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Development of a Smart Wheelchair for People with Disabilities

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***Abstract*—The intelligent power wheelchair (iChair) is designed to assist people with mobility, sensory, and cognitive impairment lead a higher quality, more independent lifestyle. The iChair includes a power wheelchair (PW), laptop computer, laptop mount, multi-modal input platform, and a custom plastic enclosure for the environmental sensors, made with a 3D printer. We have developed the configuration of sensors to facilitate scientific observation, while maintaining the flexibility to mount the system on almost any power wheelchair, and remain easily removed for maintenance or travel. The first scientific observations have been used to compile ACCESS Reports that quantify a location or event's level of accessibility. If barriers exist we collect a 3D point cloud to be used as evidence and to make recommendations on how to remedy the problem.**

The iChair will serve a wide variety of disability types by incorporating several input methods, voice, touch, proximity switch, and head tracking camera. The HD camera and 3D scanner have been mounted in such a way as to provide reliable data with the precision necessary to detect obstacles, build 3D maps, follow guides, anticipate events, and provide navigational assistance. We evaluate the human factors in the current prototype to ensure that the technology will be accepted by those it is designed to serve, and propose a wheelchair skills test for future trial participants.

Keywords: Smart wheelchair, Human factors, 3D mapping, Structure scanner

I. INTRODUCTION

Some power wheelchair (PW) users cannot use a traditional joystick to navigate their PW, so they use alternative control systems like head joysticks, chin joysticks, sip-n-puff, and thought control [1]. In many cases PW users have difficulties with daily maneuvering tasks and would benefit from easy access to computing hardware, as well as some form of navigational assistance.

Smart wheelchair (SW) research is an international effort with multiple groups developing prototypes to test the latest input method, or to perfect a challenging operating mode. Other groups perform human trials to study the best ways to make people feel comfortable using the technology. [3]–[13]. A SW typically consists of either a standard PW base to which a computer and a collection of sensors have been added, or a mobile robot base to which a seat has been attached. Pineau et al. 2011 argue that the transition to wheelchairs that cooperate with the user is at least as important as that from manual to powered wheelchairs, and possibly even more important since this would mark a paradigmatic rather than merely a technological shift [2].

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Unfortunately, no commercially viable SWs have emerged, because the design either relies on heavily modifying the PW, only serves a small subpopulation of potential SW users, and/or are developed with little consideration for the human factors. For example, SWs that have laser or ultrasonic range finders, odometers, and visual displays can be installed on most PWs, but are not easily removed for airplane travel. Microphones do not work well in noisy environments, and are not very good for people with speech impediments. Touch surfaces are useless when the user cannot move their arms. Spherical vision cameras and scanners that require a mount that is above the user's head, are not practical if the user wants to enter a wheelchair accessible van.

In this paper we put forward a SW system designed by a PW user to serve a broad population of PW users, with a multi-modal interface, and sensors that are mountable on almost any PW. The proposed intelligent power wheelchair (iChair) can collect scientific quality observations with an HD camera and 3D scanner. It also has LEDs that illuminate the path ahead, help make the PW visible to others, and serve as a means of long distance communication. All this is achieved without increasing the PW's footprint or height. The plastic enclosure that houses the sensors and LEDs is designed to be modular, printed with a 3D printer on demand, and assembled by a robotic arm assembly line. The operating system will use the data stream from the sensors to help the PW user detect obstacles, follow a guide, build 3D maps, and plan trajectories.

The remainder of this paper is organized as follows: section II describes the current iChair prototype, section III presents iChair operation, and section IV is the conclusion and future work.

II. OVERVIEW OF iCHAIR DEVELOPMENT

A. System Development

The overall design of the iChair is presented in Fig. 1 and co-author Dr. Jesse Leaman (JL) is the user of this iChair. The iChair has two major components: power wheelchair (off the shelf commercially available) and human-controller interface (HCI).

