Adult-Human Learning on a Robotic Wheelchair Using a Force Feedback Joystick

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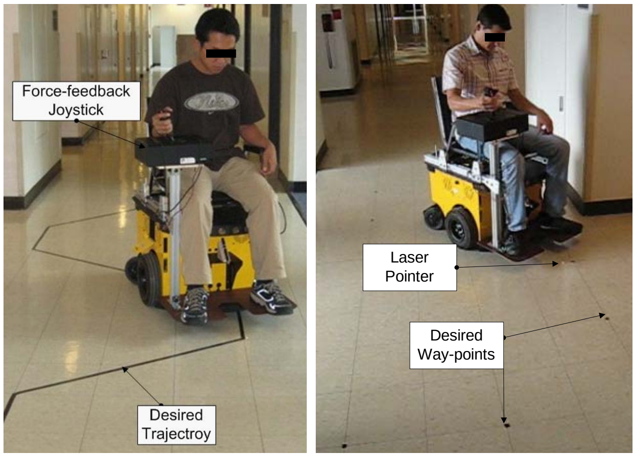
***Abstract*—Individuals with mobility impairments often find it challenging to use powered wheelchairs even after being given training. The motivation of this research was to study the effects of robotic wheelchair with force feedback joystick on adult-human learning behavior. In this study, healthy adult subjects were asked to follow a training path while driving a robotic wheelchair using a force feedback joystick. 'Assist as needed' paradigm was used to calculate the feedback force in order to train the user necessary driving skills for a particular trajectory. Two trajectory tracking algorithms, the line following and the point following, were implemented to drive the robot. The training protocol included pre-training, training and post-training sessions for each controller group. Driving skill improvements were observed using the line following trajectory tracking controller.**

Keywords – Robotic wheelchair; force feedback; human learning

I. INTRODUCTION

People with mobility impairments often find it very challenging to use the currently available powered wheelchairs for activities of daily living. Around 9-10% of the users receiving powered wheelchair training have reported to face difficulties even after the training [1]. Previous research efforts have been focused on making a smart-wheelchair, which makes the driving easier and safer for the user using numerous sensors and control algorithms [2]-[5]. In this work, we use such setups to study human learning behavior while driving.

Recently, robotic community has shown interest in using a mobile robot with a force feedback device to train people with mobility impairments necessary motor commands [6]-[9]. The force feedback devices, such as steering wheels and joysticks, are capable of providing numerous feedback cues to assist the driver. However, the user can become dependent on the force feedback guidance provided during the training session, which results in failure to learn the required motor commands [8]-[11]. In this study, we employed an 'assist as needed' paradigm to target the learning effect. The level of feedback guidance was based on each subject's performance. A higher level of guidance was provided when the subject was far away from the desired trajectory then when he was close to the desired trajectory where only a gentle level of force was used.



(a) Line following controller (b) Point following controller

Fig. 1. Two healthy adult subjects driving the robot in typical experiment environment, either straight lines or way-points were used to represent the trajectory based on the controller in use.

The goal of this work was to use a robotic wheelchair to train adult healthy subjects the required motor commands for tracking a trajectory. The motivation for such work is to develop an experimental paradigm to train mobility impaired adult patients to drive a powered wheelchair effectively. Improvement in the driving performance of healthy adults while driving a simulated wheelchair [8], [12] and of healthy or impaired kids while driving a real robotic wheelchair using some force feedback devices [6], [7], [9] has been studied in literature. To the best knowledge of the authors not much work has been reported in evaluating adult-human learning while driving a robotic wheelchair. In this study, two commonly used tracking algorithms, the line following [6], [13] and the point following (potential field based) [7], [14], were used to provide the input commands to the robot.

The paper is organized as follows: Section II describes the experiment setup and the Section III presents the controllers and force feedback description. The experimental protocol has been described in Section IV followed by results and discussion in Section V. Section VI ends with the conclusion.

II. EXPERIMENT SETUP

This section describes the equipment and the training path used during the experiment.

