Development of Vision-Based Navigation for a Robotic Wheelchair

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Abstract— **Our environment is replete with visual cues intended to guide human navigation. For example, there are building directories at entrances and room numbers next to doors. By developing a robot wheelchair system that can interpret these cues, we will create a more robust and more usable system. This paper describes the design and development of our robot wheelchair system, called Wheeley, and its vision-based navigation system. The robot wheelchair system uses stereo vision to build maps of the environment through which it travels; this map can then be annotated with information gleaned from signs. We also describe the planned integration of an assistive robot arm to help with pushing elevator buttons and opening door handles.**

I. INTRODUCTION

When you go to a meeting in an unknown building, you go through a series of steps to get there. The complexity of the task is rarely noticed because human environments have maps and signs indicating where you are, where to go, and what to do. A script identifying the major steps might look like the following if you were describing them to another person.

1) Find a building directory and determine the location of the desired room.
2) Proceed to the elevator and push the call button.
3) Enter the elevator when it opens.
4) Select the desired floor.
5) Upon reaching the correct floor, exit the elevator.
6) Look for one or more signs indicating which rooms are to the left and right.
7) If there is such a sign, determine which category the room number falls under and proceed in the corresponding direction.
8) Monitor the progression of room numbers as you move through the environment.
9) If you are moving in the wrong direction, turn and go the other direction.
10) Upon reaching the desired room, open the door and enter the room.

Clearly there are other ways of dividing the task, but these capture the essential points. While these steps are intuitive, people with physical and/or cognitive disabilities may have trouble with them. Our research explores a high-level goal-centric approach for robotic wheelchairs. We envision that the user could simply specify a destination instead of micromanaging each section of the larger task. If ambiguity were to arise, we would take advantage of the human-in-the-loop for clarification. To accomplish this vision, our research explores wheelchair navigation, human cue detection, and a robotic arm manipulator on a prototype robotic wheelchair, Wheeley.

Wheeley is a redesign of Wheelesley, a semi-autonomous robotic wheelchair [1]. It is the foundation for several research projects including stereo vision based simultaneous localization and mapping, automatic map annotation, and control of a wheelchair-mounted robotic arm. These projects are aimed towards building a robot wheelchair system that can accomplish the task described above: enter an unknown building and find a specified room. The mapping system will create a map of the environment as the robot moves through the building. Our sign detection and interpretation system will find room numbers that will be used to annotate the map as well as guide the navigation of the wheelchair towards the desired goal. Finally, the wheelchair-mounted robot arm and its associated vision system will be used to locate and push elevator buttons, as well as to open door handles, in order to make the environment fully accessible. As this system is currently under development, the sections of the paper describe work in progress.

II. BACKGROUND

The powered wheelchair is a successful and popular assistive device. Powered wheelchairs enable physically disabled people to continue with their activities of daily living (ADL). In a 1996 study, powered wheelchair users described their initial and long-term experiences [2]: they felt empowered due to their increased ability to complete tasks. In 1994, there were an estimated 1.7 million non-institutionalized people who used powered wheelchairs or powered scooters in the United States[1] [3].

An individual may be prescribed a powered wheelchair for mobility upon meeting several criteria [4]. For example, because the person does not have dexterous use of his/her upper extremities, a manual wheelchair might be inappropriate. A powered wheelchair does not require the physical contribution of the upper extremities; therefore it would be more effective for these individuals.

However, a standard powered wheelchair may not be appropriate for all patients. They may not be able to safely operate a powered wheelchair using a joystick or single switch input device. Severe upper extremity weakness,

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[1]Data based on the 1994 National Health Interview Survey on Disability.

spasticity, or cognitive impairment can all potentially limit their ability to operate basic motor controls. In such cases, powered wheelchairs may be augmented with environmental and user status sensors, as well as artificial intelligence. Such additions may broaden the scope of those who can benefit from the added mobility and freedom of a robotic wheelchair.

Research in the field of intelligent robotic wheelchairs seeks to address the following issues: safe navigation, shared control between user and robot, human-robot interfaces, and the creation of usable systems for target populations. Lankenau and Rofer [5] survey intelligent robotic wheelchair research from North America and Europe as of 2000. Haigh and Yanco [6] address robotic wheelchairs in their survey of assistive technologies in 2002. Simpson et al. [7] discuss recent and current research projects through 2005.

