Hands-free Wheelchair Navigation Based on Egocentric Computer Vision: A Usability Study

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***Abstract*—**

People who suffer from impaired upper-limb mobility find a conventional joystick-controlled powered wheelchair difficult or impossible to drive. Thus, several alternative, hands-free methods for controlling the wheelchair via the chin, the tongue, voice commands, and eye tracking have been developed. A recent method relies on an egocentric camera as the primary sensor and on computer vision technology to track the user's head motion and translate it to control signals for the wheelchair. In this paper, we evaluate this vision-based wheelchair control approach by conducting a two-round comparative usability study with 21 subjects. In each round, the subjects were required to navigate a powered wheelchair using the vision-based approach through an indoor test area. The subjects also navigated the same route using two baseline approaches: chin-based control, which is a commonly-used hands-free alternative, and manual joystick control, which is the most widely used method for driving a powered wheelchair, but requires hand functionality. We propose to use joystick control as a reference that is available to all researchers in this area. By comparing their methods to manual control, the results of studies such as ours would be immediately comparable to each other. While we do not expect hands-free control methods to enable faster navigation times compared to joystick control, the loss of efficiency can be use to quantify the effectiveness of alternative methods. Our quantitative and qualitative results show that the vision-based control approach is viable for hands-free indoor use. Moreover, the improvement in performance in the second round using our method provides evidence that users can close the gap to joystick control with practice.

I. INTRODUCTION

Powered wheelchairs are among the most commonly used assistive devices, especially for people with certain motor impairments. An estimated 1% of the world's population requires a wheelchair, regardless of whether they have access to one. According to the 2010 census, there are 3.6 million wheelchair users in the US, while approximately 49% of older adults in Canadian institutional settings use a wheelchair [31]. Wheelchair users in Europe are estimated to be in the 5 million range, with 2 million of these users suffering from reduced upper-limb motor control and having to control their wheelchairs via alternative interfaces [4]. Different studies have shown that 10% of wheelchair users require help while operating their manually-controlled wheelchairs and around 40% of users had difficulties in steering and maneuvering tasks using a powered wheelchair [7].

Most powered wheelchairs on the market are designed to be controlled through a joystick. However, people who have limited or no upper limb mobility, for instance, people who suffer from cervical spinal cord injury, or people who injured their arms and legs in an accident, may not be able to control the wheelchair via the joystick.

Research on hands-free wheelchair control is extensive. In order to achieve hands-free control, several methods, such as sip-n-puff [6], electrophysiological signal measurements [1], [3], chin-operated joystick [19], head-tilt [5], [25], tongue-operated controller [16], gaze [14], and voice control [9], [26] have been developed. However, some of them depend on specially designed hardware (e.g. sip-n-puff); some are unnatural from the human interaction perspective (e.g. tongue control); while most of them suffer from low precision due to discrete input. That is, only a small number of commands, typically less than ten can be generated from the input device and passed to the controller. Our method, on the other hand, generates continuous speed and orientation commands.

This paper presents a usability study complementing prior research on a vision-based robotic wheelchair control system that provides a hands-free control capability. The user's head-motion is detected through a head-mounted, outward-facing web-camera, as in our previous work [18]. The wheelchair moves according to the sensed head-motion of its user. Compared to chin-based or tongue-based control, a major advantage of the vision-based method is that its users do not make physical contact with the joystick. The camera is outward-facing and shares the field of view of the user. This configuration is often called "egocentric" or "first-person".

An evaluation on 21 subjects in a two-round test for the vision-based control approach was conducted along with two baseline control approaches: chin-based control, in which a modified mechanical joystick is placed below the user's chin so that the user can drive the wheelchair using head-motion, and manual control, in which the user operates a regular joystick. We treat the latter as a reference method and aim to establish relative performance with respect to manual control as a criterion for assessing the effectiveness of alternative control methodologies. We do not expect hands-free methods to be faster than the reference, but we expect that research groups will be able to test their methods against this common baseline. The evaluation was repeated twice to investigate whether users improve with practice. After each round, a survey was conducted to collect subjects' feeling and comments about the navigation.