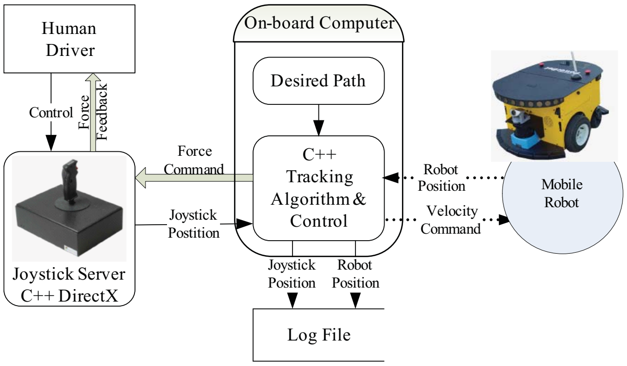


Fig. 2. A schematic of the experimental setup.

A. Equipment

The experimental setup comprised of a two-wheel Pioneer PowerBot mobile robot with a force feedback joystick from Immersion Impulse Stick, as shown in Fig. 1. This joystick can provide a continuous force of 8.5 N and a peak force of 14.5 N. The joystick was controlled through DirectX, which also recorded the joystick position and the amount of force applied on the drivers hand. Figure 2 presents the schematic of various experimental modules and their interactions with each other. The robot was equipped with encoders and an on-board computer to implement the control algorithm. All programs were executed on the robot's computer to interface with the on-board library to access the robot's pose and the joystick input in real time.

B. Trajectory

The training path comprised seven way-points, as shown in Fig. 3, and was laid on the floor at two locations to provide different visual cues to the subjects. For the line following groups, the trajectory was formed by joining the way-points using straight lines, Fig. 1(a); while for the point following groups, the trajectory was indicated using only the way-points, Fig. 1(b). First way-point was always the starting point and a laser pointer was used as the reference. The controller decided when to switch tracking between lines (or points) and which line (or point) to track based on the current position of the robot in the training area. To accomplish this, the training area was divided into various regions by the angular bisector of each pair of lines formed by three consecutive way-points. Such that, every single line formed by two consecutive way-points belonged only to one of these regions, i.e., I, II, III, etc. as shown in Fig. 3.

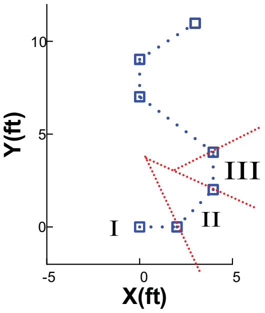


Fig. 3. Training path.

III. CONTROLLERS AND FORCE FEEDBACK

The standard no-slip kinematic model of robot, as discussed in [6], has been used here. The states of the robot satisfy the following differential equation.

$$\begin{pmatrix} \dot{x}_c \\ \dot{y}_c \\ \dot{\theta} \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v \\ \omega \end{pmatrix}}_{Bu} \quad (1)$$

x_c and y_c were the robot's center coordinates and θ was its orientation with respect to the horizontal axis, refer Fig. 4. The translational speed v and the rotational speed ω were the robot's inputs. Line following and point following controllers were used to calculate these inputs to drive the robot.

A. Line Following Controller

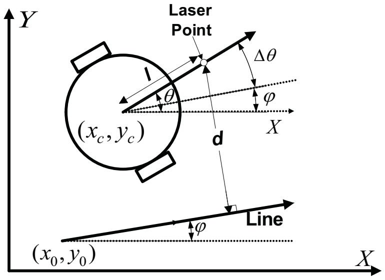


Fig. 4. Schematic of a robot intended to follow a straight line inclined at an angle φ.