Hardware implementations vary with respect to sensors, human-robot interaction, and artificial intelligence. However, researchers acknowledge that intelligent robotic wheelchairs should reduce the cognitive load of the user [8]. Because the user and intelligent wheelchair are collocated, an intuitive user interface is a must. A discussion of the joystick as the most basic and common human-robot interface is found in McLaurin [9]. McLaurin notes that it is “far from ideal for many users” and that the user should only need to provide high-level control through alternate means coupled with computer control.

Intelligent robotic wheelchairs have begun to emerge in the commercial venue. The CALL Centre’s Smart Wheelchair [10] is mentioned in the above literature surveys. It is sold by Smile Rehab, Ltd. and meets European Commission regulations. Another commercially available intelligent wheelchair is the iBOT Mobility System wheelchair [11] developed by DEKA. It was approved by the US Food and Drug Association in 2003.

Despite all of the prior work in robotic wheelchairs, systems have been unable to travel using the visual cues put into buildings to guide people to rooms. The development of this capability will greatly expand the independence of robot wheelchair users.

III. WHEELCHAIR HARDWARE

The Wheelesley robotic wheelchair system [1] was designed for indoor and outdoor navigation. Wheelesley could automatically switch between indoor and outdoor navigation modes using an environmental detector. It could also autonomously drive through doorways unassisted by the user.

Wheelesley had a shared control autonomy system. The user gave high-level commands such as “left” and “straight.” The robot handled low-level commands such as path following and obstacle avoidance. Wheelesley was designed with an easily customizable user interface which was adapted for single switch scanning and an eye tracker. Wheelesley has gone through a redesign described in the following section and has been renamed “Wheeley” (see figure 1 for a photo of the new system).

The wheelchair chasis was manufactured by Vector Mobility. Measuring 65 centimeters (25.5 inches) wide and 127 centimeters (50 inches) long, the system has a differential drive system powered by two 12V batteries. Its powerful motors combined with individual motor control allow the platform to operate in indoor and outdoor environments.

Fig. 1. UML’s implementation of a robotic wheelchair known as “Wheeley.” The camera, temporarily mounted in the seat, provides stereoscopic video to the computer, mounted on the back of the chair.

The original wheelchair, Wheelesley, used a 24V analog motor controller coupled to a joystick for user control[2]. A potentiometer knob slightly above the joystick selected the top speed. The controller also had 24V outputs for magnetic, mechanical brake releases. The system had been previously modified for rudimentary computer control by emulating the analog joystick through digital-to-analog converters. It was decided very early in the redesign process that this open-loop control system was insufficient to guarantee the safety of the wheelchair occupant. To this end, a commercial motor controller was selected that could sufficiently powered the high-torque motors while guaranteeing a high level of safety.

The AX2850 motor controller from RobotEQ was selected for several reasons. First, the motor controller provides emergency stop and active braking capabilities. Second, the controller has user configurable digital outputs, which have been configured to trigger the mechanical braking system on the motors. This second level of safety provides fail-to-stop protection from catastrophic powered loss or parking on non-level surfaces, ensuring out-of-the-box safety for the wheelchair occupant. Finally, the system provides full closed-loop control through encoders that were custom installed on the motor shafts. The closed-loop control allows us to select a very gradual acceleration profile and top speed that ensures the wheelchair will not accelerate beyond safe limits.

[2]Wheelesley’s hardware was based on the TinMan system [12].

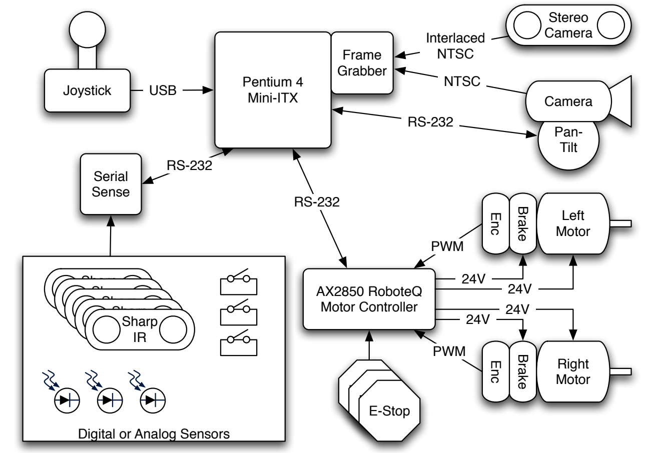

Fig. 2. Flow chart of the components of the wheelchair. The design is flexible for many different research projects and sensor configurations.

