RAPID INFUSION OF ARMY ROBOTICS TECHNOLOGY FOR FORCE PROTECTION & HOMELAND DEFENSE

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ABSTRACT

Existing robotic technology has the potential to impact the cost and effectiveness of force protection tasks and first responder missions. Using innovative and aggressive development and acquisition strategies are the key to moving our research from the lab into the hands of the user. This paper discusses activity associated with rapid development of the ODIS robot for under vehicle inspection.

1. INTRODUCTION

The Army Tank Automotive Research and Development Center (TARDEC) Robotics Mobility Lab (TRML) has been researching promising Ground Vehicle Mobility and Ground Vehicle Autonomy topics for a number of years, via both University collaboration and in-house research. The main purpose of our research is to provide ground mobile platforms to automate manpower intensive, complex and dangerous tasks. An important high-level goal is to provide platforms to place a sensor or manipulator within an effective area surrounding the threat while placing the soldier/operator outside the danger zone (Figure 1).

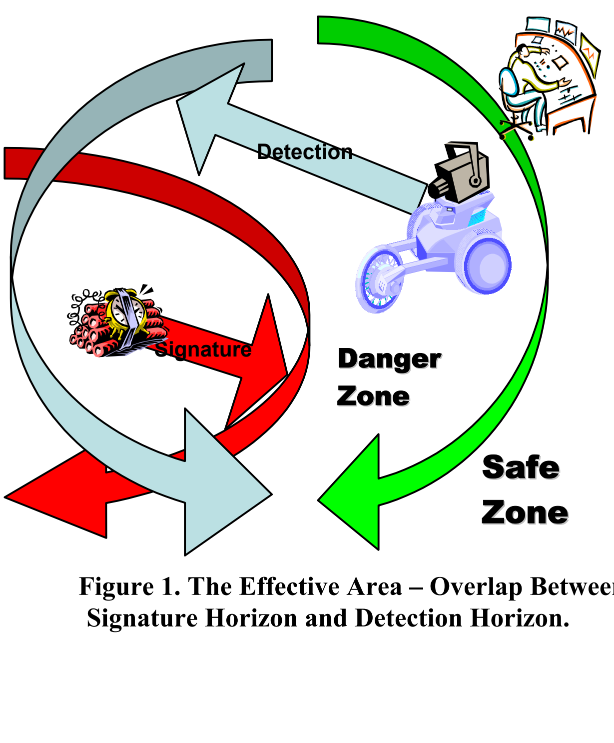

Figure 1. The Effective Area – Overlap Between Signature Horizon and Detection Horizon.

The TRML has investigated many different mobility concepts over the years, including systems with track, wheel and hybrid configurations. Omni-Directional Vehicle (ODV) technology is one of our more advanced topics. One manifestation of ODV technology is the Omni-Directional Inspection System (ODIS) robot. ODIS was designed to converge several lines of research, omni-directional running gear, control software for multiple omni-directional wheels and autonomous navigation into a mobile robotic research platform. The research was coupled to an (at the time) interesting mission, under vehicle inspection via a visual camera.

The events of September 11th led us to realize that we had technology in our development pipeline that could quickly be moved up to address new critical national concerns and priorities. Vehicle checkpoint inspections and parking lot surveillance are two missions that are well suited to robotic technology. We immediately began taking steps to apply the ODIS robot to these missions. But, as we discovered, there are several interrelated issues that must be addressed when rapidly introducing technology. The first and most important is user trust in the technology, a related close second are metrics to assess if the technology is ready for the user, and other issues include development strategy, training and a means to collect user input. In the first few days after September 11th, we addressed these issues in an ad hoc manner, but then quickly began to focus. We addressed metrics first and embraced the Technology Readiness Level (TRL) Scale. NASA created the TRL for assessing flight readiness of space technology. Next we recognized that a traditional development cycle would not be responsive enough to move quickly and we borrowed the Spiral Development technique from the Software engineering arena. Spiral Development is an evolutionary, risk driven approach to system development. Finally, as a means to gain user input and proceed into testing, we to planned and executed a Limited Objective Experiment at Ft. Leonard Wood, MO. By taking an aggressive stance and employing a spiral development technique, we were able to move the Omni Directional Inspection System (ODIS) robot (Smuda et al., 2002) from TRL 4 to TRL 6 by February 02, TRL Level 7 by August 02 with TRL Level 8 in the pipeline.

