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A Novel Eye-Gaze Controlled Wheelchair System for Navigating Unknown Environments: Case Study with a Person with ALS

Mohamad A. Eid, Nikolaos Giakoumidis, and Abdulmotaleb El Saddik

***Abstract*—Thanks to advances in electric wheelchair design, persons with motor impairments due to diseases like the Amyotrophic Lateral Sclerosis (ALS) have tools to become more independent and mobile. However an electric wheelchair generally requires considerable skill to learn how to use and operate. Moreover, some persons with motor disabilities cannot drive an electric wheelchair manually (even with a joystick) because they lack the physical ability to control their hand movement (such is the case with people with ALS). In this paper, we propose a novel system that enables a person with motor disability to control a wheelchair via eye-gaze and provide a continuous, real-time navigation in unknown environments. The system comprises: a Permobile M400 wheelchair, eye tracking glasses, a depth camera to capture the geometry of the ambient space, a set of ultrasound and infrared sensors to detect obstacles with low proximity that are out of the field of view for the depth camera, a laptop placed on a flexible mount for maximized comfort, and a safety 'off' switch to turn off the system whenever needed. First, a novel algorithm is proposed to support continuous, real-time target identification, path planning and navigation in unknown environments. Second, the system utilizes a novel N-cell grid-based Graphical User Interface (GUI) that adapts to input/output interfaces specifications. Third, a calibration method for the eye tracking system is implemented to minimize the calibration overheads. A case study with a person with ALS is presented and interesting findings are discussed. The participant showed improved performance in terms of calibration time, task completion time and navigation speed for a navigation trips between office, dining room and bedroom. Furthermore, debriefing the caregiver has also shown promising results: the participant enjoyed higher level of confidence driving the wheelchair and experienced no collisions through all the experiment.**

***Index Terms*— Eye gaze tracking, eye gaze calibration, wheelchair control system, grid-based graphical user interface, unknown environment tracking.**

This paragraph of the first footnote will contain the date on which you submitted your paper for review. It will also contain support information, including sponsor and financial support acknowledgment. For example, "This work was supported in part by the U.S. Department of Commerce under Grant BS123456".

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I. Introduction

MOTOR disabilities of people resulted by diseases like the Amyotrophic Lateral Sclerosis (ALS) have a dramatic effect on their quality of living. For years, people with motor disability have learned to cope with their restricted autonomy thanks to advances in electric wheelchair design. However an electric wheelchair generally requires considerable skill to learn how to use and operate. Moreover, some persons with a motor disability cannot drive an electric wheelchair manually (even with a joystick) because they lack the physical ability to control their hand movement (such as persons with ALS).

In order to enable a user to control a wheelchair safely and easily, researchers have explored various interfacing technologies such as speech recognition, head arrays, eye tracking, Electroencephalography (EEG) based brain-computer interfaces (BCIs), electro-oculography (EOG) systems, and sip-and-puff (SnP) switches [1]. However, each device has limitations that prevent its use in daily life. For instance, BCIs are useful for those with high level of paralysis [2], but they are prone to motion artifacts and interferences, and cannot be easily adapted to daily activities [3]. Even though speech recognition systems allow people to type efficiently [4], they are not efficient for cursor or wheelchair navigation [5], and are unreliable in noisy environments [6]. Head arrays and SnP switches are popular for individuals with tetraplegia as they are affordable and relatively simple, but they offer only a limited number of commands and require users to have some physical abilities [7].

Individuals with ALS lose their mobility one step at a time and may end up completely dependent on caregivers or trapped in their beds without the correct mobility device [8]. They lose muscle strength gradually and often end up having difficulty reaching and gripping that make the driving mechanism a problem; for instance using a joystick. Their ability to speak is also very limited. These physiological limitations imply that individuals with ALS cannot use existing electric wheelchair interfaces such as voice, head movements, and hand- or chin-operated joysticks.

Eye trackers are efficient for controlling a mouse cursor on a computer screen and do not require any physical interaction [9]. Furthermore, most of the persons with ALS have healthy

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control over their vision and can move their eyes with ease [10]. A control system can be constructed to detect where the user looks at and turn or move the wheelchair towards a target point. That is why eye tracking and gaze recognition technologies have emerged as a novel interaction paradigm with machines where a user's gaze (pupil movements) is captured and translated into actions without requiring any physical action [11]. Eye tracking technology seems a promising technology for people with motor disabilities to improve their communication, mobility, and independence.

The first system for controlling an electric wheelchair using the eye movement was introduced in 2007 where a standard web camera is mounted on a head-mounted display (HMD) to capture the user's face and send the video stream to a computer [11]. The computer processes the captured video, estimates the line-of-sight to find out where the user is looking, and actuates the electric wheelchair to move to a desired location. Several research challenges have impeded the widespread use of this technology, such as the quality of eye gaze detection and tracking, the impact of environmental conditions, and the extensive calibration required for an acceptable quality of detection or tracking [12].

The goal of the proposed research is three-fold: (1) continuous, real-time detection of targets, path planning and navigation to a desired destination in unknown environments. The system uses a depth camera (Microsoft Kinect) to capture the 3D geometry of the ambient environment and derive a desired path for navigating while avoiding obstacles along the path, (2) adaptation of a graphical user interface to input/output systems specifications (eye-tracking input system and screen display system). The screen is divided into an N-cell grid based on the resolution/accuracy of the eye tracker and the quality of display, and (3) easy and quick calibration method for the eye-tracker that is robust against head movements. Note that the proposed system is useful for several other types of individuals with disabilities such as individuals with tremor, limited hand movement, or partial upper limbs.

The remainder of the paper is organized as follows: section 2 reviews related literature in the area of eye gaze tracking and wheelchair control systems. Section 3 introduces the high level architecture for the proposed system, the eye tracking calibration method, and the N-cell grid graphical user interface. Section 4 presents a novel algorithm for navigating unknown environments using a depth camera mounted on top of the wheelchair system. In section 5, we introduce the implementation details about the developed prototype, both in software and hardware. Section 6 presents an experimental study with a participant with ALS and discusses our findings. Finally, section 7 summarizes the paper contents and provides perspectives for future work.

II. Related Work

A. Eye-Tracking Methods

Generally eye-tracking systems measure the eyeball position and determine gaze direction of a person, and are categorized into two approaches: Electrooculography based and video based.

Al-Haddad et al. [13] proposed controlling the wheelchair using Electrooculography (EOG) signals. The navigation method calculates the goal point direction and distance based on the gaze angle that the user is gazing at. In a subsequent research [14], a hands-free wheelchair control algorithm, named Bug2, is proposed to enable the user to look around the surrounding environment freely during the navigation process. EOG traces the eye-movement by recording the corneal–retinal potential polarity from de-polarizations and hyper polarizations existing between the retina and cornea via five electrodes. The user only needs to look at the desired destination, and then blink to give the signal to the controller to start navigating. By scheming the gaze angle of the wheelchair user, the controller is able to obtain the desired point location, distance and direction to the destination. A comparison between Bug2 and Tangent-Bug algorithms is conducted in [15]. However, the accuracy is low (around 10°) and thus a robust control system may not be possible. A limitation with EOG technology is that it requires the attachment of surface electrodes around the eyes. This limitation, among others, has led researchers to attempt image-based eye gaze tracking.

Video-based tracking setups vary greatly; some are head-mounted and may require a stable head, and some function remotely and automatically track the head during motion. Existing video-based gaze tracking methods can be further divided into two categories: active Infrared approaches such as [16][17] and image-based passive approaches such as [18-20]. Infrared lighting is used to capture the physical properties of the pupils along with their dynamics and appearance to extract the regions containing the eyes. Arai and Mardiyanto [17] utilized an IR camera that is mounted on the user's glass to eliminate uncertainties related to changes in illumination, the user's movement, and the movement of the user's head. A system that utilizes a novel image-processing algorithm to execute the corresponding movement of the user's eyes is presented in [21]. Whenever the eye looks straight, the system remains idle. When the user moves his eyes to his left/right or up/down, the wheelchair starts moving left/right or front/back accordingly. This approach is cognitively overloading and does not allow users to perform any other task than navigation, and requires a continuous gazing for successful control.

