Intelligent Robotic Behaviors for Landmine Detection and Marking

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should absorb most of the blast energy 6, also, all the expensive sensors and computers are enclosed in a watertight, rugged box, which is being refined to meet military specifications for explosion proofing.

Good Support and Growth

Although completely student-led, Cor- nell MineSweeper has greatly benefited from the assistance of two professors in the robotics and sensors area at Cornell: Dr. Ephrahim Gar-
cia and Dr. William Philip. Garcia is currently the head of Cornell’s Laboratory for Intelligent Mechanical Systems, and contributed many years of experience in the development of dis-
tributed intelligence in small robotic swarms and autonomous robots. His experience as a Defense Advanced Research Projects Agency Project Manager has also been an important asset to the team. Philip is currently the Asso-
ciate Director of the School of Civil and Environ-
mental Engineering and the Program Leader for Remote Sensing at the Cornell Institute for Resource Information Systems. His research experience in the physics of optical remote sens-
ing, spatial and spectral pattern recognition, and image processing has proven extremely helpful.

During a recent visit to Cornell University, Nobel Peace Prize laureate Rae McGrath had the chance to meet with Cornell MineSweeper. "I really want to congratulate Cornell for allow-
ing this young team the freedom to develop the idea. What excited me the most was that the team…hasn’t made the mistake of so many other groups that set out to find the solution. They’re really doing their research and they’re developing something that’s very flexible. The next step for them is to go to somewhere with the problem of landmines," said McGrath. With its fresh design, quality of advisors and humanist purpose, Cornell MineSweeper is starting to grow in the Cornell engineering community. Initially comprised of only six members, the team has expanded in only one semester to 41 committed students coming from all engineering fields and is still growing. In the beginning, people thought Cornell MineSweeper was a group of engineers that liked the computer game Minesweeper so much they gathered to play it; now students inquire about the robot. MineSweeper is nor-
th a game nor an idea anymore; it will soon be ready to be field-tested.

See Endnotes, page 114

News Brief

Cambodia Pushes Back Mine Clearance by 10 Years

The government of Cambodia announced in late 2007 that its mine clearance efforts would not be completed until at least 2020. Representing one of the world’s most contaminated countries, Cambodian Prime Minister Hun Sen said that predictions made in 2000 for a 10-year window of clearance were overly optimistic.

Details or rationale for the extension were not given by Hun Sen at a Cambodian de-
mining efforts, although the Prime Minister did say that the government expects a budget for landmine clearance to increase in coming years.

Every year, hundreds of Cambodians become casualties to landmines and other explosive remnants of war, which still litter the country after decades of conflict. Denying groups from around the world have been collaborating with the government’s own demining agency to clear the country-
side since 1992. More than 2,900 square kilometers (1,120 square miles) remain contaminated, and progress in demining these areas has been slow.

Prime Minister Hun Sen cited a large number of U.S. landmines and unexploded ordnance items, left behind in Cambodia from massive bombing campaigns in the 1970s, as an enduring problem for the nation.

This article discusses experimental results achieved with a robotic countermine system that utilizes autonomous behaviors and a mixed-initiative control scheme to address the challenges of detecting and marking buried landmines. By correlating aerial imagery and ground-based robot mapping, the interface provides context for the operator to task the robot. Once tasked, the robot can perform the search and detection task without the use of accurate global positioning system information or continuous communication with the operator. Results show that the system was able to find and mark landmines with a very low level of human involvement. In addition, the data indicates that the robotic system may be able to decrease the time to fi nd mines and increase the detection, accuracy and reliability.

by David J. Bruemmer, Douglas A. Few, Curtis W. Nielsen and Miles C. Walton [Idaho National Laboratory]

Landmines are a constant danger to soldiers during conflict and to civilians years after conflicts cease, causing thousands of death and injuries every year. It has long been thought that landmine detection is an appropriate application for robotics because it is a dull, dirty and dangerous task. The reality, however, has been that the operational nature of the task demands a reliability and perfor-

mance that most robots have not been able to provide. On the one hand, many autonomous strategies rely on assumptions of accurate global positioning systems. When GPS is inaccurate or when it is unavailable, the performance of this approach degrades quickly. On the other hand, tele-

operated strategies are limited by the fact that the combined demands of navigation, sweep coverage and signal interpretation severely overload the human operator and can lead to poor performance.