2. PRELUDE - OMNI DIRECTIONAL VEHICLES

Omni-Directional Drive Vehicle (ODV) running gear uses 3 or more, independently driven intelligent wheels communicating with a master computer or micro-controller. The T1 robot (Figure 2) was the first of a series of research vehicles designed to assess ODV mobility, path planning and proprioceptive autonomous operation (Moore and Flann, 2000). The T series robots all have the ability to translate fore or aft left or right and rotate about arbitrary centers, alone or in combination. The T1 robot weighs in at about 75 pounds and is about the size of a small coffee table. The T1 vehicle with 6 wheel drive and omni-directional steering shows exceptional mobility both in crowded cubicle mazes and on rock fields with rocks up to 8” in diameter. A follow on vehicle, T2 weighs in at about 1400 pounds and was created to demonstrate the scalability of the ODV concept. The final vehicle of the series, T3 weighs in at about 120 pounds and adds active Z-axis control to each of the 6 legs. The T3 vehicle demonstrates the ability to maintain a level platform and a limited ability to climb step obstacles.

Figure 2. T1 Robot

As mentioned in the introduction, during 2000 and 2001several lines of research were converged to create ODIS (Figure 3). The ODIS research platform was equipped with an array of propreciopetive and navigation sensors including laser rangefinder, IR proximity, sonar, compass and gyro required to conduct an autonomous under vehicle inspection. It was also equipped with a pan/tilt camera assembly with active lighting as a mission package. In the summer of 2001, ODIS was demonstrated at AUVSI in Baltimore, MD and on September 5, 2001, ODIS was demonstrated at Ft. Leonard Wood. The operational scenario for this research was ODIS inspecting vehicles in a parking lot (Table 1).

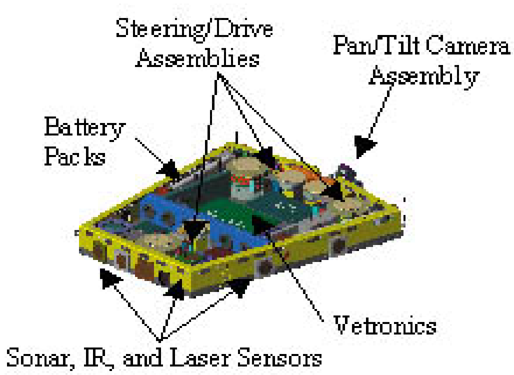

Figure 3. Original ODIS Research Platform

1	Based on an internal map, find a stall in a parking lot.
2	Using sonar, IR and laser sensors, determine if stall is occupied.
3	If stall is occupied, move into position under rear bumper location using upper sonar.
4	Using laser, find positions of rear tires.
5	Move forward and find position of front tires.
6	Compute map of vehicle underside.
7	Plan search pattern of vehicle underside.
8	Execute search.
9	Exit vehicle underside.

Table 1. Autonomous Search Algorithm

Omni-Directional drive technology coupled with robotic operations can provide the force protection personnel with a family of inspection tools to reduce rote work, increase the quality of inspections while providing standoff capability. We consider the ODIS robot as the first of a family of similar robots to accomplish a variety of inspection tasks. ODIS family robots can be used at ad-hoc checkpoints in or around a secured area. ODIS is especially useful for inspecting parked vehicles in a parking lot. They can be used equally as a tool at deployment debarkation points to inspect vehicles entering the secured area. A sibling robot to the ODIS will be used to inspect vehicles that are parked dockside, awaiting deployment. This robot will also be useful to inspect fuel and chemical tankers for leaks. Maintenance technicians inspecting vehicle drive trains for damage or wear and searching out oil leaks will also use it. An ODIS robot or sibling robot can be used to inspect under railcars while the train is in motion or stopped.

ODIS robot variants have been suggested for searching office areas. The ODIS robot can move through office areas, under desks, credenzas and other office furniture all the way up to the wall. Then it can tilt its visual camera to look up behind common office objects. The recent anthrax incidents have been extremely costly, not to mention stressful to the public safety personnel that are required to don unwieldy and uncomfortable hazard suits to collect samples. A variant in the family could be fitted with a short robotic arm to collect samples of suspicious substances.

