Development of Modular Sensors for Semi-Autonomous Wheelchairs

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Abstract – This paper provides an overview of the sensor network and mounting hardware used to convert a commercially available powered wheelchair into a semi-autonomous wheelchair. Emphasis is placed on modular design and ease of use. Although the sensor packages are used for the semi-autonomous navigation of a powered wheelchair, the sensor network presented has the potential to be used in a number of different robotic applications.

Keywords – semi-autonomous; wheelchair; modular; sensors; navigation

I.   INTRODUCTION

Semi-autonomous wheelchair technologies have the potential to improve the quality of life for millions of handicapped individuals throughout the United States who are limited in mobility [1]. Equipped with a suite of range-finding and visual sensors, these wheelchairs are fully capable of navigating and mapping indoor and outdoor environments without requiring human intervention. Through the use of semi-autonomous wheelchairs, a wide variety of handicapped individuals would be able to live more independent lifestyles and experience higher levels of self-esteem and personal empowerment [2,5,-7]. For individuals who are limited in mobility and in need of more capable rehabilitative technologies, semi-autonomous wheelchairs could be the solution.

Semi-autonomous rehabilitative technologies fall under the domain of human-in-the-loop cyber physical systems (HiLCPS) [3]. An inherent characteristic of these systems is shared control between the human operator of the system and the system itself. Several research questions have emerged from this concept of a shared autonomy framework: "Who takes the control of the system, human or machine, and when?", "Under what circumstances, a decision is overridden by the human or by the machine?", and "How does the human-in-the-loop CPS decide on the level of autonomy in an adaptive way?" [3]. In [4], authors present shared control architectures for brain-computer interface (BCI) control of semi-autonomous wheelchairs. The control framework is designed to keep as much authority with the users as possible, while the shared controller couples the intelligence and intent of the user with the precision of the machine, enabling both experienced and inexperienced users to safely complete navigation tasks [4].

The modular sensors described in this paper are designed to rapidly provide the framework necessary to conduct HiLCPS

research using commercially available wheelchairs. Figure 1 illustrates the application of these sensors that can be used for various semi-autonomous operations involving a shared control architecture.

Figure 1: Wheelchair equipped with sensors modules has the framework necessary for semi-autonomous navigation

Some of the earliest semi-autonomous wheelchairs were developed in the 1980's [2]. Over the past three decades, research and development advanced the capabilities of semi-autonomous wheelchairs. Although numerous semi-autonomous wheelchair prototypes have been assembled, tested, and documented – such as OMNI, an advanced wheelchair with omnidirectional maneuverability and navigational intelligence suited for vocational rehabilitation [5] and the Wheelesly robotic wheelchair system, capable of navigating within indoor environments through an eye tracking interface [6] (both shown in Figure 2) – a common design architecture or sensor suite has yet to emerge. As with most mobile robot applications, semi-autonomous wheelchairs are capable of implementing a wide variety of sensors to successfully implement navigation algorithms. These sensors are strategically selected based upon performance specifications and are mounted in advantageous locations on the wheelchair for optimal data collection.

While testing a semi-autonomous wheelchair system it is often beneficial to be able to rapidly interchange or relocate sensors to compare performance. Unfortunately, the process of reconfiguring sensor suites is rarely trivial, often requiring new mounting hardware and over-complicated modifications

to source code. The project presented in this paper offers a unique solution to this problem through the use of a headrest sensor and hardware mounts, as well as circuitry developed as part of a sensor network.

Figure 2: OMNI and Wheelesly Wheelchairs

II. PROBLEM STATEMENT

Assistive technology has been developed for decades to enhance ease of transportation, movement, and communication for physically handicapped individuals. These devices improve the quality of life and the independence of individuals with disabilities. The access to a means of independent mobility with powered wheelchairs promotes a feeling of self-reliance, helping to aid physical and mental struggles to the disability [2]. Mobility impaired individuals who are unable to use direct control wheelchairs often need an assistive device in order to function on their own. A semi-autonomous wheelchair, for instance, would assist them in a number of activities of daily living (ADL), such as independently navigating from the bedroom of their home to the kitchen. Such a wheelchair would require a number of sensors, hardware, and software components. Because powered wheelchairs are a commercially viable and popular assistive device, the overall goal of this project is to outfit a powered wheelchair with reconfigurable sensor packages and hardware mounting devices necessary for semi-autonomous operation. The wheelchair will require sensors mounted in advantageous locations in order to detect obstacles and be able to perform simultaneous localization and mapping (SLAM).

