Autonomous urban reconnaissance using man-portable UGVs

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ABSTRACT

For the Wayfarer Project, funded by the US Army through TARDEC, we have developed technologies that enable man-portable PackBot Wayfarer UGVs to perform autonomous reconnaissance in urban terrain. Each Wayfarer UGV can autonomously follow urban streets and building perimeters while avoiding obstacles and building a map of the terrain. Each UGV is equipped with a 3D stereo vision system, a 360-degree planar LIDAR, GPS, INS, compass, and odometry. The Hough transform is applied to LIDAR range data to detect building walls for street following and perimeter following. We have demonstrated Wayfarer's ability to autonomously follow roads in urban and rural environments, while building a map of the surrounding terrain. Recently, we have developed a ruggedized version of the Wayfarer Navigation Payload for use in rough terrain and all-weather conditions. The new payload incorporates a compact Tyzx G2 stereo vision module and a high-performance Athena Guidestar INS/GPS unit.

1. INTRODUCTION

We have developed urban navigation capabilities for the man-portable iRobot PackBot as part of the Wayfarer Project funded by the US Army Tank-Automotive Research, Development, and Engineering Center (TARDEC). The Wayfarer PackBots are designed to perform fully-autonomous reconnaissance missions in urban terrain, reducing the risk to warfighters by keeping them out of harm's way. Each Wayfarer PackBot is equipped with a SICK LD OEM 360-degree planar LIDAR, a stereo vision system, an INS/GPS, compass, and odometry.

In previous papers, we described the Scaled Vector Field Histogram (SVFH) obstacle avoidance technique[5] we developed for Wayfarer (an extension of Borenstein and Koren's Vector Field Histogram[2]), and the autonomous mapping capabilities that we integrated with autonomous perimeter-following behaviors[6]. In combination, these techniques enabled Wayfarer to perform fully-autonomous perimeter reconnaissance missions.

In this paper, we report our recent progress in developing autonomous route reconnaissance capabilities using street-following behaviors. We also describe a ruggedized version of the Wayfarer Navigation Payload that we have developed for use in rough terrain and all-weather conditions.

2. ROUTE RECONNAISSANCE

2.1. Street-Following Behavior

The Wayfarer *follow-street* behavior uses a Hough transform[1] to detect linear features in the 360-degree planar LIDAR range data. Each line is then classified based on whether it is on the right or left side of the robot:

$$side(L) = \begin{cases} left & if\ \theta_{left\,\min} < \theta_L < \theta_{left\,\max} \\ right & if\ \theta_{right\,\min} < \theta_L < \theta_{right\,\max} \\ none & otherwise \end{cases}$$

where L is a line, *side(L)* is the side of line L, θ_L is the orientation of line L, $\theta_{left\,\min}$ and $\theta_{left\,\max}$ bracket the region of interest on the left side and $\theta_{right\,\min}$ and $\theta_{right\,\max}$ do the same for the right side. Currently $\theta_{left\,\min} = 0$, $\theta_{left\,\max} = \theta_{right\,\min} = \pi$, and $\theta_{right\,\max} = 2\pi$, so all lines except those orthogonal to the robot's current heading are classified as being on the left or right.

The line headings are used to update separate accumulator arrays for the left and right sides of the robot. The accumulator arrays filter out transient lines generated by the Hough transform and produce a more stable desired heading.

The value of the accumulator bins at time *t* is given by:

$$a_{left,i,t} = (1-\lambda)\, a_{left,i,t-1} + \lambda \sum_{\forall j:\, i\beta < \theta(H_j) < (i+1)\beta,\, side(H_j)=left} v(H_j)$$

$$a_{right,i,t} = (1-\lambda)\, a_{right,i,t-1} + \lambda \sum_{\forall j:\, i\beta < \theta(H_j) < (i+1)\beta,\, side(H_j)=right} v(H_j)$$

where $a_{left,\ i\ ,t-1}$ is the left accumulator bin value at the previous timestep, $a_{right,\ i\ ,t-1}$ is the right accumulator bin value at the previous timestep, λ is the decay rate (between 0 and 1), H is the set of lines detected by the Hough transform, H_j is the jth line from this set, $v(H_j)$ is the number of points voting for this line, $\theta(Hj)$ is the orientation of the line, and β is the bin size. Note that all of these orientations are in world coordinates, not robot-relative coordinates.