3. REALIZATION – ODIS DEVELOPMENT

3.1 Spiral Development

Spiral development (Boehem, 1988) is an evolutionary, risk driven approach to system development. The spiral development process for software development (Figure 4) has been successfully

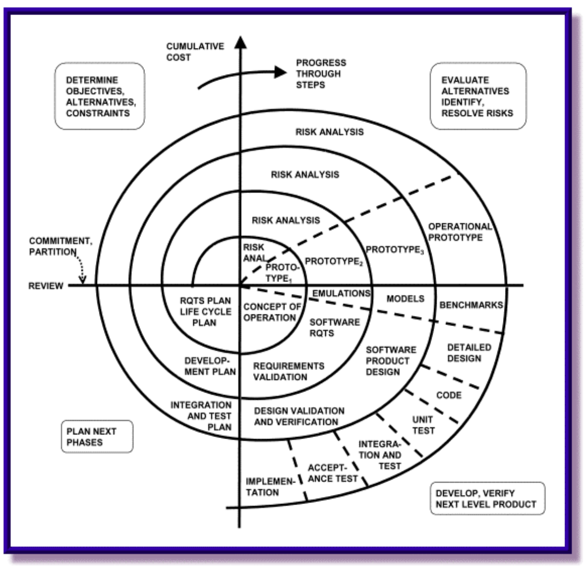

Figure 4. Software Spiral Development Model

used in a number of DoD software acquisitions and fits well with the DoD Instruction 5000.2 preferred evolutionary acquisition strategy. The spiral development process requires user involvement and frequent testing. It is particularly useful when the system requirements are not clear up front.

A complete spiral cycle includes, 1) client communication, 2) planning, 3) risk analysis, 4) engineering, 5) construction, and 6) client evaluation.

For each cycle (spiral) the client and developer closely work together to ensure a functional prototype. Early reassessments of risks and assumptions are considered to meet current contractual requirements while leaving room for visionary growth.

3.2 Early Research

The original effort contracted for with Utah State University (USU) was initiated in June of 1998 with the purpose of developing a more robust mobility system for unmanned ground vehicles using novel running gear and intelligent mobility systems.

The initial product of this effort produced a family of vehicles with Omni directional wheels, providing a significant increase in vehicle mobility. In effect, each wheel on the UGV could translate and rotate as needed to perform necessary mobility functions. The independent rotation and translation of each wheel node, combined with an intelligent system to control and synchronize the movements of all wheel nodes produced a UGV with the ability to perform zero radius turns, omni directional motion in any orientation, and if desired the ability to behave as if it were a traditional Ackerman steered vehicle.

The first such system developed, T1 is a 75 pound UGV with six independent wheel nodes. The only external sensors for this system are a three axis FOG for dead reckoning. The system is able to follow a preplanned route via dead reckoning, as well as be tele-operated in manual mode, using either omni or Ackerman steering modes.

Following systems were similar in operational nature, but had incremental increases in functionality. T2; the second system produced was again a six wheeled system in the 1400 pound category, whose operation was augmented by GPS, and additional passive suspension technology. It was used to prove that the technology was scalable and viable in larger formats. T3 was the last of the six-wheeled series. A 120 pound variant using active Z-Axis control of each wheel node in order to allow the system to dynamically change its center of gravity, or keep the UGV body level while traversing a slope by moving the Z axis level of the legs independently to compensate for terrain. Efforts to have this system climb stairs using the active Z-axis ability were partially successful, however since the system did not have appropriate sensors on board to fulfill this mission scenario, the effort was stopped due to time and fiscal constraints.

Approximately 24 months (June 2000) into the effort the scope of research was modified to have the contractor produce an Under Vehicle Inspection System (ODIS). This first prototype was a fully autonomous system, capable of sensing the location of the subject vehicles (passenger car/truck) tires using a Sick laser scanner, then based on tire location planning a path underneath the vehicle to ensure a complete sweep of the underside of said vehicle. The UGV is approximately 3.5 inches tall (in order to be able to fit under subject vehicles), and approx 24” wide and long. It is equipped with three Omni-directional wheel assemblies, however due to height restrictions, has no suspension. This restricts the use of the system to structured surfaces, such as concrete, asphalt, and groomed gravel areas.

The sensor used for inspection was a CCD camera mounted on a pan-tilt mechanism which allowed the user to “look” at various portions of the underbody as the system translated through its planned path.

3.3 Accelerated Development

After several months of testing in the lab and other controlled environments, the system was tested in October, 2001 by the US Army Tank-automotive and Armaments Command in a “real world” environment at the command’s main gate truck inspection station. This station was being used as an additional security checkpoint, after the 9-11 terrorist attacks in New York and Washington D.C.

