

EVALUATION OF THE HEPHAESTUS SMART WHEELCHAIR SYSTEM

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ABSTRACT

Hephaestus, the Greek god of fire, craftsmen and smiths was the only Olympian with a disability. Hephaestus was injured when his father, Zeus, flung him off Mount Olympus for siding against Zeus in a dispute with Hephaestus' mother, Hera. To compensate for his disability Hephaestus built two robots, one silver and one gold, to transport him. The Hephaestus Smart Wheelchair System is envisioned as a series of components that clinicians and wheelchair manufacturers will be able to attach to standard power wheelchairs to convert them into "Smart Wheelchairs." This paper describes a prototype of the system and presents the results from preliminary user trials involving both able-bodied and disabled subjects.

BACKGROUND

Independent mobility is critical to individuals of any age. While the

needs of many individuals with disabilities can be satisfied with power wheelchairs, there exists a significant segment of the disabled community who find it difficult or impossible to operate a standard power wheelchair. This population includes, but is not limited to, individuals with low vision, visual field neglect, spasticity, tremors, or cognitive deficits.

To accommodate this population, several researchers have used technologies originally developed for mobile robots to create "Smart Wheelchairs." Smart wheelchairs typically consist of a standard power wheelchair base to which a computer and a collection of sensors have been added. Smart wheelchairs have been designed which provide navigation assistance to the user in a number of different ways, such as assuring collision-free travel, aiding the performance of specific tasks (e.g.,

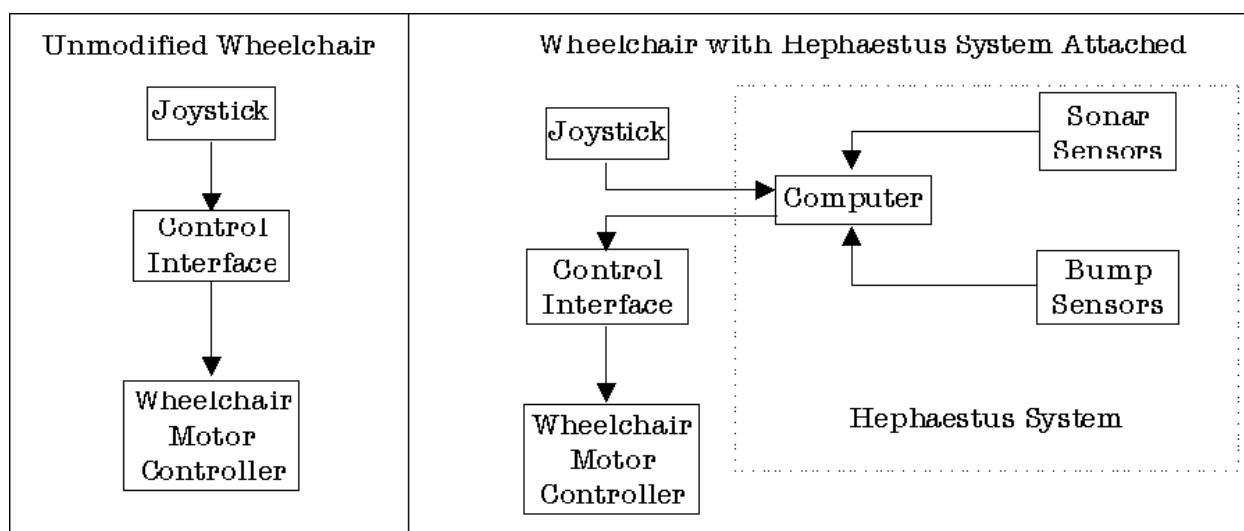


Figure 1. Overview of Hephaestus Smart Wheelchair System

Table 1. Questions (and associated extreme answers) given to each subject

Question #	Question	Leftmost Extreme	Rightmost Extreme
1	How difficult was the task when the wheelchair did not provide navigation assistance?	Not difficult at all	Very difficult
2	How difficult was the task when the wheelchair did provide navigation assistance?	Not difficult at all	Very difficult
3	How noticeable was the navigation assistance?	Not noticeable at all	Very noticeable
4	How often did you disagree with the assistance provided by the wheelchair?	Never	All the time
5	How helpful was the navigation assistance provided by the wheelchair?	Not helpful at all	Very helpful
6	What effect did the presence of navigation assistance have on your performance?	Positive effect	Negative effect
7	Which condition did you prefer?	Navigation assistance	No navigation assistance

passing through doorways), and autonomously transporting the user between locations.

