Wunderbot IV: Autonomous Robot for International Competition

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Abstract— We analyze the Elizabethtown College Wunderbot IV, an autonomous robot entry for the 2008 IGVC. Wunderbot's fourth incarnation will include enhanced obstacle detection and avoidance capabilities, as well as innovative path-planning techniques, both of which are discussed, along with all other subsystems that yield a competitive entry in the competition.

Inadequate obstacle detection methods employed in 2006 will be enhanced by introducing a laser range-finder. Building upon experiences in two prior IGVC competitions (2004 and 2006), Wunderbot IV's new advanced equipment integrating within the existing framework will make it a strong competitor for its upcoming third appearance in international competition.

I. INTRODUCTION

Autonomous robots serve mankind in areas ranging from search and rescue to space exploration. In attempt to elicit new, creative designs from college students [1], the Association for Unmanned Vehicle Systems International (AUVSI) holds the annual Intelligent Ground Vehicle Competition (IGVC), an engagement of roughly 30 unique robots designed by colleges and universities from various countries, including the United States, Japan, Canada, and India. Their objective is to excel at complex autonomous tasks used to measure the robots' navigability and strength of design.

At Elizabethtown College in Pennsylvania, the Wunderbot autonomous robot project has been progressing for over five years. From the financial assistance and donations of numerous corporate sponsors, new equipment and software is added to the robot between competitions. Its primary objective is to compete in the IGVC, with the potential of administering future automated tours on the college campus. Wunderbot IV is led by the team of James Painter, David Coleman, and Jeremy Crouse, with support from Chris Yorgey and Daniel Fenton, and advised by Dr. Joseph Wunderlich. The project has become a staple of the school's Physics and Engineering Department, attracting prospective students and drawing the attention of local industry and media.

II. IGVC

The IGVC provides an excellent opportunity for students to explore the possibilities of unmanned vehicles. 2008 will mark the 16th anniversary of the competition and the third entry for Elizabethtown's Wunderbot. IGVC consists of four challenges for the autonomous robot, each outlined below [2].

A. Autonomous challenge

The autonomous challenge pits the robot against an outdoor obstacle course, traversed by remaining on a path of grass approximately three inches tall, bounded by spraypainted solid or dashed lines. The robot must avoid obstacles, including fences, construction barrels, trees, and shrubs. Potholes, inclines, and sand pits may also be strewn about the course. Scores are calculated based on the distance traveled through the course and the elapsed time.

B. Navigation challenge

In the navigation challenge, a field of approximately one acre is marked with a number of GPS waypoints (approximately ten). Each team is provided with the coordinates in latitude and longitude of each waypoint. Obstacles similar to those on the autonomous challenge course may also be placed randomly on the navigation challenge course. Scores for the navigation challenge are determined by the number of waypoints traversed by the robot and the time taken to do so.

C. JAUS challenge

The challenge for Joint Architecture for Unmanned Systems, although not mandatory, demonstrates the robot's ability to communicate using a standardized wireless messaging system that is growing in popularity in engineering fields [3]. A section must be included in the written report that describes the robot's JAUS capabilities, and the robot must demonstrate a pre-defined working ability to communicate using the JAUS message type.

D. Design challenge

The design competition exists as a separate entity of competition, in that the robot's performance has no influence on the design score. The design competition measures the team's procedures, workmanship, and innovation to determine product quality. Each team must submit a typed report prior to the main competition date, detailing the conceptual design of the vehicle and its components, and emphasizing design changes from the team's previous contest entry as well as technological innovations that distinguish it from the rest of the field. Teams must also prepare a ten-minute oral presentation. The third component of the design challenge involves judges' hands-on examination of the robot, for such aspects as neatness, safety, originality, and style.

III. RELATED WORK

Wunderbot's most closely-related work is in the IGVC competition itself. In any given year, roughly 30 other robots, all having identical objectives, are available for comparison. Following each competition, the organizers make all teams' design reports publicly available online, encouraging the spread of successful ideas. As such, we find trends in particular subsystems among the contest entrants. The laser range-finder, for example, has become standard for obstacle avoidance, having been built into nearly all of 2007's competing vehicles. So successful has been the Sick line of laser range-finders that they were embraced by 20 of the 32 teams [4].

