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Design of a Novel Mobility Device Controlled by the Feet Motion of a Standing Child

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***Abstract*—Self-generated mobility is a major contributor to the physical, emotional, cognitive, and social development of infants and toddlers. When young children have disorders that hinder self locomotion, their development is at risk for delay. Independent mobility via traditional power mobility devices may prevent this delay, but do little to encourage the child's development of gross motor skills. This research aims to develop a bio-driven mobile-assistive device that is controlled and driven by moving the feet, which may encourage the development of gross motor skills.**

In this study, system feasibility is shown by experiments on five typically developing toddlers and one special needs toddler with spastic cerebral palsy. Children were placed in the bio-driven device and instructed to navigate through a maze. All subjects were able to successfully complete the maze in multiple trials. Additionally, two toddlers showed evidence of improved driving skill by completing the maze in shorter times in successive trials on a given testing day. The results suggest that such a device is feasible for purposeful driving. Recommendations are given for the device and protocol redesign for related future testing.

I. INTRODUCTION

The development of gross motor skills for independent mobility is a causal factor for many developmental domains, such as cognition, perception, and socialization ([1]–[5]). Certain mobility impairments, such as cerebral palsy and spina bifida, have impacts on a child's physical development and can lead to negative cognitive and psychological consequences [6]. Power mobility is commonly used by special needs children and adults. Recent research on early power mobility training for both typically developing and special needs children suggests that very young children can learn to drive a power wheelchair, even as early as 7 months of age ([7]–[10]).

While it is thought that power mobility may decrease the risk for developmental delay, the gross motor abilities of a child driving a power chair are not addressed within this paradigm. That is, gross motor development continues to be delayed while a child sits in a power chair. To address this problem, children with mobility impairments often have gait training, such as treadmill training, while their leg movements are assisted by a physical therapist [11].

For walking assistance and training, intelligent robotic walkers were developed in recent years for elderly or people with visual impairments to provide weight support through hands and help them navigate and ovoid obstacles ([12], [13]). However, children with severe mobility impairments often need partial weight support through the trunk or hip to walk.

Other options like a pediatric walker [14] are available to help support the body weight so that children with special needs can concentrate on walking. NF-Walker [15] is a passive walker and can help children with severe walking disabilities by restraining the trunk and legs. However, children with mobility impairments using such devices usually show limited walking range, causing their exploration of the environment to be limited. Another hybrid mobility device Standing Dani [16] was recently developed for better muscle and bone development, where children keep a standing posture. However, they have to drive this device either by hand, like a conventional wheelchair, or through a joystick, like a power wheelchair.

Currently, there exists no power mobility device that 1) encourages children to walk and amplify their small body movements into functional and developmentally relevant motions, 2) provides walking training and exercise, and also 3) provides partial body weight support, all so that a child with weak musculature can travel normal distances by moving his feet, rather than a joystick. The aim of this research is to develop a "bio-driven" mobile-assistive device that encourages children to explore the environment while developing gross motor skills by reinforcing large physical movements. Such a device may have positive exercise effects for the child (i.e. potentially improved bone health and cardiopulmonary function over time). Specifically, an infant or a toddler drives this device by minimal leg movement that mimics walking, while sitting in a partially body weight supported seat. The similar idea was also used on our another mobility device made for infants in prone position [17].

This paper is organized as follows: Sec. II gives a system overview of different components. Sec. III presents the detailed design of the walker including considerations of system center of mass to ensure stability and safety. Sec. IV describes a single-camera-marker system used in the human-robot interface. The feasibility of our drive interface is shown by experiments conducted on five typically developing toddlers and one special needs toddler. Results are described in Sec. V.

II. SYSTEM OVERVIEW

Fig. 1 shows the various modules of the walker system. The mobility device used in this research is a commercial robot Pioneer 3-DX from MobileRobots, Inc., which is a two-wheeled differentially driven system with a third passive caster wheel. It is equipped with various sensors such as encoders and sonars (currently not used). It has 23kg payload limit and its dimensions are 44.5cm long × 39.3cm wide × 23.7cm high.

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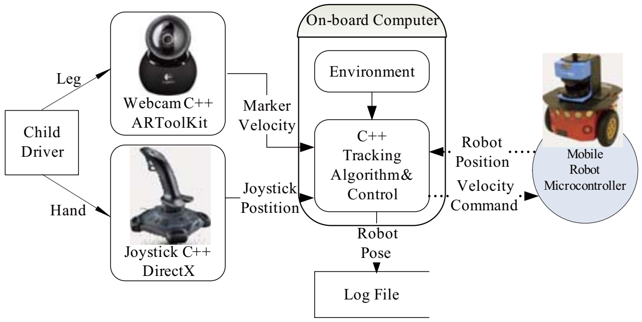

Fig. 1. A schematic of the robot drive interface

An onboard computer runs the Windows XP operating system. The robot platform was controlled by C++ programs which have access to robot pose information and sensors inputs.