In response to the limitations of both autonomous and teleoperated strategies, we present a mixed-initiative approach that allows the oper-

ator and robotic assets to work together to accomplish a countermine mission. Researchers at the Idaho National Laboratory, Carnegie Mel-

lon University, and the Space and Naval Warfare Systems Center San Diego have developed a system that combines aerial imagery from an unmanned ground vehicle and a mixed-initiative control scheme to address the challenges of detecting and marking landmines both in the physical world and in a digital representation of the world. The system’s effectiveness was rigorously evaluated by the United States Army Test and Evaluation Command and by the U.S. Army Maneuver Support Center Futures Center (MANSCEN) at Fort Leonard Wood in Missouri.

Mission Requirements

The purpose of this research was to evaluate the effectiveness and suitability of an Autonomous Robotic Countermine System to proof a one-meter (3.2-foot) mined lane by searching for, marking and reporting suspected landmines and marking the boundaries of the proofed lane. The intent was to provide a system that is military effective with an effec-
tive alternative to demilitarized lane countermine operations. MANSCEN determined that although accurate digital marking of landmine locations

within a terrain map was desired, accurate physical marking of the mine locations was considered essential for the mission requirements.

Developing a successful solution required a complete understanding of the end-user’s goals and requirements. This was accomplished with over two years of dialogue with MANSCEN and the U.S. Army Engineer School to address the mission requirements. Furthermore, numerous conversations with the Vision and Electronic Sensor Directorate at Fort Belvoir, Virginia were required to discuss the capa-
bilities and limitations of current sensor technologies.

Previous studies by MANSCEN had shown that real-world missions would involve limited bandwidth communication, inaccurate terrain data and sporadic availability of GPS. Consequently, task commands had to be handled down from MANSCEN demanding minimal dependence on network connectivity (e.g., wireless Ethernet and radio communica-
tions); centralized control (e.g., off-board motion planning); GPS; and accurate terrain data.

MANSCEN also emphasized the need for reduced operator work-
load and training requirements. The military operational requirements document specified that within the future combat system unit of action, there would no longer be dedicated engineers focused on the counter-
mine mission; instead, anyone within the unit of action should be able to task the system. A final requirement was that the robotic system be able to handle cluttered outdoor environments. Although the robot platform and sensor suite was important considerations, the goal of this effort was not focused on a particular robot platform or a particu-
lar countermine sensor; rather, the stated goal was to “provide porta-
ble, re-configurable tactical behaviors to enable teams of small UGVs [unmanned ground vehicles] and UAVs [unmanned aerial vehicles] to collaboratively conduct semi-autonomous countermine operations.”

Technical Approach

Software behavior development. The control of the vehicle, mine detection and marking system were all integrated into the Idaho National Laboratory Robot Intelligence Kernel (RIK) integrates algorithms and hardware for perception, world-modeling, adaptive communication,
dynamic tasking and behaviors for navigation, exploration, search, detection and plate mapping. The system is based on a variety of sensors, including visible-light and thermal imaging, and can provide high-quality information about the environment. To accomplish the overall countermine search behavior, the RIK requires an adaptive avoidance, way-point navigation, path planning and mine-detection coverage behaviors, and human input (e.g., joystick and computer control). A key component of the deliberative capabilities of the robot is an occupancy-grid-based map building algorithm developed by Carnegie Mellon University. This algorithm uses probabilistic reasoning to reason about the robot’s location with respect to the map and when features exist in the environment, the algorithm provides relative positioning accuracy of +/- 10 centimeters (4 inches) even when GPS is unavailable.