The iChair HCI is designed so that the user can interact and operate the iChair though voice, touch, proximity switch, and head tracking camera. It provides seemless access and control for users with severe disabilities, like co-author JL who is paralyzed from his shoulders down. Figure 1 is an image of the prototype configuration, with the 3D scanner and HD camera mounted on the front of the chair providing range data and localization information for the various operating mode algorithms. The range data used by the iChair software is provided by the Structure 3D scanner,

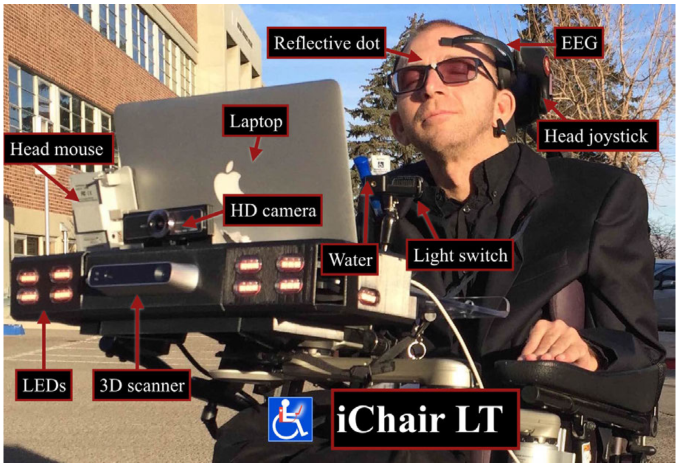

Fig. 1. iChair prototype developed at the Advanced Robotics & Automation (ARA) laboratory at the University of Nevada, Reno. iChair has the HD camera and 3D scanner mounted to collect data that is consistent from one observation to the next. Co-author JL is testing an EEG sensor, but it is not used for navigation because it is only able to detect concentration and meditation.

which can collect 640 x 480 resolution, 58 x 45 degree FOV images at a rate of up to 60 frames per second.

The mechanical design for building the HCI using Sketchup software is presented in Fig. 2 and the associated component description is provided in Table I. Fig. 3 shows a 3D rendering of the assembled components from Fig. 2, while Fig. 4 shows electronic components found inside the HCI, as shown in Fig. 1. This HCI is designed to be modular (if one piece fails you do not have to replace the whole system), upgradable, with parts that can be 3D printed, and assembled by robotic arms.

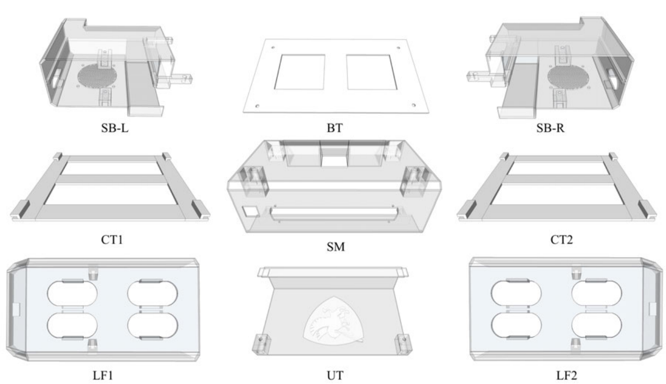

Fig. 2. iChair enclosure (ENC) parts, designed with 3D printing and robotic assembly in mind. See Table I for a description of the labels.

B. iChair Communication and Sensing

1) Light communication: Communication with other powered wheelchairs becomes important in places like rehab clinics and retirement communities where users may travel in group formation, or where they assemble in such a way that most facilitates communication with caregivers and between users. The iChair has ten LED micro modules wired

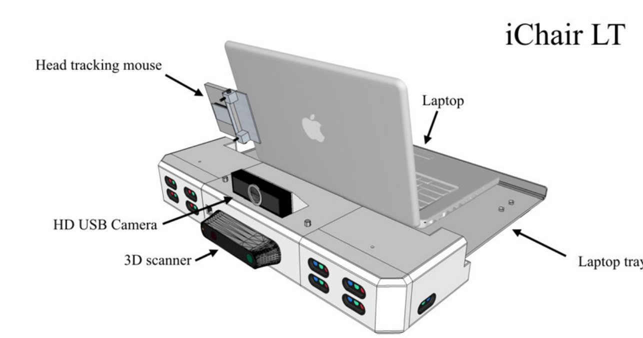

Fig. 3. 3D sketch of the iChair prototype after assembly of components in Fig. 2.

Fig. 4. iChair electronics (ELE) inside the enclosure. See Table II for a description of the labels.

in channel A & B, where A has 8 modules pointing forward and B has 2 side pointing modules, one on each side (see Fig. 5). The iChair can communicate with people and other iChairs using light signals, such as turn signals, emergency signals, and guiding signals (Algorithm 1).