The selected heading corresponding to the maximum bin in each accumulator is given by:

$$\theta_{left} = (i+0.5)\beta : \forall j : a_{left,i,t} \geq a_{left,j,t}$$

$$\theta_{right} = (i+0.5)\beta : \forall j : a_{right,i,t} \geq a_{right,j,t}$$

The behavior then computes the average of the left and right headings as defined by:

$$\theta_{desired} = \theta_{left} + \frac{\Delta(\theta_{left}, \theta_{right})}{2}$$

$$\Delta(\theta_{left}, \theta_{right}) = \begin{cases} \theta_{right} - \theta_{left} & if\ -\pi < \theta_{right} - \theta_{left} \leq \pi \\ \theta_{left} - \theta_{right} & otherwise \end{cases}$$

Follow-street then sends $\theta_{desired}$ as the desired heading to the SVFH obstacle avoidance behavior[5].

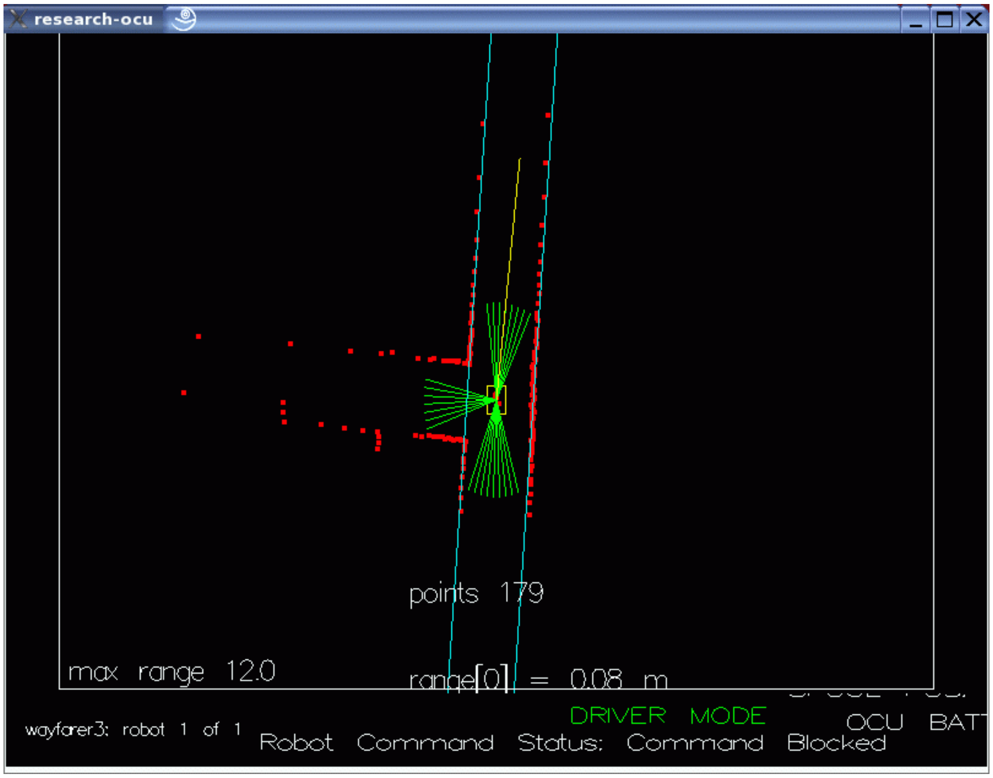

Figure 1: Line pair detected by *follow-street* at hallway intersection

Figure 1 shows the *follow-street* behavior operating indoors in a hallway. The blue lines indicate the line pair (strongest lines on left and right sides) detected by the behavior. The yellow line indicates the desired heading computed as the average of the maximum left and right accumulator values.