A limitation with camera-based eye gaze tracking is that they require the user to maintain the head in static position [22-24]. Nguyen and Jo [25] presented a wheelchair control using head pose free eye-gaze estimation where a 3D orientation sensor is included to take into consideration the head pose. The system comprises an electrical wheelchair and an eye gaze tracker. The eye-gaze tracker was built by combining a glasses frame, an infrared camera with two LEDs on both sides and a 3D orientation sensor attached to a side of the frame. The proposed system is complicated and requires significant calibration efforts.

Researchers have also tried to combine gaze actions and facial orientations as a new hands-free interface for controlling

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a wheelchair [26]. The face image was captured in real-time to the computer through a web camera and the change in darkness area of the nostrils was observed to detect the face directions. The gaze action recognition system works in a way such that when the operator gazed to the control computer, the facial orientation was reflected to operate the auto-wheelchair, instead of a joystick interface. Jia and Hu [27] proposed to use head gesture based control of an intelligent wheelchair. By detecting frontal face and nose position using Adaboost face detection, head gesture is estimated and used to control the wheelchair. These systems cannot be used for persons with ALS as they lack the ability to move their head.

Mobile eye-tracking technologies are commercially available; SMI[1], ASL[2] and Tobii[3] are among the largest manufacturers. Three devices were serious options to purchase for the system implementation: the SMI (SensoMotoric Instruments) Glasses 2.0, the Tobii Glasses 2 and the ASL XG Eye. The ALS XG Eye has a large head-mounted device, which makes it uncomfortable to wear for the individual with ALS, and thus was eliminated. The SMI Glasses 2.0 is a pair of 3D glasses that use a pair of small cameras mounted to the eyeglasses rim to track human gaze. The SMI device is adopted due to the following reasons: First, the device is convenient and comfortable to wear (just like regular glasses). Second, since two cameras located on the rim of the glasses are used to capture eye movements and map the gaze point it is highly accurate (0.2°accuracy). Finally, the glasses do not block the line of sight and are immune to changes in the ambient environment conditions (such as light conditions). On the other hand, we acknowledge that the SMI glasses are expensive to use and thus a cheaper solution may be used instead [28].

B. *Wheelchair Control Systems Via Eye Gaze*

While traditional electric wheelchairs, built to facilitate maneuvering in indoor and outdoor environments, have helped millions of people with disabilities, many of them do not fully serve persons with severe disabilities [29]. For instance, many existing systems use a joystick that acts as a control input to drive the wheelchair electric motors, which is not an option for persons with ALS who are not able to move their limbs. Eye gaze interfaces are advantageous in such applications, as they require no physical interaction.

Optical eye-gaze tracking was studied in [21][24][25][30]. For instance the work in [24] utilized a camera in front of a wheelchair user to measure gaze direction and eye blinking properties. The gaze direction and eye blinking are used to provide direction of movement and timing when the wheelchair should move, respectively. In order to control the velocity, the wheelchair received a velocity command as well as the direction and timing commands. The system requires continuous and consistent gaze during navigation time, and the user is not allowed to look around the surrounding environment through all navigation.

Several researchers have utilized target-based navigation for the wheelchair control. For instance, Al-Haddad and colleagues proposed Electrooculography (EOG) based control for target navigation [13-15], however they required the attachment of surface electrodes around the eyes. They proposed two methods to control the wheelchair: manual and automatic. In the manual method, the user looks up to go straight, look right to turn right, look left to turn left, and look down to stop. In the automatic method, the user gazes at a desired destination and blinks (right to start and left to stop) to start navigating the wheelchair to the target position. However, although this technique decreases cognitive workload, it is constraint by a well-defined and known environment. Furthermore, a lengthy calibration process renders the whole technique unpractical to use for daily life activities.

Researchers have also looked into controlling a wheelchair system in unknown environments. A wheelchair exploring an unknown environment requires real-time map generation and path planning for efficient and obstacle-avoiding navigation. This is usually achieved through the addition of sensors to scan the ambient physical environment and construct a real-time map. Some well-known examples of these in research include [31-32] SENA [33], Rolland [34], Hephaestus [35] and Navchair [36]. All these systems assume a predefined environment. A vision-based navigation for an electric wheelchair using the ceiling light landmark is presented in [37]. The wheelchair is equipped with two cameras that are used for self-location and obstacle avoidance. The fluorescent ceiling lights are chosen as landmarks since they can be easily detected and do not require any additional installation. This approach requires the use of ceiling light as landmarks and is unable to navigate completely unknown environments.

This paper focuses on the design and evaluation of a novel eye-gaze controlled wheelchair system for navigating unknown environments that minimizes mental loading as well as calibration efforts. We present a novel algorithm that identifies local targets and generates navigation paths from obstacle centroid for automatic, real-time navigation of unknown environments. Furthermore, we addressed the calibration issue by proposing an easy and quick calibration method with about 30 seconds calibration time. An N-cell grid-based graphical user interface that adapts to input/output interface specifications is introduced. Finally, we also present a case study to assess the proposed system with a subject with ALS and discuss our findings.

III. Proposed Eye-Gaze Control System

A. *System Architecture*

The proposed system empowers people with physical disability and mitigates the limitations of the everyday life to which they are confronted. For the long run, the system aims at assisting people with physical disability to pursue daily living autonomously via a tablet device such as the iPad or

[1] www.smivision.com
[2] www.asleyetracking.com
[3] www.tobii.com/

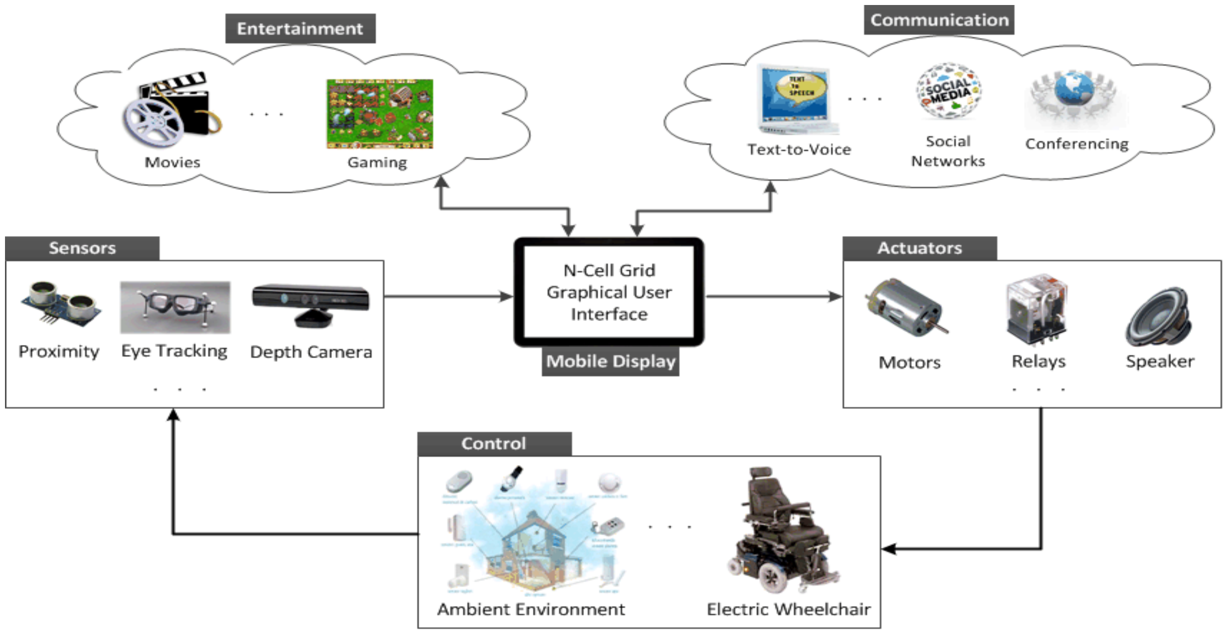

Fig. 1. Architecture for the proposed system.