The main contributions of this paper include:

1) the use of conventional joystick control as a reference

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for evaluating different approaches for wheelchair control leading to a well-understood, universal criterion which will hopefully be adopted by the research community;

2) a two-round user study indicating that the proposed vision-based method is viable, since comparisons to two baseline approaches, both of which rely on a mechanical joystick, show a moderate loss of navigation speed between 10-20%;
3) an analysis of quantitative and qualitative results of the above study showing that user performance improves with time and that users gave more positive evaluation to the vision-base control approach as they got more familiar with it.

II. RELATED WORK

In this section, we review hands-free technologies for wheelchair navigation and relevant usability studies, especially focusing on methods that do not need users to physically contact a mechanical joystick. Fully autonomous navigation by the robot is out of scope here.

A. *Hands-free wheelchair control methods*

Many hands-free wheelchair control methods have been developed as alternatives to manual control. Some of them have been commercially applied, while others are still confined in research laboratories.

Sip-n-puff is an early method for controlling a wheelchair for severely disabled users who have limited head-mobility [6]. Its drawback is that it disrupts the user's breath because commands are given by "sipping" or "puffing" in a pneumatic tube. Methods based on the use of the chin or tongue were also among the first alternatives for controlling a wheelchair. In early work by Lipskin [19], a re-designed joystick is placed below the wheelchair user's chin, allowing the user to control the wheelchair. However, the customized joystick may still cause fatigue to the user's neck and facial muscles as it is a mechanical device on which the user must apply force. Tongue motion can be detected via contact with a small oral mechanical joystick, or more recently with electronic sensors, such as acoustic [22], inductive [21] and magnetic [12], [16] sensors. The need, however, for the user to wear special mouthguards or externally visible magnets is a limitation of these methods.

Voice control is among the hands-free solutions. Voice recognition technology [9], [26], which requires only a microphone and a computer in terms of hardware, has recently demonstrated reliable performance in general. Users can utter short phrases, such as "move forward", to give commands. The challenges of this approach are, firstly, that the commands must be discrete leading to jagged behavior of the wheelchair, secondly, that the system may receive accidental commands during conversation and, thirdly, delay between speech and its interpretation.

Technologies that sense neuromuscular activation have also been investigated. For example, electromyography, which measures muscular activity [11], [34], [8], [35] electrooculography, which measures eye movements [1], [34], [35] and electroencephalography, which measures brain activity [20], [8], [3] can all be used for detecting user's intention for wheelchair control. These methods have great potential to help severely disabled individuals with very limited mobility. However, only a very small number of discrete commands are available to the user and these interfaces require his or her full attention. Furthermore, mastering a brain-computer interface (BCI) requires extensive training over a period of weeks or months to generate stable volitional control [3].

Since our primary focus is to develop a hands-free solution for quadriplegic patients, research using head-motion as the input is of great interest to us. Head-motion is a natural way to control a wheelchair by mapping it to wheelchair motion. One technology for sensing head pose is via the use of tilt sensors, such as those found on most smartphones [5], [25].

Alternatively, head-motion can be measured by cameras. Vision-based approaches can be categorized as inward-facing, in which the camera is fixed on the wheelchair focusing the user's face [13], [14], [28], [37], and outward-facing or egocentric, in which the camera faces the environment [10], [15], [18]. Jia et al. [13] map facial gestures to commands by tracking facial features of the user. Purwanto et al. [28] use the pan angle of the gaze and eye blinks to control the wheelchair. In a similar approach, Ju et al. [14] use the inclination of the user's face to determine the direction of the wheelchair and the shape of the user's mouth for moving forwards and stopping. Rechy-Ramirez and Hu [30] detect four head motions and two facial gestures, which are converted to commands for the robotic wheelchair. Xu et al.'s wheelchair [37] receives input from the gaze of the user. Sensors mounted on the wheelchair, as well as markers and beacons placed in the scene, are combined for navigation and obstacle avoidance.

