PackBot: A Versatile Platform for Military Robotics

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ABSTRACT

The iRobot PackBot is a combat-tested, man-portable UGV that has been deployed in Afghanistan and Iraq. The PackBot is also a versatile platform for mobile robotics research and development that supports a wide range of payloads suitable for many different mission types. In this paper, we describe four R&D projects that developed experimental payloads and software using the PackBot platform. CHARS was a rapid development project to develop a chemical/radiation sensor for the PackBot. We developed the CHARS payload in six weeks and deployed it to Iraq to search for chemical and nuclear weapons. Griffon was a research project to develop a flying PackBot that combined the capabilities of a UGV and a UAV. We developed a Griffon prototype equipped with a steerable parafoil and gasoline-powered motor, and we completed successful flight tests including remote-controlled launch, ascent, cruising, descent, and landing. Valkyrie is an ongoing research and development project to develop a PackBot payload that will assist medics in retrieving casualties from the battlefield. Wayfarer is an applied research project to develop autonomous urban navigation capabilities for the PackBot using laser, stereo vision, GPS, and INS sensors.

Keywords: Robotics, UGV, UAV, chemical and radiation sensors, casualty evacuation, autonomous navigation.

1. INTRODUCTION

The iRobot PackBot is a rugged, man-portable, all-terrain, all-weather mobile robot that has been combat tested in Afghanistan and Iraq. Soldiers in the 82nd and 101st Airborne Divisions and Special Operations have used PackBots to search Al Qaeda caves in Afghanistan and hunt for chemical and nuclear weapons in Iraq. The PackBot also provides a versatile platform for modular payloads that can be used in a wide range of missions. PackBot EOD robots equipped with a seven degree-of-freedom manipulator and disruptor payloads have been deployed to Iraq to enable EOD specialists to remotely disarm improvised explosive devices.

In this paper, we will describe a number of completed and ongoing R&D projects using the PackBot as a base for developing new payloads for a variety of applications. These projects include:

- **CHARS:** A chemical and radiation sensor payload that has been deployed on PackBots to search for chemical and nuclear weapons in Iraq.
- **Griffon:** A man-portable hybrid UGV/UAV based on the PackBot with a gasoline engine and a parafoil wing.
- **Valkyrie:** A man-portable battlefield casualty extraction robot based on the PackBot.
- **Wayfarer:** A project to develop autonomous urban navigation capabilities for PackBots and other UGVs.

This work demonstrates the utility of having a small, rugged UGV that can be applied to perform many different tasks. These projects also show how the modular payload capability of the PackBot facilitates rapid development of a diverse set of payloads.

2. CHARS

The CHARS (Chemical weapons, Hazardous gas, And Radiation Sensor) Project was a 45-day rapid development effort to develop a chemical/radiation sensor payload for the PackBot that could be deployed immediately to the battlefield in Iraq. CHARS was funded by the Navy Space and Naval Warfare Systems Command (SPAWAR) in San Diego, California under the direction of the Robotic Systems Joint Projects Office (RS JPO) in Huntsville, Alabama. SPAWAR had developed an initial prototype payload that interfaced standard off-the-shelf sensors with their Urbot research robot via an IP Engine single-board computer. iRobot was contracted to develop a new payload that used the same sensors and IP Engine but interfaced with the PackBot and was sufficiently rugged for battlefield use.

In six weeks, iRobot engineers developed a PackBot CHARS payload that allowed a PackBot to carry and communicate with three standard-issue sensors: the JCAD chemical weapons sensor, the MultiRae hazardous gas detector, and the AN/UDR-13 Radiac radiation sensor. The SPAWAR IP engine communicated over the serial interface on the standard PackBot payload connector, and the PackBot CPU relayed the sensor data via the 802.11b wireless network to the PackBot OCU. These PackBots are also equipped with fiber spoolers that enable operators to control the robots via a fiber optic tether, without any RF transmissions. The PackBot OCU displays the values from the sensors in real-time as the operator teleoperates the PackBot using the onboard digital video cameras.

Four PackBots with CHARS payloads were delivered to the RS JPO and deployed to Iraq in November of 2003. These robots are currently being used by the Army to search for chemical and nuclear weapons (Figure 1).

