PackBot with Mapping Kit

Real-time 2D Mapping and Safeguarded Teleoperation

Jon Brookshire
iRobot Corporation, 8 Crosby Drive, Bedford, MA 01730
Phone : (781) 430-3581, Fax : (781) 430-0201
Email : jbrookshire@irobot.com
URL : http://www.irobot.com

Abstract

Successful, remote operation of unmanned ground vehicles requires that operators project themselves into the robot's perspective. Raw feedback, such as real-time video, audio, and sensor data, provide significant advantages to teleoperators, allowing them see and interact with the vehicle's world. Though valuable, raw feedback has a number of shortcomings as the data can require significant concentration by the operator and the transmission of the data requires significant communications bandwidth.

Our work addresses these issues by providing the operator with fused information that provides (1) real-time 2-D mapping and (2) safeguarded teleoperation capabilities. Using a Laser Detection and Ranging (LIDAR) sensor, the robot constructs an online map of its environment as it is teleoperated. This map is then transmitted back to the operator in real-time and displayed along side raw video. The robot also implements a safeguarded teleoperation capability that uses the LIDAR range data to detect obstacles and autonomously adjust the operator's drive

commands by slowing and limiting steering in order to avoid detected obstacles. Such a capability allows for a faster and safer process when operating in cluttered environments and can reduce the operator's workload.

This paper provides an in-depth discussion of the techniques used for the real-time mapping, safeguarded teleoperation, and operator interface features. The culmination of this work is the iRobot PackBot with Mapping Kit Unmanned Ground Vehicle (UGV) system, which consists of an integrated UGV and user interface solution.[1]

1 Introduction

Robots have the potential of removing humans from harm's way. Explosive Ordnance Disposal (EOD) is a prime example. In Operation Iraqi Freedom, for example, the iRobot PackBot EOD disrupts explosive devices while soldiers remain at a safe distance. In the case of a road side bomb, operators can deploy an EOD robot, navigate to the target, and commence operations. The situation becomes more difficult, however, if the explosive is believed to be hidden in a building or during building inspection and clearing operations. In such missions, a significant burden is placed on the operator as he simultaneously searches the video stream for objects of interest and maintains a mental map of the building's interior to be able to reference the location of these objects.

Bomb threats are also an issue for America's school systems. For example, the Missouri Department of Public Safety reported 65 bomb threats in 2007, the majority of them in high schools. [2] In such cases, large school buildings must be manually cleared by police. Hostage situations present another instance where knowledge of a building's interior, without sending people into the building, may provide advantages (see Figure 1). Clearly, the decision to use an

[1] For sales and additional technical information, please see http://www.irobot.com/sp.cfm?pageid=137

UGV to clear or map a building's interior depends on many situational details. For example, the UGV is sometimes expendable, but it may not be as covert as a well trained human team.

Figure 1 – Police determine strategy from a safe distance during a hostage situation in Rochester, N.H. in November, 2007. [3]

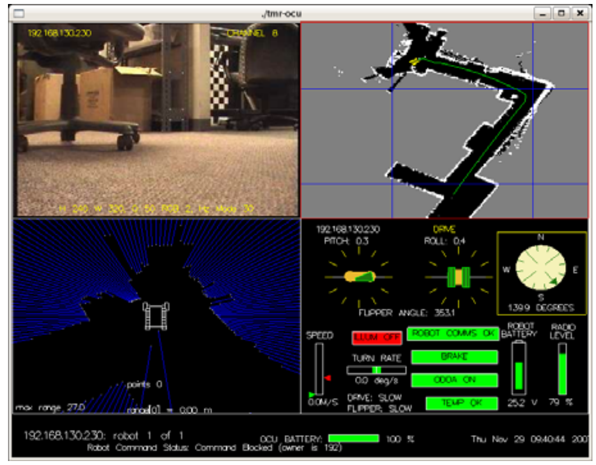


Figure 2 – A screen shot of the PackBot with Mapping Kit OCU. Video data (upper left), map (upper right), range data (lower left), and robot telemetry (lower right) are displayed.