Fig. 5. iChair LED color options and their operation is followed by Algorithm 1. These lights are not just for show, even though being seen is vital when attempting to avoid collisions. With 7 color, 10 pattern, and 5 different speed options we can enhance observations and communicate over long distance.

2) Collision avoidance: Fig. 6 and 7 demonstrate what happens when the scanner approaches an object, while Fig. 8 shows a 3D map that can be used to support iChair

TABLE I. ICHAIR ENCLOSURE (ENC) PARTS DESIGNED TO BE 3D PRINTED (SEE FIGURE 2), IN THIS CASE A ZPRINTER 450 BY Z CORPS AT A COST OF $2.61 PER ML OF CORE POWDER USED + $0.22 PER ML OF CLEAR BINDER USED.

Name	Code	Cost ($)	Source
Speaker boxes	SB-L, SB-R	120	UNR
Battery tray	BT	20	UNR
Circuit board trays	CT1, CT2	20	UNR
Sensor mount	SM	100	UNR
Light fixtures	LF1, LF2	40	UNR
USB tray	UT	80	UNR
Bolts		14	Amazon
Total		345	

TABLE II. ICHAIR ELECTRONIC (ELE) PARTS AVAILABLE FROM COMMERCIAL US VENDORS (SEE FIGURE I).

Name	Code	Cost ($)	Source
3D scanner	3DS	350	Occulos
Light system	LC, LA1-8, LB1-2	90	Xpglow
USB HD camera	HDC	40	Amazon
USB hub	USBh	15	Amazon
USB sound card	SC	30	Amazon
IMU-GPS	IMU	35	Amazon
2 inch speakers	SP-L, SP-R	19	Amazon
12V Li-ion Battery	BAT	17	Amazon
Wires		15	Amazon
Total		611	

Algorithm 1: Light communication (LC)

```
Data: IMU, UIE, bf, color_{1-7}, L_min
Result: Photons (led, color, frequency)
Step 1: Read IMUyaw(t), UIE, bf, color_{1-7};
Step 2: Determine Δyaw;
Δyaw = yaw(t_2) − yaw(t_1);
if Δyaw > 0 then
  | Photons(LB1, amber, bf)
end
if Δyaw < 0 then
  | Photons(LB2, amber, bf)
end
Step 3: Check for Emergency;
if UIE = 1 then
  | Photons(LA1-8, blue, bf)
end
Step 4: Check lighting conditions L;
if L < L_min then
  | Photons(LA1-8, white, 1)
end
Step 5: Check scanner;
if 3D scan = 1 then
  | Photons(LA1-8, red, 1)
end
```

navigation and collision avoidance. The range data and trajectory can be used to determine whether a collision is imminent, and give the user visual and audible feedback (Algorithm 2). Some tasks are at odds with the behavior expected from a more general collision-avoidance mode. While passing through a doorway the system must allow the wheelchair to come close to objects to pass through narrow door frames, at the expense of travel speed. It is important to have a robust system, but it must be adjustable to each user's individual comfort level.

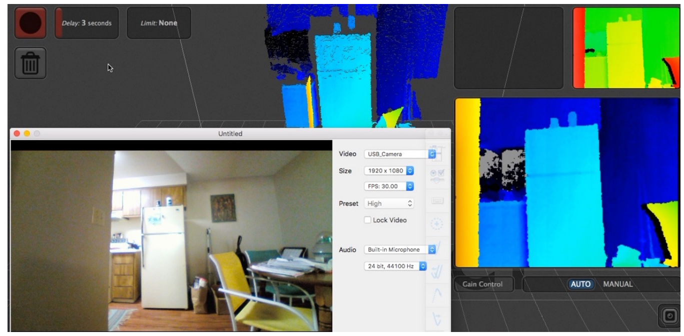

Fig. 6. Data collected with the Structure 3D scanner and HD camera. The iChair is approximately 8 feet from the refridgerator at the center of the image.

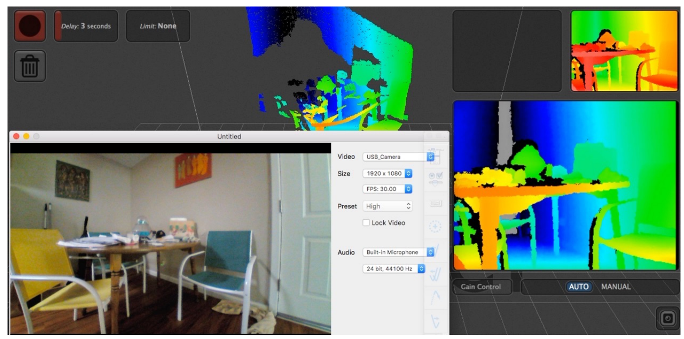

Fig. 7. Data collected with the Structure 3D scanner and HD camera. The iChair is approximately 4 feet from a potential docking location between chairs under the table.