The system requirements in which the team must address to warrant a successful end result are listed below:

- System must be able to detect static and dynamic obstacles.
- System must detect obstacles outside of 6 inches and within 20 feet.
- System must be able to detect and avoid cliffs, such as a stairwell.
- System must be fully functional within an indoor environment (similar to that of the first floor of a common household).
- Sensors packages are compatible with commonly used powered wheelchairs.
- System must be able to support a minimum of 30 sensors.
- System must be able to retrieve odometry data from the wheelchair.
- System must have the ability to conduct 3D mapping of indoor environments.

III. SYSTEMS ENGINEERING APPROACH

The development process associated with complex systems, such as semi-autonomous wheelchairs, is often enhanced through the application of systems engineering practices. By formally identifying all product stakeholders, client needs can be extracted. From these needs, system requirements can be identified, setting the standards by which the project may be evaluated. With these system requirements in mind, system architectures (such as hardware, software, and power distribution) can be designed to best meet the needs of the stakeholders. Test cases are then developed to verify the functionality and performance of each component and subsystem. The results are then compared to the specified minimum requirements. Test cases that fail to meet predetermined requirements reveal critical flaws within the design. These flaws must be corrected through a revised design. By maintaining this development cycle methodology a higher quality end product (one that satisfies the needs of all stakeholders) is ultimately realized.

In accordance to the systems engineering development cycle presented, the first action taken towards developing a semi-autonomous wheelchair was to identify all primary stakeholders involved in the project. The primary stakeholders that were identified for this project are listed below:

- Individuals who suffer from medical conditions that severely reduce mobility and prevent the use of traditional powered wheelchairs. These people will act as the primary operators of the semi-autonomous wheelchair.
- The National Science Foundation (NSF) that provided the funding for this project-based research and influences the primary objectives of the project team.
- Intel Cornell Cup USA, whose judges will evaluate the project's accomplishments. This competition emphasizes the use of proper design and testing practices.
- Roboticists who will apply the modular sensor network in numerous ways.

With the primary stakeholders of the project identified, the needs and respective system requirements could be derived. All needs were weighted to emphasize the most important aspects of the project, such as semi-autonomous navigation and the ability to rearrange the sensor configuration. Use cases were then developed to assess the practicality of the primary functionalities of the system. Based upon the requirements elicited through this process, important design decisions were agreed upon. Test cases were then created for all individual components and subsystems to meet the necessary demands of the overall system. By following this development process, quantitative and qualitative data was collected and used to justify design decisions and system performance.

IV. PROPOSED SOLUTION

A distinct characteristic of the modules being designed is that they are easy to assemble and mount onto a given powered wheelchair, granting the ability for someone with a specified level of skill to assemble the system in a relatively short amount of time. To meet this requirement, modularity became a major theme for the project, which all developments followed. Since the wheelchair needed sensors, a sensor network was developed, allowing them to connect over a standardized interface to the main controller. Sensor modules could be any combination of sensors and processors, as long as they used the specified interface. All sensors also needed to have a standard communication protocol, so any sensor could be plugged in to the network, and the controller would understand the data without any reconfiguration.

V. COLLECTING ODOMETRY DATA

SLAM requires odometry data in order to provide accurate maps. Odometry is the use of data describing the movement of a system. A sensor used to gather motion data is an encoder, which can be used to measure the wheel rotation of the wheelchair. If each wheelchair used the same motors or wheels, this task would be trivial. However, since wheel diameter, wheel thickness, motor sizes, and gearboxes are often different from wheelchair to wheelchair, a universal encoder can be challenging to design. Simply coupling encoders to wheel shafts or gear boxes would require an incredibly large number of mounting components due to the incredible variations from one powered wheelchair design to the next. Even when the encoder is mounted, the software or motor driver board would need to be configured to the gearbox ratio or the diameter of the wheel. Each motor driver also has a specific range of counts per revolution and, therefore, a specific encoder would be needed for each design. Ultimately, a different approach to collecting odometry data is necessary.