2.1.1. Mixed Urban/Rural Street Following

We tested Wayfarer's street following software in an area of mixed urban and rural terrain near iRobot Headquarters in Burlington, Massachusetts. The outdoor test environment consists of an unmarked road that runs through a wooded area and then behind an urban factory. The total length of this road was approximately 200 meters each way.

During these trials, the robot was able to successfully follow roads at speeds up to 2 meters/second (4.5 mph), the maximum speed of the PackBot platform. This is particularly notable given the vast difference between the irregular outline and texture of the wooded tree line and the flat walls previously tested during street and perimeter following.

Figure 2 shows Wayfarer autonomously following the rural section of this road uphill. Figure 3 shows Wayfarer autonomously navigating around a fallen tree as it follows the road. SVFH obstacle avoidance is seamlessly integrated with the street following behavior. The *follow-street* behavior provides a desired heading, and the *avoid-obstacles* behavior steers the robot towards the clear heading closest to the desired heading. After the robot steers around the obstacle, *avoid-obstacles* smoothly guides the robot back to following the street heading provided by *follow-street*.

Figure 4 shows Wayfarer automatically transitioning from following the rural section of this road to following the urban section behind the factory. A key feature of our behavior-based approach to navigation is how it enables robust navigation in very different environments. Wayfarer uses exactly the same behaviors to follow urban streets as to follow rural roads. No parameters need to be changed and no user intervention is required as Wayfarer follows the road from a rural to an urban environment.

Figure 2: Wayfarer autonomously following rural road downhill

Figure 3: Wayfarer autonomously navigating around fallen tree

Figure 4: Wayfarer automatically transitioning from rural to urban street following

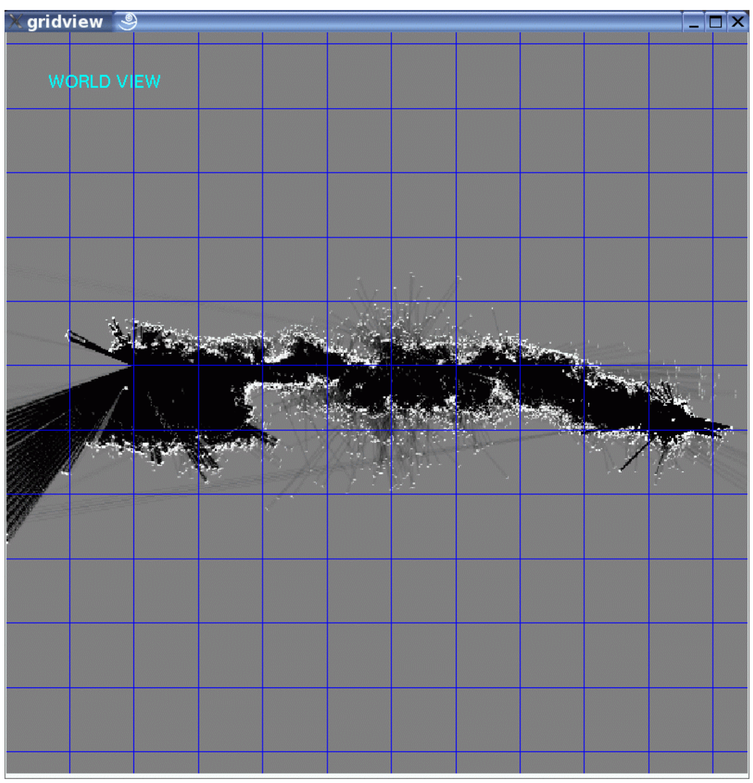

Figure 5: Map of urban/rural terrain built by Wayfarer
(10 meter grid spacing)

Figure 5 shows the occupancy grid map[3] built by Wayfarer as it autonomously followed the road uphill through rural and urban terrain. Wayfarer started at the right edge of this map (rural) and followed the road uphill to the left, where it emerged in the urban terrain behind the factory.