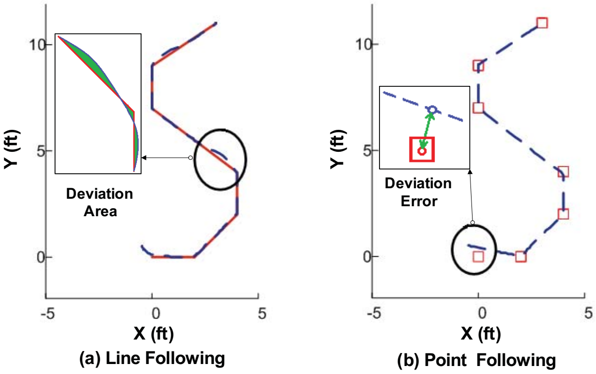
Figure 4 shows the schematic of a robot with the goal to follow a line inclined at an angle φ from the horizontal. The current heading of the robot is shown at an angle $\Delta\theta$ from the line, l is the distance from the robot center to the laser point and d is the normal distance between the laser point and the inclined path. With a representative point (x_m, y_m) on the line, it follows that:

$$d = (y_c + l\sin\theta - y_m)\cos\varphi - (x_c + l\cos\theta - x_m)\sin\varphi \quad (2)$$

The solution to the line following problem with a constant translational speed v_{des} such that $d \to 0$ and $\Delta\theta \to 0$ as time increases is given by Eq. (3), with k_1 as a scaling factor.

$$\left\{ \begin{array}{l} v = v_{des} \\ \omega = -\frac{k_1 d}{l \cos \Delta\theta} - \frac{v_{des}}{l} \tan \Delta\theta \end{array} \right. \tag{3}$$

Figure 5(a) shows the simulation of a path when such a strategy is applied autonomously to a mobile robot.



(a) Line Following

(b) Point Following

Fig. 5. Simulation of the robot trajectory, initial condition $(x, y, \theta) = (-0.5ft, 0.5ft, 0)$, using (a) Line following controller (b) Point following controller.

B. Point Following Controller

The controller proposed in this section uses a potential field to guide a user to the goal point. The potential function (U) was selected from the perspective of achieving only the goal position and not the orientation of the vehicle. The control law proposed by authors in [7] for such problems was used.

$$u = \begin{pmatrix} v \\ \omega \end{pmatrix} = -(K_1 B^T + K_2 F)\nabla U \tag{4}$$

where

$$K_1 = \begin{pmatrix} k_1 & 0 \\ 0 & k_1 \end{pmatrix}, K_2 = \begin{pmatrix} k_2 & 0 \\ 0 & k_2 \end{pmatrix}, k_1, k_2 > 0$$

$$\nabla U = \begin{pmatrix} \frac{\partial U}{\partial x_c} & \frac{\partial U}{\partial y_c} & 0 \end{pmatrix}^T, F = \begin{pmatrix} 0 & 0 & 0 \\ -\sin\theta & \cos\theta & 0 \end{pmatrix}$$

The potential function was chosen such that it was independent of robot orientation and had only one global minimum at goal $\mathbf{p}_g = (x_g, y_g)$, i.e.,

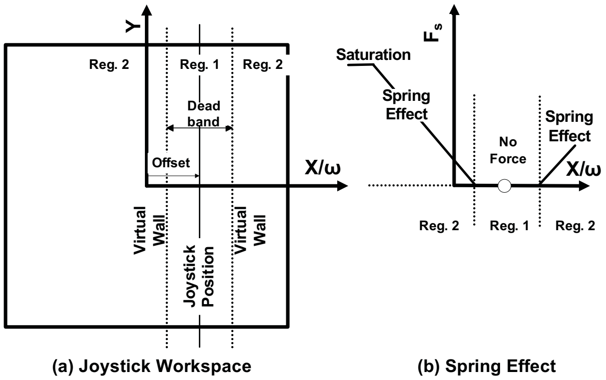
$$U(\mathbf{p}_l) = \frac{1}{2} k_a \left\| \mathbf{p}_l - \mathbf{p}_g \right\|^2 \tag{5}$$

where $\mathbf{p}_l$ is the laser point:

$$\mathbf{p}_l = [x_c + l \cos\theta, y_c + l \sin\theta]^T \tag{6}$$

With these properties, $\frac{\partial U}{\partial x_c} = 0$ and $\frac{\partial U}{\partial y_c} = 0$ if and only if $\mathbf{p}_l = \mathbf{p}_g$, which is true as per our assumption of only one minimum. Figure 5(b) shows the simulation of a path when such a strategy is applied autonomously to a mobile robot.