Research on outward-facing cameras is more recent due to the challenges associated with interpreting images of a dynamic environment under potentially unpredictable illumination. Halawani et al. [10] argue that an outward-facing camera is superior to an inward-facing one in terms of tracking resolution due to its wider field of view. They mount a web-camera on the user's hat and orient it downwards to capture the user's clothes and the wheelchair so that the observed motion is due to head-motion rather than wheelchair-motion. Five discrete commands are activated based on the estimated motion of the web-camera. The approach of Kim et al. [15] is also realted to our work. They present a robotic wheelchair with a pan-tilt-zoom (PTZ) camera and utilize special visual markers, which contain black-peaks that move according to the viewing angle. Hence, with the help of these special markers, the robotic wheelchair can localize itself more accurately to complete challenging tasks, e.g. passing through a door.

Our method is built upon the work of Li et al. [18], which is based on a head-mounted, forward-facing camera. To address the difficulties of motion estimation in a dynamic environment, it relies on a fiducial marker mounted on the wheelchair itself to estimate the motion of the user's head relative to the wheelchair frame. Compared to the method of Kim et al. [15], it does not require instrumentation of the scene, but relies on visual loop-closure techniques to localize itself in the map. The other important aspect of [18] is that camera motion is translated to continuous direction and speed commands for the robotic wheelchair, as opposed to the majority of related work that generates discrete commands from the user's input.

B. *Usability studies for hands-free wheelchair control*

We now turn our attention to usability studies of powered wheelchairs. Many of the papers surveyed above included rather small usability studies with no more than ten subjects. However, there are a few exceptions including the system of [14] was tested on 34 subjects, half of whom were disabled, and the system of [8] was tested on 25 subjects.

Parikh et al. [27] conducted a study on 50 subjects comparing three paradigms for navigating an intelligent wheelchair: a deliberate mode in which motion plans are made a priori based on maps and other information, a reactive mode in which obstacles are detected by the sensors and avoided using reactive controllers, and a manual mode in which the user drives using the joystick. Based on these modes three levels of operation were evaluated: autonomous control that combines the deliberate and reactive modes, manual control with the reactive controllers for collision avoidance and semi-autonomous control that combines all three modes. The effort required by the user varies with the level of operation as expected; autonomous control leads to the fastest completion times, while semi-autonomous control is the slowest, but the differences are small.

Boucher et al. [2] designed a robotic wheelchair that can be controlled in multiple ways, including via discrete commands given by voice or from the keyboard and via continuous commands given by a joystick. 17 individuals, including eight wheelchair users, participated in comprehensive experiments comparing the vocal interface to the joystick in various tasks. Subjects who were able to use the joystick were also able to achieve more precise control.

Wei et al. [36] published a usability study of a wheelchair control system relying on EMG signals and facial gesture recognition, to generate six discrete commands. Five users navigated a trajectory using this interface as well as using a joystick. They concluded that the proposed method is effective in controlling the wheelchair, but navigation times were at least three times longer compared to joystick-based control.

Finally, in our preliminary evaluation, a study comparing discrete and continuous (omnidirectional) motion commands was conducted [18]. Ten subjects controlled a wheelchair in a corridor with obstacles using head-motion estimated by an outward-facing camera. When head-motion was translated to five discrete commands, navigation time was almost 150% longer than when the commands were continuous.

III. ROBOTIC WHEELCHAIR

In this section, we present the hardware and software components and the design of our robotic wheelchair.

A. *Hardware architecture*

Figure 1 shows the hardware components of our robotic wheelchair. A commercially available wheelchair (Titan transportable front wheel power wheelchair, model TITAN18CS) is modified to serve as the platform for our project. In order to control the wheelchair by our software, the manufacturer-provided joystick is replaced by our customized steering module, in which an Arduino Mega micro controller is used to convert the received commands from our software to motor control signal.