3. RUGGEDIZED WAYFARER NAVIGATION PAYLOAD

3.1. Tyzx G2 Stereo Vision System

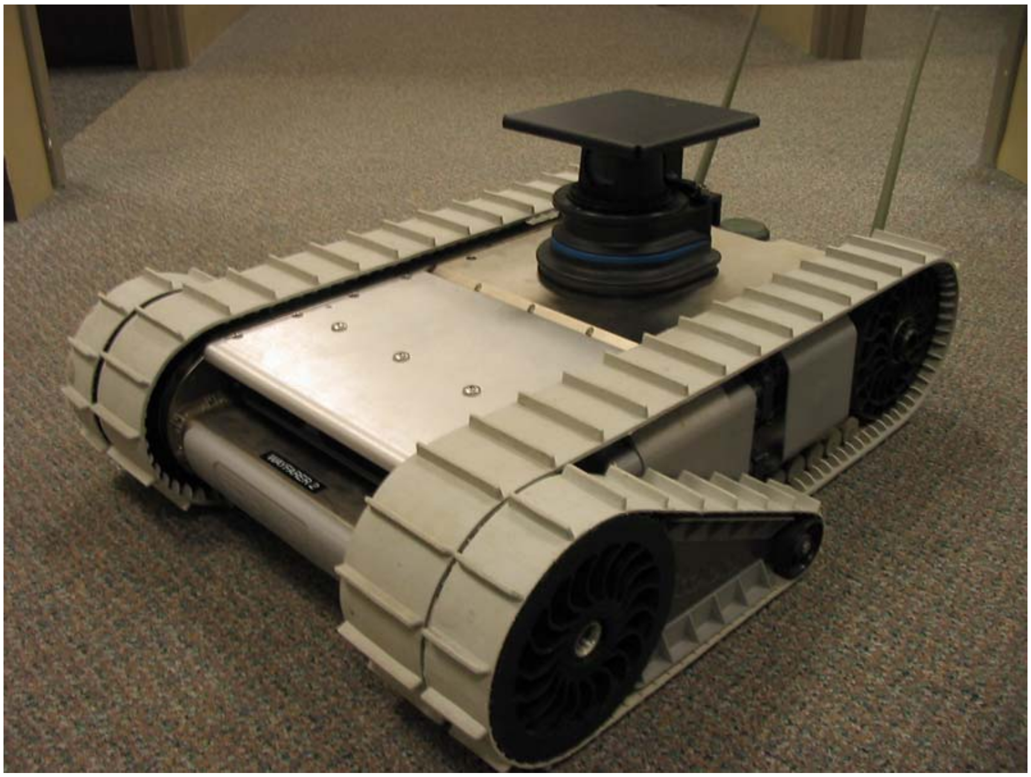

Figure 6: Wayfarer PackBot with ruggedized navigation payload

We have recently developed a ruggedized payload housing (Figure 6) for the Wayfarer sensors. This payload integrates a Tyzx G2 Stereo Vision Module, a SICK LD OEM LIDAR, and an Athena Guidestar GS-111m INS/GPS in a rainproof housing. The housing includes an integrated rain shield/roll plate above the SICK LIDAR, and a rubber sheath around the lower LIDAR housing that prevents water from seeping into the payload. While this payload is not immersible, it is suitable for use in rain or snow.

We replaced the earlier prototype's Point Grey Bumblebee stereo vision system and Plug-N-Run vision CPU with a single Tyzx G2 stereo vision module. The G2 provides 512 x 320 depth images at 30 Hz, using a custom ASIC chip along with a COTS Texas Instruments DSP to perform stereo image processing.

The G2 module is smaller the standard PackBot Scout head and is mounted to a rugged upper metal bracket within the Scout head volume. The G2 module uses its lower surface as a heat sink, so we mounted the sensor with a space between the G2 underbody and the PackBot Scout chassis. This allows the G2 to dissipate heat effectively.

The G2 is fully-integrated with the Wayfarer hardware and software, providing 3D obstacle avoidance capabilities for Wayfarer. To increase speed, the obstacle detection software focuses on a horizontal region 100-pixels high near the center of the image, roughly corresponding to obstacles to obstacles that are too tall to climb but too low to pass under.