A computer was mounted on the back of the chair's frame inside a waterproof and hardened Pelican case. This "backpack" configuration allows the computer and accessories to stay within the footprint of the wheelchair base. This sizing is important to ensure that the controlling computer does not hit anything in the environment, potentially damaging hard drives and other shock sensitive equipment.

A 24V-12V, DC-DC powered supply was added to powered 12V components along with a 24V-5V powered supply for sensors and accessories. These were all mounted using custom laser-cut 6.35 millimeter (0.25 inch) acrylic. The acrylic was used due to its strength and transparency, allowing the users to view inner electrical components and mechanical systems. The CAD design of the acrylic sheets was created from the mechanical specifications of the components and chassis measurements.

A sensor platform was designed for mounting directly below the wheelchair seat. The 40.64 centimeters (16 inches) wide by 58.42 centimeters (23 inches) long by 6.35 millimeter (0.25 inch) thick acrylic sheet was cut with holes on a 2.54 centimeters (1 inch) grid. This "optics table" configuration gives the ability to quickly position sensors at 90 or 45-degree angles using nylon-ties or set screws. Prototyping any given sensor configuration is then quickly accomplished by fastening the new sensor to this board and running the cables back to the acquisition devices mounted to the rear of the board.

Currently, two sensor data acquisition board configurations are used and can be quickly swapped out if needed. First, a PIC based digital and analog acquisition device known as the SerialSense [13] can be employed. This student-designed board can be used for infrared range finders and other analog or digital input devices. Second, the newly developed Blackfin Handy Board [14], which was developed jointly by UMass Lowell and Analog Devices, can be used for virtually any sensor integration task. In both cases, the acquisition board outputs serial data to the on-board computer. A block diagram of the system can be seen in figure 2.

The camera hardware is a Videre Design's STH-V1 Stereo Head shown in figure 3. The head measures 19 centimeters (7.5 inches) long by 3.2 centimeters (1.25 inches) wide. The small form factor is beneficial on a platform such as a robotic wheelchair where space is limited. The baseline between cameras is 69 millimeters (2.7 inches) and each camera has a focal length of 6.5 millimeters (0.26 inch). The horizontal field-of-view is 60 degrees. For testing, it is currently located where the occupant would sit in the wheelchair. In the future, the stereo head will be mounted above the occupant's legs on a locking swing-away arm.

The Manus Assistive Robotic Manipulator (ARM) is a wheelchair-mounted robotic arm, shown in figure 4 [15]. It has a two-fingered gripper end-effector and is a 6+2 degree of freedom unit with encoders and slip couplings on its joints. The Manus ARM weighs 14.3 kilograms (31.5 pounds) and has a reach of 80 centimeters (31.5 inches) from the shoulder. The gripper has a clamping force of 20 newtons (4 pounds force), and the payload capacity at maximum stretch is 1.5 kilograms (3.3 pounds). The Manus ARM is controlled by accessing menus using a keypad, a joystick, or a single switch. Two different modes provide individual joint control and cartesian space translation. In addition to manual control, the Manus ARM can be controlled by communication from a PC, and thus is programmable. Our Manus ARM has been outfitted with a Canon VC-C50i pan-tilt-zoom camera mounted over the shoulder and a small PC229XP CCD Snake Camera within the gripper.