This particular robot is driven by the motion of two wheels. The wheels are located on the same axle but are capable of rotating independently. The robot was adapted so that a child can stand on the robot with full or partial body support. In addition, the human-robot interface consisted of a camera and a joystick. The camera was responsible for tracking the child's feet motion, and the joystick acquired rotational velocity. The inputs from the camera and the joystick together controlled the motion of the robot.

III. BASE EXTENSION AND CHILD SUPPORT

The following fixtures were added to Pioneer 3-DX mobile base: (i) an extension base to improve its stability, and (ii) a support seating for the child. These are described in more detail in this section.

A. *Extension of the Robot Base*

Using anthropometric data, the center of gravity and height of an average three-year-old is estimated to be 0.754m and 0.930m from the ground, respectively [18]. The robot base was extended to achieve a higher stability as the child stands on the robot and the center of mass is higher. This extended base was constructed using planks of plywood in the form of triangular trusses and caster wheels. Two sets were made and placed on the left and right sides of the robot. This was done to avoid interference with ultrasonic sensors placed along the periphery of the robot. Two sets of caster wheels were placed on the left and right sides of the robot. With the addition of the extension, the modified dimension of the robot becomes 91.4cm long × 55.9cm wide.

The support base was first placed on top of the robot. Then trusses of the extension base were slid on the top plate of the robot. Each truss also acts as a clamp to secure the extension base to the robot. Finally, the trusses are braced to each other via 22" long bolts (Fig. 2).

Fig. 2. Starting from the base of the Pioneer 3-DX robot, an extension base was added to improve stability so that a child would stand on the robot.

Fig. 3. Full standing design for Pioneer 3-DX robot

B. *Child Support*

A design was then constructed to support a child in the standing position on the robot (Fig. 3). A standing board was constructed from lumber and plywood, given the limited payload of the Pioneer 3-DX model. A playground swing chair was attached to the standing board with nylon ropes and secured through the use of cleats. The chair is height adjustable to accommodate children of approximately 1 meter, roughly 95th percentile height of three years old. The DX model can withstand a payload of only 23kg, which includes the weight of the standing board and the child. With this consideration, a standing board was constructed with the goal of a lightweight but strong design. The final design was capable of supporting a 15.88kg child approximately, the average weight of four years old or the 95th percentile weight of thirty months old. Children can either stomp or swing their legs on the board.

IV. HUMAN ROBOT INTERFACE

In order to make this design "bio-driven", a new control mechanism that involves mimicking a walking motion was necessary for the robot. The movements of the child's feet are used as signals to move the robot. Considering the cost and space constraints, a camera and marker system was chosen. A web camera placed underneath the swing chair can track the motion of 5cm by 5cm square markers attached to each of the child's calves. When the camera recognizes motion of the markers, a signal is sent to the robot to cause forward motion with a speed proportional to the speed of the legs and feet.

Due to the essential difference between walking and differential driving, we did not use this information to accurately control the rotational velocity. To make the robot easy to turn and capable of traveling complicated paths, the rotational motion was controlled by a joystick situated on a small table in front of the child. Thus, forward motion was controlled by feet movement and turning by a hand-controlled joystick. This solution was considered to be low cost and easily implementable.

A. Single-Camera-Marker System

We used ARToolKit [19] as the camera-marker system. ARToolKit is an open-source software library for building Augmented Reality (AR) applications. With the specifically designed marker, the depth information can be extracted by a single camera. Even though it is built for AR, the program is easily adapted to detect the marker position. The features of ARToolKit include:

1) Measurement of depth information with a single camera using specifically designed marker.
2) Requirement of only web camera - while a high quality camera may result in better tracking, a web camera can give satisfactory measurements of velocity.
3) Possibility to track multiple markers simultaneously and detect motion of both feet.

Two specialized markers were chosen from the ARToolKit library and used. The augmented reality software cannot directly track the velocity of a marker, but only the position. As a result, the velocity of each marker must be approximated by numerical differentiation:

$$v_{\mathrm{f}} = \frac{d_{\mathrm{m}}(t+dt) - d_{\mathrm{m}}(t)}{dt} \tag{1}$$

where v_{f} is the foot velocity and $d_{\mathrm{m}}(t)$ is the marker distance to the camera at time t.