While many teams may share similar components, each year brings new innovation in overall design. Part of the initiative in this matter is the scoring of the design challenge. The scoring is partially dependent on the vehicle's display of a significant subsystem or software upgrade over that which represented the team previously.

One vehicle subsystem of much diversity at the IGVC is vision. The competition has seen many different camera types and configurations, as well as an assortment of corresponding software packages for image processing. Some teams opt for camcorders, some use industrial cameras, and others choose to mount webcams [5]. Stereo vision has given robots the advantage of a line of sight extending to the sides or rear of the vehicle [5]. Once images have been grabbed, teams have performed successful filtering through the use of Intel's OpenCV library [6], MATLAB [7], and LabVIEW [5]. Alas, the IGVC has no cookie-cutter winning formula. In fact, oft-champion Virginia Tech's traditional three entries per year are all structurally distinct from one another [4], a further testament to the competition's flexible path to success.

IV. HISTORY OF WUNDERBOT

In 2001, Matt Lister conceived "MultE-bot" [8], which sparked the series of autonomous vehicles at Elizabethtown College collectively known as Wunderbot. The first Wunderbot was fabricated in the fall semester of 2002. At a cost of $800, the team equipped the robot with RF communication, a digital compass, ultrasonic sensors, and a simple web-cam. Too primitive for competition, the robot sufficed as a computer engineering senior project.

Work on Wunderbot II began one year later and continued until fall of 2005. This second incarnation saw the robot fitted with a new digital compass and the marked the beginning of LabVIEW software integration, all behind an approximated $25,000 total in donated monies and parts. Artificial neural networks and symbolic artificial intelligence were investigated for obstacle avoidance, environmental mapping, and path planning. As the first Wunderbot to enter national competition, Wunderbot II did not qualify for the main events at the IGVC, due to untimely hardware malfunctions. However, it placed 12th out of 27 in the design competition.

The second Wunderbot to enter the IGVC was Wunderbot III. Work on this version from fall of 2005 until the competition in June of 2006 entailed the design of a new custom-welded steel frame, implementation of a donated industrial camera valued at approximately $17,000, wire connection blocks, fuses, and wiring conduits, all managed by a new industrial PC with LabVIEW fully implemented. At the competition, Wunderbot III qualified, and then placed 9th of 17 in its group for the design competition, 18th in a field of 32 in the autonomous challenge, and 9th of 32 in the navigation challenge.

The Wunderbot project continues to strengthen, and the upward trend in its performance at the IGVC is promising, given the addition of more advanced equipment for the forthcoming 2008 competition. The initiatives of the project have led to many professional and graduate school entrances, including Stanford, Notre Dame, and Dartmouth, and has helped facilitate the creation of dedicated robotics and machine intelligence lab space at Elizabethtown College [9].

Fig. 1. Wunderbot IV.

V. WUNDERBOT SUBSYSTEMS

All of the Wunderbot's equipment is mounted on a two-tier steel chassis. For protection from collisions and water, clear plexiglass panels were fastened to the sides with velcro strips. The transparency enables easy debugging during equipment testing, as error code LEDs on the various electronics can be seen without having to disassemble the sidewalls.