IV. SIMULTANEOUS LOCALIZATION AND MAPPING (SLAM) USING STEREO VISION

Robots can use maps to effectively navigate in human spaces. Typically, maps are not known a priori. However, even if maps are provided, static maps do not accommodate changing environments. To allow for traversal of new or changing environments, dynamic map construction occurs as a robot drives through an unknown environment and

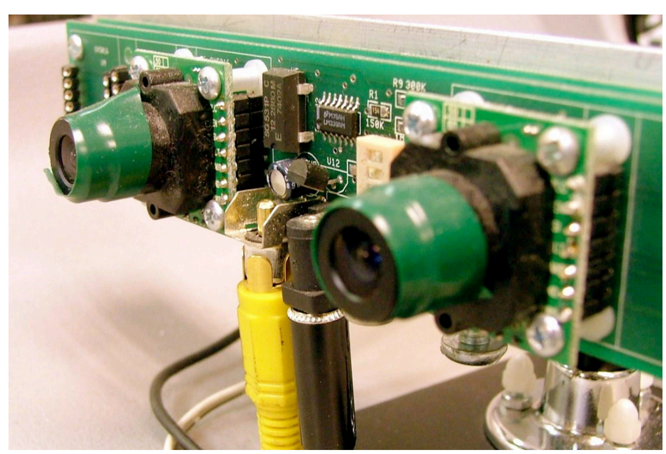

Fig. 3. The stereo head in this project is the Videre Design's STH-V1. Its minimalist design and simple interlaced NTSC signal specification allowed for quick integration with open source tools and vision libraries.

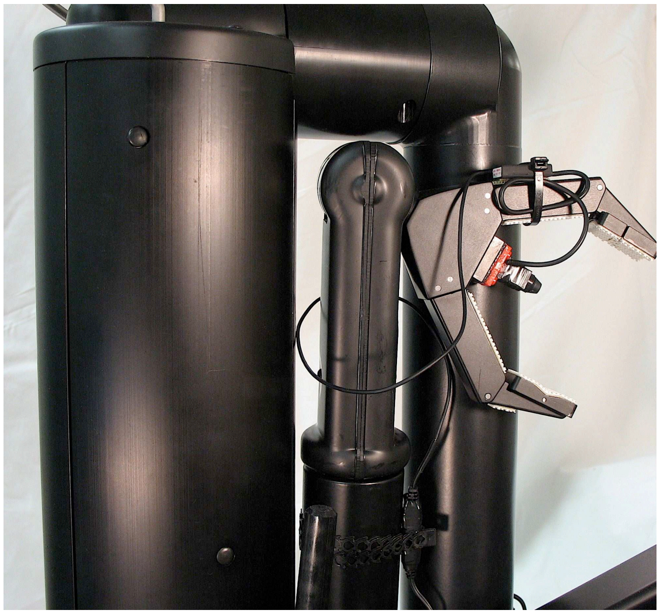

Fig. 4. The Manus Assistive Robot Manipulator (ARM), a wheelchair-mounted robot arm. The robot arm will aid in environmental manipulation, such as pressing elevator buttons and opening doors.

collects ranging sensor information. As the map is generated, the robot can determine its relative location and use the map for navigation. This dynamic map construction with the robot's knowledge of its position on the map is known as simultaneous localization and mapping (SLAM). (For an overview of SLAM, see Thrun [16].)

Generated maps may include some error due to odometry or sensor issues; for example, dead reckoning and specular reflection. This error will accumulate over time rendering an increasingly inaccurate map. Current SLAM techniques use probabilistic models to incorporate new sensor readings.

SLAM traditionally uses active ranging sensors such as laser range-finders and sonar. These sensors are appropriate for a variety of situations where the application requires minimal human involvement. Several concerns were identified when selecting sensors to be collocated with the wheelchair occupant. Laser range finders are expensive. Sonar sensors, a less expensive alternative, produce an audible clicking noise that can become intrusive over time. These considerations helped to guide the selection of a passive camera as the primary range sensor [17] [18].

An additional benefit to cameras is the ability to see a full picture. For instance, in a situation where the wheelchair is approaching a table or chair, a laser may only detect the four legs and mistake the surface area as open space. This could create a dangerous situation for users with limited reaction time and/or mobility. The stereo vision implementation used allows for processing over the entire image, making the detection of objects at various heights possible. The table or chair in this instance would be interpreted as a solid object, and therefore avoidable.