We are developing a system for converting standard power wheelchairs into smart wheelchairs, called the Hephaestus Smart Wheelchair System. Wheelchairs equipped with the Hephaestus System will be able to assist users in two distinct ways: as a *mobility aid*, the smart wheelchair will present users with an immediate opportunity for independent mobility, and as a *training tool*, the smart wheelchair will allow users to safely develop and refine the skills necessary to operate a power wheelchair without the need for technological assistance. Thus far, a working prototype of the system has been developed using an Everest and Jennings¹ Lancer2000 power wheelchair as a testbed. The prototype requires no modifications to the wheelchair's electronics or motors (making it easy to install the system or transfer the system between wheelchairs) and bases its navigation assistance behavior on the navigation assistance behavior developed for the

NavChair Assistive Wheelchair Navigation System [1].

IMPLEMENTATION

Figure 1 gives an overview of the Hephaestus system. As shown in the figure, the Hephaestus system interrupts the connection between the joystick and the controls interface. The user's joystick input is intercepted by the computer, modified by the navigation assistance software, and then sent to the control interface in a manner transparent to both the user and the wheelchair.

The prototype accepts input from a standard analog joystick that, in unmodified power wheelchairs, connects directly to the E&J Specialty Controls Interface (EJSCI), which provides an interface between the wheelchair and a set of potential input and display units. On the Hephaestus prototype, the cord connecting the wheelchair joystick and the EJSCI has been cut in two, to allow the Hephaestus system to intercept and modify the user's joystick inputs. The only other physical modifications made to the wheelchair were the addition of a lap tray to provide a surface to mount sonar sensors and an electrical connection made to the wheelchair's

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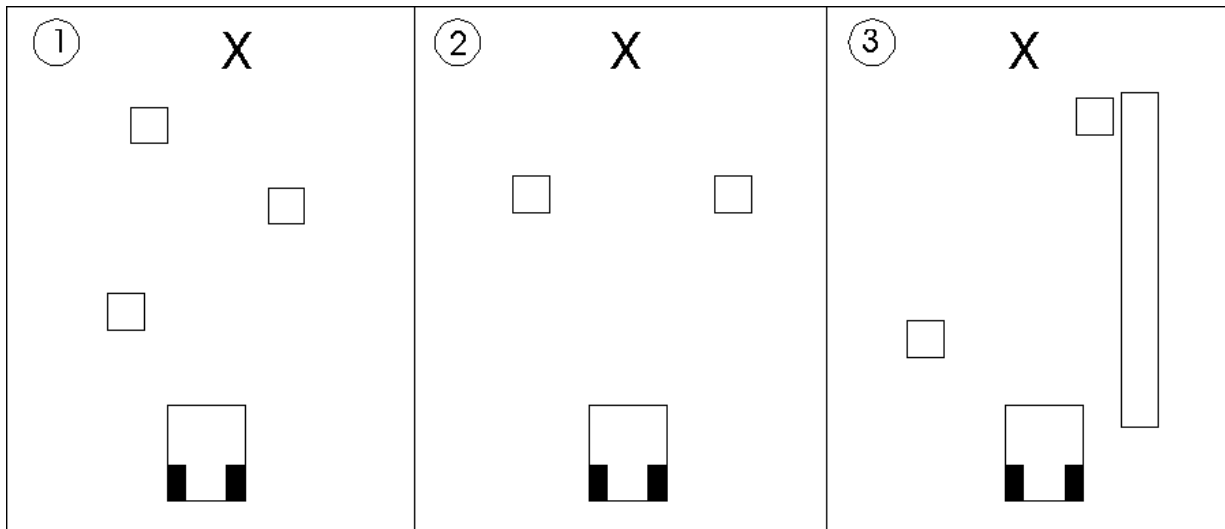


Figure 2. Experimental Tasks for User Trials. Each subject performed each task eight times -- four times with navigation assistance, four times without navigation assistance.

batteries to provide power for the sonar sensors.

