like robot," in Robot Motion Planning and Control Anonymous Springer, 1998, pp. 171-253.

[14] P. N. Guerra, P. J. Alsina, A. A. Medeiros and A. P. Araújo Jr, "Linear modelling and identification of a mobile robot with differential drive." in ICINCO (2), 2004, pp. 263-269.

[15] P. F. Muir and C. P. Neuman, "Kinematic modeling of wheeled mobile robots," J. Robot. Syst., vol. 4, pp. 281-340, 1987.

[16] P. Jacobs and J. Canny, "Planning smooth paths for mobile robots," in Non-holonomic Motion Planning Anonymous Springer, 1993, pp. 271-342.

[17] A. Scheuer and M. Xie, "Continuous-curvature trajectory planning for manoeuvrable non-holonomic robots," in Intelligent Robots and Systems, 1999. IROS'99. Proceedings. 1999 IEEE/RSJ International Conference on, 1999, pp. 1675-1680.

[18] H. J. S. Feder and J. E. Slotine, "Real-time path planning using harmonic potentials in dynamic environments," in IEEE International Conference on Robotics and Automation, 1997, pp. 874-881.

[19] R. Daily and D. M. Bevly, "Harmonic potential field path planning for high speed vehicles," in American Control Conference, 2008, 2008, pp. 4609-4614.

[20] C. I. Connolly, "Harmonic functions and collision probabilities," The International Journal of Robotics Research, vol. 16, pp. 497-507, 1997.

[21] M. Gillham, G. Howells, S. Spurgeon, S. Kelly and M. Pepper, "Real-time doorway detection and alignment determination for improved trajectory generation in assistive mobile robotic wheelchairs," in Emerging Security Technologies (EST), 2013 Fourth International Conference on, 2013, pp. 62-65.

[22] M. Gillham, B. McElroy, G. Howells, S. Kelly, S. Spurgeon and M. Pepper, "Weightless neural system employing simple sensor data for efficient real-time round-corner, junction and doorway detection for autonomous system path planning in smart robotic assisted healthcare wheelchairs," in Emerging Security Technologies (EST), 2012 Third International Conference on, 2012, pp. 161-164.

[23] M. Gillham and G. Howells, "A dynamic localized adjustable force field method for real-time assistive non-holonomic mobile robotics," International Journal of Advanced Robotic Systems, Accepted for publication May 2015.