Samsung Galaxy Tab. Daily living activities include communication, control and entertainment. Figure 1 provides a general architecture endorsing comprehensive functionalities such as communication with social media, interaction with entertainment tools, and control for ambient environment. Note that communication and entertainment components are not considered in this study. Here is a short description for each subsystem:

- *Control Subsystem:* The Control subsystem provides an interface for continuous, real-time navigation and control for the wheelchair using eye gaze (such as moving forward, right, left, and stop). The Control subsystem constructs the 3D geometry of the ambient environments based on the depth camera data and implements an algorithm to identify, plan and navigate to a particular target. Furthermore, the control module could enhance the user's independent living by controlling the ambient environment (such as turning on/off the lights and the TV, opening/closing a window or a door, bed position and wheelchair configuration, etc.) via eye gaze.
- *Communication Subsystem:* The Communication subsystem enables a user with physical disability to communicate with people in their physical proximity (particularly if they cannot speak) or with people at a physical distance via social and communication networks (such as Facebook and Twitter) to express their thoughts and feelings. The user types text by staring at keys on the N-cell grid virtual keyboard. Once a phrase is typed in, the user chooses the "speak" button to play the phrase via ambient speakers or the "send" button to send the phrase as a message to a designated destination.
- *Entertainment Subsystem:* The Entertainment subsystem provides the user with higher accessibility to manage diversified entertainment (such as movies and games) via the eye gaze interface. An adaptation of the entertainment interfaces, depending on the characteristics of the contents (movies or games), is adopted. For instance, the patient may guide a game character along the game using direct eye gaze control, or may use an N-cell grid interface to control a video player while watching a movie.
- *Actuators Subsystem:* The Actuators subsystem receives control commands from the mobile display subsystem and performs a physical action in the Control subsystem. Examples of actuators include DC motors to control the wheelchair movements, electrical/mechanical relays to control ambient environment such as TV, door, light, AC, etc., and audio speakers.
- *Sensors Subsystem:* The Sensors subsystem captures various parameters about the user and the ambient environment and feeds the data to the Mobile Display subsystem to process and make decisions. One major sensory device is the eye tracking sensor that captures the eye gaze movements and blinking in real time. A depth camera (Microsoft Kinect) is also used to capture the geometry of the ambient space and automatically generate a desired path towards a particular target. This will provide the user with maneuverability in undefined environments. Finally, various types of proximity sensors (ultrasonic and Infrared sensors) are used to detect objects along the wheelchair pathway, and avoid collisions with nearby objects.
- *Mobile Display Subsystem:* The mobile display subsystem provides the computation infrastructure to process sensory data and produce control signals to the actuators. Furthermore, the mobile display module implements the N-cell grid graphical user interface software to provide a reliable and efficient way for the user to communicate with the proposed system and

it's various components (entertainment, communication, wheelchair control, etc.).

B. *Eye Tracking Calibration Method*

The goal of a gaze calibration method is to collect samples of eye gaze at known points in the output screen, and calculate an accurate gaze-to-display mapping [38]. Using fewer calibration points results in faster, inaccurate calibration whereas too many calibration points results in slower calibration and poor usability [39]. Furthermore, the quality of calibration (calibration time and accuracy) is highly dependent on the input device in use as well as the display size and resolution [40]. A common thrust is to develop advanced geometric models to reduce the number of calibration points that need to be sampled to achieve good accuracy (a generally agreed accuracy target is 1° of visual angle) [41].

In this paper, we adopt an adaptive calibration approach where the number of calibration points is determined based on the complexity of the graphical user interface [39]. The proposed calibration method defines the desirable number of calibration points to meet a required calibration accuracy/time. For instance, a small number of controls on the GUI imply that fewer calibration points will be used. The complexity of the GUI is calculated based on the algorithm proposed in [42].

Once the number of tracking points is defined, the calibration procedure starts when the SMI Eye Tracking Glasses 2.0 device extracts the pupil center and the glint center. The pupil center and the glint center are connected to form a 2D pupil-glint vector υ that is represented as (υ_x, υ_y). The gaze point S_s on the GUI page is represented by (x_{gaze}, y_{gaze}) in the screen coordinate system. The calibration method is based on acquiring a specific gaze function that will map the extracted pupil-glint vector to the user's fixation point in the GUI page at the current head position. The specific gaze mapping function $S_s = f(v)$ can be modeled by the following nonlinear equations [43]:

$$x_{gaze} = a_0 + a_1 * v_x + a_2 * v_y + a_3 * v_x * v_y \quad (1)$$

$$y_{gaze} = b_0 + b_1 * v_x + b_2 * v_y + b_3 * {v_y}^2 \quad (2)$$

Where the $(a_3 * v_x * v_y)$ term in x_{gaze} and $(b_3 * {v_y}^2)$ term in y_{gaze} accommodate most of the nonlinearities associated with the tilt of the computer screen within the range of the GUI page. The coefficients a_0, a_1, a_2, a_3 and b_0, b_1, b_2, b_3 are estimated from a set of pairs of pupil-glint vectors and the corresponding gaze points on the GUI page. These points are collected during the calibration procedure where the user is required to visually stare at a flashing dot as it displays (one at a time) at desirable locations on the screen (Figure 2 demonstrates an example with four calibration points on the GUI page). Each dot will continue to flash until the user achieves a decent accuracy of staring. During this procedure, the subject must keep her/his head as still as possible. After the four dots are correctly identified, the coefficients of equations (1) and (2) are computed and eventually the gaze workspace is defined. When calibration is successfully completed, the user is forwarded to the main N-cell grid GUI.

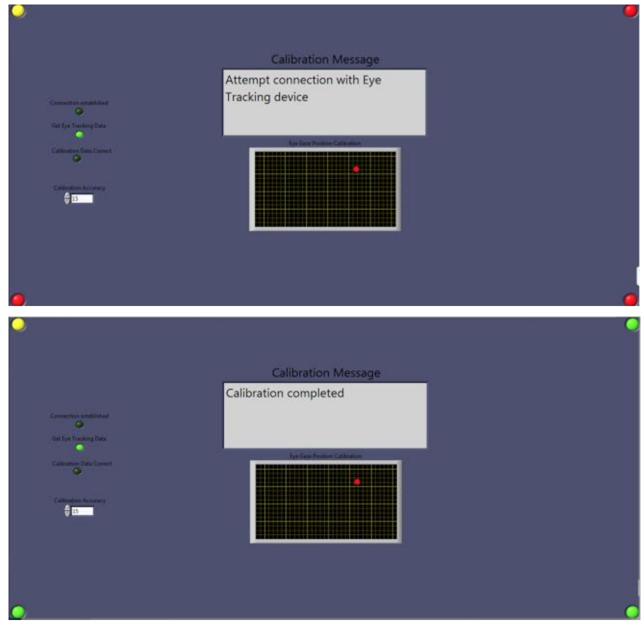

Fig. 2. Calibration method with four calibration points.

When the user moves her/his head too far away from the position where the gaze calibration is performed, the calibrated gaze mapping function will fail to estimate the gaze point on the GUI page. This is detected using an accelerometer that is attached to the SMI Eye Tracking Glasses 2.0. In this case, the system pops up the calibration page for re-calibration. Note that the calibration method is independent of the screen size and/or eye tracker resolution.

C. *N-Cell Grid User Interface*

The main GUI page is divided into an N-cell grid for convenient navigation. According to the extension of Fitts's law to two-dimensional tasks [44], the time required to reach a target decreases with increasing target size. Other studies have shown that button size has a significant effect on selection speed and eye strain. The number of cells (N) is defined based on the complexity of the page (number of controls and their respective locations), the target usability (eye strain and selection speed for the time being), and the eye tracker accuracy. An example grid layout for (N=45) is shown in Figure 3.

The main GUI interface for the proposed system is shown in Figure 4. The left-most grid column is used for the main menu with three items (namely navigation, communication, and entertainment). When one item is selected from the main menu options, a nested menu will open next to the main menu (second left-most) displaying the contents of the selected item. In the snapshot of Figure 4, the navigation item is selected from the main menu, and thus a sub-menu displaying the main functionalities related to navigation is displayed (manual navigation, assistive navigation, autonomous navigation, and navigation configuration). The remaining grid cells display GUI elements related to a selected sub-item. For instance when selecting manual navigation, the grid displays manual navigation GUI elements (four buttons for moving forward, left, right, and stop), as shown in Figure 4.

