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Control of a Semi-autonomous Powered Wheelchair

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Abstract. A model reference controller for a powered wheelchair is described. The chair is fitted with sensor systems to assist a disabled user with steering their chair. The controller can cope with varying circumstances and situations. Non-linear terms are compensated for using an adaptive and automatic scheme. Consistent and dependable veer-controll is considered and the system was able to deal with uncertainties, for example changing surfaces, different shifting weights of users, hills, bumps, slopes and differences in tires and wheels. The controller has a quasi-linear closed-loop behaviour and that means that extra outer control loops can be appended later, for example path-following algorithms. An assistive agent was also created so that sperate wheelchairs will be able to communicate with each other in the future.

1. Introduction

Many systems have been created to help with driving and control [1-3] and a few have moved from research and development prototypes to become successful and useful devices [4,5]. Semi-autonomous powered wheelchairs [6-8] have recently moved out of academic and research institutions [9-11] to become available to wheelchair users.

Intelligent powered wheelchairs have become more affordable and reliable [12-14] but some specific applications still depend on the human driver. That is because intelligent control still lacks sufficient robustness and reliability, and it is expensive for assistive technology applications. That has led to a requirement for innovation, and a redefinition of methodologies and concepts for effective interaction with wheelchair users, guidance, assistance and control [15,16]. This work presents a new innovative powered wheelchair controller.

A new innovative and intelligent controller is presented in this paper that can adapt to various conditions, from being unable to manoeuvre to a human driver lacking the spatial awareness or ability to precisely position a transducer. An advanced control system was required to implement commands provided by disabled users and to provide them with assistance, while compensating for faults or external disturbances. The controller described in this paper to achieve that used machine-learning. A new assistive agent was created that allowed the wheelchairs and sensor systems to cooperate with users by sharing information between them. The research forecasts the use of semi-autonomous assistive agents to provide cooperation between wheelchairs and systems in the future.

2. Bobcat II Wheelchair

A Bob Cat II Powered Wheelchair is shown in figure 1. Robust and simple ultrasonic sensors were installed [2,4,5]. The demand signals from the wheelchair joystick could be sent straight to the controller, or a microcomputer could modify the demand signals depending on information from the sensors and new systems described here. Three rules were employed: The wheelchair user had overall control and systems only interfered when necessary; and Turns were to be smooth and controlled.

Misreads were filtered out to improve the sensor data and the data was placed into a grid. The sectors in the grid were labelled: closest, midway and farthest. If something was detected ahead of the chair then it would be classified as one of the three labels (closest, midway or farthest). Several sensors were fitted to the wheelchairs with their beams overlapping ahead of the chair. Various sensors and controllers could be attached to the microcomputer and therefor the wheelchair. The microcomputer controlled the two wheelchair motors. Software and hardware were based on commercial modules.

3. Control

Veer was corrected using a model referenced controller. Non-linear terms were compensated automatically using an adaptive method. The development of the processes was inspired by Ioannou and Sun [1] and the methods discussed by Bibuli *et al* [17]. The work described in this paper extends the method to compensate for non-linear dynamics associated with veer so that the wheelchair reliably deals with veer and mitigates for modelling uncertainty. The controller provided a quasi-linear closed-loop behaviour and that would allow other external control loops to be included, for example path-planning or navigation and guidance arrangements.

3.1. Modelling

It is difficult to develop an accurate adaptive controller because the dynamics' wheelchair model changes and is inherently uncertain. For example, the size and shape of each human driver will be different, they will have different mechanical assistive systems and devices, and life support, systems, and each driver will have different abilities.

Controllers and models were developed in the University of Portsmouth by the Systems Engineering research Group [2, 4] based on work presented in [18]. The form of the dynamics was:

$$m \dot{u} = k_u u |u| + c_{ur} u |r| + b_u f_u \tag{1}$$

$$m \dot{v} = k_v v |v| + c_{vr} v |r| + b_v f_v \tag{2}$$

$$I_r \dot{r} = k_r r |r\backslash + c_{ru} r |u| + c_{rv} r |v| + b_r \tau \tag{3}$$

Where u was surge speed, v was sway speed, i was veer-rate, f_u was input surge force, f_v was input sway force, τ was input torque along the veer axis, c_{ur}, c_{vr} and c_{rv} were velocity coupling terms, b_u, b_v, and b_r were input coefficient terms, m was the mass of the chair and I_r was the moment of inertia along the veer axis.

Dynamics were uncertain because of the diverse masses and proportions of the human users / drivers and the different apparatus that they used. So several potential ways of controlling a chair were unsuitable.

3.2. Controller

Equation (3) described the veer motion behaviour. An appropriate law was developed for the input torque τ. The law made the closed-loop system behave linearly. It was then possible to define reference models. Reliable closed-loop tracking of veer-rate and reliable model tracking were required. There were two main time varying components in the law in order to achieve that: one to track desired reference veer-rate and another to provide compensation for non-linear dynamics.