Figure 1: PackBots with CHARS Payloads Searching for Chemical Weapons in Iraq

3. GRIFFON

The Griffon Project was a Phase I Small Business Innovation Research (SBIR) project to develop a man-portable hybrid UGV/UAV based on the PackBot. The goal of this project was to develop a prototype for a UGV/UAV that a single soldier could transport, launch, fly to a destination, and use to deliver a payload. Griffon was funded by the Army Tank-automotive Command Armaments Research, Development, and Engineering Center (TACOM-ARDEC) at Picatinny Arsenal, New Jersey.

The Griffon prototype consisted of a PackBot equipped with an Air Mobility System (AMS). The AMS includes a gasoline-powered propeller engine, a steerable parafoil, and a superstructure that attaches to the PackBot and provides mounting points for the engine and parafoil. The total vehicle weight, including the PackBot, is 57 pounds.

The operator controls steering and velocity using radio-controlled servos on the AMS. Two steering servos are attached to the parafoil control lines, one on each side of the vehicle. By retracting the lines on one side and extending the lines on the other side, the control system can control the vehicle’s turn rate. An additional servo controls the engine throttle. When the throttle is increased, the vehicle ascends. When the throttle is reduced, the vehicle descends.

Figure 2: Griffon Ascent (left) and Close-Up of Griffon in Flight (right)

In June 2003, we conducted a flight demonstration of the Griffon prototype at the California National Guard airfield in San Luis Obispo, California (Figure 2). We launched the Griffon on three separate flights, to altitudes of up to 200 feet and flight times of up to 89 seconds. The Griffon prototype achieved flight speeds in excess of 20 MPH.

4. VALKYRIE

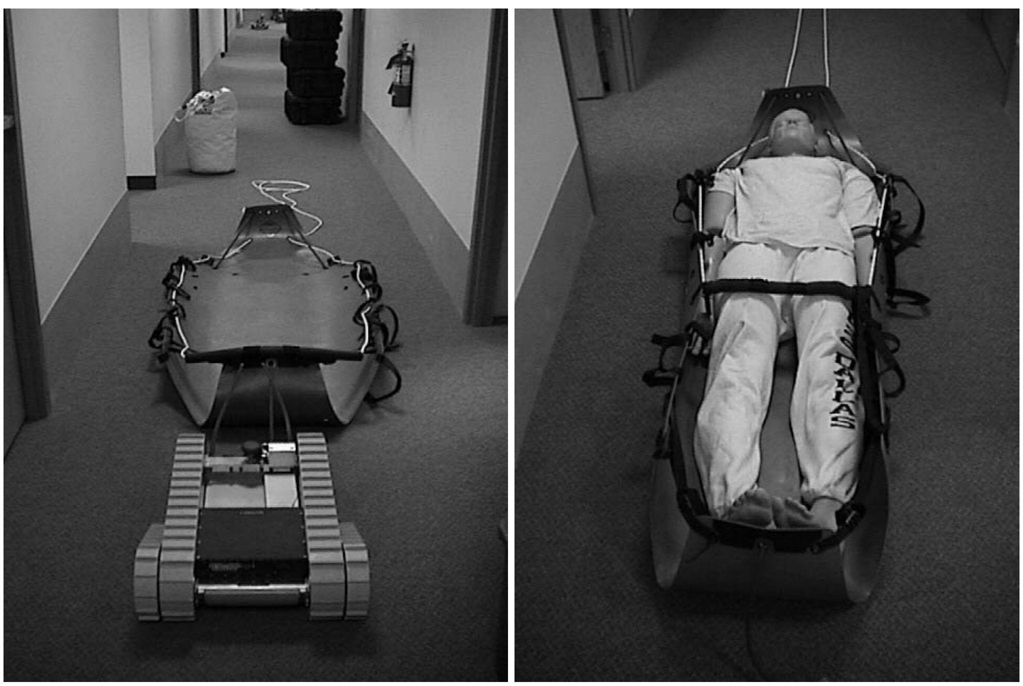

Figure 3: PackBot Towing EP (left) and Rescue Manikin Secured in EP (right)

Valkyrie is a project funded by the Army Telemedicine and Advanced Technology Research Center (TATRC) at Fort Detrick, Maryland to develop a battlefield casualty extraction payload for the PackBot. Over half of all medics who die in combat die while trying to recover a casualty. The PackBot Extraction Payload (EP) will enable combat medics to rescue injured casualties without exposing themselves to hostile fire. This work was initially funded by a Phase I SBIR, and follow-up funding was continued through a TATRC Broad Agency Announcement (BAA) award.