The velocity of the robot was linearly proportional to the max velocity of the child's feet, i.e., as the child moves his legs and feet more and faster, the robot moves faster, reinforcing the gross motor skill:

$$v_{\mathrm{r}} = k \max\{v_{\mathrm{lf}}, v_{\mathrm{rf}}\} \tag{2}$$

where v_{r} is the robot translational velocity, k is a constant, v_{lf} and v_{rf} are the left and right foot velocity respectively.

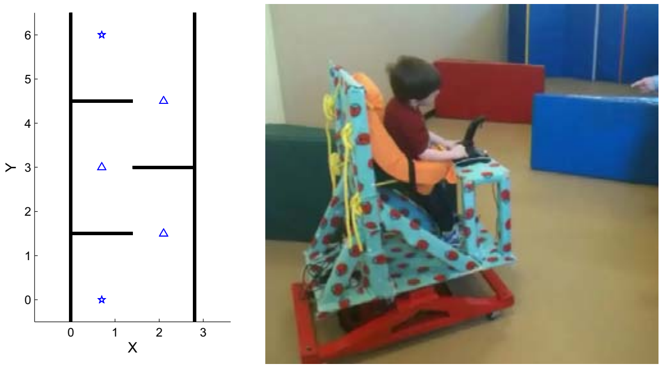

Fig. 4. Training Environment. ☆marks the start and finish points. △ marks the junctions.

The maximum forward velocity was chosen based on the average walking speed of a toddler [20]:

$$v_{max} = 0.4\mathrm{m/s} \tag{3}$$

B. Turning Velocity

We used a commercial joystick from Logitech (Fig. 3) to control the turning velocity ω of the robot. If the infant pushes the joystick handle to the left/right, the robot turns left/right with maximum turning velocity:

$$\omega_{max} = 26°/\mathrm{s} \tag{4}$$

V. SYSTEM FEASIBILITY

The objective of this research was to determine whether or not toddlers can learn to drive a bio-driven mobile-assistive device purposefully and improve their driving skills over time. Five typically developing toddlers, aged 34 to 39 months, and one special needs toddler with spastic cerebral palsy, aged 49 months, used this device at the University of Delaware's Early Learning Center. The special needs toddler had no cognitive delay and was involved in previous related research [9] and thus had certain driving experience using a joystick. Prior to beginning this research, parents of children signed a consent form that was approved by the Institutional Review Board of the University of Delaware.

All of the children were instructed to "march." That is, we told them to pick up their feet and place them back down on the board beneath them. This was more like a "stomping" motion than a gait pattern. A gait pattern would not have been possible for the current device, since there was no treadmill under their feet, but rather a stationary board.

A. Methods

The toddlers were shown and placed in the robot and verbally explained and physically shown how the robot functions. The children were asked to complete a simple maze with barriers constructed from foam wedges. A researcher stood at different junctions of the maze and verbally encouraged the children to complete the task. A birds-eye model and a floor-level view of the maze are show as Fig. 4. The start and finish points are represented by a star and junction points are represented by triangles. The subjects were trained to drive back and forth through the maze.

The robotic onboard computer recorded position and time data every tenth of a second. The path followed by the subjects was plotted for each trial. For the trials where the subject traveled in the opposite direction through the maze, the position plots were reflected about the y-axis for easier visual comparison. The time to completion was also recorded and analyzed for each trial. A total of six trials were recorded for each typically developing subject and ten trials for the special needs subject over the course of several visits. The number of trials completed per day was dependent on the child's ability to be on the robot each day. When a toddler announced that he was done, the trials were continued on another day.

B. Results of Typically Developing Toddlers

Fig. 5 shows the path traveled over six trials of five typically developing toddlers. All the toddlers succeeded during all the six trials. These results suggest that our system is toddler friendly and easy to use to accomplish complex tasks. Note sometimes the path crossed the obstacles since the toddler bumped into the wedges (obstacles) and pushed them away. This can be addressed in the future by combining the robot sensor and obstacle avoiding algorithms.

Fig. 6 shows the travel time over six trials of all the five toddlers. Toddler 3 showed significant linear decrease in the travel time data ($R^2 = 0.8085$, $p = 0.015$). Others were fairly stable and did not show significant sign of improvement. If we consider the average performance of the first two trials and the last two trials, the mean time decreased from 137.34sec to 130.17sec, but not significantly (paired t-test, $p = 0.862$). This could result from several factors. (i) Initially, except for Toddler 3, travel time was already small. The driving skill may not improve significantly in six trials. (ii) Due to the muscle fatigue, the travel time may increase during each day.