A. Vision and Mapping Software Libraries

Phission [19][20] is a vision toolkit developed in our lab. It is a concurrent, cross-platform, multiple language vision software development kit. It constructs a processing subsystem for computer vision applications. Phission abstracts low-level image capture and display primitives. Phission comes with several built in vision algorithms and custom algorithms are easy to integrate.

Videre Design's Small Vision System (SVS) [21] is a complete stereo vision software package. The library contains a set of algorithms that include methods for camera calibration, image capture, calculating disparity, and data display. SVS is able to process stereo video stream at full frame rate.

The University of Southern California's Simple Mapping Utilities (pmap) [22] is a particle filter implementation of SLAM for 2D environments using laser-ranging data. There are four main components. The *laser stabilized odometry* library takes the raw odometry and laser scans and corrects the robot's pose estimation. The *particle-based mapping* library maintains a particle filter over possible maps. Each particle represents a complete map. Laser and odometry data is used to incrementally update the filter, and re-sampling concentrates the particles on likely maps. The *relaxation over local constraints* library uses an iterative closest point algorithm to perform local refinements of the final map. The *occupancy grid mapping* library creates an occupancy grid map from laser scans.

B. Implementation

The on-board computer on the robot wheelchair runs the vision software that processes the stereo video stream into distance range information. This application also keeps track of the robot's odometry and allows a joystick to control the wheelchair's motors.[3] A second computer connected across a wireless network runs the mapping server. Once the vision software has range information ready, it sends that information to the mapping server to update the map. The map is updated in real-time at approximately 15Hz. A third application, running on the on-board computer, connects to the mapping server to allow the current map to be seen while it is created.[4]

Phission is used to capture 160x240 pixel frames from the stereo head. The wheelchair's odometry is recorded simultaneously. The odometry software is a straightforward implementation of the well known odometry equations for differential drive vehicles [23]. The captured image is then de-interlaced into a left and right image of size 160x120. Both images are smoothed using a Gaussian blur algorithm with a kernel size of 3x3. This preprocessing eliminates

[3]In the current implementation, the wheelchair is not navigating autonomously during mapping, allowing us to test the ground truth of the maps being generated. We are currently developing the shared autonomy system for the robot.

[4]The mapping server is currently run remotely across a wireless network, which severely limits the places the wheelchair can be used. This restriction was acceptable during the initial development of the stereo vision SLAM system, but will be eliminated in our future development by outfitting Wheeley with a second computer to run the mapping server locally.

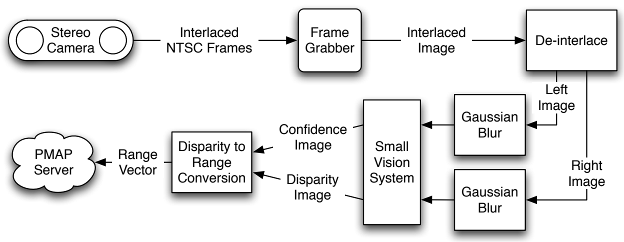

Fig. 5. Signal and data flow from the stereo camera, through the SLAM process, and into the PMAP server. This modularized flow allowed for quick debugging of the individual components and analysis of performance bottlenecks.

pixel noise that can degrade the results from the stereo algorithm. The input images are then passed to SVS to calculate disparity and confidence images.

Each column of the resulting disparity image is scanned to find its highest value. These values are stored into an array along with their corresponding confidence values. Next, each disparity value is converted into meters. The 160 range values need to be translated to 60 values, one range value per degree of the camera's field of view. Three values overlap each degree of the camera's viewing angle. The value of the three with the most confident is chosen as the final range value for the given angle.

The mapping server expects range information in the form of 181 distances spread across 181 degrees. This format is achieved by padding each side of the 60 range values with predefined infinity values. The ranging information is packaged with the robot's odometry that was recorded during image capture. These are then sent to the mapping server (see figure 5).

The mapping system is a customized version of pmap. This was originally developed during our research on user interface design for urban search and rescue [24]. Instead of reading a player-stage log file of laser and odometry information, the mapping server accepts a network connection to receive data. However, the software was too slow to create maps in real-time. In order to achieve real-time SLAM, the GNU Scientific Library and pmap were compiled using the Intel C++ compiler. This optimization gave the mapping server a 400 percent boost in performance as compared to the GNU g++ compiler. The mapping server is now able to process over twenty range data sets per second on a 2.26GHz Intel Pentium 4 processor.