A. Software Environment

Wunderbot III was the first in the Wunderbot series to use LabVIEW as the robot's primary software package, replacing a motley combination of Visual Basic, C, and 80251 assembler [8]. Version 7.1 is our current version and quite handily takes as inputs the data sent by all of the hardware subcomponents. Using closed-loop control and an intricate system of inter-connected LabVIEW virtual-instrument (VI), block-diagram coding, Wunderbot is able to dynamically adjust to all stimuli while on the path of traversal. In addition, with LabVIEW, we design a graphical user interface (GUI) that presents the acquisition and logging of data, interfaces with instrument control, performs measurement analysis, and generates reports.
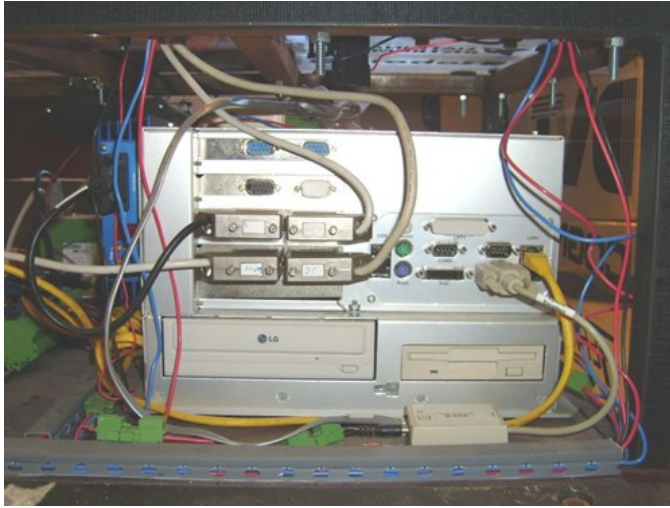
B. PC

Fig. 2.   Phoenix Contact IPC5500 Industrial PC, fully connected.

The Phoenix Contact IPC5500 Industrial PC, shown in Figure 2 houses and runs the Wunderbot's code. Running on a 1.6GHz Pentium-M processor with 512MB RAM, the PC operates using Windows Server 2000 SP4. Phoenix Contact's line of Industrial PCs fulfills our need for multiple serial ports, which are the connectivity interface for the majority of Wunderbot's hardware components. The IPC5500 contains 11 serial ports, along with 3 USB 2.0 and 2 ethernet. Although it also provides access for keyboard, mouse, and monitor, wireless remote administration from a laptop provides the most convenient form of access to the operating system. Section V-I details the method by which wireless communication takes place.

C. Electrical

Power to the on-board components is supplied by two 12V batteries connected in series. The PC takes the 24V source directly, while any device requiring lower voltage is connected to the PC's 12V and 5V power lines. A major overhaul for Wunderbot III was organizing and simplifying the wiring scheme, as shown in Figure 3. All low-current power is carried by 16AWG (1.29mm) wire, with added fuse blocks, while the wire running from the batteries, to the motor controller, to the motors is car stereo 2AWG (6.54mm). Connections with this wire were made via permanent butt splices. In consideration for their location on the underside of the robot (motors for the wheels), the butt splices were completely water-sealed.

D. Remote Control

A remote control was implemented for ease of maneuverability in manual-control mode. Intended for model airplanes, the Spektrum DX6 shown in Figure 4(a) is equipped with a multitude of buttons, switches, and axes. It operates on rechargeable batteries, utilizes the 2.4GHz band with Digital Spread Spectrum Modulation (DSM), and has a range of over 600 meters. In our application, the DSM is particularly useful
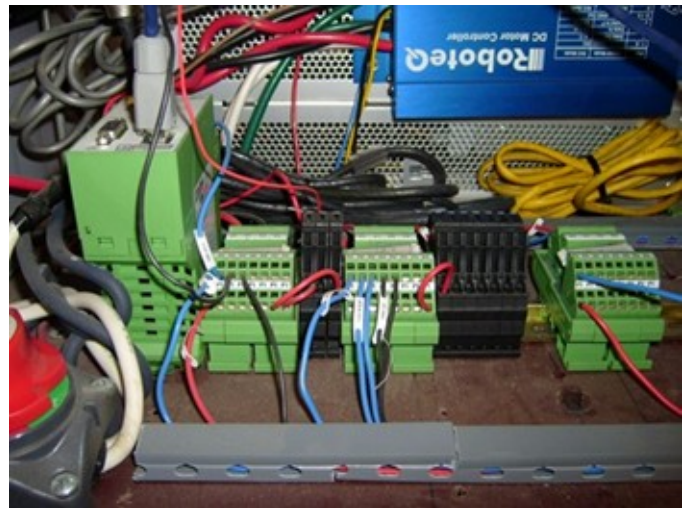