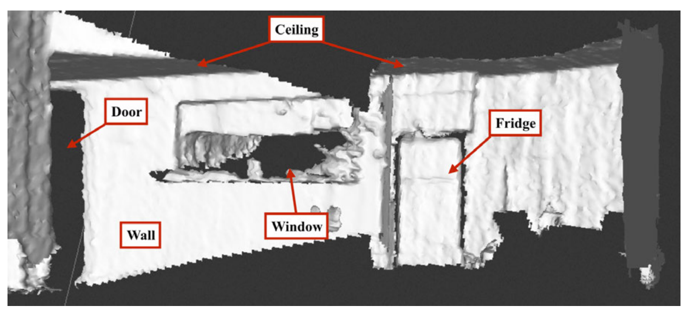

Fig. 8. Data collected with the Structure scanner, and processed by Skanectreveals details like infrared shadows that show depth and separation.

Algorithm 2: Collision avoidance (CA)

```
Data: 3D point cloud, c_1, c_2, d_min
Result: Play sound (A, ω)
Step 1: Find distance (d) to the closest point;
Step 2: Set the amplitude (A) and frequency (ω) of
  the beep;
A = c_1 * d;
ω = c_2/d;
Step 3: Alert when approaching objects;
if d < d_min then
  | Play sound(A, ω)
end
```

3) Emergency signal: In the case of an emergency the iChair will send a text message to the user's emergency contact list, blink lights, and broadcast a distress call. The basic package included with the hardware can detect emergencies like tipping back or falling over by monitoring IMU data, and future upgrades will use biofeedback to detect stress (Algorithm 3).

Algorithm 3: Emergency signal (ES)

```
Data: IMU, UIE
Result: Emergency signal
Step 1: Read in ϕ and θ every t seconds;
if ϕ or θ > 45° then
    Emergency = true
end
Step 2: Call for help;
if Emergency = true or UIE=1 then
    Emergency signal
end
```

III. iChair Operation

This section first presents the operation of the iChair via different input methods, then discusses the human trials, event anticipation and skills test for the iChair.

A. Input methods

The power wheelchair is the base for every iChair, and the components are mountable on almost any PW. The PW can support the additional 15 pounds of computing and sensory technology, and provide power from it's massive batteries. The choice of wheelchair control method is up to the user, and will depend on their individual level of dexterity and endurance. The iChair can be controlled by touch, voice, computer vision (head tracking), and brain waves (EEG), although the latter is still in its experimental phase.

1) Touch: PW users with the manual dexterity to use a smart phone or tablet will be able to control the iChair via touch screen application. Since many people feel very comfortable using mobile devices today, it is likely that the elderly of the future will trust these touch screens to help them operate their PW [14].

2) Voice: For those PW users without the use of their arms a reliable commercial solution is to interface with the computer via voice recognition (VR). Co-author JL used voice recognition as his primary input method starting in 1996, providing an efficient means of composing lengthy documents, but a rather slow solution for making mouse movements.

In recent years VR has become very reliable, and in turn humans now regularly talk to their mobile computers fully expecting it to understand, and even formulate an appropriate response. Siri, and all of her abilities are available to iChair users.

3) Head tracking: Co-author JL's input method of choice is the HeadMouse, which is an infrared camera that emits infrared photons that reflect off of reflective tape on the user's head (hat or glasses). The HeadMouse works with the KeyStrokes software to click the mouse when it dwells on a location for more than a second. Other methods like pupil tracking, and head tilt [15] are less reliable outdoors and require the camera to be positioned very close to the user's eye, which may be uncomfortable for some PW users.

The increase in efficiency when using head tracking over voice recognition is most notable when considering mouse movement one click at a time. If you want to move the mouse from the center of the screen to the top left with VR you say: "Mouse Grid 1 1 1" then "Mouse click," to move the mouse from the center of the screen to the bottom right you say: "Mouse Grid 9 9 9" then "Mouse click."