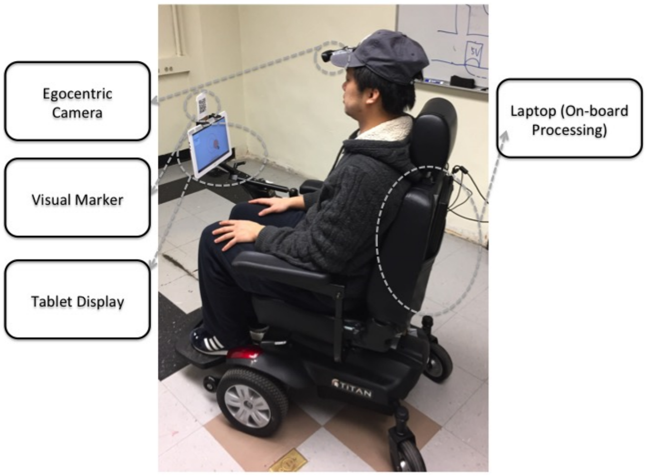


Fig. 1: Hardware components of the robotic wheelchair

The head-mounted camera is attached to a baseball hat and serves as the only sensing component. It is used to estimate the user's head pose relative to a fiducial marker that faces the user. A tablet below the fiducial marker is used to display a virtual joystick and feedback. Additional sensors that support autonomous navigation are out of the scope of this paper and are not presented here.

B. *Software system*

Our software system is built on the Robot Operating System (ROS) [29], which is a framework for robot software development. ROS manages robot software and hardware components and defines standard communication messages and services among the components. Figure 2 shows a diagram of our software system and the interactions among its components. The direction of flow of commands and information between components are indicated by the arrows. Some of the components are for all control modes and some others are only for one mode. For example, the motor component is needed by all three mode; the chin-based control module is only for the chin-based mode.

For the vision-based control, there are four active components. Head-pose is estimated using the video from the head-mounted camera. Then, the detected head-motion is translated into the motion of a cursor, which is displayed on the tablet. The cursor operates a virtual joystick, which can send driving commands to the motor. During manual control and chin-based control, the corresponding modules directly control the motor.

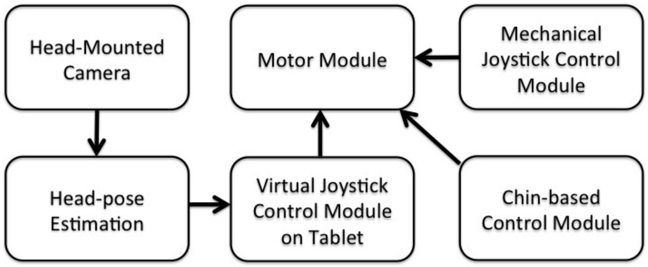


Fig. 2: Diagram of robotic wheelchair system. The arrows indicate data flow. The motor is shared by all control methods.

IV. NAVIGATION MODES

Currently, there are three navigation modes to control the robotic wheelchair: a manual mode using a hand-operated joystick, a chin-based mode using head-motion generated when the user physically manipulates a mechanical joystick below the chin, as well as a vision-based mode also using head-motion which is sensed indirectly by a head-mounted camera.

A. *Manual navigation mode*

In this mode, the wheelchair is driven by a manufacturer-provided joystick. The joystick is omnidirectional, i.e. the wheelchair can be commanded to move towards any direction since the heading angle is read from the joystick and propagated to the control module as a continuous variable. This mode can only be used by users who do not suffer from upper-limb mobility impairments.

B. *Chin-based navigation mode*

Chin-based control is among the oldest hands-free methods for driving a wheelchair [19]. In order to compare our vision-based method with other existing hands-free control methods, a customized chin-control device was made for the chin-based navigation mode. As shown in Fig 3, the chin-control mount has adjustable height to accommodate different users.

In this mode, the wheelchair is driven by the manufacturer-provided joystick with our own customization for chin-control. The joystick is also omnidirectional and generates continuous linear and angular velocity commands. Similar to the vision-based mode, this mode can be used by users who suffer from upper-limb mobility impairments.

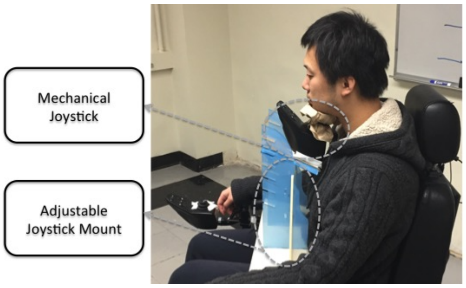


Fig. 3: The setup for chin-based mode.