The Hephaestus system currently makes use of sixteen sonar sensors (configured to detect obstacles a maximum distance of one meter from the wheelchair and a minimum distance of 8 centimeters from the wheelchair). Thirteen sonar sensors are mounted on the lap tray facing forward or to the side of the wheelchair and three sonar sensors are on the battery box facing backwards. Currently, the prototype has two “blind spots,” one on each side of the chair near the middle of the wheelchair. These blind spots make it possible to collide with an obstacle, despite the navigation assistance provided by the smart wheelchair system, by pulling up next to an obstacle and pushing the joystick directly to the side towards the obstacle.

Bump sensors represent the “sensors of last resort” on the smart wheelchair. When a bump sensor is activated it brings the chair to an immediate halt. Bump sensing is implemented using

simple contact switches placed on the leading edges of the wheelchair. In the prototype system, up to 24 switches can be mounted on any available surface on the wheelchair.

METHODS

An evaluation of the prototype was performed using both able-bodied and disabled participants. All subjects were asked to perform the same three distinct tasks under two conditions: navigation assistance active (condition NAA) and navigation assistance inactive (condition NAI). When navigation assistance was not active, the wheelchair behaved exactly like a normal power wheelchair. Performance was compared between conditions based on (1) quantitative measures of the chair's behavior and (2) subjective responses to questionnaires completed by each subject upon completion of all trials.

The configuration of the wheelchair was fixed for all four able-bodied subjects. Following the trials involving able-bodied subjects, modifications were made in response to feedback from the subjects during their trials.

Table 2. Experimental Measures of Performance

Parameter	Explanation	Units
Time	Time required to complete task	Seconds
Collisions	Total number of collisions that occurred in a trial	NA
Success	Did subject successfully complete the task within the time limit (two minutes)	NA

The configuration of the wheelchair was not kept constant for the four disabled subjects. Each subject required different seating and positioning interventions, different joystick placements, and different settings of the wheelchair's velocity and acceleration parameters. The changes required by each disabled participant underscored the diversity of the target user population.

Several results were expected based on investigators' previous experience with the NavChair Assistive Wheelchair Navigation System [2]. Able-bodied subjects were expected to take longer to complete the experimental tasks with navigation assistance than without and to prefer to operate the chair without navigation assistance. The variety of abilities within the small sample of disabled subjects made it impossible to predict the impact of the system on their performance. What was expected was a highly subject-dependent effect of navigation assistance for disabled subjects.

Subjects

Eight subjects (four able-bodied, four disabled) participated in the user trials. All able-bodied subjects had no sensory, motor, or cognitive disabilities that interfered with their ability to operate a power wheelchair. The four disabled subjects were drawn from the local population. Three of the subjects were diagnosed with cerebral palsy, the fourth was diagnosed with post-polio syndrome. None of the able-bodied subjects had previous experience with a power wheelchair. The four disabled

subjects had extremely diverse previous experience with power wheelchairs, ranging from daily use to limited previous experience.

Protocol

Before the experiment, each subject received instructions and training to familiarize them with the purpose of the experiment and the operation of the smart wheelchair. Subjects began by driving the wheelchair without navigation assistance active to familiarize themselves with the wheelchair. Once subjects reported that they understood how the wheelchair operated without navigation assistance, navigation assistance was activated and subjects were again instructed to drive the chair around the testing area until they were comfortable operating the wheelchair. During training, obstacles were placed in the testing area but they were not in any of the configurations used during trials.

After training, subjects completed the three navigation tasks shown in Figure 2. Each subject completed each task eight times (corresponding to eight separate trials). The order of experimental condition (navigation assistance active, navigation assistance inactive) was counterbalanced across subjects, but all four trials for each condition were performed in succession. The order of tasks was the same for all subjects.