Robotic design. The air vehicle of choice was the Arcturus T-15 (see Figure 1), a fixed-wing aircraft that can maintain long flights and carry the necessary video and communication modules. For the countermine mission, the Arcturus was equipped to fly two-hour reconnaissance missions at altitudes between 200 and 500 feet (61–152 meters). A spiral development process was undertaken to provide the air vehicle with autonomous launch and recovery capabilities as well as path planning, waypoint navigation and the ability to create an autonomous visual mosaic. The resulting mosaic can be geo-referenced if compared to a priori imagery, but at the time of this experiment, did not provide the positioning accuracy necessary to meet the 10 centimeter (4 inch) accuracy requirements for the mission. On the other hand, the interconsistency of the mosaic is very high since the image processing software can reliably stitch the images together.

Carnegie Mellon University developed two ground robots (see Figure 2) for this effort. The robots were modified humanitarian demining systems equipped with inertial systems, compass, laser range finders and a low-bandwidth, long-range communication payload. A MiniLab FC44A actuator was mounted on both vehicles together with an actuation mechanism that can raise and lower the sensor, as well as scan it from side to side at various speeds. CMU developed the software processing to analyze the output from this sensor and provide the robot behaviors with a centroid location relative to the robot’s position. A force torque sensor was used to calibrate sensor height based on sensors present in the environment. The mine-sensor actuation system was designed to scan at different speeds and at varying angles. In most cases, it was obvious to the user how the aerial imagery could be used to improve the decision-making process and ground representation especially when error such as positioning inaccuracy and camera skew play a role. Even with geo-referenced imagery, real-world trials showed that the GPS-based correlation technique does not reliably provide the accuracy needed to support the countermine mission.

In most cases, it was obvious to the user how the aerial imagery could be used to improve the decision-making process and ground representation especially when error such as positioning inaccuracy and camera skew play a role. Even with geo-referenced imagery, real-world trials showed that the GPS-based correlation technique does not reliably provide the accuracy needed to support the countermine mission.

As a result, correlation tools were developed that allowed the user to select common reference points within both representations. Examples of these common reference points included the corners of buildings, fence posts or vegetation marking the boundary of roads and intersections. In terms of the need to balance human and robot input, it was clear that this approach required very little effort from the human (a total of four mouse clicks) and yet provided a much more reliable and accurate correlation than an autonomous solution. It is also important to note that the same interface tool that correlates aerial imagery with the ground map can also use satellite imagery or other forms of terrain data.

Once the imagery and the map are integrated, the imagery serves as a backdrop for the operator to task the robot to previously unknown areas. The representation used for this experiment implements a three-dimensional, computer-game-style representation of the real world constructed on-the-fly. The three-dimensional representation maintains the relative sizes of objects in the environment and illustrates the map built by the robot as it relates to the aerial image and the position of the robot, obstacles, mines, and the path cleared by the robot. Figures 3 and 4 illustrate different perspectives of the interface used for the experiment. This fusion of data from the ground vehicles is more than just a situation-awareness tool. It supports a collaborative positioning framework that exists between air vehicle, ground vehicle and human operator. Each team member contributes to the shared representation and has the ability to make sense of it in terms of its own, unique internal state.

Experiment. To test the proposed system and mission requirements, personnel from the U.S. Army Maneuver and Support Center and the U.S. Army Test and Evaluation Command, both based at Fort Leonard Wood, Missouri, conducted an experiment 20–28 October 2005 at the Idaho National Lab’s UAV airdrome. The U.S. Army TKO funded the experiment plan, performed the field experiments and controlled all data collected. The experiment consisted of repeated trials of a disturbed route-sweeping task, and data collected included measurements of human, robot and overall team performance of the resulting system. Sweeping a disturbed lane required the robot to navigate a path to a target location while physically and digitally marking detected mines and the boundaries of the searched lane. A test lane was prepared on a 20-meter (65-foot) section of an undisturbed road near the INL UAV airdrome. Six 0.3 meter (1-foot) wide lane-sweeping behaviors. Altogether, this included a total of three button clicks on the operator control unit. Since the repeated use of color-dye could produce confusion regarding the lane, water was used instead of dye throughout the experiment.

