Counter Tunnel Exploration, Mapping, and Localization with an Unmanned Ground Vehicle

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ABSTRACT

Covert, cross-border tunnels are a security vulnerability that enables people and contraband to illegally enter the United States. All of these tunnels to-date have been constructed for the purpose of drug smuggling, but they may also be used to support terrorist activity. Past robotic tunnel exploration efforts have had limited success in aiding law enforcement to explore and map the suspect cross-border tunnels. These efforts have made use of adapted explosive ordnance disposal (EOD) or pipe inspection robotic systems that are not ideally suited to the cross-border tunnel environment. The Counter Tunnel project was sponsored by the Office of Secretary of Defense (OSD) Joint Ground Robotics Enterprise (JGRE) to develop a prototype robotic system for counter-tunnel operations, focusing on exploration, mapping, and characterization of tunnels.

The purpose of this system is to provide a safe and effective solution for three-dimensional (3D) localization, mapping, and characterization of a tunnel environment. The system is composed of the robotic mobility platform, the mapping sensor payload, and the delivery apparatus. The system is able to deploy and retrieve the robotic mobility platform through a 20-cm-diameter borehole into the tunnel. This requirement posed many challenges in order to design and package the sensor and robotic system to fit through this narrow opening and be able to perform the mission.

This paper provides a short description of a few aspects of the Counter Tunnel system such as mobility, perception, and localization, which were developed to meet the unique challenges required to access, explore, and map tunnel environments.

Keywords: robotics, tunnel, mapping, lidar, autonomy, 3D sensor, perception, localization

1. BACKGROUND

Illegal international border crossings into the United States through man-made tunnels and utility culverts have become more prevalent. In particular, the border between Mexico and the southwestern United States is a target for drug smugglers bringing illegal drugs into the United States. Many technological and legal problems exist in detecting, securing, and decommissioning these tunnels. Often, these access tunnels are tens to hundreds of meters long, can have significant elevation gradients, and may contain water and/or various types of debris.

There are several categories of tunnels being built to gain entry into the U.S. These tunnels range in depth and dimensions. They can be elaborate (sophisticated, symmetric, professionally engineered), or hastily built (hand dug, shallow, unreinforced). Some tunnels are dug to connect into city storm drain systems allowing circumvention of the border, such as in Nogales, Arizona. A few tunnels have been documented to be over one mile long. The extreme variances in conditions that exist within the tunnels, and the fact that many are used sporadically, make identifying their existence and locating access points to the tunnels a very difficult task.

Previous work performed with robots working in tunnels and mines for teleoperation and mapping and has been leveraged by this project. Some of the earlier work, documented by Laird,[1] laid out some of the basic vehicle teleoperation issues for tunnel exploration and reconnaissance. Mapping tunnels and mines tends to be difficult because of the relatively nondescript nature of the walls, which is why many of these tunnel/mine mapping systems integrate lidars into their localization systems.[2] Carnegie Mellon University (CMU) has performed their mine mapping experiments in the abandoned mines in Pennsylvania using Simulataneous Localization and Mapping (SLAM) using a custom-built robot called the Groundhog.[3] Other mine mapping systems[4] have used

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stop/start scanning with 2D lidars: obstacle avoidance while the vehicle is moving, then stopping to allow the robot to generate a stable 3D scan of the environment. This 3D data was then used with Markov Random Fields, an A* search, and C-space maps to generate 3D maps and plan future motion. Nüchter et al.[5] discussed a 3D SLAM algorithm designed to handle the six degrees of freedom inherent in a subterranean environment, reduced point clouds, and a fast iterative closest point (ICP) variant to locally and globally register the point clouds.

This counter-tunnel effort was funded by the Joint Ground Robotics Enterprise (JGRE) from fiscal year 10-13, run jointly by SPAWAR Systems Center (SSC) Pacific and Air Force Robotics Lab Airbase Technologies Division (AFRL/RXQ) Tyndall, and was a complementary development effort to the Rapid Reaction Tunnel Detection (R2TD) Joint Capability Technology Demonstration (JCTD), which addressed the objective tunnel exploration requirements.