C. *Vision-based navigation mode: operation*

When driving in this hands-free mode, the user gives commands to the wheelchair by head-motion. The user only needs to wear a head-mounted camera to operate the wheelchair. This technique has been used and described in our previous work [18], but has not been evaluated as thoroughly as in this paper.

Head-motion is estimated from the difference of the pose of the head relative to the wheelchair frame in two consecutive frames. It is much easier to use head-pose estimates with respect to the wheelchair and not the scene for this, since, otherwise, the joint motion of the head and the wheelchair would have to be separated. To this end we rely on two hardware components: the head-mounted camera and the visual marker, which is mounted on the wheelchair and provides multiple fiducial points. Figure 1 illustrates the placement of these two components. Using the position of the visual marker in the captured images, the user's head pose can be estimated by comparing consecutive frames to estimate the displacement of the head and translate it to 2D commands for the cursor on the screen.

To increase the computational efficiency and gain robustness of the system, we track the marker after detecting it instead of trying to detect it again in every frame. We use the QR marker detector from the ViSP library [23] to detect the marker and the Consensus-based Matching and Tracking of Keypoints(CMT) [24] to track the marker.

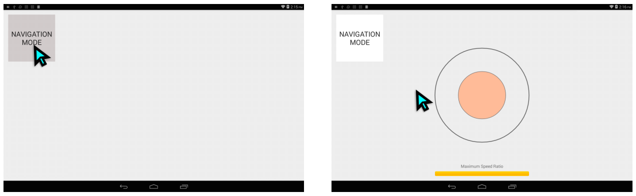
The graphical user interface (GUI) is an Android application we developed that runs on a generic tablet. While the user moves his or her head, our system estimates the relative head-pose and moves the cursor on the tablet's screen. Figure 4 shows our GUI. By keeping the cursor over a button for a predefined length of time, a button click command is invoked. The following is a typical workflow of the system, where the user would:

1) move the cursor over the navigation mode button on the top left corner;
2) keep the cursor in place for three seconds to activate the vision-based navigation mode;
3) move the cursor to the virtual joystick (circle in the middle of the screen);
4) keep the cursor in place for another three seconds to pick up the virtual joystick;
5) move the joystick to control the wheelchair continu-

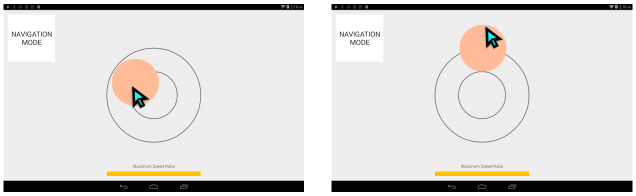
ously according to the location of the cursor in the screen;

6) adjust the speed of wheelchair by moving the cursor closer and further to the center of the screen (virtual joystick original position).
7) if a stop is desired, move the cursor to the middle of the screen and keep the cursor in place for three seconds until the virtual joystick is released by the cursor;
8) move the cursor over the navigation mode button to the top left corner and keep the cursor in place for three seconds until the vision-based navigation mode is deactivated.

A stop command is also issued when the user looks away from the screen.



(a) Activate the vision-based mode (b) GUI of the vision-based mode



(c) Turn left slowly (d) Move forward

Fig. 4: The GUI of the robotic wheelchair

V. EVALUATION OF EGOCENTRIC VISION-BASED CONTROL SYSTEM

In order to test the usability of the proposed vision-based navigation mode, an experimental evaluation was conducted. Chin-based control and manual joystick control are used as baseline methods to establish reference times for completing the tasks. The evaluation was repeated twice on the same set of subjects to study whether and to what extend users can improve their skills in each control mode over time. The purpose of this analysis with baseline methods is to test the viability of the vision-based method for navigation. We expect that there is a loss of speed due to hands-free operation with our method, but it may be the only option for some wheelchair users.