The iRobot PackBot with Mapping Kit provides teleoperators with increased situational awareness. The PackBot UGV is equipped with additional processing capacity – a SICK LIDAR sensor [1] and video cameras. The LIDAR range data and robot odometry are fused to provide the operator with a real-time 2D map: as the robot moves, the range data is continuously integrated to produce the map. The LIDAR range data is also used to detect nearby obstacles and retard teleoperated motion in that direction. As shown in Figure 2, the range data and map are displayed remotely on the Operator's Control Unit (OCU). The safeguarded teleoperation capability allows the robot to be effectively employed with a faster tempo of operations. The operator no longer has to be concerned about colliding with obstacles during teleoperation and can focus on the high-level navigation and mission goals.

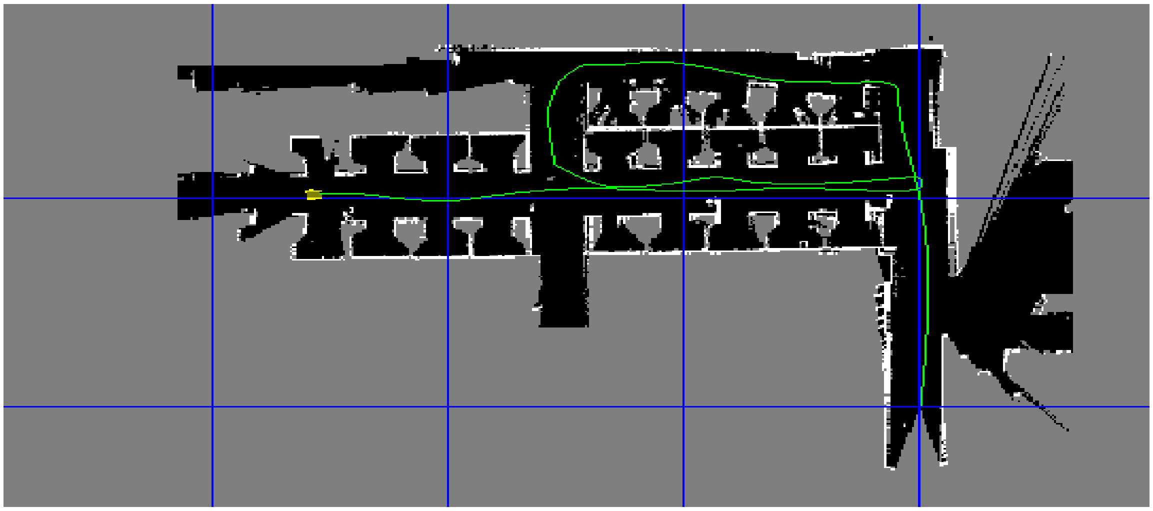


Figure 3 – The yellow robot was teleoperated along the green path to generate this map over a period of several minutes. The blue grid lines are spaced at 10m.

2 Background

2.1 Wayfarer

The iRobot Wayfarer project developed reconnaissance functions for the PackBot including mapping, obstacle avoidance, perimeter following, and street reconnaissance. Each robot was equipped with a SICK LD-OEM LIDAR, a Tyzx G2 stereo vision system, and an Athena GuideStar Inertial Measurement Unit.

Wayfarer used an evidence grid [7], similar to the one used for this Mapping Kit, to generate a 2D map of its environment. The evidence grid is discussed further in Section 3.2. The evidence grid was then used to generate a Scaled Vector Field Histogram (SVFH). The SVFH converted the evidence grid into polar wedges which were then classified as either blocked or passable. To achieve obstacle avoidance, the robot would travel in a direction classified as passable and closest to its desired direction. The SVFH differed from the VFH because, at greater distances from the robot, occupied cells affected neighboring wedges. [4]

Wayfarer also applied the Hough transform to detect building walls and street boundaries in order to perform perimeter following and route reconnaissance. [5]

2.2 Sentinel

The Sentinel project sought to enable a single operator to control multiple PackBots simultaneously. Each robot was equipped with a pan-tilt 3D SwissRanger camera, video camera, SICK LIDAR, and an auxiliary computational payload. Key features included obstacle avoidance using the Wayfarer SVFH technique and off-line map generation. A* path planning and localization algorithms could then use this map to perform autonomous driving. All robots used the same, static map, and the operator controlled all robots using a tablet PC interface.