The EP consists of a Sked flexible stretcher, a drawstring Casualty Securing Mechanism (CSM), and a Remote Release Mechanism (RRM) that attaches to the PackBot. When a casualty falls at a location exposed to enemy fire, the medic will be able to teleoperate the PackBot to deliver the EP to the casualty. The casualty will roll onto the Sked, and the medic will use the RRM to release the EP. Rescuers will then use a rope attached to the Sked to pull the casualty to safe cover. As the rope is pulled, the CSM will automatically close the Sked around the casualty, securing the casualty to the Sked even over rough terrain.

We have developed a prototype of the EP (Figure 3), including the CSM and RRM. This prototype will be ready for field tests by April 2004.

5. WAYFARER

5.1 Urban Reconnaissance Task

Wayfarer is an ongoing research project to develop autonomous urban navigation capabilities for PackBots and other UGVs. The goal of the Wayfarer Project is to develop the technologies that will enable UGVs to perform urban reconnaissance tasks autonomously. Wayfarer is funded by the Army Tank-automotive and Armaments Command (TACOM) Tank-Automotive Research, Development, and Engineering Center (TARDEC) in Warren, Michigan.

Wayfarer focuses on three specific urban reconnaissance tasks:

- **Route Reconnaissance:** Move forward along a road for a specified distance and return to the starting point with video and FLIR image data and well as a map of the terrain.
- **Perimeter Reconnaissance:** Move around the perimeter of a building complex and return video/FLIR images and map data from all sides of the complex.
- **Street Reconnaissance:** Follow a route specified using GPS coordinates of intersections and bearings of selected streets, and return with video/FLIR images and map data.

The PackBot includes digital video, FLIR, and GPS capabilities, along with an onboard mobile Pentium III processor, a wireless teleoperation interface, and full Operator Control Unit (OCU) hardware and software. For the Wayfarer UGV, we will add sensors and perception software for autonomous navigation. These sensors will include a Point Grey Bumblebee/Triclops stereo vision system that will provide 3D range data, a SICK LMS laser rangefinder that will provide high-resolution, high-accuracy planar range data, and a Crossbow Inertial Measurement Unit that will provide precise position and orientation information. The data from both range sensors will be fused to detect obstacles, build a map of the surrounding environment, and determine street bearings for road following. Figure 4 shows the Wayfarer hardware architecture.

Figure 5 shows the Wayfarer Software Architecture. In order to perform urban reconnaissance tasks, the Wayfarer UGV will need the following novel capabilities:

- **Urban Street Tracking:** The ability to detect the bearing of the current street in a complex urban environment with moving vehicles and people.
- **Perimeter Tracking:** The ability to track the perimeter of a building complex, despite the presence of both static obstacles (e.g. trees, structural supports, rubble) and dynamic obstacles (e.g. people, vehicles).
- **Intersection Detection:** The ability to detect the presence of intersections and determine the bearing of all streets adjoining each intersection.
- **3D Obstacle Avoidance:** The ability to detect and avoid obstacles in an environment with complex 3D structure, where the UGV may be tilted at any orientation and not parallel to the ground plane.