A. Evaluation metrics

The metrics are selected by referring to [17]. Several papers on hands-free wheelchair control use similar metrics in their evaluations. Our selected metrics are the following:

1) Navigation time for each section of the route. Navigation time reflects the user's skills and the ease of use of a particular control method. We record time per section since different sections of the route require different skills [2], [8], [11], [13], [16], [37].
2) Number of collisions. This reflects the safety of each mode [11], [13], [37].
3) Surveys and comments. These complement the metrics with subjective evaluations [11].
4) Practice time. Although not reported in previous publications, this metric reflects the subjects' own estimation of their skills in the respective control mode before the timed experiments.

B. Evaluation methods

21 subjects (19 male and 2 female) were recruited for this study. 11 of these subjects were in age between 20-29; 10 were between 30-39; and 1 was above 50. In each of the two rounds, the subjects were required to navigate through a test area using all three modes described in Section IV. Since previous studies have shown that familiarity plays an important role in such experiments and that subjects had little difficulty in manual mode, all subjects started the tests in manual mode. After becoming equally familiar with the test area, the subjects were split into two groups: the first group continued with chin-based and then with vision-based control, while the second group followed the opposite sequence.

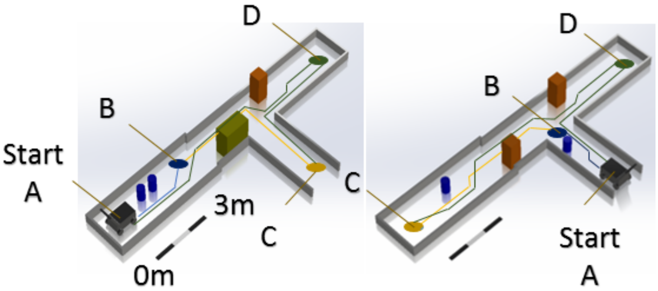


Fig. 5: Test area with approximate route. Left: first round test; right: second round test

The test area was set up in a hallway as shown in Fig. 5. Obstacles, including chairs and boxes, were placed in the scene. Chairs are "see-through" obstacles (i.e. subjects were able to observe the scene behind them and be prepared in advance); boxes are opaque obstacles.

Before navigation in a given mode, each subject was given a brief introduction to it and was allowed to practice by navigating freely outside the test area. When subjects felt ready, they navigate the designated route. Practice time varies across subjects, but it serves as a proxy for familiarity with the user interfaces.

The same set of subjects participated in the second round, which took place 2-5 days later following the same procedure. The designated navigation route in the second round was different, but of comparable difficulty. Descriptions and dimensions of the test routes are listed in Table I.

A questionnaire, shown in Table VI, was also given to the subjects after they completed the tests. Subjects were

TABLE I: Sections of designated route

Section	Round 1 distance	Round 2 distance	Note
A→B	5.5m	4.5m	Short distance navigation with forward-turn
B→C	10m	11m	Medium distance navigation and a 90° turn-in-place
180° turn	0m	0m	180° turn-in-place in a narrow corridor
C→D→A	25.3m	25.3m	All of the above combined

asked to answer each question in a 5-point Likert scale: strongly disagree, disagree, neither agree nor disagree, agree, and strongly agree. Results can be seen in Table VI.

C. Analysis of navigation time

Table II shows the average time and standard deviation (SD) for each section in each navigation mode in the first round. Vision-based control has the longest practice time, the longest navigation time in most sections with few exceptions, and the longest overall time; not surprisingly, manual control has the shortest. On average for navigation (excluding practice time), chin-based control is 19.6% faster than vision-based control; while manual control is 26.4% faster. From the results of the different sections, it can be seen that the biggest difference between the vision-based control and the other two baseline approaches is the 180° turn-in-place: the time for turning using the vision-based control is almost twice longer than that using the chin-based control and the manual control.