Based on our observations, all toddlers were trying to catch breath during the last a couple of trials of each day, suggesting they were getting certain amount of exercise. Note that the mapping between the marker velocity and the robot velocity can be adjusted so that we can control how much effort a toddler must exert to drive the robot. In other words, we can adjust the exercise intensity.

C. Results of a Special Needs Toddler

Toddler 6 was a four years old special needs male with cerebral palsy. Because the research is ultimately focused on developing devices to assist special needs children, more attention was given to this subject. This child had full passive range of motion in both arms and legs; however, all limbs had limited active range of motion and displayed spasticity and stiffness. He also had difficulty initiating and isolating movements. He was unable to crawl but could produce steps with a walker with moderate assistance to remain upright, steer, and turn. The child had previous experience of driving a power mobility device using a joystick. He was able to quickly adapt to the new driving method using our device. He also showed great joy during the driving.

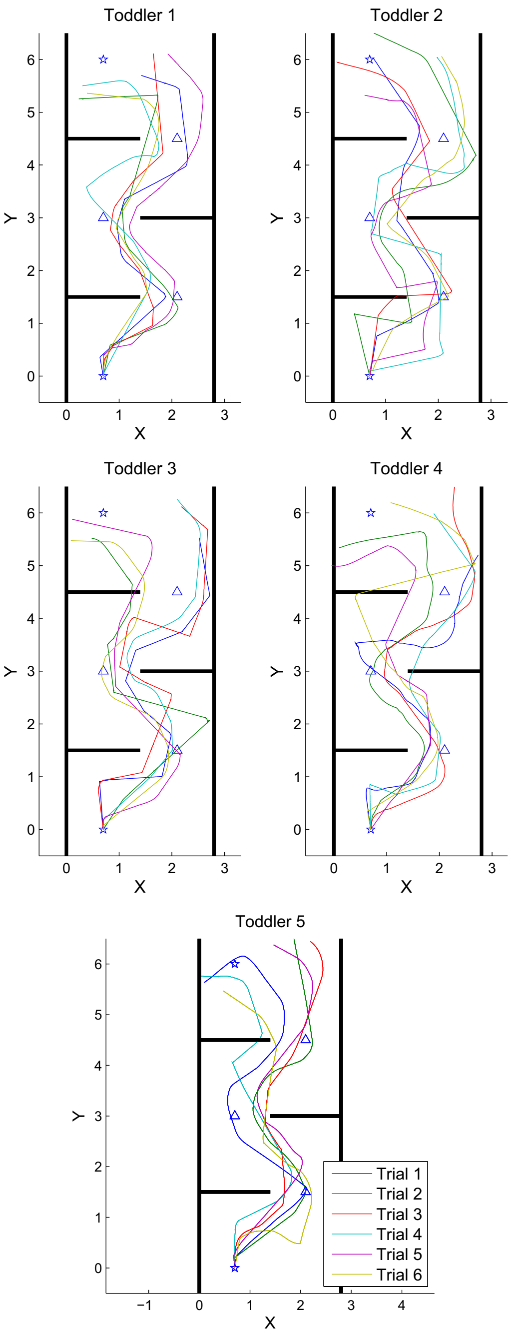

Fig. 5. Path traveled over six trials of five toddlers

This subject conducted ten trials and successfully completed all of them (Fig. 7). He was able to finish six trials during the first day and the rest four during the second day.

The times to completion for Toddler 6 ranged from 136sec to 648sec. This is the largest range exhibited by any of the six toddlers. This is as expected, considering the mobility impairment of Toddler 6. Interestingly, for Toddler 6 with previous experience of driving, the quickest time to completion