C. Force Feedback



(a) Joystick Workspace

(b) Spring Effect

Fig. 6. 'Assist as needed' force field.

The control commands for v and ω, computed by the controllers in Eq. (3) and (4), could be viewed as ideal commands for an autonomously driven robot. However, during the experiment an user gave the movement commands through the joystick. Thus, given the mapping of velocity commands to the physical motion of the joystick, the instantaneous force tunnel for the joystick using these ideal v and ω commands can be set. In the current work, robot's angular velocity was correlated with the joystick position in the left-right direction. Robot's translational velocity was not correlated with the joystick position but taken to be the ideal controller output. The left/right joystick position was scaled using maximum value of $\omega_{\max} = 30°/s$.

Figure 6 shows the joystick workspace, where the angular speed predicted by the controller represents the correct joystick position along the X axis shown as Offset, positioning along the Y axis was immaterial. A dead band (10% of the total range) was set around the correct position, i.e., no force feedback in Reg. 1. In Reg. 2, Spring Effect applies a restoring force to bring the joystick handle back to Reg. 1. This force was normal to the virtual wall and proportional to the distance from the wall, such that

$$F_s = k_s \left(x_j - \left(\text{offset} \pm \frac{\text{deadband}}{2} \right) \right) \tag{7}$$

where k_s is the spring constant and was selected to be the maximum allowable value in DirectX. Therefore, the force applied on to the handle was calculated based on the actual and the desired joystick position. This force feedback describes the 'assist as needed' paradigm, i.e., the force increased when the subject deviated further from the designated path. The variation of $|F_s|$ against the joystick position is shown in Fig. 6, where the small circular dot denotes the desired joystick position.

IV. EXPERIMENTAL PROTOCOL

The experiment protocol was approved by the University of Delaware Internal Review Board (IRB) and all subjects were asked to provide their consent. The experiments were conducted with 28 adult subjects (6 females) within 18 to 40 years age range and they were randomly assigned into 4 groups. Each subject participated in the experiment for two consecutive days, and was asked to track the training path as shown in Fig. 3. The data on robot position, joystick movement and total travel time were recorded during the experiment. There were one control and one training groups for each controller algorithm. Control group had 5 subjects and the training group had 9 subjects. Control group indicates that subjects were trained without force feedback, while training group indicates that subjects were trained with force feedback. The force feedback was based on 'assist as needed' paradigm.

Line Following: Subjects from both control and training groups were asked to keep the laser pointer as close as possible to the straight lines joining the way-points. In the training mode, force feedback assisted the driver to track the lines. During the experiment, only the rotation speed was decided by the driver while the forward speed of the robot was kept constant, a safe and challenging value of 0.25m/s was used. This removed the time variability from the data. The *deviation error* was determined by integrating the deviation area from the desired path, as shown in Fig. 5(a).

Point Following: The trajectory for both the control and the training groups comprised only the way-points. Each subject was asked to take the laser pointer as close as possible to each of these way-points. Feedback force assistance during the training mode was such that the robot chose the shortest path between its current and the goal position. During the experiment, only the rotation speed was decided by the driver while the forward speed of the robot was calculated by the controller (maximum limit was taken to be 0.5m/s). During each trial, the closest distance a subject went to each way-point was recorded and the mean of all these values (seven in total) was represented as the *deviation error*, as shown in Fig. 5(b).

The training protocol consisted of the following sessions:

1) *Pre-training*: Trial without any force feedback on Day 1 and 2 to collect the baseline data. Referred as Pre1 and Pre2 in the text.
2) *Training*: Three trials with force feedback on Day 1 and Day 2 to train the subjects. For control groups, this session consisted of trials without any force feedback. For brevity, T1 and T2 were used to imply training session on Day 1 and 2 respectively.
3) *Post-training*: Trial without any force feedback, to access the immediate learning on Day 1 and 2, referred as Post1 and Post2.