1.1 Objectives and Scope

The project objective is to develop and demonstrate technologies that will enable insertion of a robotic system through a small borehole into a suspect tunnel cavity for the purpose of conducting precision mapping and characterization operations in austere tunnel environments (hand-dug border tunnels, caves, etc.).

To accomplish this objective, the scope of the effort has been divided into three major technology thrusts:

1. Development of an Unmanned Ground Vehicle (UGV) mobility platform capable of insertion through a maximum 20-cm-diameter borehole.
2. Development of a borehole deployment capsule to support insertion and retrieval of the UGV system and provide a communications node at the tunnel insertion point.
3. Development of a perception system, small enough to fit inside the borehole deployment capsule and provide localization, obstacle detection, and 3D mapping.

The scope of this paper limits the discussion to mobility of the target platform, the perception system, and localization. Topics such as the borehole deployment and retrieval capsule, communications, additional tests, and more detailed results have been left out of this paper and can be found in the technical report to be published by SSC Pacific.[6]

1.2 System Requirements

- Deploy and retrieve UGV through an 20-cm borehole into tunnels 3 to 30 m in depth
- Transit up to 800 m round trip
- Traverse 2 horizontal 45-degree turns
- Climb a 30 cm vertical discontinuity (i.e., a step)
- Traverse a 30 cm gap or crevice
- Operate over varied and rough terrain including mud, loose gravel, areas of limited traction, and up to 20 cm standing water
- Autonomously explore, localize, and map the tunnel
- Localize the entry within 1 m of accuracy
- Generate 3D model of the tunnel environment for characterization, measurement and analysis

2. ROBOTIC PLATFORMS

2.1 Prototype *Counter Tunnel Exploitation Robot* (*CTER*) Platform

The *Counter Tunnel Exploitation Robot* (*CTER*), built by Raytheon Sarcos Integrated Defense Systems (IDS), is a high degree of freedom (DOF) UGV designed to address the counter-tunnel mission and is shown in figures 1, 2, and 3. Two of these platfoms were delivered: one to AFRL Robotics at Tyndall AFB, FL and one to SSC Pacific Unmanned Systems Branch, San Diego, CA.

The *CTER* has a camera mounted on arms at the rear of the aft track, and it can rotate 180 degrees for 360-degree viewing. There are also arms on the front track for payload attachment. The robot was delivered with a fiber-optic tether for communication. This tether provides a link for commands, status, video feedback, and mapping sensor data. Wireless communication has been explored for this application using Cobham radios. The dimensions of the *CTER* is 17 cm wide x 172 cm long x 17 cm tall (no payload).

The *CTER* has an on-board real-time controller for joint control, drive motor control, and camera compression. The unique joints and motors arrangement between the tracks of the *CTER* allow for step climbing, roll prevention, and side-by-side track operation. The robot is also designed to be submerged in up to 20 cm of water (although this was not tested during this project).

There are multiple modes available to the robot operator including: Find Zeroes, Uncommanded, Zero Torque, Step Climb, Anti-Roll, Bend, Follow-the-Leader, Cobra, and Tank. The Find Zeroes mode is the initialization procedure that the robot needs to run every time it is powered on. The Uncommanded and Zero Torque modes disable all motion by the robot, and allow it to be manipulated manually with no motor driving. Step Climb driving mode will successfully climb 30-cm steps. Anti-Roll mode is a driving mode that offsets the tracks and actively corrects for roll. If a condition occurs where the mode cannot prevent a roll, the robot will go into the Uncommanded mode. Bend mode is a driving mode that allows the operator to offset the tracks at varying angles in order to provide stability. Angles of 15, 30, and 45 degrees are available. When turning in this mode, the tracks turn into each other in a C-shape. Follow-the-Leader is another driving mode in which the rear track attempts to exactly follow the path of the front track. Cobra mode raises the aft track in order to give the camera a better vantage point. In Tank mode (figure 3), the robot will position the tracks in parallel with each other, and operate as a skid-steer vehicle.