Time-varying components needed to be defined for tracking and stability. The control law was required to provide a stable and bounded linear closed-loop behaviour:

$$\dot{r}_m = a_m r + b_m r^* \tag{4}$$

Where r_m was desired veer-rate response, r^* was desired veer-rate reference, b_m was the input coefficient *and* $a_m > 0$ was a stable linear coefficient. Equation (4) represented the 'reference model'. The r_m state could then be tracked by the veer-rate signal by defining a τ control law as:

$$\tau = -\gamma(t) r + \lambda(t) r^* \tag{5}$$

$\gamma(t)$ and $\lambda(t)$ were the compensating coefficients for the adapted dynamics. The adaptive coefficients were as shown in [1], obtaining the following:

$$\dot{\gamma} = -\eta_\gamma\, e\, r\, sgn(br) \tag{6}$$

$$\dot{\lambda} = \eta_\lambda\, e\, r\, {*}sgn(br) \tag{7}$$

η_γ and γ_λ were gains for tuning the adaptation rate, e was tracking error ($e = r - r_m$) and $sgn(.)$ was the sign function

Figure 2 shows actual veer rate of the powered wheelchair and the model reference state with respect to a desired input. The $r(t)$ signal is irregular because of disturbances but it does manage to track reference $r_m(t)$.

Figure 1. Bobcat II Wheelchair.

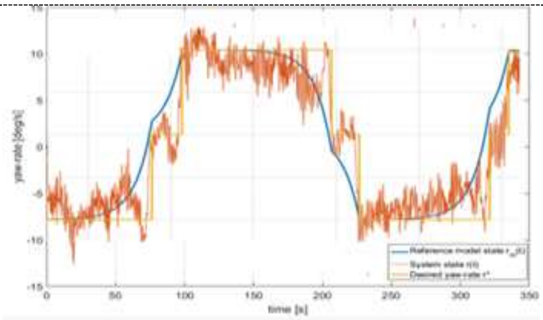

Figure 2. Step response of the veer-rate controller during experiments.

The veer-rate controller was tuned. Then external loops could be added, for example to regulate the heading of the wheelchair. Proportional-Derivative (PD) control was used. Integral terms were not used to avoid long oscillations that could have made tuning phases last for longer times. The response of the heading controller is displayed in figure 3. A constant direction was demanded of the powered wheelchair and a slight deviation from desired direction was seen. The deviation was due to environmental disturbances and the absence of an integral within the controller.

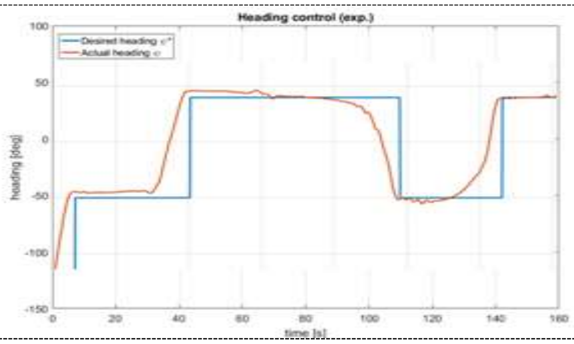

Figure 3. Response of the Heading Controller - desired direction and actual direction.

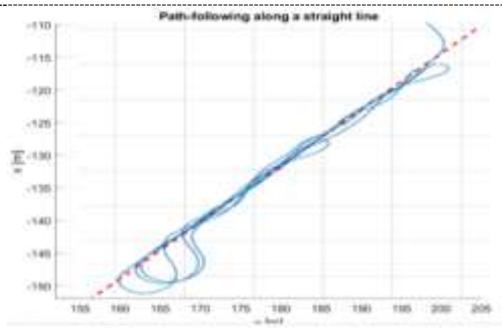

Figure 4. Results from attempting to follow a straight line.

3.3. *Path Follower*

A naive path-follower was created that was based on systems described in [18] where a Lyapunov-based technique guaranteed robustness and convergence of the system. A veer-rate reference was created to counteract veer and steer the chair along a desired path. Since the naive path-follower was decoupled from the low-level controller, it was straightforward to add the path follower. Performance was satisfactory and some results are shown in figure 4. The wheelchair was commanded to track a straight line (out and back). Results were especially suitable as the test area contained some slopes that tended to make the wheelchair veer off course.

4. Machine Learning

Developing assistive technology for powered wheelchairs faces various societal and legal issues. The general public have not really accepted powered wheelchairs and other powered mobility devices driven by disabled users being used outside of institutions and close to other human beings. It is difficult for the systems to understand complicated situations and unstructured environments, with complicated interactions and dynamics. In this work, AI provided an ability to adapt to different drivers and users, and different environments and was also used to make efficient decisions. Reinforcement learning techniques were used because it could capture human user behaviour. Deep learning was used to navigate the wheelchairs, and that was then extended to include collision avoidance and some situation awareness.