The difference in time between saying that phrase and simply looking at a different location is at least 6 to 1, and can be more when you do not know the right number combination ahead of time.

4) Brain waves: The iChair will be able to extract the user's thoughts via electroencephalograph (EEG) [1]. This method is still under active research and development, but with blue tooth the hardware is now more comfortable, and several games can reliably distinguish between concentrating and meditating. Safely operating a PW is in principle possible with a single switch, but ideally we will extract left, right, forward, reverse, and stop from the EEG stream.

B. Human trials

The iChair has the potential to significantly improve the quality of life for people who use PWs, but only if it is trusted by the people it was designed to serve. Since 1999, Medicare has spent $8.2 billion to procure power wheelchairs and scooters for 2.7 million people [16] and tens of thousands of people start using PWs every year.

We plan human trials to optimize the user experience with a system that is customizable to the individual user's preferences (see Table III for options), and mountable on almost anybody's PW.

The first phase of human trials is already underway, conducted by co-author JL, who is an astrophysicist and uses a PW for his daily mobility needs. JL is paralyzed from the shoulders down, and has been making modifications to his PW since his first NASA internship in 1998. He is now an expert in human factors and used the scientific method to optimize his SW design.

The prototype provides visual and audible feedback, but cannot control the PW. JL will test the feedback accuracy and user experience until there are no more detectable bugs. Once the iChair software is deemed ready by the group, five students and a few local PW users will be recruited to test the system on campus. One at a time participants will borrow an iChair from the Nevada Center for Excellence in Disability (NCED) library, and perform several tasks. At the conclusion of the trial participants will answer a survey to evaluate the iChair's functionality and overall experience. We hope to asses the user's ability to customize their experience and whether this improved their level of comfort.

Participants who sign up may include people who have recently experienced the onset of disability or somebody who has been living with cognitive/motor/sensory impairment for most of their lives. We will work with institutions worldwide who have a SW research program and have worked with, or know of, PW users who would benefit from the iChair. With successful outcomes in the phase 2 trails, we will begin printing and assembling the HCI into packages that are shipped with a beta version of the iChair software that helps avoid collisions, sends emergency messages, and facilitates light communication.

TABLE III. CUSTOMIZABLE VARIABLES TO BE TESTED DURING THE HUMAN TRIALS.

Operating mode	Description	Variable	Section
Obstacle detect	Beep constants	c_1, c_2	II-B2
Light comm	Favorite colors	$color_{1-7}$	II-B3
	Blink frequency	bf	II-B1
	Min lighting level	L_{min}	
Object class	Max distance	d_{max}	II-B2
Docking	Safe zone	h_{safe}, w_{safe}	II-B2
Following	Tracking velocity	v_{tr}	II-B2
3D mapping	Room size, height	s_{room}, h_{room}	II-B2
Path planning	Destination coords.	lon_d, lat_d, alt_d	II-B2
Auto nav	Max vel., min dist.	v_{max}, d_{min}	II-B2
Event anticipation	Update frequency	ν_{update}	III-C

C. Event anticipation

The concept comes from statistical astrophysics, a skill co-author JL picked up while using the control time method to estimate the rate of supernova explosions in the local universe [17]. When keeping accurate event detection logs, where time, location, and type are recorded at regular intervals, it is possible to calculate the event rate and predict the probability of that event type taking place at a particular place and time in the future.

Each time an object is detected, classified, and added to the 3D map a log entry is created to track it's location in time. By computing the control time for each object we can determine the rate (ν_{obj}) at which it will be found be at a particular location at any given time.

$$\nu_{obj} = \frac{N_{obj}}{Tct_{obj} \times V_{obj} \times Corr_{obj}} \tag{1}$$

where N_{obj} is the number of times the object has been detected in a particular volume of space V_{obj}. $Corr_{obj}$ is a correction that is applied for certain objects that may suffer from an observational bias, for example flatware on a table will go undetected in observations by sensors that are below the height of the table. Tct_{obj} is the total control time since the first time it was observed.

$$Tct_{obj} = \sum_{i=1}^{N_{obj}} ct_{obj,i} \tag{2}$$

where $ct_{obj,i}$ is the individual control time, i.e the duration of a particular detection (i) of the object.