Fig. 3.   Power wires running at the heart of the electrical system, from connectivity blocks (green) and fuses (black) mounted on a DIN rail, and then neatly tucked away in mounted plastic conduits. Phoenix Contact RAD-80211-XD wireless access point mounted on far left of rail.
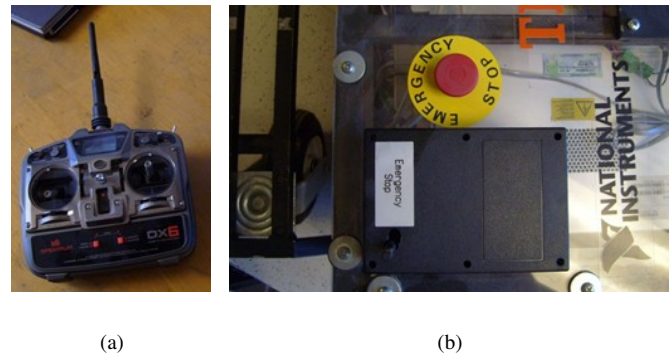

(a)   (b)

Fig. 4.   (a) Spektrum DX6 model airplane remote control. (b) Wired pushbutton emergency stop and wireless emergency stop receiver.

for its ability to avoid interference with the thirty other robots on the competition grounds. As the transmitter disperses pulse-width modulation signals, the PIC16F917 8-bit microcontroller in the receiver performs the translation into simplified strings via custom assembly code. These strings are fed through to LabVIEW, where they are parsed, and finally sent to the motor controllers. Reasons for choosing the PIC16F917 include its:

1) On-board Universal Synchronous/Asynchronous Receiver/Transmitter (USART)
2) High-resolution 16-bit timer
3) Ample on-board memory for our application
4) Rewritable and non-volatile flash program memory
5) Sufficient number of pins to perform our custom decoding and communication

E. Emergency Stop

In accordance with official IGVC rules, Wunderbot IV was fitted with both wired and wireless emergency stop buttons. During competition, one official judge is provided with the

wireless e-stop for safety purposes. Depicted in Figure 4(b), The robot's wired e-stop is a pushbutton that works by shorting the two leads from the motor controller when the button is pressed, which mechanically locks it in the down position. The wires remain shorted until the pushbutton is lifted. A simple two-button remote control is used for the wireless e-stop, the receiver for which is shown in Figure 4(b). Button one tests the signal range, beeping whenever pressed and two-way contact is established with the robot. Button two performs the same action as the wired e-stop, shorting the motor controller connection. The difference from the wired e-stop is that the button is spring-loaded and will not lock in place. Thus, a second action is performed upon button engagement. A signal is sent to the LabVIEW software to halt all commands to the motor controllers. The primary (steering) remote control houses its own wireless e-stop, in the form of a switch. When flipped, it signals the on-board software to halt all commands sent to the motor controllers. For the 2008 IGVC, this remote will trigger the hard-wired e-stop, replacing the simple two-button remote altogether.

F. Laser Range-Finder

As Wunderbot IV's most significant design change over Wunderbot III, the addition of two SICK LMS 200 laser range-finders substantially enhances the robot's obstacle detection capabilities. The obstacle avoidance system no longer relies strictly on the camera, which, as our experiences at past competitions have shown, is less than ideal for such a purpose. With a 180-degree range of view and a specified 80-meter range, one LMS 200, shown in Figure 5(a), enables us to detect obstructions on the path of forward orientation. By using two devices, we can sense objects located laterally to the robot or behind the vehicle. Knowledge of side and rear obstructions has importance when the robot must make sharp turns or move in reverse. This type of movement is not uncommon, given the occasional tight, winding segment(s) found on the autonomous challenge course.

The current analysis case studies involving LMS placement on the Wunderbot will resolve the yet-to-be-determined placement of the two laser range finders. The LMS 200 features built-in synchronization capabilities that avert any interference problems encountered when the ranges of two devices overlap [10]. In theory, by using a single LMS scanning the 180-degree region in front of the vehicle, a well-constructed path planning system will map all objects that Wunderbot IV would ever find within range. Thus, only undetected flaws in the path planning system necessitate a side or rear laser range-finder.