Before each task, subjects were given instructions on how to complete the task, including the path of travel they should follow and their target destination. Before each trial, the

Table 3. Results from user trials, averaged within each subject. NAA = Navigation Assistance Active, NAI = Navigation Assistance Inactive

Subj	Task	Condition	Time	Collisions	Success	Subj	Task	Condition	Time	Collisions	Success
1	1	NAA	36.59	0.00	100	5	1	NAA	18.27	0.00	100
		NAI	18.86	0.00	100			NAI	18.66	0.00	100
	2	NAA	36.59	0.00	100		2	NAA	21.39	0.00	100
		NAI	14.97	0.00	100			NAI	14.10	0.00	100
	3	NAA	18.45	0.00	100		3	NAA	16.70	0.00	100
		NAI	17.82	0.00	100			NAI	15.90	0.00	100
2	1	NAA	18.06	0.00	100	6	1	NAA	71.67	0.25	50
		NAI	14.50	0.00	100			NAI	51.29	0.00	100
	2	NAA	48.08	0.00	100		2	NAA	45.15	0.00	100
		NAI	12.91	0.00	100			NAI	41.79	0.00	100
	3	NAA	15.85	0.00	100		3	NAA	37.75	0.25	100
		NAI	13.48	0.00	100			NAI	55.82	1.50	100
3	1	NAA	21.09	0.00	100	7	1	NAA	52.92	0.00	100
		NAI	15.33	0.00	100			NAI	21.69	0.00	100
	2	NAA	36.67	0.00	100		2	NAA	43.13	0.00	100
		NAI	12.73	0.00	100			NAI	15.54	0.00	100
	3	NAA	14.04	0.00	100		3	NAA	19.53	0.00	100
		NAI	13.47	0.00	100			NAI	11.13	0.00	100
4	1	NAA	29.25	0.00	100	8	1	NAA	13.13	0.00	100
		NAI	14.02	0.00	100			NAI	12.37	0.00	100
	2	NAA	28.11	0.00	100		2	NAA	12.37	0.00	100
		NAI	13.25	0.00	100			NAI	10.05	0.00	100
	3	NAA	14.10	0.00	100		3	NAA	13.66	0.00	100
		NAI	13.43	0.00	100			NAI	11.06	0.00	100

wheelchair was positioned in the same starting location and subjects navigated to the same ending location. Subjects were given two minutes to complete each trial.

After all trials were completed, subjects were asked to fill out a questionnaire on their subjective impression of each condition. All responses were given by placing marks on a line four inches long. At each end of the line for a question were vertical markers with phrases indicating extreme answers to the question being asked. Subjects' answers were converted to numerical scores between 1 and 5 by measuring the distance of the subject's mark from the leftmost extreme of the scale (which corresponded to an answer of 1.0). A mark on the rightmost extreme

corresponded to an answer of 5.0 and a neutral answer (placed exactly between the two extremes) corresponded to an answer of 3.0. Table 1 lists each question and associated extreme.

The performance measures used in this experiment are shown in Table 2. Data for all measures was compared between subjects using a two-factor (navigation assistance condition, trial) repeated-measures ANOVA for each experimental measure. Statistical significance for all comparisons was defined as $p < .05$.

RESULTS

Table 3 shows the results for all subjects. As can be seen from the table, able-bodied subjects were consistently faster without navigation assistance active. The difference in

Table 4. Averages of Responses to the Questionnaire. 1.0 was the leftmost extreme, 3.0 was the neutral answer, 5.0 was the rightmost extreme.