Sentinel used a particle filter engine for localization to maintain a set of discrete hypotheses. As the robot moved, odometry and range data (compared against the static map) were used to update the particles. Sentinel's off-line map building ability used a Simultaneous Localization and Mapping (SLAM) algorithm. This process resulted in maps that could easily be used for robot navigation. [6] The SLAM algorithm relied on range scan matching and lacked the ability to back-propagate new sensor information. As a result, loop closure was not always successful.

The OCU was a key component of this work. It depicted the position of all robots from an overhead map view. The operator could pan, zoom, adjust the position of robots, define path waypoints, and create patrol loops.

3 Mapping

The Mapping Kit seeks to provide the operator with enhanced situational awareness and more effective control during teleoperation by providing real-time 2D mapping capabilities and safeguarded teleoperation. The system is built as a modular payload for the iRobot PackBot, which is augmented with additional processing and sensing capability. The software is implemented using the iRobot Aware 2™ Robot Intelligence Software.

3.1 Hardware System

The PackBot is a tracked vehicle with two actuated flippers. On a full set of batteries, the PackBot can travel at 4.5 MPH for 8 hours. The PackBot has an internal 700 MHz Pentium II with 256 MB of RAM, a 300 MB compact flash storage drive, and a 2.4 GHz 802.11b radio Ethernet. For our system, this internal processor is used only for low level control of the robot, and the Navigator Payload, an auxiliary computational package for the PackBot, performs the safeguarded teleoperation and mapping functions. The Mapping Kit is also equipped with a SICK LD-1000 360° planar LIDAR.

The Navigator Payload occupies three of the modular payload bays on the PackBot in a plug-and-play fashion. The payload includes a 1.8 GHz Intel Pentium M, 1 GB of RAM, and an 8 GB solid-state flash memory hard drive. An Ublox Antaris 4 GPS receiver and a Microstrain 3DM-GX1 six-axis micro-electro-mechanical system (MEMS) inertial measurement unit (IMU) are also included. The GPS receiver is capable of determining the robot's position accurately to within approximately 2-4 meters. The IMU determines the orientation of the robot and has a drift rate of less than 1 degree per minute.

Figure 4 – The Mapping Kit is an iRobot PackBot augmented with a modular payload consisting of a LIDAR, a computational payload, and real-time mapping software.

3.2 Mapping

The 2D map is constructed using the range data from the LIDAR and is implemented as part of the Aware 2™ architecture. The map is represented as an evidence grid with a resolution of 10 centimeters and is 250 meters on each side. Each cell in the grid contains a logarithmic probability in the range [0.0, 1.0]; a higher probability means that the cell is more likely to be occupied. As the robot moves through the environment, the readings from the LIDAR are integrated into the map at the robot's current position. The LIDAR data provides a series of distances to nearest obstacles and bearing angles. The mapping algorithm adds data to the map by processing each bearing angle as follows: (1) Up to the distance of the return, the evidence in the grid for obstruction is reduced by 5%. (2) At the distance of the return, the evidence in the grid for obstruction is increased by 10%. When a portion of the grid map is updated with this new data, the affected cells are classified by thresholds to be unexplored, occupied, or clear. This data is compressed and transmitted to the OCU.

Although simple, we have found the evidence grid to be robust for mapping applications. First, because the grid is composed of the logarithm of probabilities, evidence cells can be quickly updated by adding new values. Second, the grid is robust to moving objects. As people walk within the field of view of the LIDAR, they are temporarily added to the map. However, as the robot continues to collect data and people move away, the occupied cells quickly dissolve. Third, evidence grids provide a straightforward means to fuse and integrate data from different sensors into an integrated map. For example, in other efforts we are using evidence grids to fuse radar sensor data. Fourth, because the map is stored in a spatial form, it is straightforward to add a path planner (e.g., such as that described in Section 2.2).

3.3 Safeguarded Teleoperation

Although cameras provide valuable situational awareness when navigating, they do not offer a full view of the robot itself. The result is that the teleoperator must estimate the robot's position relative to obstacles and attempt to avoid collisions. The 360° LIDAR data does provide full circle view. This view, as shown in Figure 5, is helpful for navigating in narrow environments because the operator can see the robot's position relative to range readings. This LIDAR data is used to implement a safeguarded teleoperation capability that allows the robot to stop or alter course if a collision is imminent. Note that the LIDAR data provides planar data – so objects below or above the laser plane will not be registered and can still obstruct the robot's path (see Section 4).