TABLE II: Practice and navigation time for the first round

Section	Vision-based		Chin-based		Manual	
	Mean	SD	Mean	SD	Mean	SD
Practice	123.8	50.7	85.5	38.2	77.0	32.8
A→B	14.7	4.3	11.8	2.5	11.2	3.1
B→C	31.5	8.4	26.2	4.3	24.0	3.6
180°-turn	11.7	4.9	6.1	1.5	6.2	1.3
C→D→A	86.3	16.2	71.9	9.2	64.7	5.3
Total A→A	144.2	25.6	116.0	12.9	106.1	9.6

Table III shows the average time and SD for the overall navigation time in the second round. Similarly to the first round, the mode with the slowest navigation is still the vision-based one. Manual navigation is still the fastest and chin-based control comes second. The former is 19.1% faster than the vision-based mode, while the latter is 11.3% faster. It appears that practice is more beneficial for the vision-based method since it is the least familiar form of control to the subjects. The difference in the 180° turn-in-place is no longer as pronounced as in the first round, showing that subjects are able to learn how to execute specific maneuvers relatively fast. Four subjects skipped the free practice in the second round for chin-based control, six for manual control and 7 for the vision-based control. These choices were not always linked with good performance in the test. It may be worth investigating whether they were due to over-confidence or discomfort with one or more navigation modes.

TABLE III: Practice and navigation time for the second round

Section	Vision-based		Chin-based		Manual	
	Mean	SD	Mean	SD	Mean	SD
Practice	49.3	46.8	40.4	32.9	35.1	29.9
A→B	9.9	1.4	9.7	1.4	9.4	1.1
B→C	28.1	7.6	23.2	2.5	22.3	1.7
180°-turn	6.9	1.6	5.8	1.5	5.0	0.8
C→D→A	80.1	11.7	72.3	9.3	64.5	4.2
Total A→A	125.0	17.8	110.9	12.4	101.1	6.3

Table IV shows a comparison of the two rounds in terms of overall navigation time, as well as in terms of the number of subjects whose navigation time increased, decreased, or remained constant. On average, for the vision-based control, the overall navigation time (excludes practice time) was reduced by 19.2 seconds (13.3% of first round).

TABLE IV: Change of overall navigation time between two rounds.

	Vision-based	Chin-based	Manual
Average time decreased (s)	19.2	5.1	5.0
Decrease in ave. time %	13.3%	4.4%	4.8%
Decrease in SD %	30.5%	3.5%	34.6%
Number of subjects whose navigation time...			
decreased	18	14	12
increased	3	7	6
stayed the same	0	0	3

D. Analysis of safety

Collisions are categorized into "major" and "minor". We use the following specifications when recording collisions during the tests. We record a major collision when the subject needs to come to a complete stop and requires assistance. We record a minor collision when the wheelchair grazes an obstacle and the subject is able to correct the trajectory without external help. Table V lists the number of collisions. From the table, it can be seen that in the first round subjects are able to avoid major collisions only using the manual control mode. There is a substantial improvement in all modes in the second round. The only major collisions occur in the vision-based mode, but for under 10% of the subjects.

TABLE V: Number of collisions in both rounds

Mode	Vision-based	Chin-based	Manual
Round 1 Major	8	3	0
Round 1 Minor	6	5	2
Round 2 Major	2	0	0
Round 2 Minor	6	2	1

E. Survey results

The survey statements and results are listed in Table VI. A 5-point Likert scale is used, with 5 being strongly agree and 1 being strongly disagree. The results show that vision-based control receives lower ratings in all questions. The ratings, however, are positive for all methods. Considering that vision-based navigation requires the least physical effort, it can still be a realistic option for wheelchair control especially for individuals with limited use of their hands.

TABLE VI: Survey statements and results

Question/Round	Vision-based		Chin-based		Manual	
	Mean	SD	Mean	SD	Mean	SD
1. My overall experience of this navigation method was satisfactory.						
Round 1	3.7	0.8	3.6	1.0	4.9	0.3
Round 2	3.9	0.6	3.9	1.0	4.7	0.9
Increase %	5%	-25%	7%	0	-3%	200%
2. In this method it was easy to learn to operate the wheelchair.						
Round 1	3.9	0.9	4.1	1.0	5.0	0.0
Round 2	4.1	0.7	4.1	0.9	5.0	0.0
Increase %	4%	-22%	0	-10%	0	0
3. I felt safe when I navigated using this navigation method.						
Round 1	3.0	0.9	3.9	0.9	5.0	0.0
Round 2	3.7	1.0	3.9	1.1	4.8	0.5
Increase %	18%	-11%	0	22%	-4%	N/A
4. I felt my performance improved, comparing to the first time.						
Round 2	4.3	1.1	3.9	1.0	4.3	1.1

The last question in the second round shows that the subjects have confidence in improving their vision-based navigation skill through practice. This matches what we have found from the analysis of navigation times.