Results from that test were promising, however the system as built was a laboratory grade UGV, and never intended for sustained field use. Feedback from the force protection community urged a fast turnaround of the system with field grade robustness. The contract was immediately modified to produce three prototype systems, which would perform similarly, but only in a tele-operated mode and in field conditions. The systems were designated ODIS-T (Figure 5).

Figure 5. ODIS-T Robot

Consumer cost and risk concerns evolved the ODIS-T prototype. A price reduction of the autonomous-dependant sensors also led to increased product robustness. The TRML and USU team of mechanical, software, and electrical engineers spiraled their way through the prototype’s development. Each segment is worked out and a go/no-go risk analysis determined. The teams worked each component of the project in a parallel approach, which enabled all pieces to fit together in minimal time. For the ODIS project a close-knit client communication was enforced, as frequent modifications were necessary. A new cycle into the complex system of software and Vetronics was necessary for each modification. The ODIS platform is an example of spiral development taken to an entirely new level.

We decided on tele-operation after we analyzed risk and realized that the user was not ready for our autonomous system, that we didn’t fully understand how the user would use the robot and that an autonomous system based on the original ODIS would be too expensive. As noted above, we built several tele-operated ODIS-T robots with the goal of using them to gain user input and as baseline platforms. We formed a closer relationship with Utah State University, going as far as to assign an engineer to Utah State for six months. We also initiated dialog with the user community, by frequently visiting Ft. Leonard Wood and discussing ODIS application at the Maneuver Support Center (MANCEN).

Three systems were completed during the first two months of 2002. Each system consisted of a mobility platform, Operator Control Unit (OCU), and visual sensor (CCD camera with active lighting and near IR capability) located in a “payload bay” on board the UGV. This was the only sensor included on the platform at the time, both due to the fast ‘emergency’ turn-around of the system, and the fact that it is only meant for tele-operation. It should be noted that the payload bay is capable of hosting other types of sensors, within size and power constraints.

The ODIS-T robots completed in February 2002 were the first prototypes and represent one cycle in our spiral development effort. The second spiral revisited some of the early requirements refined by our discussions with users and added support for an IR camera and mission packages such as chemical and radiation sensors (Figure 6). The prototype visual package also underwent revision to make it more robust.

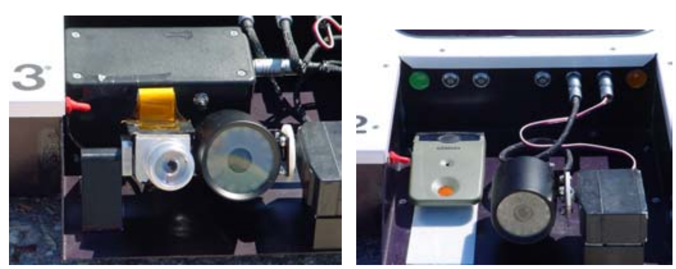

Figure 6. IR (left) and Radiation Mission Packages

Of the three systems built, one was kept in a lab environment to conduct further testing and the other two were taken to various user communities interested in the technology in order for them to unofficially evaluate and comment on their particular needs, as well as how they felt the system could be improved.

In August of 2002, ODIS-T was officially evaluated during a Limited objective experiment held at Ft. Leonard-Wood, MO hosted by the MP school and their UGV evaluation team. The preliminary results of this experiment will be discussed in section 5.

Concurrently, from previous demonstrations of ODIS-T, there was interest in upgrading the system to have some semi-autonomous behaviors. Discussions were held at SPAWAR robotic facility in San Diego during the summer of 2002. A third turn of the spiral was launched before the second turn was complete. In September 2002 the contract was once again modified to develop and produce a semi-autonomous version of the UGV. This system (ODIS-S) will use much of the existing hardware for the mobility platform, however additional sensors and improved Vetronics and power management will be implemented to allow the system to sense it's immediate surroundings for obstacle detection and collision avoidance, as well as pre-plan a path under a vehicle for search once it has been "staged" at a point near the subject vehicle.

The ODIS-T platforms used a variant of the T1 robot Vetronics. This architecture is proven and the software is well understood. Each of the three intelligent wheels has a dedicated micro-controller. The micro-controllers are in turn driven by a master micro-controller. While this architecture is robust and well understood, it requires considerable real estate in the robot chassis (Figure 7).