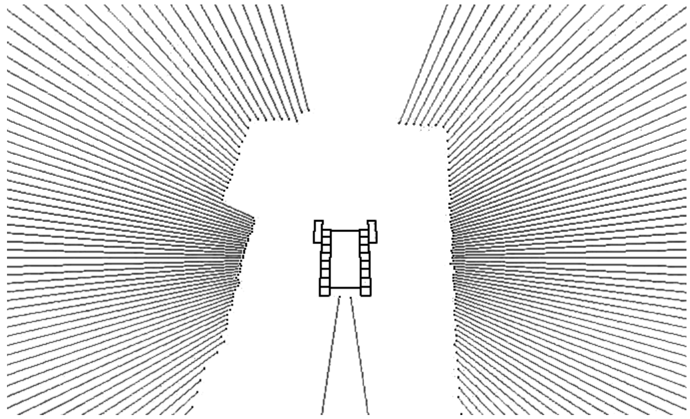


Figure 5 – LIDAR data provides distance to nearest obstacles in the plane of the sensor. The Mapping Kit uses this data to guard the teleoperator from collisions.

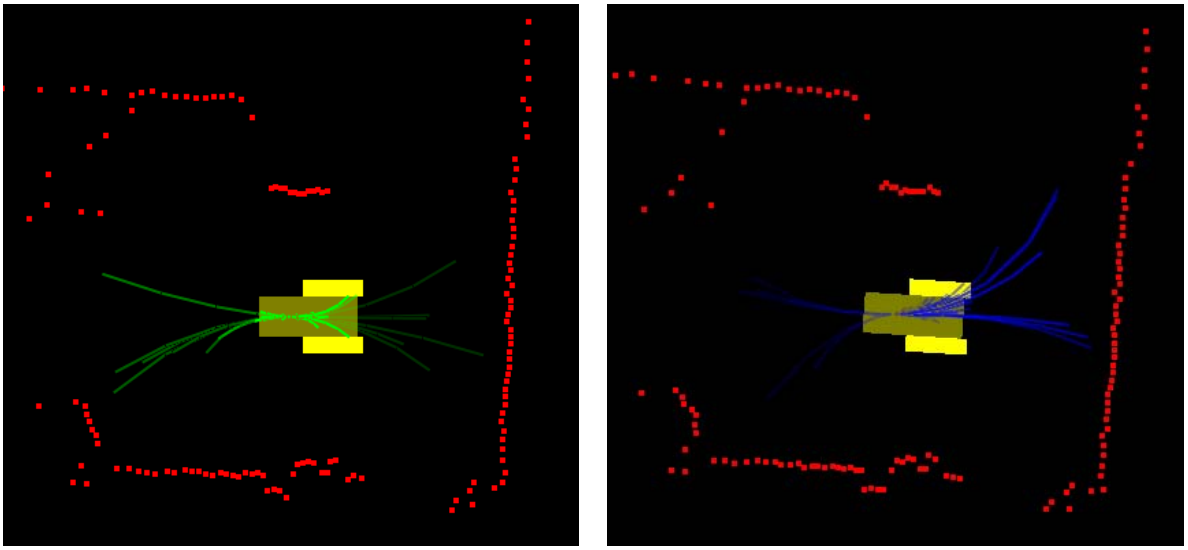
An algorithm is incorporated which implements obstacle detection using this LIDAR data. Our algorithm integrates with the iRobot Aware 2™ architecture and prevents the operator from driving into objects which are visible to the LIDAR. When LIDAR range returns are less than some minimum distance, the algorithm retards robot movement in that direction.

The Aware 2™ architecture implements a behavior based control scheme, where several modules run in parallel and each contributes to the robot's final action. Rather than using a typical sense-plan-act methodology, Aware 2™ does not require that all sensor data be fused into a coherent frame prior to planning. The advantage is that each algorithm can focus on achieving a specific goal. The actions of each behavior are then aggregated to form a single action for the robot to take.