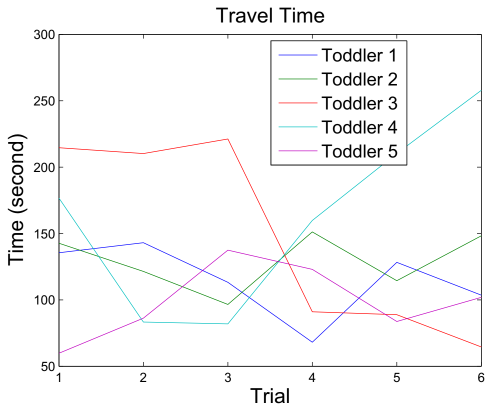

Fig. 6. Time taken for each trial versus trial number for five toddlers

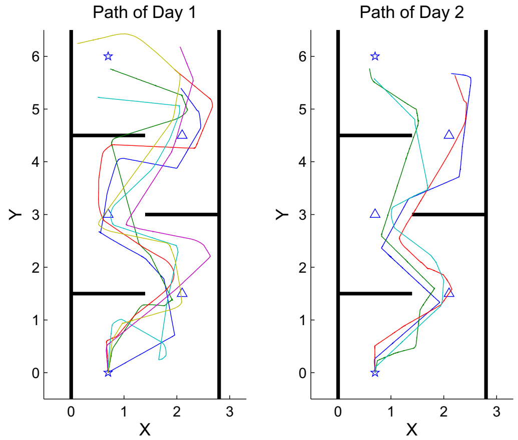

Fig. 7. Path traveled over ten trials of Toddler 6

was comparable to some of the trial times posted by the typically developing toddlers. This suggests that Toddler 6 is not necessarily as hindered in driving the mobile-assistive device as one might initially believe.

The time data did not show improvement over ten trials (Fig. 8). However, if we examine the results from each day of testing separately, we observe significant decrease in travel time. This can be seen from the linear regression results. Each trend line has a negative slope.

All four trial times from the second day of testing are longer than the six trials from the first day of testing. Factors such as fatigue, muscle tension, and task attractiveness may have had an effect on the toddler's ability to move his legs and his range of motion on the second day of testing, resulting in the slower times. Additionally, the trends exhibited on the two days of testing support the toddler's ability to retain driving ability between the two days. The slope of the trend line steepened from -40.45 to -100.86 from the first day to the second day, respectively. This increase, and more than doubling, in magnitude of slope of the trend line suggests that Toddler 6 became more adept at driving more quickly on the second day of testing.

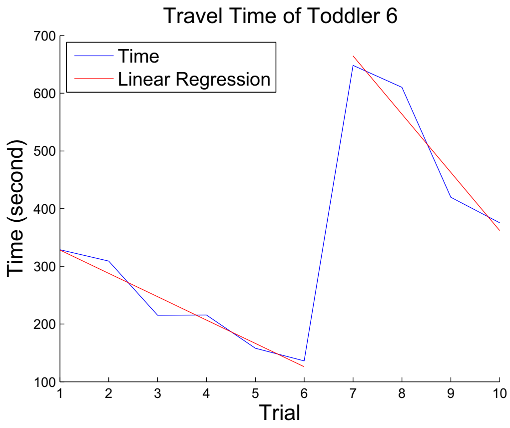

Fig. 8. Time taken for each trial for Toddler 6. The red lines show linear regression results with slope -40.45 and -100.86.

VI. Discussion and Conclusion

The main objective of this research was to develop a useful pediatric, bio-driven, mobile-assistive device. The novel driving interface of the mobile robot, activated by feet motion, was successfully used by six toddlers to independently move around in a maze. We believe that the integration of marker-camera system, as opposed to joysticks found in conventional powered wheelchairs, can be more accessible to toddlers, as movements of the feet require less fine motor skills. The proposed drive interface simultaneously provides an opportunity for exercise and allows children to explore their environment, just as they would in a power chair.

The feasibility of this interface was evaluated by experiments on five typically developing toddlers and one toddler with mobility impairment. All of the children were able to purposefully drive the device and successfully navigate through the maze for a number of trials. This suggests that the device is relatively intuitive or easy for the children to drive. Each child was able to activate and drive the robot, and to coordinate both leg movement and arm movement without extensive training.

The promising results of this experimentation with the initial device encourage further developing and testing. Several changes could be made to the device to improve its function and application to the "real world" setting for children, i.e., the preschool classroom, the gym, outdoors, and the home. The overall system can be redesigned to reduce its size. Additionally, a more powerful camera with a faster frame rate could improve the resolution and accuracy of the marker velocity approximations. In the future, it may be beneficial to remove the joystick entirely from the device. Instead of using a joystick, a child could drive by turning or leaning his or her torso in an indicated direction. Such a control mechanism would further encourage physical development for the children. Finally, for some children with mobility impairment such as spasticity, an "adductor bar" can be added to the device to help them move their legs without "scissoring", that is, crossing their legs during walking.

Additionally, long-term developmental effects of driving the device may be assessed by administering standardized developmental tests, such as the Bayley Developmental Assessment Test, before, during and after driving training. To demonstrate short-term effects of driving, we can measure the child's heart rate or breathing rate before and during testing to assess whether the device is providing adequate exercise for the child. In summary, we hope to explore the various relationships between children's ability to drive the device, the amount of time they drive, and changes in their gross motor skill function that may correlate with driving experience.

VII. ACKNOWLEDGMENT

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