As the robot proceeded, data personnel followed the robot placed red poker chips at the location of each wet spray mark. These poker chips allowed personnel to accurately measure distance from the center of the dye spray to the center of mine as shown in Figure 5. The water then dried before the next trial. Throughout the experiment, all mine locations reported to the operator control unit were checked and a copy of the data log recording the markings from the OCU were saved. A photograph of each mine and its location was taken, and a video of each run was recorded. Data sheets recorded meteorological data, mine

digging.

Figure 1: The Arcturus T-15 air vehicle. The large red box on its fuselage is a mine sensor.

Figure 2: Countermine robot platform.

occupancy grid map built by the robot. One lesson learned in terms of air-ground teaming was that it may not be possible to automatically generate or perform a correlation on the ground representation especially when error such as positioning inaccuracy and camera skew play a role. Even with geo-referenced imagery, real-world trials showed that the GPS-based correlation technique does not reliably provide the accuracy needed to support the countermine mission.
Figure 5: Example of mine marking

Figure 6: Proofed Lane marking.

Figure 7: Mine and lane display on the interface (OCU).

Figure 8: The iRobot Packbot outfitted with the Cyterra AN/PSS-14 mine sensor.

Figure 9: Example of mine marking

Figure 10: Proofed Lane marking.

Figure 11: Mine and lane display on the interface (OCU).

Figure 12: The iRobot Packbot outfitted with the Cyterra AN/PSS-14 mine sensor.

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marking errors, missed mines, false detections and other comments from those conducting the experiment. After the robot had completed its mission, the operator drove it back to the starting point. At the conclusion of the trial, the distance from each mine mark to the center of the mine was measured and recorded.

Results. There were four criteria to the tested requirements in this experiment: finding mines, marking mines, reporting mines and marking the proofed lanes. During the 26 runs executed through the experiment the robot correctly detected 124 of 131 mines (95 percent). Of the seven mines not detected, two were due to a miscalibration of the height of the sensor at the beginning of the runs, two were due to low battery levels on the mine sensor and three were not detected during sharp turns to avoid obstacles. All missed mines were at or near the edge of the proofed lane.

Autonomous Robotic Countermine System had a single false positive detection during all the runs. One mine was detected and reported twice, once on the leading edge of the mine and once on the trailing edge. This gives a false detection rate of less than one percent.

All of the mines detected by ARCM System were physically marked on the ground. The distance between the center of the physical mark and the center of the mine was measured for 91 mines and the average marking error was 12.67 centimeters (4.98 inches) with a standard deviation of 8.56 centimeters (3.37 inches).

For each of the trials, the lane boundaries were marked in the physical and digital environments as shown in Figures 6 and 7. Of the 124 mines detected only one mine was not digitally reported to the operator control unit, the remainder were automatically reported and logged. A test file with the GPS coordinates of each mine was logged in a repeatable run file, and screen shots of each run were made showing the location of each mine within the robot’s terrain map.

The ARCM System was successful in all runs in autonomously negotiating the 50-meter (55-yard) course and marking a proofed one-meter lane. This was true even when the lane was covered by a high density of clutter, including brush, boxes and large stones.

The 26 runs had an average completion time of 5.79 minutes with a 99 percent confidence interval of +/- 0.31 minutes. The maximum time taken for any run was 6.167 minutes. Another interesting finding is that the average level of human input throughout the counter-mine exercises was less than 2 percent when calculated based on time. The U.S. Army Test and Evaluation Command indicated that the ARCM System achieved “very high levels of collaborative tactical behaviors.” When the MANSCEN applied the “autonomy levels for unmanned systems” rubric, which includes indices for operator interaction, environmental difficulty and task complexity, to evaluate the overall autonomy of the system, a level of eight to nine was applied out of a possible 10.