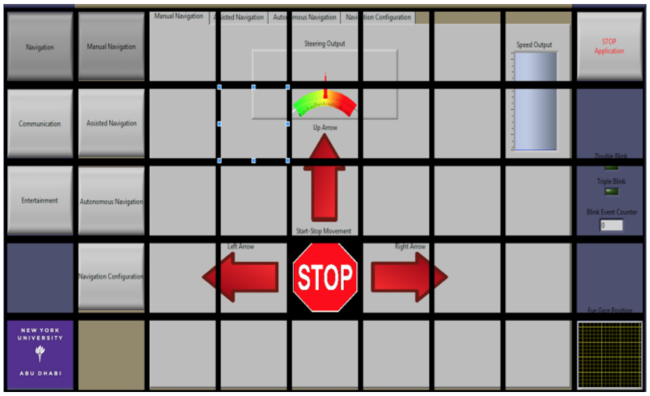

Fig. 3. An example of N-cell grid GUI (N=45).

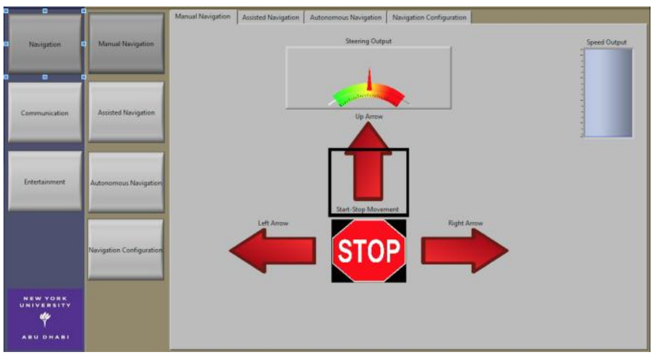

Fig. 4. Main GUI page.

The interface works as follows: each cell contains a single GUI element to be controlled (such as a button, text field, radio button, etc.). Whenever the user looks into a particular cell, the corresponding GUI element will be highlighted and thus a double blink would correspond to clicking on the corresponding control element. For example, in order for the user to move the wheelchair forward, they have to look at the cell corresponding to the "Up Arrow" button, and once highlighted double blink to execute the action.

To facilitate usability, the assistive navigation is implemented such that looking at a point at the left makes the wheelchair start moving towards this point, looking up or ahead makes the wheelchair moves forward, and looking anywhere on the right makes the wheelchair moves to the right. To ensure the system safety, whenever the user looks down the wheelchair will stop immediately. Autonomous navigation enables the user to select a target (such as living room, kitchen, etc.) and the system will automatically navigate the user to the desired target (presented next in section IV).

IV. Navigating Unknown Environments

Consider a person entering a physical space for the first time, for example a shopping mall. The person would enter the shopping mall, look around to scan the physical environment, identify interesting targets and generate paths to these targets. The proposed algorithm for navigating unknown environments works in a similar manner. We propose an algorithm that allows a user with motor disability to navigate his/her wheelchair like any other person entering the mall for the first time. The Kinect camera mounted on the wheelchair system will scan the physical environment, identify local targets and generate navigation paths. The proposed algorithm provides the user with a temporary local map of the area that he/she is experiencing. The map contains the user's current location as the initial point and prompts the user to choose his/her target on the temporary map provided. The choice is made through selecting a target point that has already been generated on the grid. Once the user chooses the next target to move to, the wheelchair system will move to the selected target and a new temporary map will be generated. This procedure is repeated until the user reaches his/her final destination. Figure 5 introduces the problem definition.

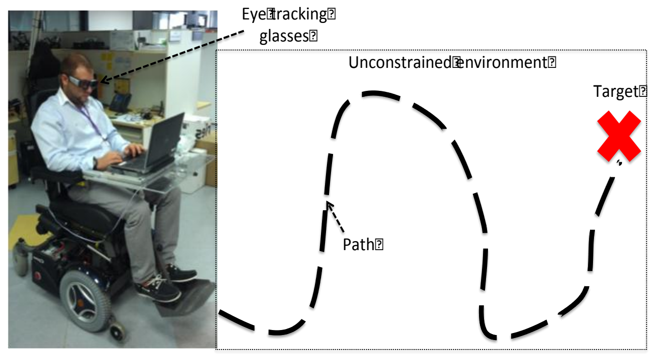

Fig. 5. Navigating unknown environments.

Most of the literature present on the subject of path planning assumes that the environment is already given in accurate and calculated detail. The algorithm is given a start position and an end position along with the map details. After calculating the optimal path, while taking predefined obstacles into consideration, the algorithm calculates a path to reach a given destination. There is barely any attention given to path planning for completely unknown environments [45-46].

Stentz [47] introduced an algorithm that was capable of planning paths in unknown and partially known environments. It is assumed that a robot operates with a sensor and a map that can either be known, unknown or partially known. The unknown regions of the map contain approximated information while the algorithm computes the path using the approximated information; this is called the PROCESS-STATE. When the robot encounters an obstacle, the map is updated to include this obstacle and start again; this is called MODIFY-STATE.

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a) A example local map (6 obstacles) b) binary transformation c) Extracted Boundaries (2 obstacles)

Fig. 6. A summary of the boundaries extraction phase.

More recently, there have been plenty of approaches proposed in terms of real-time autonomous path planning and navigation such as potential field method [48], neural network models [49], sampling-based methods [50], fuzzy logic [51], sensor-based techniques [52], wavefront approach [53], and graph-based methods [54]. For instance, Yazici et al. [52] developed a sensor-based approach for multi-robot coverage navigation. Sensor-based coverage path planning performed in narrow spaces is implemented by a generalized Voronoi diagram (GVD)-based graph that models the environmental information. Existing approaches do not deal with continuous, real-time identification, planning and navigation for potential targets.

This section presents an algorithm that addresses the challenges associated with continuous, real-time navigation and path planning for unknown environments. The algorithm has the ability to continuously process a given random and unknown grid. It also has the ability to generate points that cover the entire surface of the given grid, avoiding phenomenon of over- and under-representation. The proposed navigation algorithm comprises three parts: (1) boundaries extraction, (2) local target generation and (3) path generation from obstacles.

A. *Local Map and Boundaries Extraction*

First of all, a local map is generated from the Kinect camera based on the depth information (an example is shown in Figure 6-a). The local map is then converted to a binary map (represented by a matrix of only ones and zeros), as shown in Figure 6-b, to differentiate between the obstacles and the background (open spaces). After obtaining the binary grid, the boundaries of the obstacles are identified. This helps to determine if a number of obstacles are close enough to each other that they form one composite obstacle. The example in Figure 6 illustrates the need to find the boundaries. In Figure 6-c the number of obstacles is found to be 2 whereas Figure 6-a highlights 6 obstacles. A number of obstacles mesh together to create one big obstacle (Figure 6-c). This method helps in finding feasible paths; a path is only feasible if the wheelchair can pass through.

The boundaries extraction is based on examining the depth image stream to find the edges of obstacles. These edges are usually viewed as vertical straight lines with depth difference between the left side and the right side. The algorithm proposed by Zhou el al. [55] is adopted to detect edges of the obstacles. The obstacle location procedure is shown in Figure 7. The Feature Extraction determines three parameters about each edge: the x-coordinate, the lowest point along with the y-coordinate, and the highest point along the y-coordinate. The Obstacles Edges Location calculates and locates the distance of the vertical edges. The Scanning Line scans the whole depth image to make sure all the edges have been considered for obstacle location.

B. *Local Target Generation*

Since the subject is limited to a number of choices, we had to generate target points in a position that will approximate the path the user desires to take. In order to achieve that, we generated a large number of uniformly distributed points over the full local grid, which helps in covering the entire surface of the map. After that, we use the *k-means* algorithm to cluster the points, where k is the number of the resulting groups. The number of clusters is then equal to the number of local targets on a given temporary map.