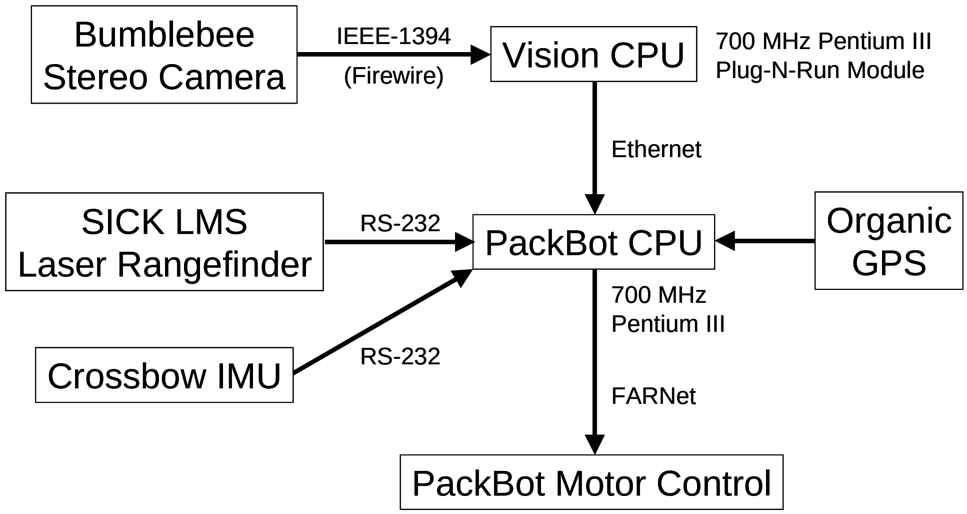

Figure 4: Wayfarer Hardware Architecture

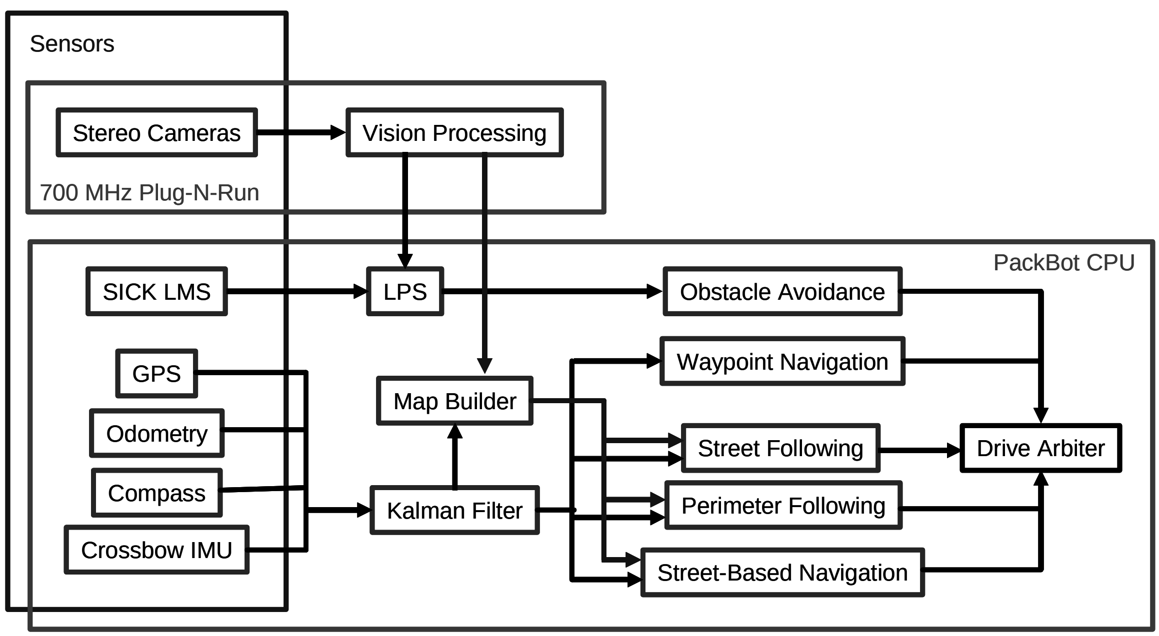

Figure 5: Wayfarer Software Architecture

5.2 Obstacle Avoidance

We have previously developed an obstacle avoidance system based on a Local Perceptual Space (LPS) represents the location of all recently detected obstacles. As the robot moves through the world, the LPS shifts to correctly represent obstacle positions relative to the robot. Unlike a permanent map, the LPS only stores obstacle locations for a limited period of time, thus reducing the effect of robot position uncertainty on map accuracy.