Table VI also shows how the subjects' opinion changed after testing all methods for the second time. It can be seen that more subjects gave higher evaluation to the vision-based mode. The score for the feeling of safety rises by 18% for vision-based control. In contrast, for manual control, the score dropped by 4%. For the chin-based mode, the score remained the same.

VI. DISCUSSION

In this section, a discussion of experiment results, comments from the subjects, and the limitations of the experiment are presented.

A. Advantages of vision-based method

Although in the evaluation the vision-based method showed higher collision rate and longer navigation time, it also showed several advantages:

1. Minimal physical effort is needed in vision-based control. Chin-based control requires the users to continuously move their neck and head, while the mechanical joystick imposes forces back to the head and indirectly to the neck. In our experiments, we noticed that, while using chin-based control, some subjects were fatigued around the end of the test navigation. A subject requested a break in the middle of the experiment while using the chin-based method.

2. Performance can be greatly improved with practice in the vision-based control: from the experimental results, the improvement in navigation time from the first to the second round is noteworthy in the vision-based method, while the improvement is minimal in the other two methods. The survey results show that for the vision-based method subjects' satisfaction improved noticeably in the second round compared to the first round. A subject commented: “I think I have already reached my best in round 1 for the chin-based control and the manual control; but using the vision-based control my performance improved in round 2.”

B. Disadvantages of vision-based method and analysis

During the evaluation, we identified the following issues with the vision-based method:

1. Some subjects showed less confidence in vision-based control than the other control methods: in round 2, some subjects referred to the vision-based as the ”hard one”.

2. Subjects were less aware of the environment: subjects devoted most of their attention to the virtual joystick on tablet, which prevented them from looking around. When the other methods are employed, users sense the position of the mechanical joystick by touching, leaving their eyes free to observe the surroundings. It should be noted, however, that no other alternatives may be available in some cases.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented an evaluation of an egocentric vision-based hands-free control system for a robotic wheelchair. Modified from a commercially sold joystick-controlled wheelchair, our robotic wheelchair can be controlled by user's head-motion without a mechanical joystick. A head-mounted camera is the only sensing device used for estimating the user's head-motion in the vision-based control.

21 able-bodied subjects participated in the two-round evaluation. In both rounds, all subjects were able to complete a 40.8-meter navigation using all three control approaches after a short practice round (less than 3 minutes). Considering on average the vision-based control is not much slower than the two baseline controls, (11.1% slower than chin-based control and 19.3% slower than manual control in the second round), we believe that the subjects' performance indicates that the vision-based control is viable as a hands-free alternative. Our findings are more encouraging than other studies. In a paper by Wei et al. [36], the authors reported that the navigation time using EMG signals and video from a user-facing camera was three times longer than using a mechanical joystick.

Our two-round experiment also confirmed that users can improve their performance in the vision-based control with practice. 85.7% of subjects' performance in the vision-based control improved in the second round. (66.7% subjects improved in the chin-based control and 57.1% improved in the manual control.) The number of major collisions was also reduced a lot for the vision-based control, from 8 collisions in the first round to 2 collisions in the second round.

Surveys show that although able-bodied subjects gave the manual control and chin-based control a higher evaluation, they agreed that the vision-based control was efficient and safe. They also felt that they could improve more in using the vision-based control than the chin-based control for hands-free wheelchair navigation. The change of survey scores between two rounds also show that the vision-based became more appealing to the users in the second round.

As we have already confirmed the vision-based control poses no danger for indoor navigation to able-bodied subjects, in our future work, we will conduct a similar study with our true target users, who suffered from limited hand usage. Besides this vision-based control, by implementing intelligent features e.g. autonomous navigation, people following, path planning in dynamic environment, etc., smart wheelchairs can reduce the navigation effort, enhance the navigation safety, and ultimately improve the quality of life of their users.

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