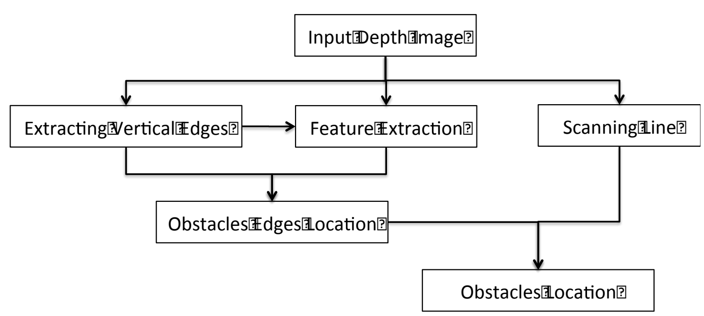

Fig. 7. The diagram of the obstacle location procedure.

The choice of *k-means* is justified by the two main properties: a) it needs the number of resulting clusters as an input, which practically is the number of target points that we want, and b) it creates circular clusters around its centroids. This enables us to make use of the centroids of the clusters as the target points. It is important here to note

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that the set of points are uniformly distributed, hence they do not really form clusters. With the aid of *k-means* we want to reduce this big number of points to k representatives. For this reason, any other fundamental type of clustering like single-linkage would result firstly in under-segmentations and also produce irrelevant results.

There are two goals that local target generation algorithm achieves: 1) generate a large number of uniformly distributed points that will cover the entire surface of the grid and 2) cluster the previously generated points to create a limited set of points that cover the surface and divide the surface into regions of equal areas. After generating all the target points, the “Bad Points”, (these are the points that share the same x-y coordinates of a pixel of an obstacle or are of very close proximity to the obstacles), needed to be filtered from the “Good Points”. The pseudo-code shown in Figure 8 describes the classification “good points” versus “bad points”.

```
Given obstacles array
Create Goodpoints array
Create Badpoints array
Good points counter g = 1
Bad points counter b = 1

Loop
    if point x intersects with obstacles
        Add x to Badpoints array
        Increment b
    Else if distance (x, obstacles)<Threshold
        Add x to Badpoints array
        Increment b
    Otherwise
        Add x to Goodpoints array
         Increment g
```

Fig. 8. Classification of “good points” and “bad points”.

The distance between each target point and the points that make up the obstacles is computed. A threshold is set in order to remove all the points that are under the threshold (See pseudocode in Figure 8), because these points are of certain proximity of some obstacle that is not allowed; meaning the distance is too small to form a path or to generate a target point in that space. If the distance between the target point being checked and the obstacle is larger than the threshold, then the target point generated is a “Good Point”. Once the “Good Points” are identified, some are found to be in clusters. Thus, a set number of clusters is given and each cluster of target points is replaced by one point that covers the region. Figure 9 demonstrates an example for tracing the “good points” along an unknown space.

C. Path Generation from Obstacle Centroid

Path planning can be achieved through various methods. One of the classic path planning algorithms, which is used in this paper, is the Voronoi Diagram algorithm [56]. The Voronoi diagram algorithm is suggested as a means of finding paths in the open space. After obtaining the processed map of the unknown grid, which differentiates between the obstacles and the open space, the Voronoi diagram is used to find the paths available in the open space. Results for the same example are shown in Figure 10.

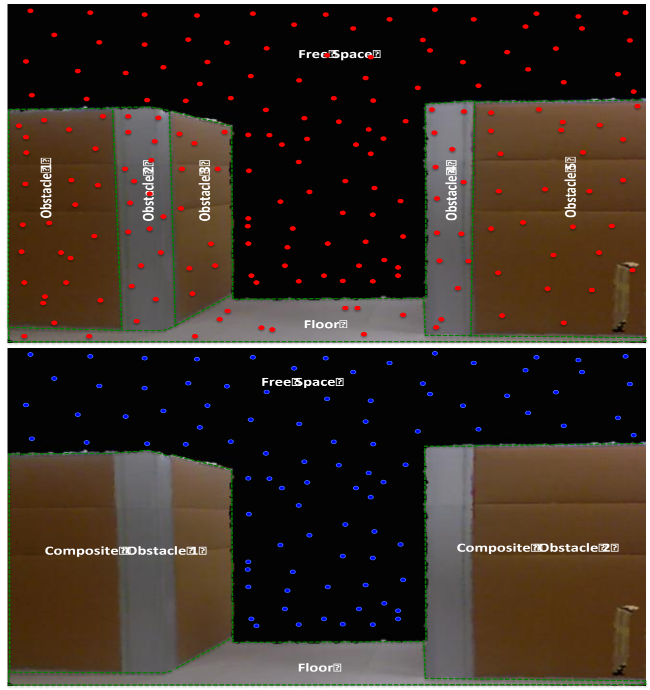

Fig. 9. Local target generation phase (Top: Uniformly distributed points cover the entire surface, Bottom: The "Good Points" as the blue dots.

D. Performance Evaluation

The areas around a local target should have the following properties:

- Cover the entire surface.
- Avoid over- and under-representation phenomena.
- From the two points above, one can infer that each area should be close to 1/k, where k is the number of targets. Note however, that this is not a very strict requirement, but only an indicator, since due to the complexity of the environment there might be some spaces that are small, however they need to be represented, in which case the area around the target would be essentially small. On the other hand, small spaces less than the acceptable thresholds are not necessary to be represented, since they do not constitute possible paths.

In order to prove the above statements we compare two different settings; the proposed algorithm settings and the random settings (another method where the local target points are chosen uniformly across the available space). Visually, the difference in performance between the two settings is not easily distinguishable. For this reason, the size of the clusters around a target point is introduced as a quantifiable measure for approximating their areas. More specifically, a big number of uniformly distributed points is generated in the available space and then clustered according to their nearest-neighbor (1-NN). Finally, the

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number of points in each cluster denotes its area. The results presented below are extracted from a simulation experiment and a set of 100 simulation runs.

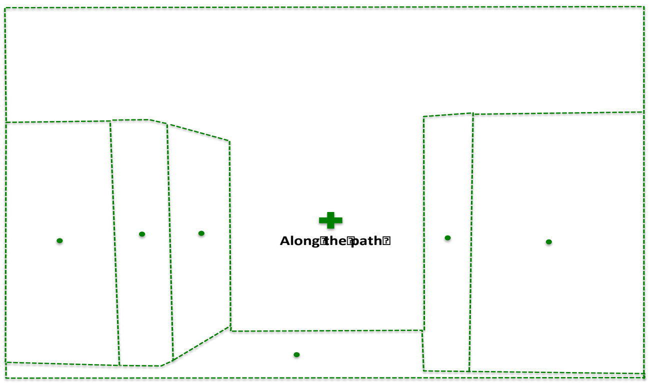

Fig. 10. The Voronoi diagram using as seeds the centroids of the clusters.

The first feature involves a measure of how stable and smooth are the generated areas. Figure 11 shows the deviations from the mean for each setting in each simulation run. It is apparent that the random setting is very unstable in contrast with our method, which is more consistent.

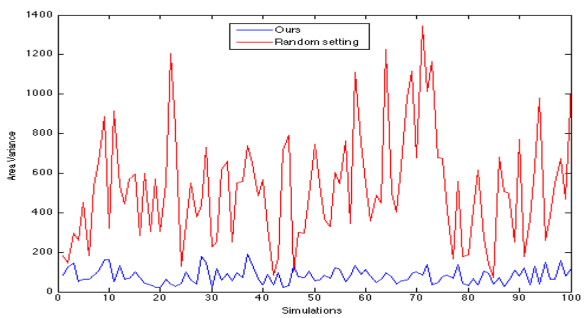

Figure 11: The variance of the areas of the two settings in each simulation run. The random setting shows great instability in comparison with our method.

The second major feature is how large and small clusters are being generated. Figures 12-13 show clearly that the random setting tends to create much bigger and also smaller clusters in comparison with the proposed algorithm. This results in over- and under-representations of each area; there are cases where 35% of the available space is covered by only one cluster and also area as low as 0.5%. On the contrary our results remain in the range 6.55% and 13.55%. Table 1 further shows the difference between the average minimum/maximum areas in the two settings.