Figure 1: *CTER* platform maneuvering around obstacles in a narrow tunnel

Figure 2: *CTER* platform fitting through tight passages

Figure 3: *CTER* platform in tank mode

2.1.1 *CTER* Testing

The *CTER* was operated for only a short time beginning in February 2013 through June 2013. The multiple driving modes, run-times, mobility, and terrain maneuvers were all evaluated.

Testing: Driving Modes and Run Times The vehicle run time was evaluated for each driving mode in a straight run, flat gravel surface, fully charged battery, and no payload installed. The vehicle was run until the battery was completely discharged. The results are shown in table 1.

MODE	DISTANCE	TIME
Anti-Roll	1356 m	69 min, 14 sec
Bend	1920 m	115 min, 57 sec
Follow-the-Leader	2240 m	112 min, 42 sec
Tank	2156 m	122 min, 32 sec

Table 1: *CTER* drive times and distances in various drive modes

The Tank mode is the most stable of all the modes, however in this mode the payload is facing the rear of the robot. The Anti-Roll mode is currently tuned to prevent roll by the robot in the basic configuration with no payload. Adding a payload and running with this mode causes continual overcorrection by the robot. In some cases this causes the payload to hit the ground on both sides as the robot oscillates. With a payload installed, tests have found that Bend mode and Follow-the-Leader mode provide the most effective driving.

The Step mode of the robot was also evaluated, and it will successfully climb 30-cm steps. The steps do however need to have a front face for the tracks to drive up. The robot will also successfully cross a 30-cm gap in all of the driving modes.

Testing: Mobility The mobility testing of the *CTER* was to evaluate effectiveness of its ability to turn around in a tunnel, climb up and down 30-cm steps, drive in 91-cm culverts, turn around in 91-cm culverts, drive over gaps of 30 cm, and evaluate effectiveness of fiber-optic spools for control of the robot.

Turning the *CTER* around in a small space was very challenging. It was determined when driving in bend or follow-the-leader mode that putting the robot in tank mode, turning around, and returning to the previous drive mode was the easiest way to turn around.

The *CTER* was able to climb up and down 30-cm steps. However, climbing required a flat floor surface and sufficient floor-surface friction. Polished concrete was found to provide insufficient friction for the snake to climb the stairs. Plywood, gravel, and carpet were all adequate floor surfaces to allow step climbing by the *CTER*.

Driving in 91-cm culverts was successful but required a close watch on the roll angle while driving. Since the culvert had no reference points to look at while driving, the roll indicator was the only way to determine if the *CTER* was driving at the bottom of the culvert. Without the roll indicator, roll-overs of the *CTER* are to be expected. Turning around in the culvert was accomplished by changing to Tank mode, turning around, and then resuming in the previous driving mode.

The *CTER* was able to cross 30-cm gaps with no problem. Due to the track length being almost double the 30-cm gap size, there was no visually perceptible drop on the front of the track when crossing a 30-cm gap.

The *CTER* is a prototype robot design, built to meet the requirements of delivery through a 20-cm borehole, driving 800 m, and communicating via fiber-optics. This platform was able to meet these requirements, however not without reliability issues. Both of the delivered *CTER* platforms had to have the joints of the center section replaced as a result of cold welding between the original joints. Additionally, a track controller circuit board had to be replaced due to a failure. The power up calibration sequence was also sometimes problematic as it would occasionally initialize in the wrong orientation. This would then require a reboot and rerun of the calibration sequence until it was performed correctly. A couple months after initial receipt of the AFRL *CTER*, it had to be returned to the manufacturer for an upgrade. This upgrade put a real-time controller on board the *CTER* and seemed to improve the responsiveness of the controls. A shipping container designed specifically for the *CTER* was also built due to problems encountered during shipping of the *CTER* at SSC Pacific. The time required for these fixes and upgrades greatly limited the amount of time available for testing and evaluation of the *CTER* platform.