C. Results

In order to test the effectiveness of stereo vision based SLAM, maps were generated in both open and cluttered environments. The wheelchair was driven as if being used in an average scenario. The left set of images in figure 6 show maps generated of an open hallway, typical of most office or school settings. As seen, the map clearly defines the wall as well as doorway openings. The right set of images in figure 6 are the same hallway but now includes one of the adjacent rooms. This case illustrates mapping in an environment where tables and chairs limit the wheelchair's degrees of freedom.

V. HUMAN CUE DETECTION

While the ability to navigate an unknown indoor environment and generate a metric map is essential to wheelchair navigation, the raw metric map is not an effective basis for interfacing with the wheelchair occupant. The environment in which we operate on a daily basis is filled with human-designed cues that help identify where we are, what to do, and where to go. Automatically annotating the map with cues from the environment gives the wheelchair and the occupant a common set of references with which to communicate about the local, or extended environment.

In order to annotate the metric map with relevant human cues, a color pan-tilt-zoom camera is mounted over the occupant's right shoulder and the image stream is used to identify relevant features of the environment. Indoors, there are many building codes concerning the location, size, color, and shape of signs, symbols, and other human cues. Examples include restroom signs, exit signs, and room numbers. This second camera can identify these cues and add them as annotation on the map as the robot wheelchair navigates through the environment. Later, if the wheelchair occupant wants to visit a previously annotated location, the wheelchair is capable of proceeding directly there. More importantly, the occupant does not need to recall the desired location on the metric map, but instead could use an annotated topological map, or even a list of annotations independent of the metric map.

The Swarthmore Vision Module (SVM) provides the basis for detecting human cues in the environment [25]. SVM currently includes a text detector and basic optical character recognition system. Signs with text are an important cue

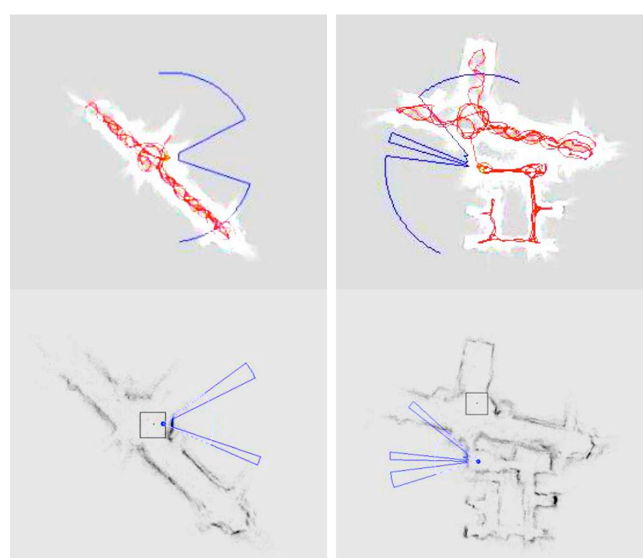

Fig. 6. Two examples of the resulting map from the CS building using the stereo SLAM implementation. The line-maps (below) shows the outside walls and boundaries. The occupancy maps (above) show the observed open space. The trails in the occupancy maps show the path traveled by the wheelchair in the environment.

Fig. 7. An example of a human cue. This sign requires identification of numbers, text, and arrows. Possible ambiguity may arise from the phrase "behind you," since it does not correspond to simple directions like "left" or "forward." The user may be prompted for clarification.

in human environments, and the text on the signs may be relevant to a robot's task (e.g. see figure 7). An example is navigating from one room to another in a numbered hallway, as in the motivating example at the beginning of the paper. In addition to text, SVM will be extended to include detection of other human cues such as doors, door handles, elevators, elevator buttons, and certain AIGA international symbols [26].