The first step in identifying a more elegant solution to this problem was to assess the designs of motorized wheelchairs and identify consistently similar features. Doing so revealed whether a mount design was worth pursuing. Although these wheelchairs appear to have similar motors, careful inspection reveals that the diameters of each motor are in fact different. Additionally, the wheel diameter and the distance from the center of the wheel to the center of the motor are variable.
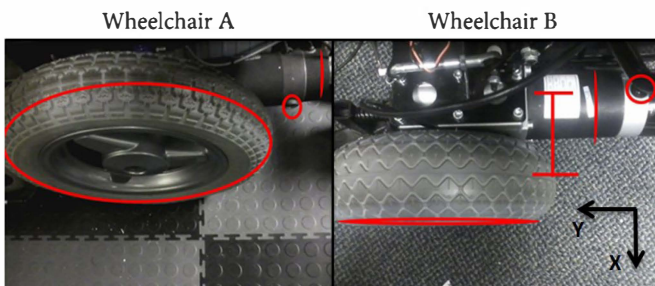

Figure 3: Side by side comparison of two wheelchairs

After reviewing the two wheelchairs in Figure 3 it becomes clear that one commonality is the location of the motor with respect to the wheel. The variability is located in four areas: the distance between center of wheel and the center motor (X direction), the shape (diameter, width) of the wheel, the diameter of the motor, and the exposed length of the motor. Therefore the mount must be configurable in the X and Y directions (as shown in Figure 3), be able to mount on different size motors, and function independently to wheel size. The final issue, circled in Figure 3, is the structural obstructions due to the wires on the motor.

In order to overcome the variations in diameter of the wheels used on commercially available wheelchairs, the project team opted to use a "wheel on wheel encoder" (see Figure 4). This abstracts the dimensions of the wheelchair's wheel diameter from the software. The encoded wheel has a predetermined diameter and therefore when the smaller wheel has traveled a distance, the wheelchair wheel has also traveled that equivalent distance. The motor diameter is variable between different wheelchairs, therefore two mounting brackets are made to fit the diameter and pipe clamps are used to prevent the mount from moving. This design also allows the mount to fit anywhere along the motor.

With the encoder mount secured to the motor, the next challenge to address is the distance from the wheelchair wheel to the encoder wheel in both the X and Y directions. The Y direction is configurable via a slider on the inside of the motor mount component. The X direction is configured by attaching the encoded wheel to the swing arm, with increments of .25 inches, as illustrated in Figure 4.
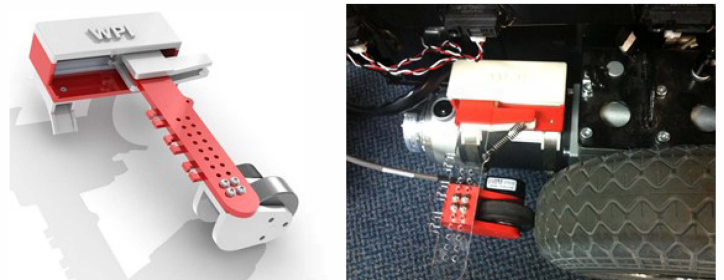

Figure 4: Wheel encoder module prototype, rendering (left) and finished product (right)

The assembly in Figure 4 allows for gathering odometry data for use in SLAM, and is able to be mounted to a wide variety of popular wheelchairs, such as the two shown in Figure 4.

VI. HEADREST SENSOR & HARDWARE MOUNT

Limited area on the upper half of the wheelchair presents an issue when attempting to add vision or range-finding sensors such as the Microsoft Kinect, stereo vision, or LiDAR. An additional mounting bracket is needed to add sensors without interference from the wheelchair's operator. Powered wheelchairs often have an option for a headrest to add support for the user's neck and head. This common feature was exploited to create a headrest sensor and hardware mount.