Reactive behaviors provide a set of potential trajectories for the robot. The obstacle avoidance behavior projects these paths onto the LPS using a template based on the robot's shape and configuration, and potential collisions are detected. The behavior arbiter then selects the trajectory that will be clear of obstacles for the greatest distance, and selects an appropriate translation speed. In an open environment, the robot can move at full speed. In a cluttered environment, the robot's speed is reduced to allow for tighter maneuvers.

For the Wayfarer project, we are extending this obstacle avoidance system to work with small UGVs in outdoor environments using a laser rangefinder. This will require extending the LPS to three dimensions and being able to determine the robot's movement through 3D space. The PackBot includes an onboard pitch/roll sensor to determine the robot's orientation, and we will add an inertial navigation sensor to determine the robot's position over short periods of time (i.e. seconds). Kalman filtering techniques, such as the ones used by JPL for position estimation on the Urban Robot[3], can also be added to improve position estimation accuracy.

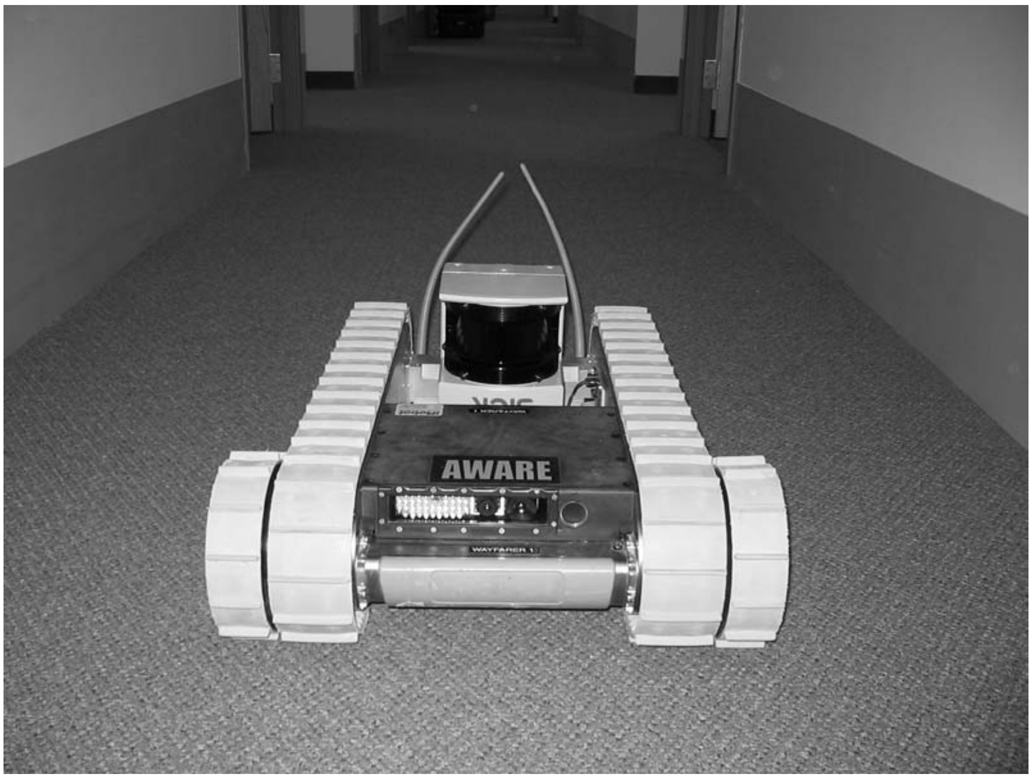

Figure 6: Wayfarer PackBot with SICK LMS Laser Rangefinder

We have integrated a SICK LMS 291-S05 laser rangefinder on our Aware PackBot (Figure 6). The SICK LMS is a planar laser rangefinder that is designed for indoor or outdoor use. This sensor provides precise, high-resolution range data with a 180-degree field-of-view, a maximum range of 80 meters, a range accuracy of +/- 45 mm, and a scan time of 26 milliseconds with an angular resolution of 1.0, 0.5, or 0.25 degrees. The sensor is hardened for outdoor use under demanding environmental conditions and includes integrated capabilities for accurate ranging through rain, snow, and fog.