G. Vision

The vision system's acquires images via a DVT Legend 554C XE high-res video camera, seen in Figure 5(b). The camera performs image processing using its proprietary software, *DVT Intellect* v2.2. First, an erosion filter is applied to the image, using a 3×3 kernel. This closes many holes of noise, such as small dirt patches that appear through the grass, while still maintaining the shape of the desired white lines, since the lines (including dashed lines) will always be

wider than three pixels. Larger kernels could produce an even more accurate image, but processing times increase sharply as the kernel grows larger.

Once noise has been filtered, an *Intellect* "line thickness" sensor is applied. This measurement sensor first uses a variable 60% intensity threshold to deduce a binary image. The sensor then scans every row in the image to find the two edges closest either side. Optionally, all edges can be found and more accurately be used as input for the line fitting algorithm to follow; however, the extra computations lengthen the processing time roughly three-fold. To help eliminate noise, all edges less than 50 pixels wide are discarded. Next, a Hough Transform with resolution of four is performed on the detected edges in order to fit two lines, one closest to the left side of the image and one closest to the right. These final lines are measured for separation width, and the average of the two is measured for straightness, contrast, and angle.

Final line pass/fail conditions are used to filter shadows and other undesirable objects in the field of view. A maximum width condition of 300 pixels is combined with a "straightness" condition that will fail the test if the sum of the distances between the data point that is farthest away in one direction, and the one farthest away in the other direction, of the resulting average line.

A formatted string is sent via TCP/IP to the on-board PC. This string contains (in units of pixels), the dimensions of the viewing window, the x- and y-coordinates of the point on the left line with the lowest y-value (nearest to the robot), and the corresponding points on the right line. Once these are received by the PC, logic is used to determine the direction in which to turn.

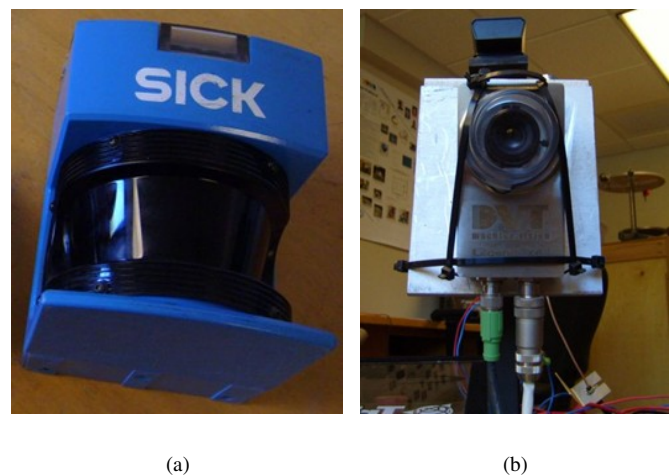(a)   (b)

Fig. 5.   (a) One of two SICK LMS 200 laser range-finders. (b) Cognex DVT Legend 554C XE camera.

Throughout the entire video capture process, *Intellect* intermittently transmits communication strings over TCP/IP through the Phoenix Contact SFN 5TX five-port switch, shown in Figure 7(a).

H. Movement

The underside of the Wunderbot's chassis houses two, 1.75 horsepower (1.77 metric horsepower) motors, driven by a Roboteq AX2550 motor controller, seen in Figure 6(a). The power is transferred to two tires, 13.5in (34.3cm) in diameter, at the front of the vehicle. On the rear corners are mounted two Hamilton Series 5000 pneumatic casters, shown in Figure 6(b) that allow for a zero-degree turning radius. The Wunderbot's low center of gravity sets it apart from the field, as rough terrain poses no threat to the robot maintaining its balance.
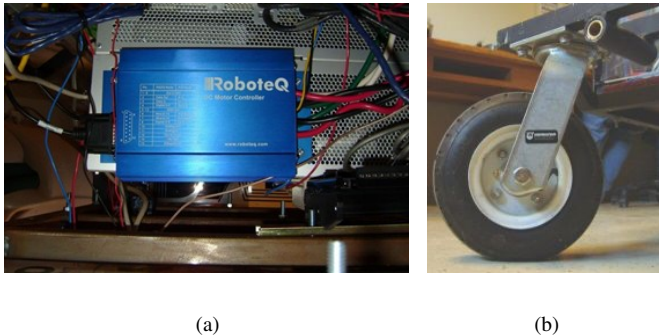