The headrest sensor and hardware mount, shown in Figure 5, provides a means to mount hardware that is out of the user's field of vision and still able to collect data for mapping the environment. The side "arms" of the mount are interchangeable and support the addition or subtraction of hardware as needed.

Figure 5: Configurable sensor and hardware mount on headrest, rendering (left) and finished product (right)

Internal wire management is also integrated into this mount's design to improve safety and aesthetics. A simple physical user interface allows for easy access to the inside compartments of the headrest sensor and hardware mount where embedded devices can be mounted and protected from damage.
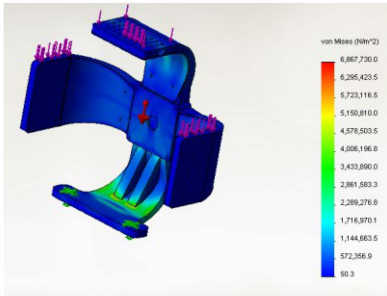

Figure 6: Static stress analysis of headrest sensor mount

Built out of ABS plastic, this component can withstand more than 5 pounds of static pressure on the end of each arm (finite element analysis shown in Figure 6. The lower mounting bracket that attaches to headrest poles is configurable and can be interchanged with a different sized bracket to account for variations in headrest sizes. The back side of the hardware mount contains mounting holes for adding hardware such as a laptop or other devices. This component is highly adaptable to commonly used power wheelchairs and adds the capability to mount vision sensors in an advantageous location.

VII. SENSOR NETWORK

In any robotic application, there will be multiple sensors with a variety of operating voltages, interfaces, and data outputs. However useful these sensors may be, roboticists still have to build an interface for the sensors - usually with an analog-to-digital converter for analog sensors and integrated peripherals (like SPI, UART, or I2C) for digital sensors. In addition, if there are several sensors in an area, running wires from their location to the main controller can be frustrating in terms of wire management. It would be easier to route all data to the main controller through a single line by plugging all sensors into a single module. The differing interfaces of the sensors, however, cannot achieve this on their own, but by standardizing the sensor interfaces, such a module could be realized.
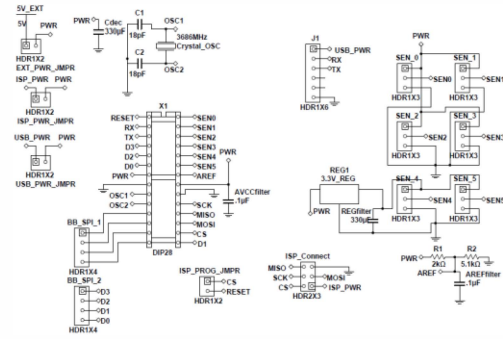

Figure 7: Sensor Board Schematic

The sensor board shown in Figure 7 can receive six analog sensor inputs (four of which operate at 5V and two of which operate at 3.3V), and two digital SPI sensors. The analog sensors connect through a three-pin header (on the right hand side) which supplies power and ground connections, and have an analog signal connection to the microcontroller (an Atmel ATMega168). This particular microchip was selected because it has SPI, UART, and analog inputs as integrated peripherals. To read the analog pins, the microcontroller compares the inputs to the reference voltage AREF, which is generated through a resistive voltage divider (bottom right). In the current configuration, the voltage drops from 5V to 3.6V, which was chosen to maximize the resolution of the sensors being used on the project. On the actual board, the resistors composing the voltage divider are "through-hole" mounted, and can be interchanged relatively easily, making it simple to select the right resolution for a wide variety of applications.

Digital interfaces on the sensor board are arranged in two groups of four and one group of six. The 2x3 header (bottom of Figure 7) is meant for programming through an in-system programming (ISP) cable, although it could also be used to talk to an SPI sensor. The other two groups of four pins (bottom left) are meant for bit-banging an SPI interface, but are merely digital I/O pins on the microcontroller, and can be reconfigured to implement an interface such as UART or I2C through bit-banging if desired. Devices using these pins, however, will need their own source of power, as the board will not supply power to any of the devices plugged in to these ports.