Furthermore, we used the 1/k constant as a baseline to compare the performance of the two settings in relation with possible over- or under-representations. Figure 14 (top) shows a big gap between the maximum and minimum areas in relation to the random baseline (red line). On the other hand from Figure 14 (bottom) we can infer that the proposed method consistently maintains a balance in all of the simulation runs and is very close to the theoretical random baseline.

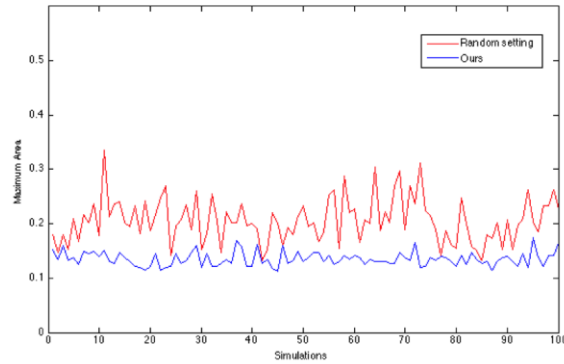

Fig. 12. The maximum covered area as percentage (%) of the entire available space

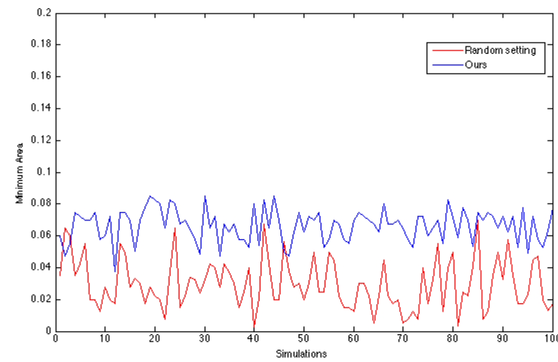

Figure 13: The minimum covered area as percentage (%) of the entire available space.

Table 1: Average minimum and maximum areas for each setting.

%	Average Minimum Area	Average Maximum Area
Random setting	2.99	20.66
Proposed algorithm	6.55	13.55

E. Discussion

Even though the Kinect with depth measurement offers a powerful and low-cost sensor system for obstacle detection, it has drawbacks as well. The Kinect depends on its infrared transmission and reflection mechanism to identify targets. Shade areas, smooth surfaces (mirror, glass, etc.) contain a large number of pixels of missing holes in depth information. This bears a significant impact on the identification of objects.

Unlike the algorithms that are currently present in the field of path planning and navigation, where the grid is known or assumed to be initially known and later modified, this algorithm has the ability to continuously process unknown environments, perform real-time identification of target and path planning. Processing the grid refers to identifying and differentiating between obstacles in the grid and open spaces. This feature gives the algorithm more

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realistic and smoother transitions from a navigation point to the next.

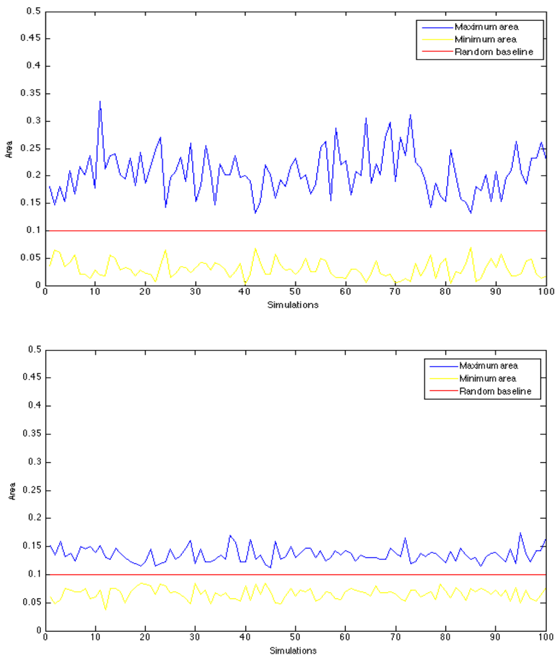

Figure 14: Maximum/minimum areas and a random baseline as percentages of the free space (top) random settings (bottom) proposed algorithm.

A person with ALS paralysis compelled us to create a smooth and easy to navigate algorithm that fit his limited ability to interact with the system. Her/his paralysis also contributed to our decision to grant the user with a limited number of targets to choose from. This makes the process of going from one grid to the next faster, more reliable and less confusing. The position of the target points was carefully studied and calculated, such that the points generated cover the entire surface of the grid given.

V. System Implementation

Figure 15 is a snapshot of the wheelchair system with highlights for the various components. The implemented system is based on the commercially available Permobil M400 mid-wheel drive wheelchair that can be used for indoor and outdoor driving[4]. The wheelchair consists of a chassis (which contains the wheelchair's electronics, power supply and drive functions) and a seat (consisting of a seat frame, seat plate/back rest, arm rest/leg rest, seat lift/fixed seat tube and other accessories such as head rest, calf rest, chest rest, chest support, etc.). It is equipped with a drive package for each drive wheel that consists of an electric motor with a drive gear and magnetic wheel lock.

[4] http://www.permobil.com/en-GB/English/C/Products/M400-Corpus-3G

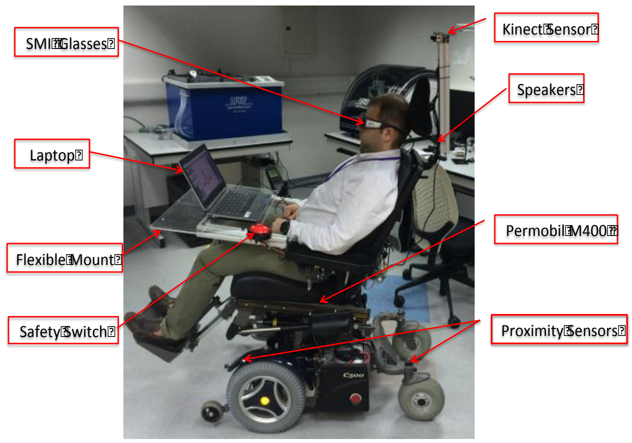

Fig. 15. A snapshot of the complete system.

A rigid mount, that provides a simple but highly adjustable support structure for mounting the laptop computer on the wheelchair, is attached to the wheelchair system. A similar mount is used on top of the wheelchair headrest to mount the Kinect camera. In order to automatically detect obstacles in the surroundings of the wheelchair system, the wheelchair structure is equipped with two types of proximity sensors: four infrared and five ultrasonic sensors. Finally, there is a safety switch in the system design to immediately stop the system whenever the button is pushed (by the caregiver or a family member).

The software of the Wheelchair control system is a combination of LabVIEW, Matlab, C++ and C codes. A summary of the pseudocode is shown in Figure 16.

```
//Define screen boundaries (dl, ul, ur, dr)
(d=down, l=left)
X=[X1, X2, X3, X4]
Y=[Y1, Y2, Y3, Y4]

//Compute grid dimensions
[rows, cols]=function(tracker_configs,
screen_configs)

//find boundaries of grid cells and store in
arrays
Yleft, Xleft, YRight, XRight, XUp, Yup, XDown,
YDown

//Find XY coordinates of all the cells of the
grid
[AX, BX] = distribute (XUp, XDown, YUp, YDown)
[AY, BY] = distribute (XLeft, XRight, YLeft,
YRight)

Retrieve eye contact coordinates (x, y)

Loop for maximum of rows*cols iterations
  If point(x,y) belongs to Cell(AX, AY, BX,
BY)
    A = Abs(AX - BX)/2
    B = Abs (AY - BY) /2
    Return cell(A,B)
```

Fig. 16. Pseudocode for computing the target cell based on eye contact.

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VI. CASE STUDY WITH A USER WITH ALS

The objective of this case study is to explore the effectiveness of the eye tracking calibration process, the ability of the participant to learn the grid-based interface, the efficiency of the proposed navigation algorithm. After running dry testing with the system for 3 weeks to make sure the system performs as intended and is bugs-free, a user with ALS was invited to participate in the experiment. The experiment took place at the user's home for increased comfort and convenience.