(a) (b)

Fig. 6. (a) Roboteq AX2550 motor controller. (b) One of two Hamilton Series 5000 pneumatic casters.

1) Navigation: For the IGVC navigation challenge, Wunderbot combines the capabilities of a Trimble AgGPS 114, an OmniSTAR differential global positioning system (DGPS) subscription, and a PNI TCM2-50 three-axis digital compass. All three devices send their data to LabVIEW. LabVIEW invokes simple trigonometric computations, approximately once per second, in order to steer the robot with the correct bearing toward the next GPS waypoint. The computations take into account the robot's current coordinates, accurate to within one meter [11], the desired waypoint's coordinates, and the current directional bearing, accurate to within 1.0 degrees [12].
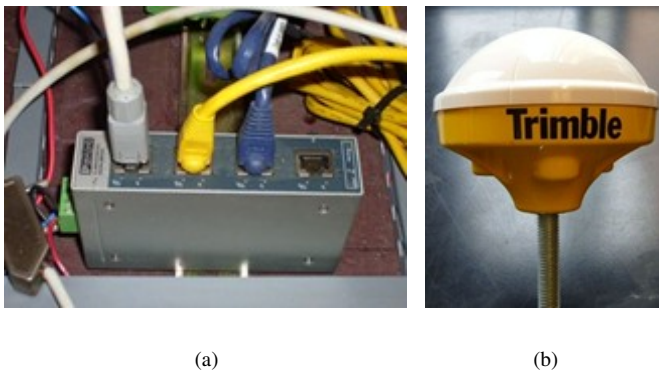

(a) (b)

Fig. 7. (a) Phoenix Contact SFN 5TX five-port switch, to which is connected, from left to right: camera, PC, wireless access point. (b) Trimble AgGPS 114.

2) Optical Encoders: Using the U.S. Digital optical encoders, Wunderbot IV is able to measure the distance traveled by the wheels. In order to match the desired moving velocity, the LabVIEW closed-loop control uses the optical encoders to measure the current actual velocity. Every 50ms we measure the speed of the motors. At 2000 ticks per rotation of the wheel (34.3cm circumference), the optical encoders measure travel distance with an accuracy of roughly 17mm. This precision grants us extremely accurate velocity measurements and prevents any undesired motion ("runaway") of the robot. Additionally, the motor controllers operate in watchdog mode, where they shut down if no commands have been received for more than one second.

3) Steering: For responding to the white line positions parsed and sent by the camera, both the x- and y-coordinates are taken into consideration. Rough scaling factors for both the x and y direction were used to convert pixels to centimeters, gave a an estimate of the depth and width of the camera view. Once these measurements were obtained, they could be used to plot the detected lines on a local map with target locations. The physical locations of these points are critical in giving the Wunderbot a global sense of position, which is used to determine how sharply to turn away from white lines and how to coordinate with other sensing subsystems, such as the GPS, digital compass, and LIDAR.

In general, when two lines are found, the target location is the average of their x-coordinates and the actual value of their y. When only one line is found, the target becomes the point directly centered between that line and either the left or right edge of the viewable region. If the line is on the left, the target is placed on the right, and vice versa. If no lines are found, the target is placed in the center on the horizon, such that the robot will move directly forward at full-speed.

LabVIEW controls were designed to adjust the weight of both depth and lateral position of the lines as they affect the vehicle's degree of turning. Additional controls enable the user to adjust the proximity (both depth and lateral - both must met) within which a detected line will force the robot to move in reverse, and another control sets the percentage of the forward speed to use when backing up.