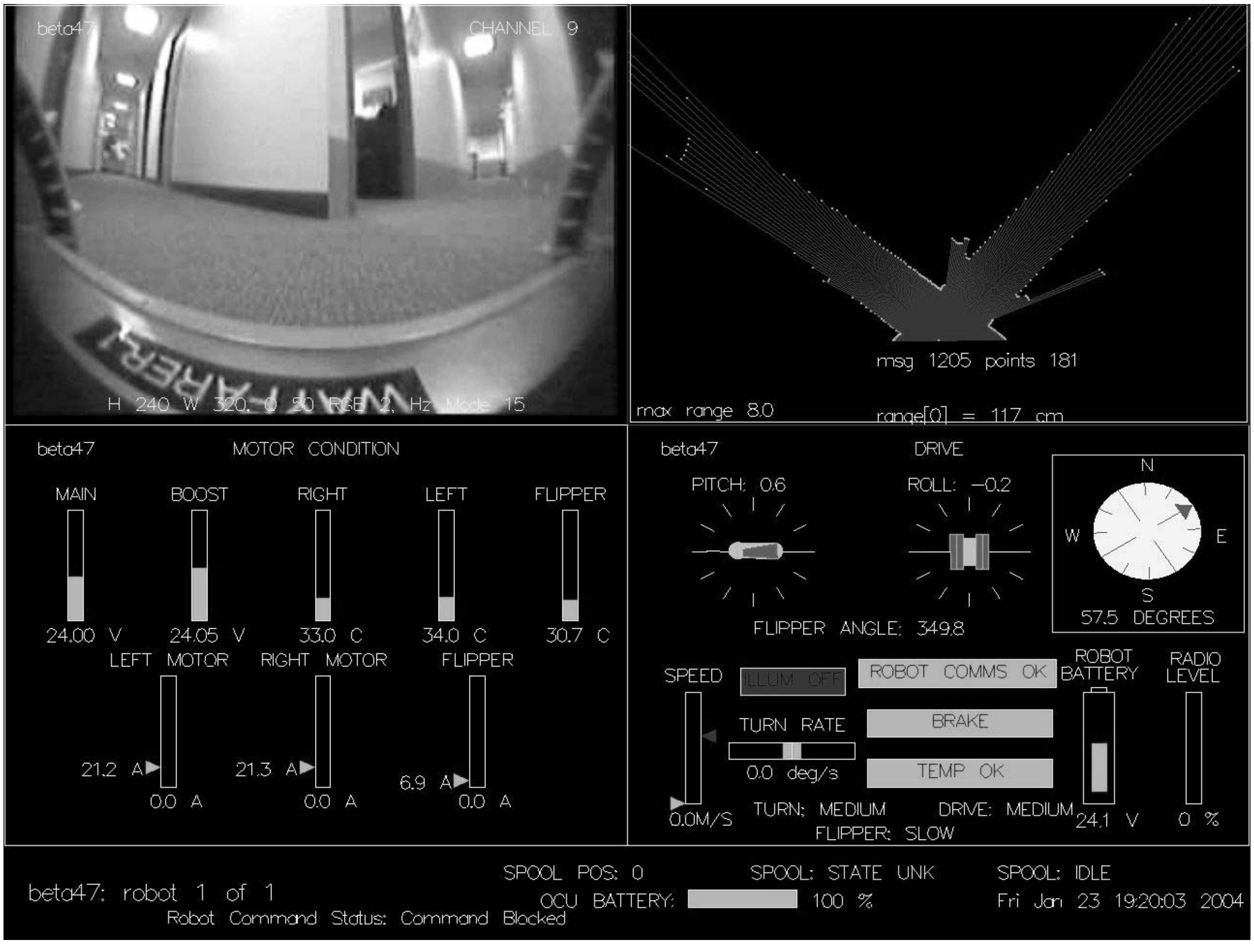

Figure 7: Wayfarer OCU Showing Video (upper left) and Laser Range Data (upper right)

We have created a modified version of the PackBot OCU to serve as the Wayfarer OCU. We have added the capability for the Wayfarer OCU to receive UDP packets containing laser range data and display this data in real-time in a sensor panel. Both the PackBot OCU and the Wayfarer OCU use the OpenGL graphics library for high-performance real-time rendering.