During each time step, a model of the robot is first used to generate a set of possible paths the robot might take. These paths are a set of random paths based on a combination of the robot's drive capabilities and the robot's current heading and velocity. Second, each of these paths is then considered and scored by relevant behaviors. For example, the safeguarded teleoperation behavior would score paths that collide with objects as undesirable. Meanwhile, the teleoperation behavior (i.e., the behavior responsible for representing the human operator's intentions) would score paths that match the operator's desires very highly. Third, the scores for the paths are weighted and summed, and the most desirable action is taken. It is interesting to note that by adjusting the weight, the system designers can tune the system. For example, if the desired operation is to always avoid obstacles (regardless of the teleoperator's commands), then the weight of the avoid obstacle behavior should be higher than the teleoperator's behavior.

The safeguarded teleoperation behavior used for the Mapping Kit scores paths based on the time until a collision. Paths that never have a collision receive a neutral weighting (i.e., desired) and paths that have more immediate collisions receive undesirable weightings. Each path evaluation cycle is based only on the current LIDAR data – no history/map is used when determining collisions. Figure 6A shows a sample set of paths considered by the safeguarded teleoperation behavior (the brightness of the paths is proportional to that path's score). Paths to the left (toward open space) scored well, whereas paths to the right toward the wall scored negatively. Note that shorter paths to the right scored most desirably because their final destination is furthest from obstacles.

Simultaneously, the teleoperation behavior is scoring paths based on how closely they match the human operator's intentions – paths that match the operator's commands are scored as desirable. Figure 6B shows the paths considered by the teleoperation behavior. (Note that these paths are different from those shown in Figure 6A because the screen captures were taken at different times; both behaviors consider the same paths at the same time). In this case, the operator was driving the robot to the right and, as a result, actions in that direction score more highly.



(A) **(B)**

Figure 6 – The yellow robot is facing to the right and LIDAR returns are shown as red squares. (A) Green lines show sample paths considered by the safeguarded teleoperation behavior (dark green paths are less desirable). (B) Blue lines show sample paths considered by the teleoperation behavior (dark blue paths do not match the human's desires well).

The weightings from the safeguarded teleoperation and teleoperation behaviors are then summed and sent to the robot's drive train. In collision-free environments, commands similar to the teleoperator's commands are executed by the robot. However, if the teleoperator's command would cause a collision, that path is weighted so negatively that it will not be executed. Instead, paths which do not cause collisions but are somewhat similar to the teleoperator's commands may be executed. In this way, the safeguarded teleoperation feature can add a level of obstacle avoidance. For example, note that some of the paths considered in Figure 6B tend to curve to the upper-right corner. This set of paths generated by the robot model was based on previously selected commands. Because previously selected paths tended to favor paths away from the right wall, but still in that direction, an avoidance-like behavior is achieved.

3.4 Operator Interface

The Mapping Kit uses the interface shown in Figure 2. The user interface is divided into quadrants, each of which can be configured to show robot telemetry, video camera feeds, LIDAR range data, the 2D overhead map, and several other optional displays. Any quadrant can be expanded to fill the entire screen. The robot is driven using a joystick.

While operating the system, we discovered that the LIDAR range data and the 2D map greatly facilitated navigation. Often, we were able to map and navigate buildings without using the video display. This is a key finding, because as communications bandwidth becomes more limited, the lower data rates needed by LIDAR and map data will prove advantageous. The video camera is most useful when inspecting objects or when navigating around objects that are not tall enough to be in the LIDAR's measurement plane.

4 Conclusions and Future Work

The Mapping Kit will benefit from several future improvements. First, the LIDAR data is limited to a plane and obstacles and map features above or below that plane will be omitted. By using a stereo vision system such as a Tyzx G2 stereo vision system, for example, we can remove the planar limitation. The stereo vision-based approach, however, often works poorly in environments with little texture (e.g., inside buildings) because the stereo system is unable to extract features. Another solution is to add a 3D imaging sensor such as Advanced Scientific Concepts' (ASC) 3D Flash LIDAR [8]. The Flash LIDAR generates a range map from the time of flight of a laser pulse. The depth information correlates with the video data, has a resolution of 128x128 pixels, and an update rate of 10 Hz. iRobot has partnered with ASC to develop this LIDAR as a commercial product. The integration of such a sensor will result in improved obstacle avoidance and a richer, more detailed map to further increase situational awareness provided to the operator.