Figure 7: Close-up for Tyzx G2 Module in ruggedized Wayfarer payload

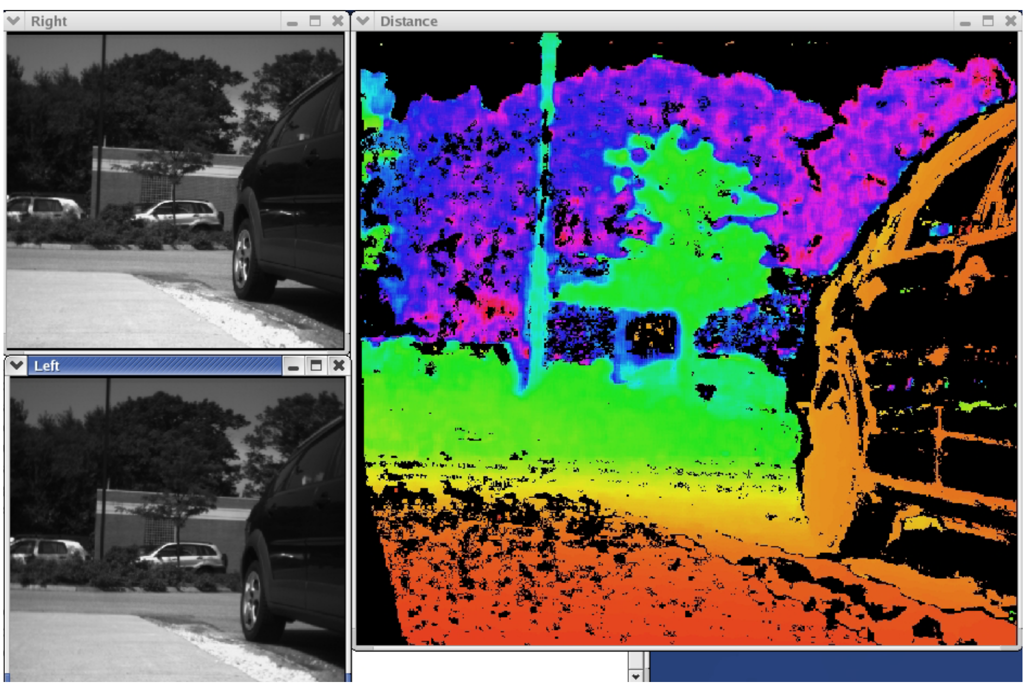

Figure 8: Optical pairs and depth image from Tyzx stereo vision system outdoors

To reduce spurious false positives in the obstacle map, contiguous regions in the image are grouped into blobs. Each blob consists of a set of pixels that are adjacent in the image and close to one another in range. Blobs smaller than a specified threshold are removed from the image. We found that this approach significantly reduces the level of noise in the range image and substantially reduces the number of false positives in the obstacle map.

Figure 8 shows the optical pairs and depth image from the Tyzx DeepSea stereo vision system outside iRobot Headquarters. G2 performance is similar. This image shows that the vision system can accurately detect a wide range of natural and artificial obstacles, including trees, cars, poles, and buildings. This also shows that the system can accurately determine the range to the ground plane, whether natural (grass) or artificial (asphalt, concrete).

3.1.1. Athena GuideStar INS/GPS System

We worked with Athena Technologies of Warrenton, Virginia to develop an improved localization payload for Wayfarer. This payload is a customized version of the Athena Guidestar GS-111m INS/GPS unit that incorporates the PackBot motion model and odometry data. By incorporating the PackBot's motion model and odometry together with INS and GPS in the Kalman filter, the Guidestar provides improved localization accuracy in areas with and without GPS coverage.

We have fully integrated the Guidestar with the Wayfarer mapping system. Our results have shown a substantial increase in localization accuracy using this system, especially over large areas and long periods of time.