A. Testing Procedure

1) Pre-test Preparations

Before proceeding to the test, three important quality checks have been performed. First of all, a cognitive walkthrough was conducted where the wheelchair system was turned on, and all the tasks supported by the system were successfully completed. Few cosmetic bugs were traced and fixed so that the application was stable and reliable by the time the participant started conducting the test.

Afterwards, a pilot test was conducted with a person without ALS to rehearse before conducting the study with a participant with ALS. The person without ALS completed all the paper work (waiver, entrance and exit questions). The problems encountered during the pilot test helped identify changes before conducting the experiment with the participant with ALS. No technical issues with the system were reported in this test. Finally, the complete checklist for experimental setup was double-checked such as the waiver, entrance and exit questions.

Then, we prepared the wheelchair system to fit the user's personal needs. We modified the position of the seat, head support, screen position and eye gaze sensor of the wheelchair to reach the most comfortable experience. This was a difficult task since the patient was not able to move any of his body muscles except his eyes. Also most of his body muscles were under ankylosis. A "patient lift" was used to transport the user between his bed and the wheelchair system.

2) Participant Background

The participant was in a late stage of ALS at the time of running the experiment. His mobility was extremely limited, and help was needed for most personal needs. His ability to speak was also very limited (his wife was the only one to understand what he spoke). The participant has been using the Permobil M400 mid-wheel drive wheelchair for more than a year via a joystick, however at the time of the meeting, he was unable to use the joystick anymore, his hands muscles were paralyzed, and thus he started looking for alternative interfaces. Eventually, he used a custom-made eye-gaze controller but described that experience as unpractical (due to lengthy calibration process) and mentally overloading (due to the primitive commands the system offered). He had to instruct the wheelchair to move right, left, forward, and stop by gazing at the proper button. He described that experience as stressing and uncomfortable. He suggested that an ideal interaction would be that he is given a list of targets, picks one, and the machine will navigate to that target without him being involved. This required that a collision detection and avoidance system (based on ultrasound and IR sensors) must be used to ensure safe navigation.

3) Navigation Tasks

Three navigation tasks were assigned to the user (shown on the floor plan of Figure 17): navigating between office and dinning table (between point B and point C), office and bedroom (point A to point C), and dinning table and bedroom (point A and point B). We chose these tasks to be almost equally complex and thus no inter-task analysis would be necessary. The furniture in the participant's home was moved around from the original layout to create as unknown navigation tasks as possible. In order to complete the navigation task, the participant had to start at the designated position, move around the obstacles along the navigation pathway and pass through doorway, until he reached the destination.

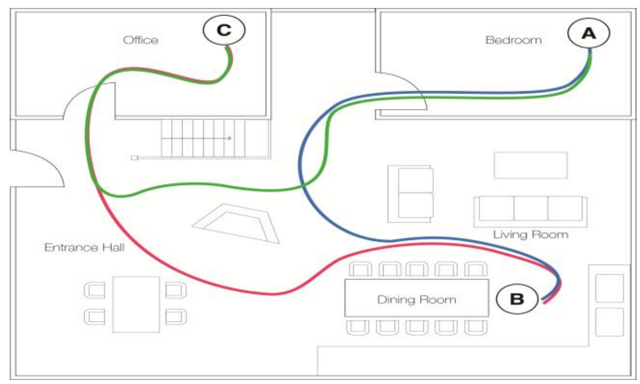

Fig. 17. The navigation tracks assigned to the subject.

4) Testing Methodology and Evaluation Measures

The test with the user with ALS started by welcoming the participant and making him feel at ease. The user was given an overview of the system and the test and was told that all his personal information will be kept private. Next, the caregiver/assistant completed the Waiver/Entrance Questions on the participant's behalf. The assistant was talking to the participant occasionally while completing the questionnaire and during debriefing, in order to make sure his thoughts were well reflected in the responses. The participant was also told that he might choose to quit any task, anytime. The user requested a break almost every 15-20 minutes during the experiment. A snapshot of the participant using the system is shown in Figure 18.

We have used quantitative and qualitative measures to quantify the participant's performance. The qualitative measures were achieved using the completed questionnaires and debriefings. The quantitative measures were obtained by monitoring the behavior of the participant while running the test, and were defined as: (1) Task Completion Time (TCT), Calibration Time (CT) and the Average Navigation Speed (ANS).

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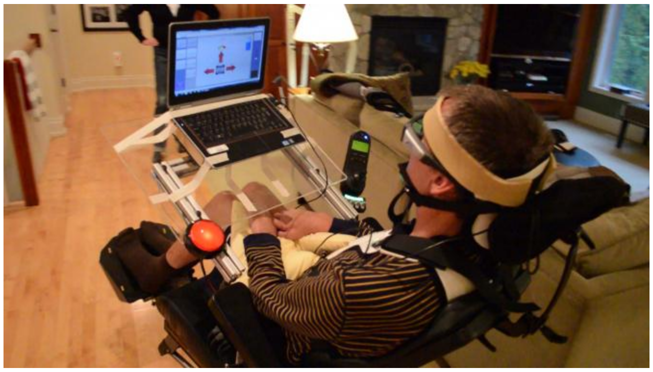

Fig. 18. The participant with ALS using the proposed system.

The participant performed a total of 20 trials of navigation tasks (between A, B, and C in Figure 17) over 2 days. Note that the furniture was re-arranged from day 1 to day 2 to create different navigation paths in order to avoid any bias from learnability of the navigation paths. For every trial, the TCT, the CT, and the ANS were noted. As a safety-critical measure, no collisions between the wheelchair and the ambient environment were reported through the entire test. The test thus showed that the proposal system is safe for continuous, real-time navigation of unknown environments.

B. Participant Performance Analysis

First of all, the ability of the participant to learn and use the calibration procedure is evaluated. The average calibration time, 20 trials of navigation trips (between the three targets A, B, and C as shown earlier in Figure 17) over 2 days, is presented in Figure 19. The participant was able to learn quickly the calibration procedure as he reached a steady state average of calibration time on the fourth/fifth trial. Also, it is observed that the participant had some difficulties focusing towards the red dots at the beginning but soon he was able to complete the calibration process quickly and with high self-esteem.

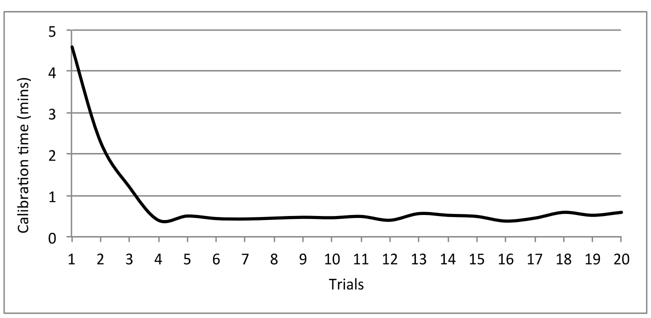

Fig. 19. Average calibration time over 20 trials experiment.

Table 2 presents the performance of the proposed calibration method in comparison with Sun et al. [57], Cheung and Peng [58], and Kassner et al. [59]. The accuracy of the proposed method is about 0.24°, which clearly outperforms the other algorithms. Furthermore, the calibration time for the proposed calibration method is the minimal among all the other methods. However, our proposed calibration method requires the user to wear the eyeglasses device, which is somehow intrusive and may be uncomfortable to use.

Table 2: Performance of different methods compared to proposed one.

Method	Accuracy (Degrees)	Calibration (min)	Approach
Sun et al. 2014	2	3	Depth camera, free head movement.
Cheung and Peng, 2015	1.28	3	Web camera, free head movement.
Kassner et al. 2014	0.6	1	Headset with optical tracker.
Our Method	0.24	0.6 (36 sec)	Eyeglasses with optical tracker, free head movement.