Testing: Terrain Maneuvers The *CTER* was driven over varied terrain and performed well (without the localization and mapping payload). Using the Anti-Roll mode, the platform was able to drive over gravel, crushed rock, and obstacles such as pieces of 2x4-inch lumber successfully without tipping over. Large obstacles such as a pile of 15-30-cm rocks was found to be too difficult for the *CTER* to navigate. Climbing over these obstacles often resulted in roll-over even in the Anti-Roll driving mode. In other modes such as Bend and Follow-the-Leader, the snake was able to successfully navigate the previously mentioned obstacles but would require care to prevent tip-over. When tip-overs did occur, the *CTER*'s Roll mode was used to roll the robot to the upright position. Corrugated plastic and steel also presented no traversal problems.

2.2 Alternative platform: iRobot *PackBot*

SSC Pacific created a plan to utilize an alternative robotic platform for testing and evaluation of sensors and autonomy algorithms. This was necessary to continue development work while the *CTER* platform was being prototyped and upgraded. Although the alternative platform would not fit through a 20-cm borehole, it would still be a viable options for ISR, mapping, and characterization of tunnels if other methods of entry were available.

The iRobot *PackBot* was the primary vehicle for sensor and autonomy development. SSC Pacific has used the *PackBot* in various other projects and even developed a tele-operation-to-autonomy conversion box that would fit inside one of the three payload bays, loaded with an Intel *Dual Core* processing board, KVH *DSP-3000* fiber-optic gyro, MicroStrain *3DM-GX2* IMU, with USB and ethernet connectors. The *PackBot* was small enough to fit into all the tunnels that were explored and provided a robust wireless communication link without any additional radios attached. The dimensions of the *PackBot* are 52 cm wide x 89 cm long x 17 cm tall (no payload).

Figure 4: iRobot *PackBot* with mounted NREC *MultiSense-SL*

3. PERCEPTION

The Counter Tunnel project had perception requirements to localize the egress points within 1 meter of accuracy after traversing 400 meters without GPS and to create a 3D model of the tunnel environment for obstacle avoidance, characterization, measurement, and analysis. A 3D model is especially important for obstacle avoidance because the tunnel environment is so varied, consisting of stairs, rocks and debris, sometimes rail and cart system, and anything else it might encounter in real-world drug tunnels. This sensor design task was fulfilled by the National Robotics Engineering Center (NREC) with their prototype 3D sensor system, now called the *MultiSense-SL*.

3.1 Perception Sensor

The *MultiSense-SL*, figure 5, was developed by the National Robotics Engineering Center (NREC) to meet the localization and mapping requirements in a small package. It uses an axially spinning Hokuyo *UTM-30LX-EW* rotating about the z forward axis, an optimal view for tunnels, which is calibrated with the left camera of the stereo pair. Four strobing LED lights surrounding the sensor provide enough lighting for accurate stereo camera analysis in no- or low-light conditions such as inside a tunnel. The software (running on a hardened computing box with an Intel *Core i7 processor*) computes the position estimate through visual odometry (VO) from the stereo cameras at 10 Hz. and a position correction from the iterative closest point (ICP) algorithm from the lidar at 3 Hz.

Figure 5: NREC *MultiSense-SL*

Tests performed by SSC Pacific demonstrated that the *MultiSense-SL* provided an accurate 3D point cloud representation of indoor and outdoor environments, tunnels, buildings, and lab spaces (see figure 6). However, because visual odometry is the primary localization method being used, position estimation becomes noisy and cannot recover when it has no visual features to detect or track (e.g. within a few centimeters against a wall).

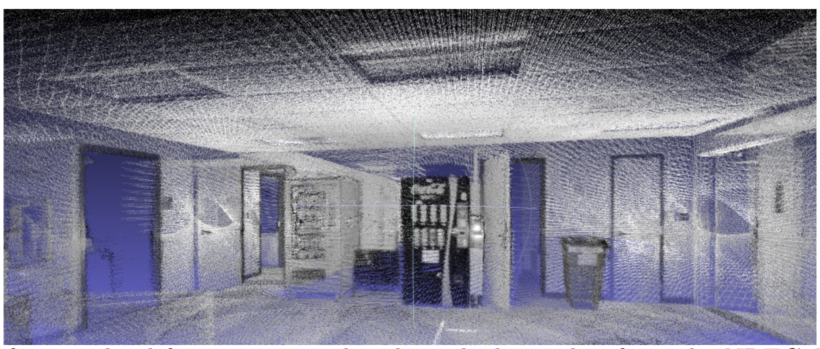

Figure 6: Lab-view of point cloud frames captured and stitched together from the NREC *MultiSense-SL* sensor