Doors and elevators are especially important to robot wheelchair navigation for both map-building and interaction with the wheelchair user. As part of the door and elevator identification algorithms, we can leverage priors imposed by the Americans with Disabilities Act Accessibility Guidelines (ADAAG), such as minimum width, swing, and type and placement of handles [27]. Doors can be located geometrically and verified visually. Likewise, elevator buttons, door handles, and AIGA symbols can also be located visually. When looking for relevant building signs, the ADAAG mandate signs to be hung centered 1.524 meters (60 inches) above the floor. While not every sign in every building will necessarily follow the ADAAG guidelines, the constraints provide for a small initial search space which can be expanded as necessary.

VI. VISUAL CONTROL OF A ROBOTIC ARM

Concurrent research in our lab [28] is investigating a visual-based interface for control over a Manus Assistive Robotic Manipulator (ARM), manufactured by Exact Dynamics [15]. The Manus ARM functions in unstructured environments, but, in its off-the-shelf state, is awkwardly controlled through menus using a keypad, a joystick, or a single switch. This control is not intuitive or natural because it requires a high level of cognitive awareness. Also, the input devices may not correlate well to the user's physical capabilities.

Our research leverages all of the Manus ARM's benefits while eliminating its weaknesses. Our vision-based system draws inspiration from people's innate abilities to see and touch. Because the wheelchair occupant is collocated with the Manus ARM, the occupant's view is the same as a camera mounted over the Manus ARM's shoulder. The occupant "zooms in" on the desired object using progressive quartering of the shoulder view, as shown in figure 8. Our goal is to acquire the object by unfolding the Manus ARM, then reaching toward and grasping the object in a manner emulating human kinematics. This human-in-the-loop control will provide simpler and more effective interaction to accomplish ADLs. To date, we have shown that a visual-based interface is easier to use than the factory-shipped interfaces [28].

We also plan to combine human cue detection with development of the arm's visual-based control. This combination will allow us to identify elevator buttons by a combination of their shape and labeling, then to push the button to get to the desired floor.

VII. CONCLUSIONS AND FUTURE WORK

This paper describes our current work towards developing a vision-based robot wheelchair system, presenting our robot hardware redesign for the first time. Wheeley was designed with user safety as its primary focus, but we also took care to ensure that the "robotic" parts of the wheelchair did not make the system look much different than a standard powered wheelchair.

The use of cameras as the primary sensing method is much more cost-effective than the laser range finders that are used in most mobile robots that use SLAM algorithms. The quality of the maps appears comparable to those generated from data from a laser range finder. The camera images can also be used for the extraction of information from signs in the environment, which is not possible with laser ranging data. Preliminary work has shown that we can find and interpret signs in some environments.

Much remains to be done to create the complete system that will perform vision-based navigation in the way we are envisioning. We must investigate how the wheelchair's user will be able to contribute to the task at hand. For example, if the system cannot disambiguate between numbers, how could we ask the user to help the system get the correct answer? We will work with users of powered wheelchairs as well as providers of these systems when developing the human-robot interaction for our system.

Wheeley will undergo additional modifications. A locking swing-away arm will be mounted to the left side of the chair. It will hold the stereo head as well as an LCD touch-screen

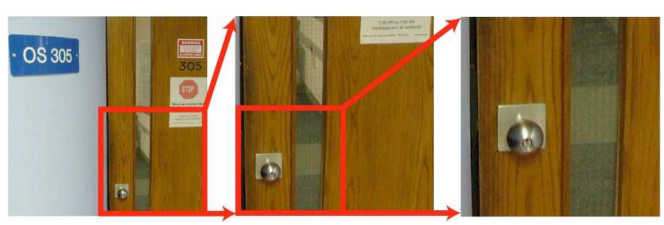

Fig. 8. The user "zooms in" on the doorknob using progressive quartering. Identification of objects like this will allow Wheeley to manipulate the environment; for example, opening doors or pressing elevator call buttons.

that will display the user interface for the occupant; the interface is being designed to allow for alternative access methods to be used for people who are unable to use the touch screen. We have already designed a visual-based selection method for the Manus ARM that employs a single-switch as the sole input device. The Manus ARM will be mounted on the right side of the wheelchair.

Despite the early stages of this work, this paper sets out our vision for a complete vision-based robot wheelchair system that will improve independence for its user. We have demonstrated progress in vision-based mapping, sign reading, and visual interfaces for robot arms.

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