The probability P_{obj} that the object will be found in V_{obj} is:

$$P_{obj} = 1 - e^{-\nu_{obj} \times Tct_{obj}} \tag{3}$$

Stationary objects like bookshelves and TVs have a near 100% chance of being in the same space in the near future, but mobile objects are more unpredictable. Chairs around a table for example will change location throughout the day, especially around mealtimes. A wheelchair size opening between chairs could be interpreted as an invitation and as a prediction for an up coming event on the table.

D. Wheelchair Skills Test (WST)

With thousands of smart wheelchairs in public areas the risk of an event resulting in injury or property damage also increases, so we will offer registration and a 12 step Wheelchair Skills Test (WST) [2] certifying that the user is safe to operate the iChair. Our proposed indoor testing area is shown in Figure 9 and the skills to be tested are listed in Table IV.

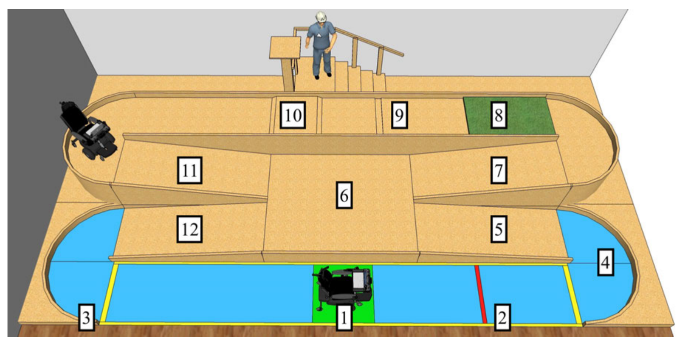

Fig. 9. Wheelchair Skills Test (WST) area where each user certifies that they can safely operate their iChair. The 12 steps leading to certification are detailed in Table IV [2].

TABLE IV. WHEELCHAIR SKILLS TEST (WST) STEPS TOWARD CERTIFICATION. THE WST TESTING AREA IS SHOWN IN FIGURE 9.

Step	Description
1	Turn on/off
2	Forward 10 ft
3	Reverse 10 ft
4	Turn left 90^o
5	Go up 5^o incline
6	Turn right 90^o
7	Go up 10^o incline
8	Traverse rough terrain
9	Cross 2 in dip
10	Cross 2 in rise
11	Go down 5^o incline
12	Go down 10^o incline

E. ACCESS Report

Co-author JL uses his iChair to collect video and range data at popular locations and events (Tab. V) and prepares reports. The level of accessibility depends on local factors such as: socio-economic status of the inhabitants, geography and topography, and political views of government representatives.

TABLE V. ACCESS REPORT LOCATIONS OF INTEREST. THE OVERALL RATING IS BASED ON THE AVERAGE OF THE INDIVIDUAL RATINGS USING THE SCALE IN TABLE VI

1	Entrance (main, secondary)
2	Seating
3	Access to goods
4	View
5	Bathrooms
6	Customer service
A	Public University, Schools, Parks
B	Commercial Hotels, Shops, Restaurants, Casinos
C	Residential Communities, Buildings

TABLE VI. ACCESS REPORT RATING SCALE

Scale	Description	Example
0	Not Accessible (illegal)	Upstairs with no elevator
1	Not Accessible (barely legal)	1-2 stairs and portable ramp
2	Barely Accessible	Standard door
3	Accessible	Door with push button
4	Above Average Access	Front row at an event
5	Universal Access	Automatic door

Almost everybody in the world either has, or knows somebody who has a disability. The ACCESS Report is an inside look at the daily lives, challenges, and triumphs of the human spirit, despite the incredible challenges faced by many people with mobility/sensory/cognitive impairments. Our goal is to raise awareness of the barriers that still exist today that either limit participation, or even segregate entire populations of the most vulnerable in our society.

IV. CONCLUSION AND FUTURE WORK

The iChair is designed to improve the lives of people with mobility, sensory, and cognitive impairments, opening up employment opportunities, and the potential for a high quality independent lifestyle. In this paper we describe the current iChair prototype which is designed to be modular, upgradable, with parts that can be 3D printed, and assembled by robotic arms.

The data collected by the onboard sensors is of the quality necessary to help identify and classify objects, build 3D maps, and eventually facilitate autonomous navigation. In the future the hardware will be bundled with customizable software, and upgraded with a power mount that will improve the durability and payload of the iChair.