4. LOCALIZATION

The vehicles operating inside the tunnel are required to do so in a GPS-denied environment, mapping, localizing, and providing a geo-referenced position of the egress point over 400 meters from the entry with only an error of 1 meter. Many localization problems need to be solved and tightly coupled to achieve this requirement. The diagram in figure 7 illustrates the challenges: GPS readings will be captured at the entry point of the borehole, the orientation, angle, and distance of the borehole apparatus needs to be calculated while moving through the borehole, the vehicle must localize itself with respect to the borehole apparatus once it has been deployed, and finally the vehicle will need to accurately calculate its odometry through the tunnel.

4.1 Borehole Apparatus Localization

One of the challenges in creating an accurate 3-dimensional mapping of any tunnel being investigated is obtaining an initial geospatial location and orientation. This initial pose anchors the 3D map in reference to known locations and entities on earth. Without an accurate initial pose, the projection of the tunnel and most particularly the exit points may have a high degree of error. The majority of the geospatial location-providing devices use Global

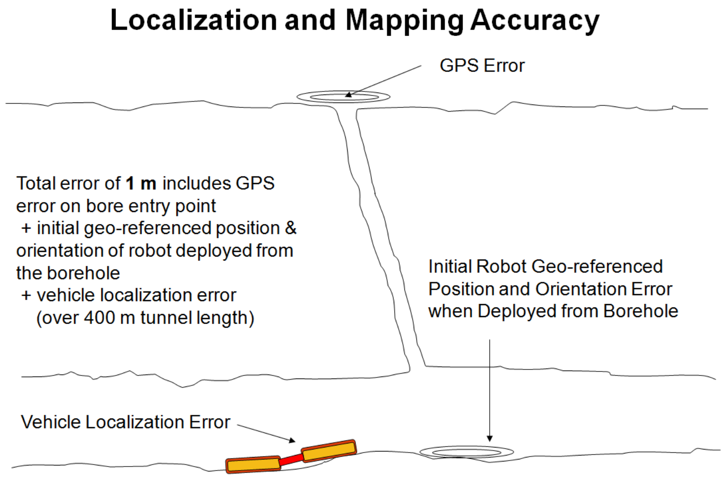

Figure 7: System localization error

Positioning System (GPS). The tunnel environment, which may be as much as 30 m below the surface, prevents GPS units from functioning effectively due to the weak signal received at those depths. The approach was to find a positioning system that can take a geodetic position while on the surface of the borehole and calculate the change in position as the delivery capsule descends through the borehole. The unit determined to be able to meet all the specifications was the Kearfott *KI-4901 T-24* INU (Inertial Navigation Unit). Tests showed that after a 32-m vertical test, the 3D position error was only 0.356 m, azimuth error was 0.022 degrees, pitch error was 0.371 degrees and roll error was 0.321 degrees.

4.2 Initial Robot Localization from a Fiducial on the Borehole Apparatus

Once the vehicle has been deployed from the borehole apparatus, it localizes itself with the apparatus, which should already be localized with the surface coordinate system (normally GPS). This is done by first detecting the exposed portion of the deployment apparatus using a rotationally invariant localization fiducial attached to the tip of the apparatus (figure 8). References for this technique can be found in the papers by Olson,[7] Zheng,[8] and Bradley.[9] With the known size and pattern of the localization fiducial, the vehicle can calculate its six-degree-of-freedom position and orientation using only a single image from a single camera. This position and orientation can then be transformed through the known apparatus coordinate frame and localize the vehicle with the surface coordinates.