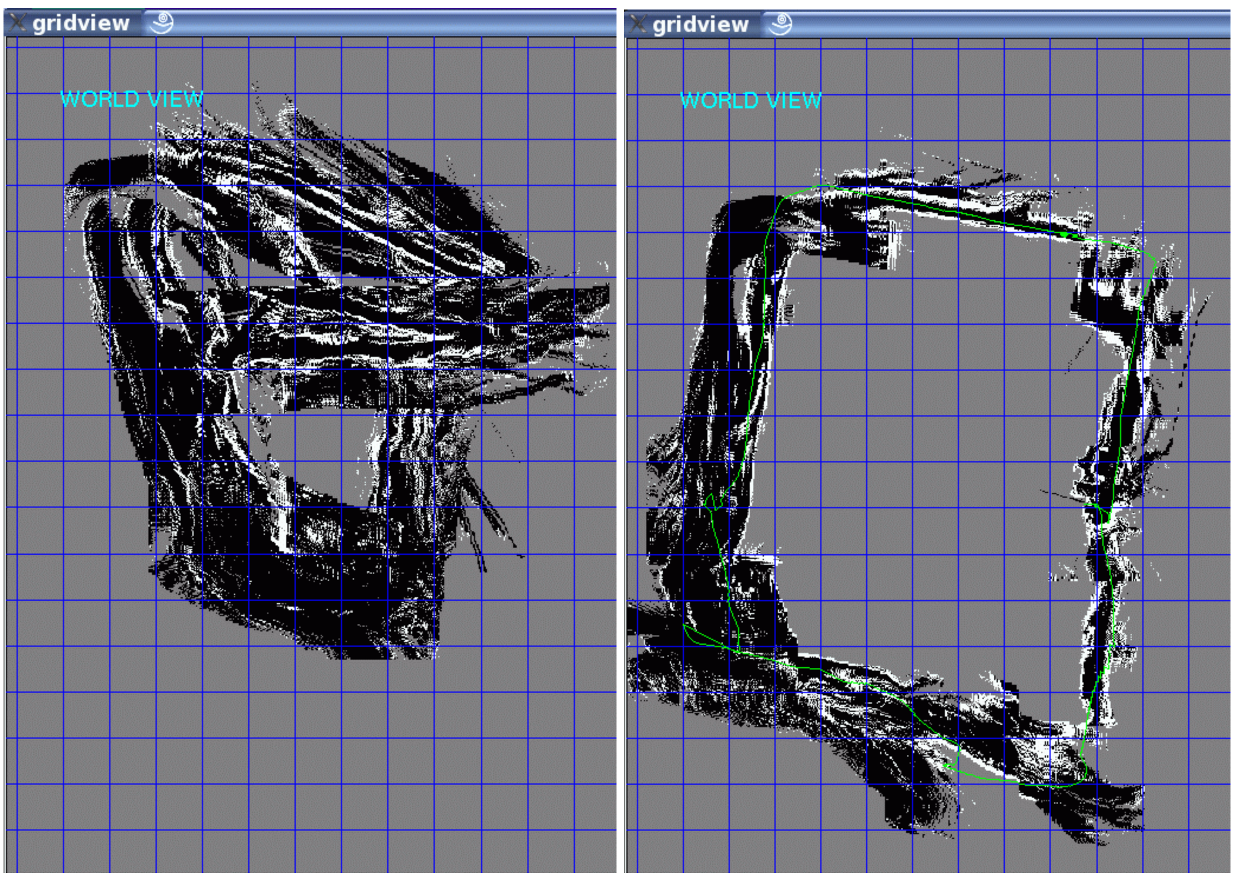

Figure 9: iRobot HQ exterior map generated using raw odometry (left) and Athena Guidestar (right)
(10 meter grid spacing)