Control and training groups for the line following algorithm were called LC and LT respectively. Similarly, PC and PT were used for the point following algorithm groups.

V. RESULTS AND DISCUSSION

Data was analyzed for all 28 subjects. The deviation error data for each group were checked for the normal distribution using the Lilliefors test [15]. Paired t-test procedure was then used to evaluate the effect of training trials on the deviation errors within each algorithm group.

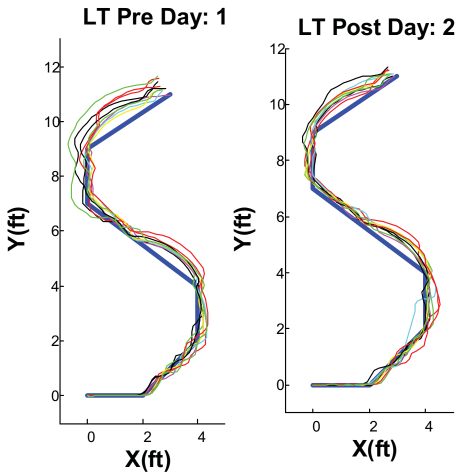


Fig. 7. Pre-training and post-training for the training group using the line following controller.

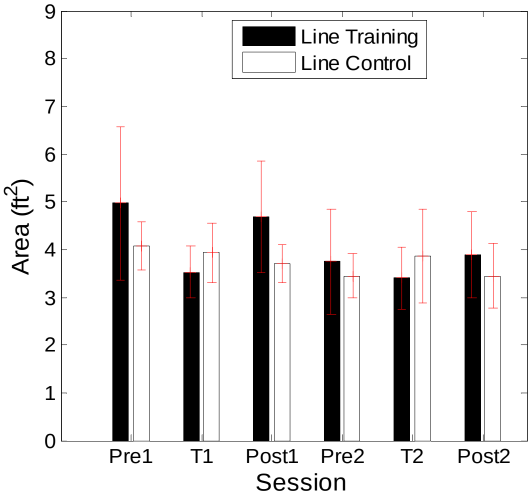


Fig. 8. Deviation errors for groups using the line following controller.

A. Results

Figure 7 and 9 shows the data collected during some of the experimental sessions for both the line and the point following groups. The desired trajectory is shown by dark blue line and squares, while the performance of subjects in each group has been overlaid on it with different colored lines.

Line following: Pre and post-training trials for the training group are shown in Fig. 7. The subjects' performance for post-training session was observed to be consistent. Figure 8 shows the mean deviation error (standard deviation in red) for both training and control groups. Following observations were made:

1) Force feedback led to a significant reduction in the deviation error as observed for sessions T1 and T2 of the training group (paired t-test, $p < 0.02$ between sessions T1 and Pre1; and $p < 0.02$ between sessions T2 and Pre1). For the control group, there were no statistical significant differences.
2) The deviation error on Day 2 pre-training (Pre2) compared to Day 1 pre-training (Pre1) decreased significantly in the training group (paired t-test, $p < 0.02$). This showed that subjects retained the previous day training. For the control group, there were no significant differences.
3) There was a consistent reduction in the deviation error for each subject in the training group as compared to control group.
4) As an aftereffect of training with the force field, the error values for post-training performance were higher compared to the same day training session.

Point Following: Figure 9 shows the pre and post-training trials for the training group. Subjects had less scatter during post-training than during pre-training. Figure 10 shows the mean deviation error (standard deviation in red) for both training and control groups. Following observation were made:

1) There was not any significant improvement in the subjects' driving performance during the training sessions, as no statistical significant reduction in deviation error values were observed.
2) The decrease in the deviation error was observed only for a few subjects.
3) Deviation errors were almost similar for both the control and the training groups during the experiment.

B. Discussion

The experimental results can provide insights to the following questions.

What are the effects of using two different trajectory tracking control algorithms on adult-human learning?