Movement of powered wheelchairs is not yet fully regulated, and there are barriers within society that have been slowing down the introduction of semi-autonomous powered wheelchairs. Especially when wheelchair drivers are interacting closely with other human beings.

An experiment was carried out in front of the engineering building at the University of Portsmouth. During the experiment, volunteers drove the powered wheelchair from a start point near the front door, with the goal of passing between building pillars, depicting a path shaped like an S. Control actions and trajectories were recorded. The recorded data was used to train an imitation system that, after accumulating enough controller and trajectory pairs, could then drive the powered wheelchair without needing any intervention.

A high interest was noted by people passing by and 41 volunteers drove the powered wheelchair. Methods for teaching a robot to perform a task (including complicated manoeuvring) using reference controllers (such as human beings), is well established as a topic of research [19]. The paradigm has been called "imitation learning". A basic form of "imitation learning" is "behavioural cloning". Behavioural cloning involves furnishing a robot with an approximating architecture that can be used to train a robot to reproduce the actions executed by a reference controller. This was achieved using supervised learning. Patterns were states that the robot visited and corresponding targets were actions made by the demonstrator (in this case, the human driver). The method isn't the most efficient, but it's intuitive and can be easily understood, and that made it useful when engaging people. Recurrent neural networks were used as approximating architectures to learn the behaviour of the human drivers.

An echo state network model was used. Weights were initially random. A reservoir computing paradigm was used to optimise the linear output layer. That assured rapid training, and that was crucial because there was only a limited amount of time to process data and display results. Operations were performed in real time in front of the audience. Echo state network models have been successfully applied to robot control in the past. The combination of echo state networks and behavioural cloning was successfully used to train the semi-autonomous powered wheelchairs and they were robust.

The system was trained using the first sixteen trajectories. Many were far from optimal, but bearing in mind the whole set of trajectories, they did all cover the range between start and finish. That was crucial for training the echo state network. Three trajectories were then executed autonomously by the powered wheelchair as shown in figure 5. All sixteen trajectories used for the training are shown in the background. The experiment was repeated as shown in figure 6. This preliminary experiment demonstrated the viability of imitation learning for driving along some basic routes.

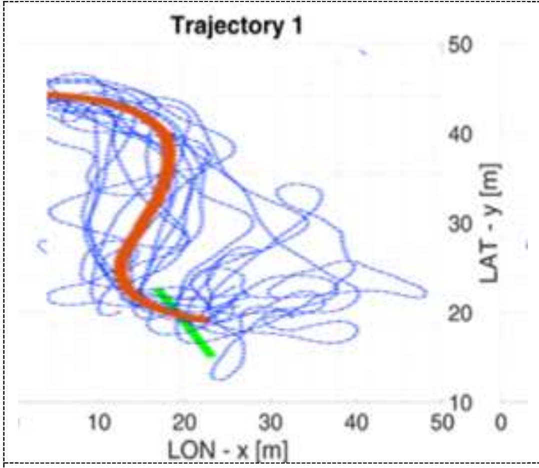

Figure 5. First trajectory performed with AI piloting the powered wheelchair.

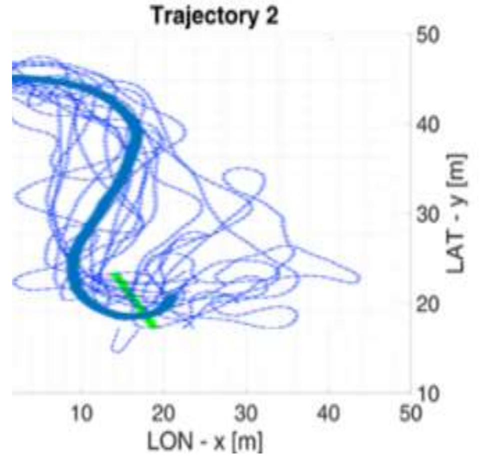

Figure 6. Second trajectory performed with AI piloting the chair.

The system only needed a relatively small number of training trajectories. Because of that success, it is now being combined with "learning-by-imitation" and experiments are being prepared in simulations and virtual environments

5. Conclusions

This paper presented a new model reference controller for a powered wheelchair controller. The chair was fitted with sensors to assist in the steering it. A controller was then programmed that dealt with varying situations and condition states. The model reference controller regulated and corrected for veer. It compensated non-linear terms using an automatic adaptive scheme.

A reliable veer controller was created that could mitigate for uncertainties, for example hills, bumpsa and slopes. The veer controller achieved a quasi-linear closed-loop behaviour and that meant that other control loops could be added outside the quasi-linear closed-loop, for example path-following or heading control.

An assistive agent for a powered wheelchair was also created so that wheelchairs could cooperate in the future and share information.

Current work is examining the use of a camera to steer the powered wheelchair and for facial recognition [20].

Acknowledgments

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