Findings

The research reported here indicates that operational success was possible with a mixed-initiative approach that defined different, complementary responsibilities and roles for the human, air vehicle and ground vehicle. The results of the real-world experiment showed that the autonomous robot countermine system accurately marked, both physically and digitally, 124 out of 131 buried mines in an average time of less than six minutes. Comparing the robot to a human performance baseline is difficult and no attempt was made to perform a rigorous comparison. In order to provide a rough juxtaposition, consider that, according to MANSCEN, it would take approximately 25 minutes for a trained deminer to complete the same task accomplished by the robot. In terms of probability of detection, a trained deminer detecting mines on a 50-meter (55-yard) training lane can expect to discover between 60 percent and 90 percent of the mines, depending on experience and the type of landmine to be detected.

Future Work

While the robot’s performance is encouraging, it is important to understand that many challenges remain. One important caveat to the work reported here is that the mines used had a high metallic content. The need to find low-metallic mines will require a more advanced sensor.

Ongoing collaboration with the Night Vision and Electronic Sensor Directorate at Fort Belvoir will result in a combined ground penetrating radar and electromagnetic induction sensor, which is being used in the next phase of this effort to improve mine sensing of low-metallic mines.

Another important caveat is that the robot platform used for the effort reported here does not meet the need for ruggedness or off-terrain mobility. The data presented here are the results of a test on an “unimproved dirt path.” To accomplish the same task in cross-country terrain is also a subject of future work. Finally, the U.S. Army Engineer School indicated that the next phase of research should support a vertical foot fixture to maintain an exact height of the sensor head above the ground and that they would like to see more collaborative UAV functions including the ability to coordinate multiple UAVs and UGVs from a single controller.

The Second Phase

Each of the areas for future work is currently being addressed by the second phase of this research, which is currently underway with funding from the United States Office of the Undersecretary of Defense Joint Ground Robotics Enterprise. The Robotic Systems Joint Program Office at Redstone Arsenal in Huntsville, Alabama, is providing programmatic direction for the effort called Autonomous Robotic Countermine Capability. As with the research reported in this article, a primary goal of ARCC is to insure seamless portability of the software behaviors in terms of moving the code between robots. Since the experiment reported here was conducted, the software behavior architecture used has been ported to several different vehicles including the (Robot Packbot, Foster-Miller Talon and the Segway RMP400).

In addition to platform portability, ARCC is also focused on insuring that the behaviors support reconfiguration for different countermine sensing payloads. Work is underway to utilize several different countermine sensors. Representatives from the U.S. Army Engineer School have requested that the Cyterra AN/PSS-14 mine sensor be utilized for the next phase of evaluation. In terms of platforms, the combat engineers have asked that the behaviors be tested on fielded systems. The ARCC project will utilize the Foster-Miller Talon and the Robot Packbot to develop and assess the new capabilities. Figure 8 shows the Cyterra AN/PSS-14 mine sensor together with the iRobot Packbot. The team is also working to utilize and empirically assess the Niitek sensor being developed under the Night Vision Laboratory and Electronic Sensor Directorate’s Advanced Mine Detection Sensor Program. According to experimentation performed by the NVEDS, this sensor has shown the greatest potential to increase probability of detection for low-metallic mines. A new effort under the direction of the Program Manager for Countermines and Explosive Ordinance Disposal at Fort Belvoir, Virginia will test how effectively the ARCM behaviors can use this sensor on the Robot Warrior, the Remote HD-1 and the FCS Small Unmanned Ground Vehicle (SSUGV) as well as the Packbot and Talon.

For the next phase of research, the U.S. Army Engineer School has suggested that the autonomous robotic technology be subjected to rigorous comparison to the human baseline. To support this, MANSCEN is developing an experiment plan that will compare a trained deminer to a robot by sale on the same lanes with consideration to probability of detection, false positives, user workload, overall operational manpower requirements and speed. Autonomous robotic sensor taking remains a major focus, and several of the experiment plan questions are focused on understanding how human input can affect overall performance throughout the mission.
In addition to the planned final experiment at Fort Leonard Wood, the AR2c effort will include experiments to evaluate rigorously the performance benefits associated with the use of a prior terrain-data and the use of live aerial imagery from a UAV.