Second, the evidence grid representation has several benefits (see Section 3.2), but lacks the ability to robustly close loops and will suffer from odometry drift when used to explore large areas. When adding data to the map, it is assumed that the robot's position is accurate. Applying a Kalman filter to the PackBot's raw odometry has proven this to be a good assumption and maps appear reasonable (distances are proportional and angles are representative). However, when exploring large areas and closing large map loops, it is possible that features may not line up properly due to accumulated odometry errors. We plan to address this problem by adding SLAM capabilities to the Mapping Kit. A SLAM algorithm will allow the system to use sensor data to correct for odometry drift and build more complete maps.

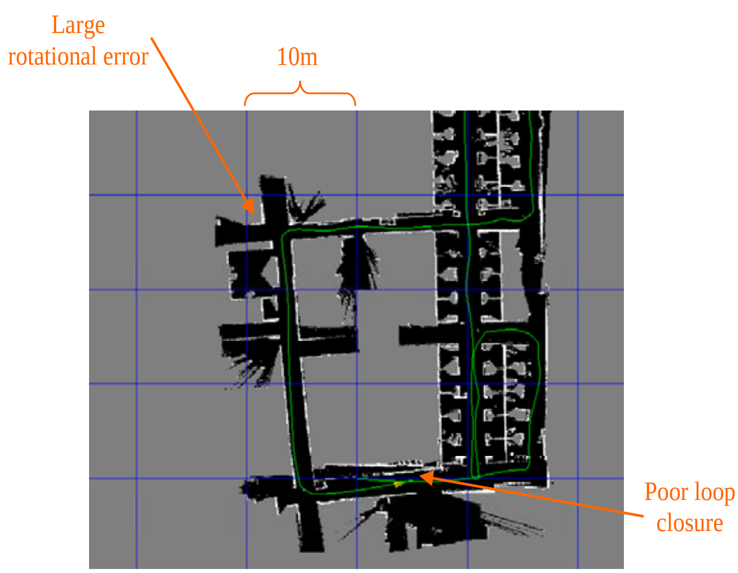


Figure 7 – The yellow robot was teleoperated along the green path, starting and stopping in nearly the same position in the hallway at the bottom of the screen. Smaller loops (on the right side of the building) generated a fairly accurate map. However, the upper left most turn on the largest loop produced rotational odometry error that caused map misalignment. The blue grid lines are spaced at 10m.

In this paper, we have provided an overview of iRobot's PackBot with Mapping Kit. LIDAR data is integrated to generate a real-time 2D map of an indoor environment using an evidence grid. A behavior-based control scheme provides safeguarded teleoperation. Because we apply the range data in this way to generate natural representations of the environment, the Mapping Kit greatly enhances situational awareness.

5 References

[1] SICK. http://www.sick.com

[2] Missouri Department of Public Safety. “Director James Details Consequences of Making Bomb Threats.” Released February 13, 2008.

[3] Friedman, Emily. “How Authorities Approach Hostage Situations.” ABC News. November 30, 2007. http://abcnews.go.com/US/story?id=3937908

[4] Yamauchi, Brian. “The Wayfarer modular navigation payload for intelligent robot infrastructure.” Proceedings of SPIE Vol. 5804: Unmanned Ground Technology VII, Orlando, FL, March 2004.

[5] Yamauchi, Brian. “Autonomous urban reconnaissance using man-portable UGVs.” Proceedings of SPIE: Unmanned Ground Vehicle Technology VIII, Orlando, FL, April 2006.

[6] Jones, Chris and Lenser, Scott. “Sentinel: An Operator Interface for the Control of Multiple Semi-Autonomous UGVs.” Proceedings of the Association for Unmanned Vehicles Systems International. Orlando, FL, August 2006.

[7] Martin, Martin and Moravec, Hans. “Robot Evidence Grids.” March, 1996.

[8] Advance Scientific Concepts, Inc. http://www.advancedscientificconcepts.com