Figure 7 shows a screen capture from the Wayfarer OCU driving the Wayfarer PackBot with the onboard SICK LMS laser rangefinder. In this example, the robot is being teleoperated through an indoor office environment and is currently located at the intersection of two hallways.

The upper left quadrant shows the live video feed from the PackBot's color drive camera. The upper right quadrant shows the real-time data from the laser rangefinder. The orthogonal walls of the hallway intersection are distorted by the wide-angle lens on the drive camera, but are clearly delineated in the top-down view of the laser range data. In this example, the laser was operated in the 1 degree resolution mode, with range readings at 1 degree intervals across a 180-degree field of view.

5.3 Map-Building

For Wayfarer, we are extending the laser-based mapping system we developed for the Bloodhound medical robot project[5] to integrate vision data with laser range data. The Bloodhound mapping system uses a SICK PLS mounted on a PackBot to build 2D occupancy grids. Occupancy grids[4] are Cartesian grids where each cell represents the probability of the corresponding point in space being occupied by an obstacle. All grid cells are initialized to a prior probability value, which estimates the overall probability of a point in space being occupied by an obstacle.

When a sensor reading is received, cells in the occupancy grid are updated based on a statistical model for the sensor type. For laser range readings, ray-tracing is used to increase the occupancy probability of the point corresponding to the obstacle detected by the laser, and to reduce the occupancy probability for all cells along the path from the sensor to the obstacle. Figure 8 shows an occupancy grid built for an outdoor urban environment (parking lot) using the Bloodhound PackBot equipped with a SICK laser rangefinder. Each grid square in this map is 10 meters on a side.

For the Wayfarer project, we will develop sensor models for the Point Grey Bumblebee stereo vision system. For computational efficiency, ray tracing will not be used for these models. Instead, the prior probability for each cell will be set to a low initial value, and this value will be increased when obstacles are detected by either the vision system or the laser rangefinder. All of the 3D range points detected by the vision system will be projected onto the 2D ground plane based on the orientation information from the IMU as well as the position information from the GPS receiver.

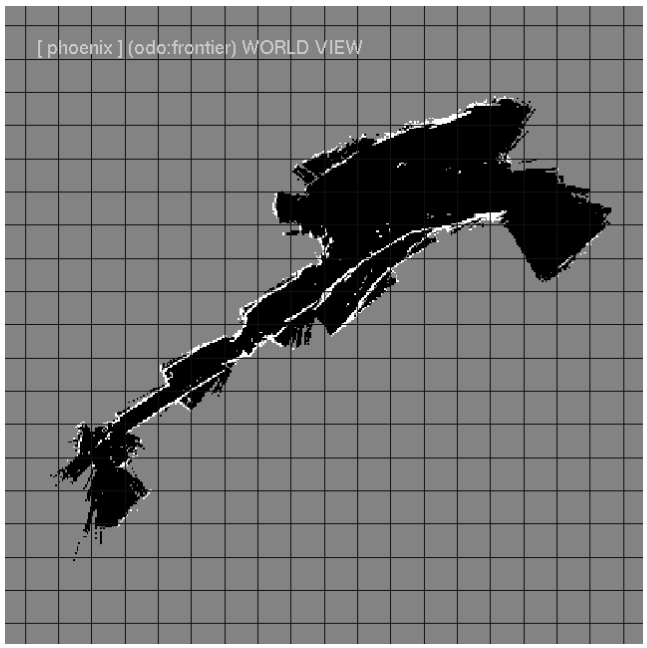

Figure 8: Occupancy Grid Map of Urban Environment

5.3 Street and Perimeter Tracking

Once the Wayfarer UGV has built a map of the environment using vision and laser data, the Hough Transform will be used to find lines in the occupancy grid map. We expect that the strongest, longest, and most consistent lines will correspond to the building faces that are parallel to the street. By determining the orientation of these lines relative to the UGV, the Urban Street Tracking system will be able to determine the bearing of the street, and the Wayfarer navigation system will use this bearing to guide the UGV.

The Hough Transform[1] is a computer vision technique that works by transforming image point coordinates into votes in the parameter space of possible lines. Each point corresponds to a vote for all of the lines that pass through that point. By finding the strongest points in the parameter space, the Hough Transform can determine the parameterized equations for the strongest lines in the image.