During our human trials we will put our system to the test while participants collect data that we use to build a complete 3D map and thorough ACCESS Report of the UNR campus. All participants will have to pass the WST before using the iChair on campus, and provide feedback that will help us produce a system fit for commercialization.

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REFERENCES

[1] J. S. Nguyen, S. W. Su, and H. T. Nguyen. Experimental study on a smart wheelchair system using a combination of stereoscopic and spherical vision. In *35th Annual International Conference of the IEEE EMBS*, Osaka Japan, July 2013.

[2] A. Atrash J. Villemure J. Pineau, R. West and F. Routhier. On the Feasibility of Using a Standardized Test for Evaluating a Speech-Controlled Smart Wheelchair. *National Science and Engineering Research Council Canada*, 2011.

[3] Y. Kobayashi, Y. Kinpara, E. Takano, Y. Kuno, K. Yamazaki, and A. Yamazaki. Robotic wheelchair moving with caregiver collaboratively. *Advanced Intelligent Computing Theories and Applications. With Aspects of Articial Intelligence.*, 1281:523–532, 2012.

[4] K. Pretz. Building smarter wheelchairs. making life easier for people who can't walk. *The Institute-IEEE*, June 7, 2013.

[5] R. Murakami, Y. Morales, S. Satake, T. Kanda, and H. Ishiguro. Destination unknown: Walking side-by-side without knowing the goal. *ACM/IEEE International Conference on Human-robot Interaction (HRI '14), New York, NY, USA, ACM*, pages 471–478, 2014.

[6] R. Suzuki, T. Yamada, M. Arai, Y. Sato, Y. Kobayashi, and Y. Kuno. Multiple robotic wheelchair system considering group communication. In *Advances in Visual Computing*, Lecture Notes in Computer Science, pages 805–814. 2014.

[7] D.K. Rathore, P. Srivastava, S. Pandey, and S. Jaiswal. A novel multipurpose smart wheelchair. In *Electrical, Electronics and Computer Science (SCEECS), 2014 IEEE Students' Conference on*, pages 1–4, March 2014.

[8] B. M. Faria, L. P. Reis, and N. Lau. A survey on intelligent wheelchair prototypes and simulators. volume 275 of *Advances in Intelligent Systems and Computing*, pages 545–557. Springer International Publishing, 2014.

[9] D. Sinyukov, R. Desmond, M. Dickerman, J. Fleming, J. Schaufeld, and T. Padir. Multi-modal control framework for a semi-autonomous wheelchair using modular sensor designs. *Intelligent Service Robotics*, 7(3):145–155, 2014.

[10] J. Leaman and H. M. La. ichair: Intelligent powerchair for severely disabled people. In *ISSAT International Conference on Modeling of Complex Systems and Environments (MCSE)*, Da Nang, Vietnam, June 8-10 2015.

[11] F. Carrino, J. Dumoulin, E. Mugellini, O. Khaled, and R. Ingold. A self-paced bci system to control an electric wheelchair: evaluation of a commercial, low-cost eeg device. In *Biosignals and Biorobotics Conference (BRC), 2012 ISSNIP*, 2012.

[12] J. S. Nguyen. *A Smart Wheelchair System using a Combination of Stereoscopic and Spherical Vision Cameras.* PhD thesis, University of Technology, Sydney, 2012.

[13] P. A. Hancock, D. R. Billings, K. E. Schaefer, J. Y. C. Chen, E. J. de Visser, and R. Parasuraman. A meta-analysis of factors affecting trust in human-robot interaction. *Human Factors*, 53(5):517–527, October.

[14] J. Tavares, J. Barbosa, and C. Costa. A smart wheelchair based on ubiquitous computing. In *PETRA '13 Proceedings of the 6th International Conference on Pervasive Technologies Related to Assistive Environments*, pages 1–4, Island of Rhodes Greece, May 2013.

[15] A. R. Trivedi, A. K. Singh, S. T. Digumarti, D. Fulwani, and S. Kumar. Design and implementation of a smart wheelchair. In *Proceedings on AIR 2013*, Pune India, Jul 2013.

[16] D. Fahrenthold. A medicare scam that just kept rolling. *Washington Post*, 8/16/2014, 2014.

[17] J. Leaman, W. Li, R. Chornock, and A. V. Filippenko. Nearby supernova rates from the lick observatory supernova search - i the methods and data base. *Monthly Notices of the Royal Astronomical Society*, 412(3):1419–1440, 2011.