The research presented here can be adapted from the military domain for relevancy to the challenges of humanitarian demining. It is important to note that humanitarian demining is significantly different from military demining. Antonic, Ban, and Zagar point out that “the military needs to breach a narrow path through the field, whereas humanitarian demining requires 100 percent detection and removal of all mines on a large area.”

To address the challenges of humanitarian demining, a multi-robot approach is being developed which will use multiple, inexpensive platforms that can provide parallel tasks to increase the probability of detection. The multi-robot strategy will also allow the behavior to be used for larger areas.

Another consideration for humanitarian demining is the price of the robotics platforms. To reduce the cost of the system, the behaviors presented in this article have now been ported to a commercial four-wheeled robot manufactured by Segway that costs less than a third of the fielded military systems under consideration.

As different robots and sensors become available, the portability and reconfigurability of the behaviors will allow them to be used across a variety of tasks and environments.

John Hegle at Electronic Sensors Directorate; Lieutenant Colonel Meister at the MANSCEN Futures Center; Clay Regis Vincent at Stanford Research Institute; andres and-rescue operations. Bruemmer was selected as an Inventive Young Engineer by the National Academy of Engineering and is a recipient of a 2006 R&D 100 Award.

Douglas A. Feiw obtained a B.S. in computer science from Rhode Island University in 1989. He subsequently joined the Idaho National Laboratory, focusing on developing intelligent automation tools. As a Principal Research Scientist at the Idaho National Laboratory, Feiw’s interests include human-robot interactions and mixed-initiative robotic systems.

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Gryphon is a remote-controlled robot tool with a mobile platform and a robotic manipulator equipped with sensors. The platform moves along the border of the minefield, but always outside of it (called “safe-approaching”). There is, therefore, no risk of accidentally triggering a landmine or setting-up an exploded mine. The manipulator can reach inside the minefield and move an array of sensors above the soil. Whenever a possible landmine is detected, the system can mark the spot and move to the next scanning position. Since it never enters the minefield, the system does not require heavy and expensive armoring. In addition, because it is based on a standard vehicle, it can be less expensive than the other armored solutions proposed.

Part of the mine-detection work can be automated; however, the entire operation is always under surveillance of the operator, as it is the data-analysis process. The operator performs delicate steps, with remote control, remaining a safe distance from the minefield. This procedure does not exclude the need for armored detoning machines. On the contrary, if the new landmine-detection procedure employed in cooperation with the machines that are already in use, it is believed that the safety—and eventually the speed—of mine clearance can be improved.

In the basic configuration, Gryphon is equipped with mine sensors and can be used as a landmine detector only (Stage II of the tasks performed inside the minefield). With some more research and modifications, it is expected that it could be equipped with other tools, such as rotary cutters and prodders, and be used also for vegetation removal (Stage I) and landmine neutralization (Stage III). By digging the soil and placing explosive charges, thus keeping the human operators away from the minefield at all times.

Subsystems

The platform is based on a commercial all-terrain vehicle. In order to control the ATV remotely, radio-controlled mechanisms have been installed for steering, throttle, braking and gear-changing. The ATV is equipped with a gasoline engine (79cc, 4-stroke) that powers an onboard generator and produces electric energy for all automation mechanisms, as well as for the sensors installed in the manipulator. The platform can operate, therefore, without interruption for one entire day, functioning as a permanent source of electricity in the field.

In addition, the ATV can be driven remotely. When commuting between the base camp and the minefield, it is preferable to have a pilot driving Gryphon. In this way, no additional vehicles for transporting the machine are required. Once Gryphon reaches the border of the minefield, it can be switched to remote-driving mode.

The manipulator is mounted on the ground platform. It is designed in a photographic configuration, so it is balanced by a counterweight in any position. Very little energy is required when moving the manipulator or when it is standing still above the minefield. The manipulator is mounted on the ground platform. It is designed in a photographic configuration, so it is balanced by a counterweight in any position. Very little energy is required when moving the manipulator or when it is standing still above the minefield. Physical markers on the minefield to identify the positions of possible landmines are a requirement of the deminers, since they cannot rely only on electronic data; however, for redundancy, all the plotted positions are also recorded with coordinates provided by the GPS device.