Question #	Able-Bodied Subjects		Disabled Subjects		All Subjects	
	Avg	95% conf. int.	Avg	95% conf. int.	Avg	95% conf. int.
1	1.97	[1.36, 2.57]	1.54	[1.17, 1.91]	1.75	[1.39, 2.12]
2	2.62	[1.43, 3.80]	2.77	[1.47, 4.08]	2.70	[1.88, 3.51]
3	3.74	[2.78, 4.70]	3.97	[2.85, 5.00]	3.86	[3.17, 4.54]
4	1.53	[1.13, 1.94]	1.95	[1.15, 2.76]	1.74	[1.30, 2.19]
5	3.29	[2.11, 4.47]	3.73	[2.22, 5.00]	3.51	[2.61, 4.42]
6	3.35	[2.93, 3.78]	1.87	[0.98, 2.75]	2.61	[1.90, 3.32]
7	4.25	[3.59, 4.91]	2.13	[1.20, 3.05]	3.19	[2.24, 4.13]

time between conditions for able-bodied subjects was significant for Task 2, but was not significant for Tasks 1 and 3. For able-bodied subjects, the effect of subject was statistically significant for Tasks 1 and 3 but was not significant for Task 2.

Table 3 also shows the variation in the performance of the four subjects with disabilities. For the disabled subject group, the effects of subject was significant for all three tasks. There was not a significant difference for any other measure for this group on any of the tasks. It should be noted that one subject (Subject 6) did collide with two obstacles.

Table 4 shows the average responses to the questionnaire. As expected, the able-bodied subjects preferred the navigation assistance inactive (NAI) condition (questions 6 and 7). The disabled subjects preferred the navigation assistance active (NAA) condition, despite the fact that it typically did not lead to immediate improvements in performance. When questioned further, subjects indicated that they liked the sense of security that the system provided and expected to achieve better performance given more time to learn to operate the system.

CONCLUSION

The results of the user trials conformed to our expectations. Because able-bodied subjects were able to complete

the tasks without any assistance from the Hephaestus system, its attempts to modify their input were viewed as intrusive rather than helpful. The Hephaestus system reduces the wheelchair's speed in the presence of obstacles, which caused most subjects to take longer to complete the experimental tasks. This was a source of annoyance for able-bodied subjects but not for disabled subjects, who preferred the added security that obstacle avoidance provided.

Many wheelchair navigation accidents are not caused by a lack of skill, but rather by a lapse in concentration and an inability to correct in a timely manner. These are the types of accidents that the smart wheelchair is most effective at correcting but are most difficult to reproduce in laboratory trials, when subjects are likely to be devoting their full attention to the navigation task. This is the primary reason why subjects with disabilities were willing to accept additional time to complete a task in exchange for increased safety provided by the Hephaestus System's constant vigilance.

The trials involving subjects with disabilities exposed two flaws in our experimental design. First, the three separate tasks were each too short and simple to draw out differences between operating the wheelchair with and

without navigation assistance. Second, subjects with disabilities did not receive enough training prior to trials. This was particularly important for the subjects with poor motor control (subjects 6 and 7), both of whom lacked experience operating a power wheelchair. Both subjects continued to improve throughout the course of the experiment (both subjects took significantly less time to complete Task 3 on average than Task 1) which indicates that neither subject reached a plateau during training.

Future experimental evaluations are planned which will incorporate the lessons learned in these preliminary user trials. More subjects will be involved, and each subject (particularly those with limited wheelchair experience) will receive extensive training prior to actual trials. The number of trials will be increased and will be spread out over several sessions, to allow subjects to receive significant experience with the Hephaestus System. The experimental tasks will also be altered to be more complex and realistic. Instead of three separate tasks, subjects will be asked to complete one complex navigation task.

The primary shortcomings in the prototype that were identified during the user trials were (1) the delay between input and response caused by the navigation assistance algorithm, particularly when obstacles were located near the wheelchair, and (2) difficulty passing between narrowly-spaced obstacles. This feedback was used to modify the parameters of the navigation assistance algorithm (but not the algorithm itself) to increase the system's responsiveness and to reduce the minimum gap the system can pass through to 76.2 cm (30 in).

ACKNOWLEDGMENTS

This research was funded by a Phase I SBIR grant from the National Center for Medical Rehabilitation Research of the National Institutes of Health. The Lancer2000 wheelchair was donated to TRAC Labs by Everest & Jennings.

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