Figure 8: Deployment of the *CTER* platform through the borehole apparatus with attached localization fiducial

4.2.1 Pattern

The localization pattern is comprised of black or white circles inscribed within oppositely colored black or white squares. This allows the pattern to contain binary data as well as be easily localized using calibration techniques. The encoded data can, in the cylindrical case, encode the yaw rotation of the pattern as it is viewed from different vantage points. In the flat case, the bits can encode the unique id of the pattern, allowing large scale localization to be done with multiple patterns. In either case, the pattern needs to be rotationally unique, e.g. no rotation of the pattern can be equal to itself or any other pattern. In the cylindrical case (figure 9), every view of the pattern needs to be rotational unique. If this uniqueness is not maintained, then localization ambiguities will arise, allowing for multiple possible solutions. Ensuring that the patterns are greatly different from each other allows for some additional error checking. To ensure this uniqueness, the targets use a solid strip of black or white circles on the top and an alternating pattern on the bottom.

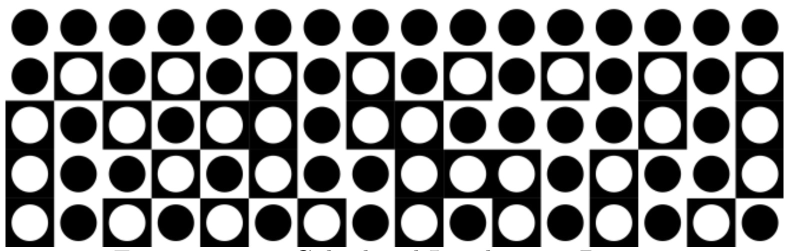

Figure 9: 5x16 Cylindrical Localization Pattern.

4.2.2 Algorithm

The localization algorithm is designed to calculate the relative position of the image with respect to the pattern. The algorithm first detects possible bits using a contour detection algorithm. Contours are detected between two threshold values and contours that are found at multiple threshold levels and a sufficiently convex are added as potential pattern bits. The values of the threshold minimum and maximum as well as the threshold step are used to determine which intermediate threshold values will be used. Larger ranges and smaller steps will make the detection algorithm more sensitive but take more time, whereas tighter ranges and larger steps will be faster but may miss some of the pattern bits. Once the potential bits are detected, they are clustered using hierarchical clustering over both location and contour diameter. The largest clusters are used to detect the presence of a bit pattern and organize the bits into a grid structure. The grid is then compared to the pattern using different rotations and different shifts. Figure 10 shows the results of these matching on cylindrical patterns. In the cylindrical case, these shifts translate to rotations about the cylinder. The rotation and shift with the greatest number of fully matched columns is used for localization. In the cylindrical case, the columns are the only fully visible portions of the pattern. Ties are broken by the total number of bits matched. Perspective-n-Point camera pose estimation is run on the pixel locations and the matched patterns 3D model points, resulting in a full six-degree-of-freedom transform from the image to the pattern. Mean reprojection error is used to break any remaining ties. When multiple unique patterns are being used, each potential pattern can be matched and ties can be broken as previously mentioned to determine which pattern best matches. This transform can be combined with the known global pose of the pattern to determine the global pose of the image.

4.2.3 Testing

Tests from this method produced results that were within 1-3 cm accuracy and less than 1 degree azimuth angle error. These results were determined using the camera images from the *MultiSense-SL* and the lidar scans from the same sensor as ground truth. The authors postponed more thorough testing of the fiducial system to implement an April Tags[7] solution for comparison. However, time and budget restrictions did not allow for additional localization implementations or more thorough testing.

4.3 Vehicle Localization

The NREC *MultiSense-SL* was designed to provide perception and localization for the system, but when the *CTER* platform and the *MultiSense-SL* sensor were delivered, testing showed significantly degraded mobility