Perhaps the most direct measure of the participant's performance is the TCT. We recorded the time it took the participant to complete a trip between his bedroom, dining room, and office (points A, B, and C in Figure 17). The average TCT over the two days experiment, each with 20 trials, is shown in Figure 20. On day 1, the participant's TCT has significantly improved since the first trial (about 60% improvement by the end of the third trial). Trial 5 and on, the TCT has a steady state value of around 1.2 min. This result may be biased by the fact that the user was pursuing the same path in all trials and thus he has learned the navigation path from the first few trials, and thus he conducted the later trials more efficiently. However, the analysis on day 2 where the furniture was re-arranged to minimize such factor, results showed clear improvement of TCT compared to day 1. This is clearly demonstrated when comparing the first trial on the two days: day 2 had around 50% improvement over day 1.

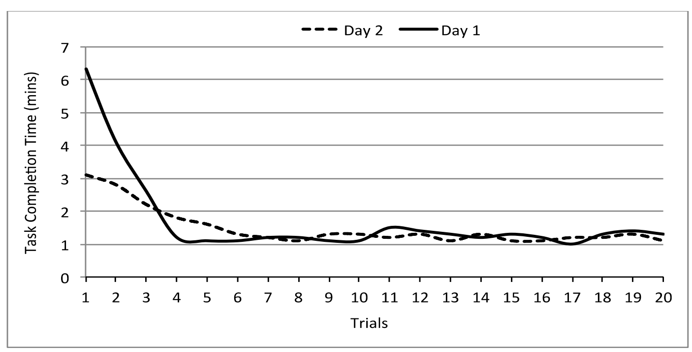

Fig. 20. Average task completion time for day 1 and day 2 analysis.

To provide a useful quantitative analysis of the participant's satisfaction and confidence using the proposed control system, the ANS was measured during every successful trial. Figure 21 shows that for day 1 the participant's average navigation speed has increased significantly compared to the first trial performance (from around 0.6 m/sec to around 1.2 m/sec, knowing that we set the speed limit to 2 m/sec for safety reasons). The increase in the average velocity shows clearly that the user has become confident using the system. Indeed, the participant requested to increase the speed limit, as he gained confidence controlling the wheelchair and thought he can navigate at a higher speed. For day 2, the participant started off with higher average navigation speed since he was already more confident about navigating the wheelchair.

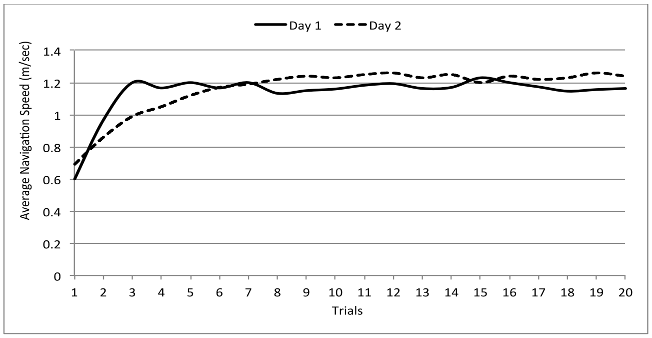

Fig. 21. Average navigation speed over 2-days experiment.

Finally, an interesting analysis was to compare the participant's performance from day 1 to day 2 (reported in Figure 22). As for the TCT, there is a 30% increase in the average TCT and 70% decrease in the standard deviation. This clearly shows that the participant was able to consistently perform the tasks more efficiently on day 2 of the experiment. The calibration time is significantly improved from day 1 to day 2 (around 50% improvement in the average and 70% improvement in the standard deviation). Finally, a 10% increase in the average navigation speed is observed from day 1 to day 2 however with 25% increase in the standard deviation.

C. Discussion

The case study test conducted with an ALS participant showed that it is feasible to drive the wheelchair safely with eye gaze control, while maintaining continuous and real-time identification of targets, path planning and navigation. The participant strongly agreed that the system has improved his ability to maneuver around with high confidence of control. In particular, the participant had adequate experience and knowledge to safely navigate the wheelchair system using the proposed N-cell grid interface in less than 30 minutes of training. The participant was also able to perfect the calibration process after only three trials.

Through a caregiver/participant debriefing, it was clear that the participant was very happy about using the proposed system and thought it was very promising. On the first trial of the navigation test, the participant was able to successfully move between office room, dining room, and bedroom. On day 1, and after completing three trials of navigation, the participant has requested to increase the speed limit, as he was more confidence controlling the wheelchair and thought he can navigate at higher speed. Furthermore, the caregiver highlighted the importance of the safety button that is mounted on the wheelchair. After completing the experiment, the participant has described his satisfaction about the system as "*It has much promise for people with physical challenges like mine. I thought that the testing work conducted here was invaluable…. not only for the technical factors, but also for the encouragement it gave me that, sometime in the not too distant future, it will be possible for people living with such physical challenges to experience a level of mobility and independence that we could otherwise only dream of.*" When asked about his opinion about the quality of the system in all, he described it as: "*I firmly believe that this technological concept and variations/adaptations thereof can and will benefit far more than just the population of ALS patients.*"

As per the interaction paradigm, the participant suggested that looking within the screen should stop the wheelchair navigation. On the other hand, looking outside the computer screen during navigation would mean the followings: looking above the screen would increase the wheelchair speed whereas looking downward will slow down the movement. If the participant looks at either sides of the screen (outside the screen boundaries), the wheelchair will start rotating clockwise or anticlockwise depending on the side the participant is looking towards.

Three limitations with the current study are highlighted, stemming from the limited resources and the participant's condition. The first limitation was the number of participants in the study. With only one participant, it is difficult to make generalized statements about the findings. Future studies with more participants are necessary to derive robust conclusions about the proposed system. The second limitation involved some uncertainties with the participant's feedback. The participant could not communicate his ideas properly due to limited ability to speak, and thus we relied on the caregiver. Perhaps the opinion of the participant may not have been exactly communicated through the caregiver. Finally, the third limitation relates to the eye movement and blink impairment for people with ALS. This system can only be used for users with ALS who have intact eye movements and blinking.

VII. Conclusion and Future work

This paper presented an eye-gaze control system for people with motor disability. The system uses an N-cell grid interface to navigate unknown environments in continuous, real-time fashion. An eye tracker calibration method is developed and tested with a participant with ALS. The participant showed improved performance in terms of calibration time, task completion time and the average navigation speed. Furthermore, debriefing the caregiver has also shown that the participant enjoyed higher level of confidence driving the wheelchair and experienced no collisions with the ambient environment.

Our immediate future work is to conduct additional studies with as many more persons with ALS as possible to have a statistically valid performance analysis. We are also working on developing some interesting features into the system, which can be useful to empower independent living of people with disability. Some of the features include the

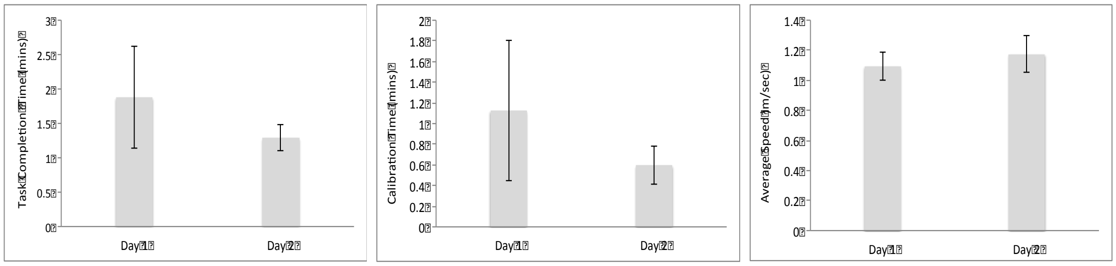

Fig. 22. A comparison of participant performance over 2 days (20 trials per day).

design of an eye-gaze virtual keyboard for writing text, an automation system to control the ambient environment (such as lights, AC, etc.), and an interaction paradigm to connect a person with motor disability to social media and entertainment systems. We would also like to investigate collaborative control (multiple persons with disability or the user with disability and the caregiver). Further development in this system will pay particular attention to the cost factor. We plan to revise the system to create the most cost-effective solution in order to make it accessible by a larger population of users with motor disability.

VIII. ACKNOWLEDGMENT

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