To communicate with the main computer, the sensor board has a 1x6 header on it which is meant for plugging in a Gravitech USB-UART module. As the name implies, this module takes UART data from the controller and passes it through to the

computer via USB interface. The device shows up in Windows as a virtual COM port, or as a ttyUSB device in Linux. To interact with the sensor, a software interface was outline and subsequently implemented. This interface provides the ability to read or stream sensor data and operates at a baud rate of 115200 symbols per second.

There are two 5V power options on the board (located top left of Figure 7): external power and USB power. Selecting these can be done with various jumpers on the board (the 2-pin headers on the left hand side of the board). Care should be taken as to ensure only one is plugged in at a time, as the board does not support multiple power inputs. In future revisions, a feature like this will be added along with an option for greater than 5V input using a DC-DC converter to step the voltage down. All power options are filtered with a 330μF capacitor to ground. Measurements taken of the 5V power pin voltage output belonging to the Gravitech USB-UART converter revealed that the true voltage of the pin is actually closer to 3.3V. It was found that this voltage can vary depending on the USB port regulation enforced by the host computer.

With a modular sensor board, there is additional freedom to choose from a wide variety of sensor components. For this project, two sensors were chosen to be interfaced with the sensor board: a Sharp GP2Y0A21YK0F infrared (IR) sensor with a range of 10-80cm and a Maxbotix LV-EZ0 ultrasonic sensor with range of over 6 meters. Both sensors are analog, operating at 5V and output voltages between 0 and 5V (0-3V for the IR, 0-5V for the ultrasonic). In general, IR sensors were always coupled with ultrasonic sensors to mitigate the risk of collision with an obstacle (for example, IR sensors tend to struggle with accurately ranging transparent objects, while ultrasonic sensors struggle with accurately ranging curved objects). By assigning ultrasonic and IR sensors to separate sensor boards, however, the voltage divider used to set the reference voltage could be set to maximize the resolution of the sensor readings. The IR and ultrasonic sensors are mounted onto the semi-autonomous wheelchair and used for cliff detection, wall sensing, and detecting whether a dynamic obstacle has crossed the path of the sensors (akin to someone walking in front of the robot while it is moving). These sensors are mounted in strategic positions along the front, back, and sides of the wheelchair chassis.

The sensor board effectively eliminates the messy wiring associated with running dozens of sensors back to the main computer and also decreases the required cables necessary for power connections and sensor-microcontroller communication. In addition, the USB bus architecture allows for easy expansion of the sensor network, requiring only an available USB port and an additional power connection. This allows the user to add and remove sensors with relatively little effort and use powered USB hubs to expand the number of available USB ports.

In addition to the sensors mentioned, a Microsoft Kinect is used in this project to do 3D mapping of indoor environments and provide greater amounts of range data. The sensor has a

built-in IR range-finder array and a color camera and is attached to the headrest sensor and hardware mount. It is the primary sensor used for mapping the environment. The Kinect will be connected to the main controller through USB, and run off a 12V rail on the wheelchair.

While the system used in this project has clean 5V power available, other applications might not have such a luxury. To make the sensor network viable as a standalone product, it must employ some form of additional circuit protection, including overvoltage, noise, and voltage spikes.
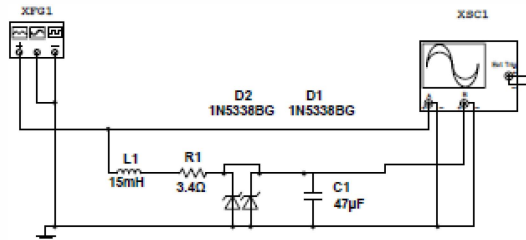

Figure 8: Potential Power Protection Circuitry

The circuit in Figure 8 is designed to filter out general signal noise, protect against voltage spikes up to 130V for 100μs, and protect against overvoltage up to 12V. It is composed of an inductor in series with a resistor and a capacitor. Between the inductor and capacitor are two 5.1V zener diodes (Mouser Electronics, 2012) connected backwards to ground. These diodes help absorb voltage spikes and provide a level of overvoltage protection by turning on when the voltage goes above 5.1V, which routes excess power to ground.