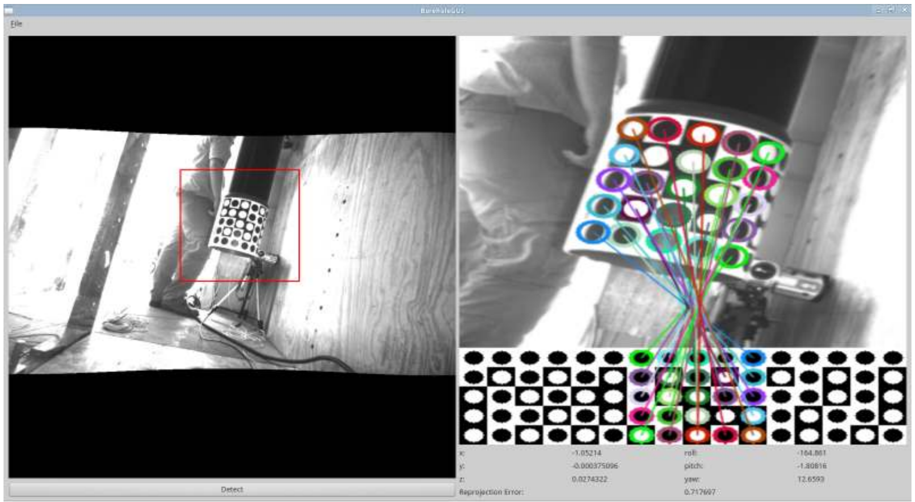

Figure 10: Fiducial matching to tilted a cylindrical pattern.

performance. A second generation of sensor miniaturization was planned but didn't go forward because of budget cuts. The *CTER* platform was very unstable with the sensor mounted on the arms of the front tracks, causing tip over. During testing, the Roll mode was used to self-right the platform, but the joint gear of bender 3 broke a tooth with the weight of the sensor, and the robot was sent back for repairs. Due to this issue, testing of localization and mapping were never conducted with the *CTER* platform.

However, localization tests were conducted with the iRobot *PackBot* platform and produced positive results. No formal characterization of the accuracy of the localization of the *MultiSense-SL* sensor was performed due to budget and time issues. SSC Pacific ran an informal test of the sensor mounted on an iRobot *PackBot* inside a 1.5 m diameter concrete storm drain, driving 450 meters in and 450 meters out (total of 900 meters traveled) multiple times and the largest position error, using only NREC's sensor's odometry, was 0.9 meters. This was an impressive feat, especially because there aren't many visual features in a uniform concrete storm drain, as shown in figure 11. A corresponding registered point cloud from the storm drain can be seen in figure 12.


Figure 11: NREC *MultiSense-SL* mounted on iRobot *PackBot* mapping and localizing itself in storm drain

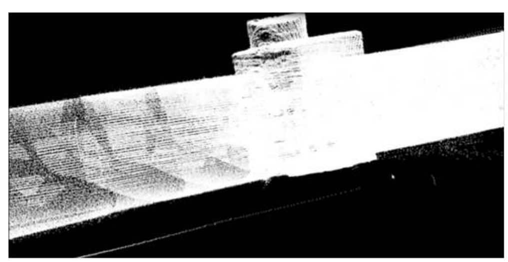
Figure 12: Point cloud of storm drain and manhole cover as recovered from the NREC *MultiSense-SL*

5. DEMONSTRATION AND TEST WITH U.S. CUSTOMS AND BORDER PROTECTION

SSC Pacific held a test and demonstration event near the border of California and Mexico with the U.S. Customs and Border Protection in November of 2013. SSC Pacific demonstrated control of the iRobot *PackBot* and the

CTER platform through three concrete storm drains. Storm drain #1 is a 45-cm culvert with no angles and length of about 10 meters, storm drain #2 is a 152-cm culvert with one 90-degree turn at 20 meters, and storm drain #3 is a 152-cm culvert with one 90-degree turn at 30 meters and another 90-degree turn at 150 meters. The *PackBot* was controlled through wireless communications displaying a video stream, and overlaid local map data on satellite imagery. Wireless communications were especially good in the concrete structures, 802.11 wifi was used to provide video to the user and send control commands to the robot for up to 450 meters away from the base station in storm drain #2. The signal was lost after the second turn in storm drain #3, about 150 meters from the base station. This was expected from previous communications tests in other tunnel locations. Manually Deployed Communication Relays (MDCR), a variant of the Automatically Deployed Communication Relays (ADCR),[10] a proven and fielded communications product developed at SSC Pacific, provided repeater relay communication nodes that were used to increase the communication distance. A repeater node was placed at the second turn which provided strong communications to the *PackBot* for the rest of the tunnel length, another 200 meters (figure 13). The autonomy system was successfully able to travel the distances of the storm drains with user interactions only at the start, the halfway point when the vehicle turned around, and the end.