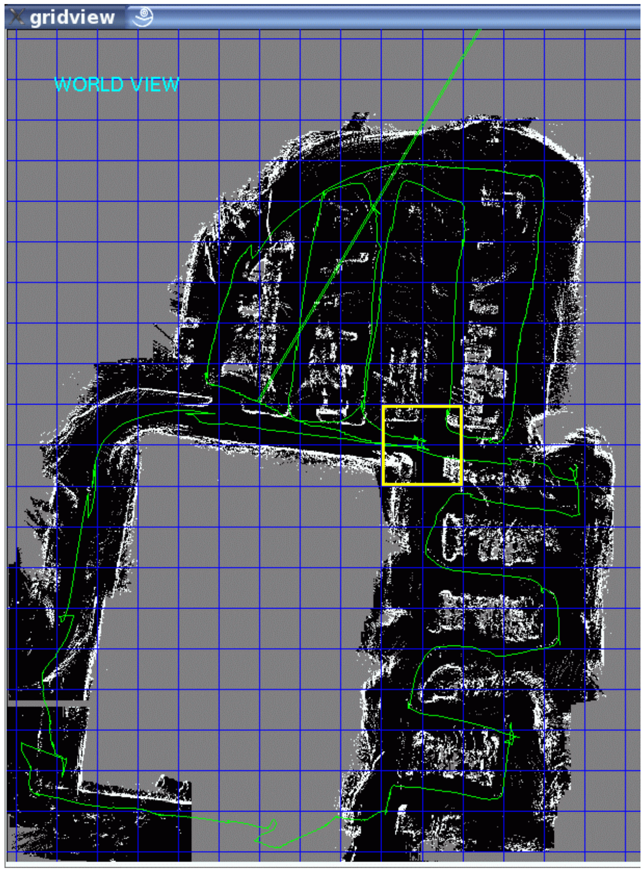

Figure 10: iRobot HQ exterior and parking lot map generated using Guidestar
(10 meter grid spacing)

Figure 11: Close-up of starting and ending points for HQ exterior and parking lot map
(1 meter grid spacing)