To test the capabilities of this circuit, two simulations were conducted. One utilized a function generator to output voltage spikes of 130V lasting for 100 microseconds in duration. The other simulated wiring the input to 12V instead of 5V.

The voltage spike simulation was designed to represent potentially high-voltage spikes generated from motors turning on. When the voltage spiked (the large square spike in the middle), the maximum voltage seen at the output of the circuit was approximately 5.2V (the lower of the two voltages), an increase of 200mV.

This is acceptable for the microcontroller in use and, depending on the sensors plugged in, the sensors as well. This protection may also suffice for longer pulses, although the voltage might rise to higher levels after the pulse. The documented safe operating range of the ATmega168 is rated up to 5.5V.

The 12V overvoltage simulation was designed to simulate a user of the system plugging a device into an incorrect voltage. 12V was chosen because our DC-DC converters have a 12V rail in addition to the 5V rail. The 12V over-volt (the higher of the two levels) was simulated as continuously running, and from the results, the output voltage never rises above approximately 5.5V (the lower of the two levels). This is also acceptable for the microcontroller, however it is not guaranteed to not damage any sensors plugged in to it. In addition, this over-volt resulted in the zener diodes each sinking 5W of

power. While the zener diodes in the simulation are rated for 5W there is no doubt that those components would run very hot and possibly damage the circuit board. If exposed to 12V for only a short duration, it is unlikely that the circuit board would receive damage, and if the zener diodes failed during the over-volt, they could be easily replaced, as the components are "through-hole" mounted.

Unfortunately, the non-ideal resistance of the inductor limits the current draw of the system. Applying Ohm's law, drawing more than approximately 150mA of current through a 3.4 ohm resistor causes a voltage drop of approximately 0.5V. While the microcontroller can operate safely with this voltage drop, the rest of the 5V sensors attached might not be able to tolerate it. This must be considered when adding such a protective circuit, and the usefulness of this circuit in future developments.

VIII.   DESIGN CONSIDERATIONS AND TESTS

In order to validate various components of the system, the project team developed a series of standard tests for various aspects of the system. These tests outline the procedure as well as the expected result. If the system under testing meets expectations, then the system is considered to be validated for use in the semi-autonomous wheelchair project. Testing conducted to validate the sensor modules is listed below:

- Reliability of the power supply for 5V components, ensuring the voltage level is appropriate and that any noise is not harmful to the boards and will not cause them to operate improperly.
- Proper construction of the boards to ensure the hardware is working as designed.
- Reliability of communications with the board, ensuring that data retrieved is not corrupted.
- Consistency of the board's software interface, confirming that it operates as intended.

These tests outline various requirements for the board, including the maximum voltage noise and maximum error rates for communication. Thus far, our sensor boards have met all requirements.

IX. CONCLUSION

This project utilizes several sensor and network modules to quickly install the framework necessary for the semi-autonomous operation of commercially available wheelchairs. **Figure 9** shows a commercially available powered wheelchair equipped with the sensor and network modules described in this paper.

To facilitate the collection of data across a large number of sensors, a sensor network was developed which allowed for efficient routing of large amounts of data and also reducing the number of wires routed to the main controller. This network abstracts away the details of the individual sensors and allows many types of data to be received by the controller. Although the physical structure of commercially powered wheelchairs varies greatly from one design to the next, modular mounting devices where developed that abstract these differences, emphasizing simplicity and ease of use. Odometry data

collected through the use of a mechanical wheel-on-wheel encoder mount which measures the wheelchair's wheel velocity through contact with a small wheel that is coupled to a quadrature encoder. Although additional testing will be conducted, all tested components and subsystems have, thus far, met all system requirements and helped the project team develop a flexible, modular sensor network architecture that can be used in a wide variety of robotic applications.

Figure 9: (A) Headrest sensor & hardware mount, (B) Configurable LiDAR module (not discussed within this paper), (C) IR and Ultrasonic sensors interfaced through sensor module, (D) Wheel-on-wheel encoder module

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