Our research effort in the Wayfarer project will be unique in applying this technique to outdoor urban navigation. Previously, Schiele and Crowley have applied the Hough Transform to finding indoor walls in occupancy grid maps[2].

The results of their research demonstrated that the Hough Transform is a powerful technique for detecting linear features in man-made environments. Our work will extend this approach to reconnaissance applications that have high value for military operations in urban terrain.

We will extend the Hough Transform algorithm developed for Urban Street Tracking to enable Perimeter Tracking of urban building complexes. For this application, the operator will indicate a particular wall for the UGV to track, and the UGV will autonomously follow this wall around the complex until it returns to its starting location.

For Perimeter Tracking, the navigation system will identify a region of interest around the line segment corresponding to the wall being tracked. The lines detected within this region will be monitored to provide a current heading for the UGV, and to determine when the orientation of the perimeter being tracked has changed (i.e. going around a corner). Perimeter Reconnaissance behaviors will guide the UGV to follow the building wall as the UGV navigates around the complex.

5.4 Intersection Detection and Street Reconnaissance

We will extend the Hough Transform algorithm developed for Urban Street Tracking to detect multiple streets that converge on an intersection. In addition, we will develop a Street Reconnaissance system that enables the Wayfarer UGV to follow a complex path through urban terrain.

For Intersection Detection, the Hough Transform will be used to detect lines corresponding to building fronts facing each of the streets at the intersection. Parallel lines separated by likely urban street widths will be paired together. The orientation of these paired line segments will be used to estimate the bearing of the streets converging at the intersection.

For Street Reconnaissance, paths will be specified as the approximate GPS coordinates of intersections along with the approximate absolute bearings of the selected streets at each intersection. The Wayfarer UGV will use Urban Street Tracking to follow roads between intersections. When the UGV arrives at an intersection, it will use Intersection Detection to determine street bearings and find the closest match to the stored route bearing. Street Reconnaissance behaviors will steer the UGV through the intersection, and then Urban Street Tracking behaviors will take control until the UGV reaches the next intersection. All of these behaviors will be integrated with obstacle avoidance to steer the UGV around any obstacles encountered on the route.

6. CONCLUSIONS

The iRobot PackBot is a rugged, man-portable, combat-tested, all-terrain UGV suitable for a wide range of military and civilian applications. The PackBot is also a versatile platform for robotics research and rapid development in many different domains. We have developed a chemical/radiation sensor payload (CHARS) for the PackBot and deployed CHARS PackBots to search for chemical and nuclear weapons in Iraq. We have developed a flying PackBot (Griffon) that combines the capabilities of a UGV and a UAV. We have developed a casualty extraction payload for a PackBot-based robot (Valkyrie) that can assist in the rescue of battlefield casualties and disaster victims. We are currently developing the Wayfarer navigation system that will allow PackBots to autonomously perform urban reconnaissance tasks, including street following, perimeter reconnaissance, and intersection detection.

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REFERENCES

1. D. Ballard and C. Brown, *Computer Vision*, Prentice-Hall, Upper Saddle River, New Jersey, 1982.
2. B. Schiele and J. Crowley, “A Comparison of Position Estimation Techniques Using Occupancy Grids,” *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, IEEE Press, San Diego, CA, 1994.
3. L. Matthies, Y. Xiong, R. Hogg, D. Zhu, A. Rankin, B. Kennedy, M. Hebert, R. Maclachlan, C. Won, T. Frost, G. Sukhatme, M. McHenry, and S. Goldberg, “A Portable Autonomous Urban Reconnaissance Robot,” *Proceedings of the 6th International Conference on Intelligent Autonomous Systems*, IOS Press, Venice, Italy, 2000.
4. H. Moravec and A. Elfes, “High Resolution Maps From Wide Angle Sonar,” *Proceedings of the 1985 IEEE International Conference on Robotics and Automation*, IEEE Press, St. Louis, MO, 1985.
5. B. Yamauchi, P. Pook, and A. Gruber, “Bloodhound: A Semi-Autonomous Battlefield Medical Robot,” *Proceedings of the 23rd Army Science Conference*, U.S. Army, Orlando, FL, 2002.