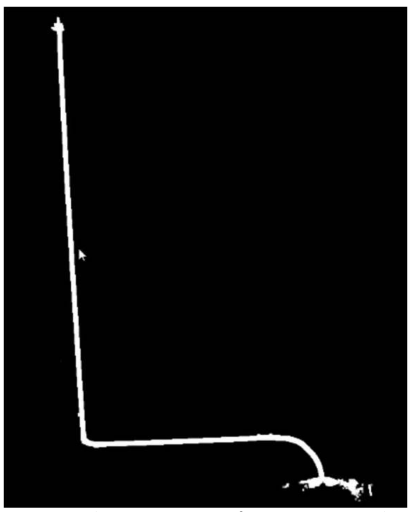

Figure 13: Top-down view of 3D point cloud tunnel capture showing two turns

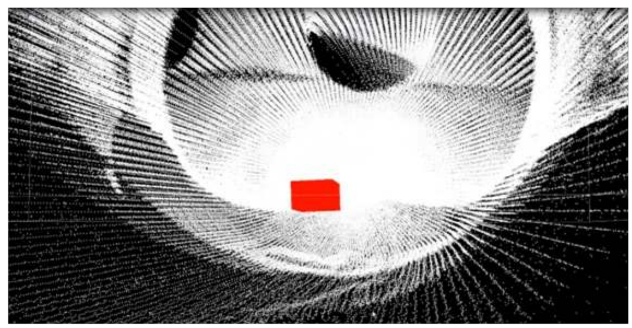

Figure 14: 3D point cloud of end of the 152-cm storm drain and red box which represents the location of the robot in the scene

A test was conducted with the *CTER* platform through storm drain #1, shown in figure 15. The *CTER* platform was connected with fiber and controlled using the *CTER* control software with video and position feedback as shown in figure 16. The small diameter the storm drain provides a very unstable surface for a single track linear platform and the *CTER* tipped over after traveling only 3 meters. The small width of the culvert made maneuvering and recovering from tipover very difficult, especially only using the video screen feedback. A supporting structure was attached to the front track section, as seen in figure 17, which allowed the platform to successfully drive the remaining length of the concrete pipe.

Additional tests were conducted at another set of storm drains that had varying degrees of ground cover: soft and moist dirt, loose sandy steps, and large rocky terrain (figures 18, 19, and 20). The U.S. Customs and Border Protection had tested other platforms at these test sites and stated that none of them were built to handle the loose, sandy steps. The *CTER* platform, with its unique control and capabilities, was able to wriggle and rotate and climb up the steps with little effort in its pre-defined Bend mode.

6. CONCLUSION

The Counter Tunnel project has focused on developing solutions to traverse, characterize, and map a tunnel-like environment. Work was performed jointly by AFRL (*CTER* snake platform testing and borehole apparatus, deployment, and retrieval) and SSC Pacific (sensors, characterization, wireless communications, localization, and

Figure 15: *CTER* platform about to enter a 45-cm storm drain

Figure 16: The video feed from *CTER* platform as it traversed through the 45-cm storm drain

Figure 17: *CTER* platform with angled fins to provide stability for the 45-cm storm drain

Figure 18: *CTER* platform traversing sandy terrain in storm drain

Figure 19: *CTER* platform traversing sandy stepped terrain in storm drain

Figure 20: *CTER* platform in bend mode traversing rocky terrain in storm drain

autonomy) with final test and demonstration events at AFRL Tyndall Mock Test Tunnel and San Diego border region.

This project has increased the knowledge-base of viable counter tunnel systems (platforms, sensors, communications, and payloads) and has furthered the work in GPS-denied navigation and 3D perception and mapping. The evaluations and expertise gained from this work will be key to providing robust and deployable systems to address tunnel, cave, and like threats.

7. ACKNOWLEDGMENTS

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