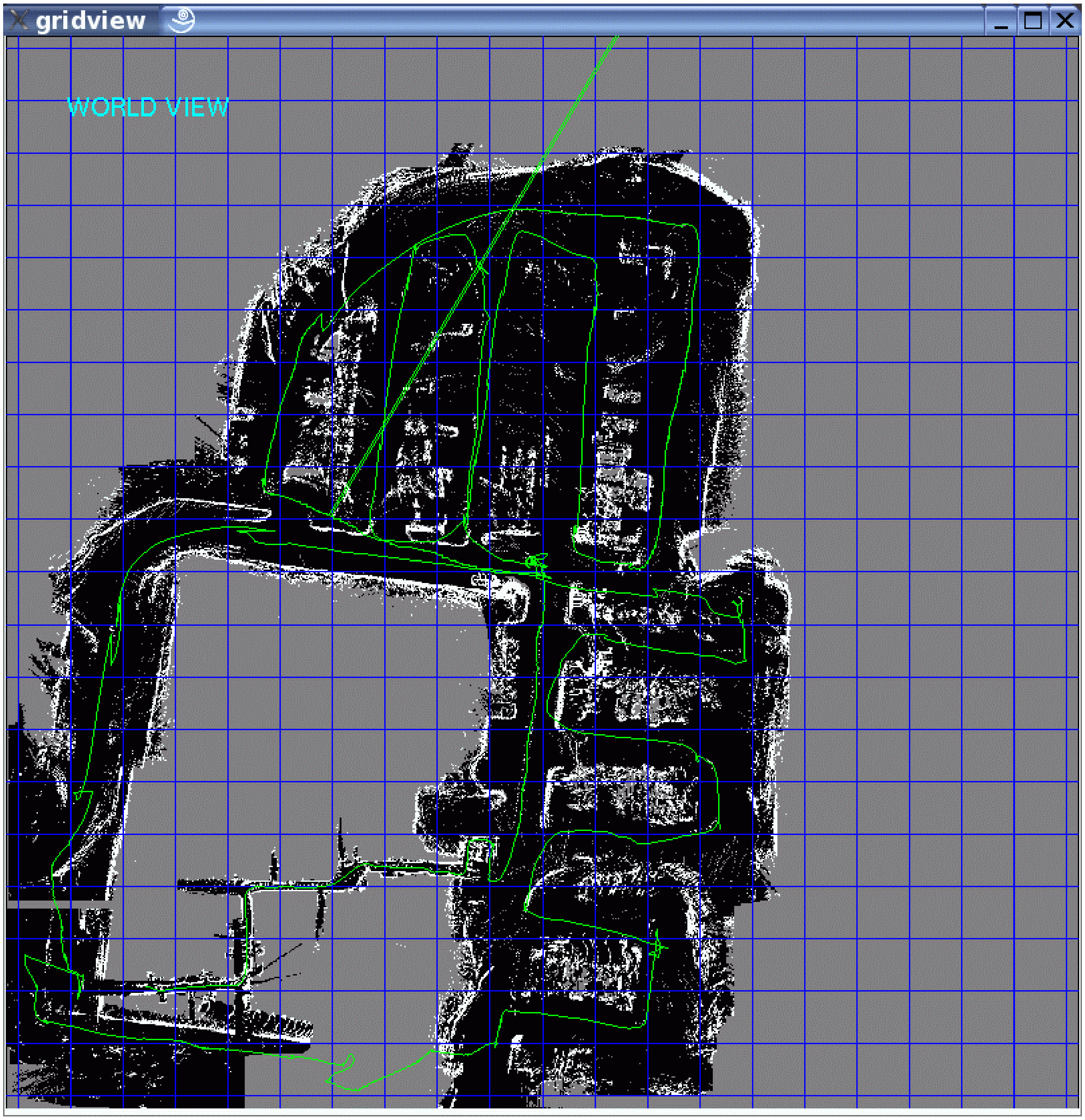

Figure 12: iRobot HQ exterior and partial interior map generated using Guidestar
(10 meter grid spacing)

Figure 9 (left) shows an (indecipherable) map of the iRobot HQ building using raw odometry. In contrast, Figure 9 (right) shows a map of the exterior of iRobot HQ generated using the Guidestar. This map was generated by teleoperating the robot while the mapper automatically constructed a map of the robot's environment using the SICK LIDAR. The green line shows the path taken by the robot. The white areas represent obstacles; the black areas represent open space; and the gray areas represent unknown territory. The blue lines are spaced at 10 meter intervals. The total distance traversed by the robot is approximately 500 meters. At the end of this run, we drove the robot back to its starting position, and its measured position was within 2 meters of its actual position.

Figure 10 shows a map of both the iRobot HQ exterior and the adjacent parking lots generated by the mapper using the Guidestar for localization. The time required to generate this map was approximately 45 minutes. The total distance traversed was over 1 kilometer, and the area mapped covers roughly 25,000 square meters. At the end of this run, we drove the robot back to its initial position, and its measured position was within 4 meters of its actual position. Figure 11 shows a close-up (1 meter grid spacing) of the starting position of the robot (START), and the measured position when the robot was moved back to the starting position at the end of the run (FINISH).

After mapping the HQ exterior and parking lots, we drove the Wayfarer PackBot inside the HQ building, and the Guidestar and the mapper automatically transitioned to localization based on INS and odometry alone (without GPS). Figure 12 shows a partial map of the interior hallways of the HQ building generated as we drove the PackBot from the doorway to my office.

4. CONCLUSIONS

We have developed autonomous route reconnaissance capabilities for the Wayfarer PackBot. Wayfarer is able to follow both urban and rural roads, as long as road-aligned features exist on at least one side of the road. As Wayfarer explores the route, it automatically builds an occupancy grid map of its surroundings.

We have also developed a ruggedized version of the Wayfarer Navigation Payload. While previous experiments were conducted with a loosely-integrated prototype, the new payload is designed for use in rough terrain and in all-weather conditions. The rugged payload includes a compact Tyzx G2 stereo vision module and a high-performance Athena Guidestar GS-111m INS/GPS system. We have integrated the G2 with our obstacle avoidance system, and we have integrated the Guidestar with our mapping system.

In future work, we intend to transition the Wayfarer Navigation Payload to a product for the iRobot PackBot product line, providing fully-autonomous navigation capabilities for man-portable robots in urban terrain.

5. ACKNOWLEDGMENTS

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