In this study, two commonly used trajectory tracking algorithms were implemented. One tried to minimize the distance of the robot from a line while the other used a potential field to guide the robot to a goal point. How these algorithms affect the learning behavior of adults is discussed as follows:

- *Line following:* In this case, the deviation error was determined by integrating the deviation area throughout a trajectory. This error value gave a measure of subjects' driving performance. A decreasing trend in the deviation error value was observed for the training group. This trend was not observed in the control group. Further, the subjects in the training group also showed retention of the driving skills learned on the previous day as compared to the subjects in the control group.

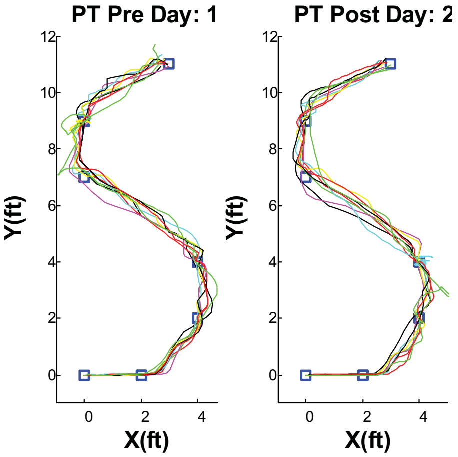


Fig. 9. Pre-training and post-training data for training group using potential field controller.

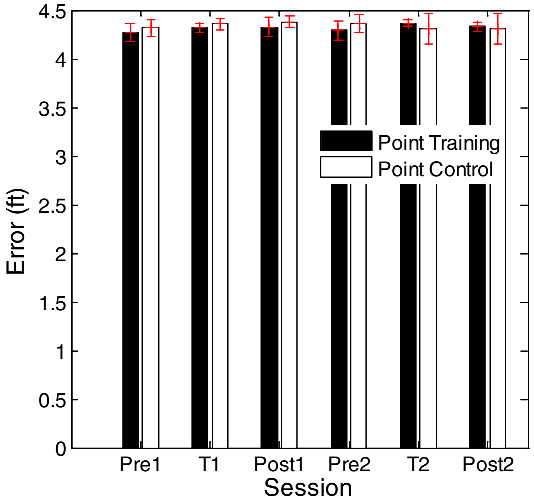


Fig. 10. Deviation errors for groups using point following controller.

- *Point following:* In this case, the deviation error was calculated by averaging the perpendicular distance from each way-point on to the path traversed by a subject. This error value gave a measure of how close a subject went to each way-point. As pointed in the results section, the deviation error for both control and training groups did not show any decreasing or increasing trend. This observation could be related to the robot speed dependence on the controller used. The point following controller provided the speed depending on the distance from the goal point, such that the forward speed decreased around a goal point during the experiment. Thus reducing the level of difficulty while driving the robot.

What are the implications of 'assist as needed' paradigm?

For the training groups, 'assist as needed' paradigm was used, i.e., the joystick provided a bias force based on the actual and the desired joystick position. Therefore, the feedback force rose whenever the subject deviated further from the designated path in an attempt to reduce the error. This approach had two significant implications.

- *Reduced deviation error:* The training protocol of pre-training, training, and post-training sessions with 'assist as needed' paradigm showed decrease in the deviation error for the line following training group.
- *Training after effects:* During post-training sessions of line following group, the deviation error increased when compared to the training sessions. This finding relates to the aftereffect of training, as subjects expected the feedback force during the post-training session as well.

VI. CONCLUSION

In this work, it was observed that the driving performance of healthy adults improved in the presence of force feedback assistance while using the line following control algorithm. Improved subjects' performance on the second day indicated that the subjects were able to retain previous day learning. Therefore, an experimental protocol based on 'assist as needed' paradigm to provide force feedback assistance can be used to train adults necessary driving skills. In future study, mobility impaired adults will be asked to drive the robotic wheelchair using the force feedback joystick. The goal would be to study their driving performances on several trajectories using the 'assist as needed' paradigm.

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