The front casters were the source of costly inaccurate vehicle motion response. When operated on smooth indoor surfaces, Wunderbot was able to move in the general intended direction, but once the vehicle was tested outdoors on grass, motion response had a large degree of error. The casters require a disproportionate amount of force in order to change direction, but the introduction of a PID controller helped amend this steering problem.

The PID closed-loop control was developed in LabVIEW, with the three constants all user-adjustable via the front panel, and with feedback coming from the optical encoders. Very subtle variations in the derivative constant led the robot to accelerate out of control. A PID controller's derivative constant in general is highly susceptible to noise, and therefore an adjustable low-pass filter was designed for the 'D' [13]. This kept the it from fluctuating too rapidly, while still allowing it to quicken the output's rise time.

I. Wireless Communication

Revisions to the Wunderbot's software are performed wirelessly through the Phoenix Contact RAD-80211-XD wireless radio transceiver, shown in Figure 3. This multi-function device is capable of acting as an access point, client, or bridge. We use it strictly as an access point to communicate directly with our LAM Computers laptop, facilitated by Windows remote administration software. The RAD-80211-XD also conforms to all three of the major IEEE 802.11 wireless standards: a, b, and g. Since the laptop utilizes the wireless connection for diagnosis and uploading revisions, strictly short-range activity, our laptop's dated 802.11b capabilities are sufficient. Only the primary remote control holds the responsibility of performing long-range communication.

J. Path Planning

We consider two different approaches to path planning for the IGVC autonomous challenge and navigation challenge. When traversing the autonomous challenge course, the Wunderbot's path traversal decisions must use dynamic inference, similar to the notion of a robot exploring an unknown planet. It encounters unforeseen obstacles in a planned direct path and must intelligently choose an alternate route. Path planning in the autonomous challenge will employ A* heuristics with dimensional constraints in the cost functions, as shown in [14] and [15]. By weighing obstacle detection data as inputs from both the laser range-finders and the color camera, Wunderbot will choose the most optimal path.

Path planning in the navigation challenge, where we can pre-arrange the Wunderbot's waypoint traversal order, will follow team member David Coleman's proposed O^3 method [16]. This method entails assigning weights to paths on the directed graph of waypoints.
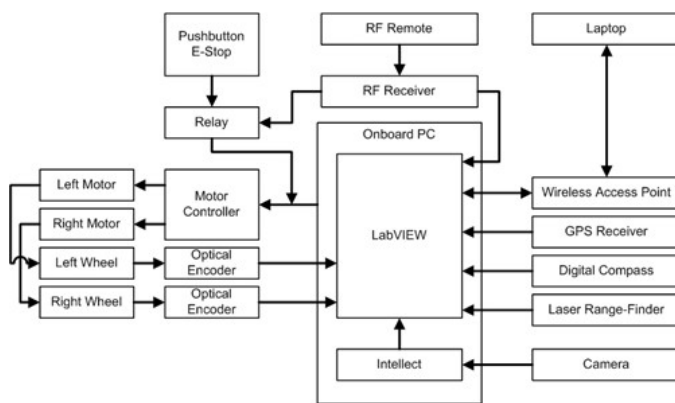

Fig. 8. Block diagram of Wunderbot IV subsystems.

VI. Conclusion

We have discussed Wunderbot IV's hardware and software systems, diagrammed in Figure 8, and the aspects tailored to the IGVC. Future developments include further strengthening of the vision system, with research into the possible introduction of neural networks. With a heavily-tested, reliably safe machine, we plan to begin implementing the robot as an autonomous tour guide at Elizabethtown College, which would stream a live, user-controlled camera feed to the Internet. Another planned addition to the Wunderbot is a robotic arm for collecting environmental samples, which has direct application to outerspace exploration, among other areas. Future testing strategies for the robot center on accurate software simulations. Upon modeling the courses at the competition, as well as creating a dynamic model of the robot itself, we will be able to quickly perform large sets of time-consuming test runs, foreseeing problems and addressing them as necessary.

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