Figure 7. ODIS-T Chassis Interior

The improved Vetronics in the ODIS-S will reduce the micro-controller count and free up real estate in the chassis for navigation sensors and mission package support.

Two ODIS-S systems will be delivered in late January 2003. These systems will be given to SPAWAR systems center and input into their "robot pool", where they can be obtained by the user community for use, testing, and evaluation.

4. REALITY -RESEARCH CHALLENGES

4.1 Mobility Platforms

In general, the effectiveness of a small robotic platform is a function of its mobility. Thus, a general-purpose platform requires a high mobility over a large range of terrains. This adds weight and cost to the platform. Conversely, a special purpose platform needs only enough mobility to complete its mission. This can result in platforms smaller, simpler platforms that can be built at lower cost.

This is not to say we design platforms to specific tasks. What we need to do is consider families of platforms for related tasks. As we proceed through spiral design cycles, we attack more complexity by improving the prototype. In the case of a family of ODIS inspection robots, we can use common software components and control algorithms by branching our development path to address new requirements. For instance, the ODIS-T platform mobility is restricted to prepared surfaces. This constraint is dictated by the ground clearance necessary for inspection of automobiles. A variant ODIS for inspecting trains or trucks in a deployment zone has a reduction in the severity of this constraint because we can now relax the maximum ground clearance of the vehicle.

Further research is required to develop metrics to help categorize the terrain characteristics of small robots and to assess the ability of small mobility platforms to traverse a particular terrain. The typical tool for analyzing large vehicles, over 2000 pounds, is NRMM (Ansorge, 1999). It is doubtful that NRMM will scale down to very small robot mobility. A tool or extension to NRMM needs to be developed to compare small robot mobility concepts.

4.2 Operator Control Unit (Man Machine Interface)

The current state of robotic technology (and for the immediate future) precludes full autonomous operation making an Operator Control Unit (OCU) a mandatory component. Joysticks have their place, but voice and haptic interfaces are all candidates for future OCUs. Additionally, OCUs need to provide support for mission packages. Indications from mission sensors and control of active devices are all items that need to be considered during OCU design. The OCU for the original ODIS robot was a one of a kind OCU designed to tele-operate the ODIS platform in a research environment. Similar OCUs exist for each of the T series robots. The ODIS-T is no exception. The ODIS-T OCU is a portable tele-operator station. It is a connected to the robot via a wireless modem.

The ODIS-T OCU is a self-contained unit using of-the-shelf commercial products. There are two joysticks on the OCU, one joystick controls the camera tilt, and the other drives the robot. It also contains a 4” LCD video monitor for portable operation. The current plan for the ODIS-S variant is to use an OCU developed at SPAWAR.

There are many possible OCU configurations; we need to be responsive to the needs of the user and to existing OCUs. Software methodologies based in part on real-time software prototyping work at the Naval Post Graduate School are being investigated in TRML to assist developers in wrapping the software interfaces of the OCU, robot and other components. A framework based on the Prototype System Description Language (Luqi et al., 1988) will allow rapid prototyping, technology insertion and field configuration of robotic tools.

4.3 Sensor Fusion / Mission Planning / Mission Awareness

These topics are usually associated with autonomous operation, but can also apply to mission package data. In either case, the goal is to provide some hardware/software module to reduce the data load on the operator and/or enable automation of robotic operation.

Integrating these modules is similar to the OCU issue discussed above. This is a software intensive task in most cases. To be responsive to user need, we must have tools and architectures in place to rapidly integrate sensors, mission planning and mission awareness modules as they mature. This can best be accomplished automating the integration task using domain specific, graphical computer languages within the framework of a defined spiral development process (Douglass, 2000).

4.4 Cost / Manufacturing / Time

Spiral development has its roots in software engineering, where manufacturing is replaced by coding. Coding is a manpower intensive process, and is not usually inhibited by lead times as is the material manufacturing process. Additional experience is required to tune the spiral development process to rapid development of robotic systems.

Often, the trade-off for time is money. To avoid prohibitive cost increase, concise priorities must be defined to allow concurrent engineering and parts manufacture. A good working relationship between the design team and the parts vendors is also required to allow maximum flexibility.

5. RESULTS TO DATE

On August 2, 2002 TACOM initiated a Limited Objective Experiment (LOE) at Fort Leonard Wood (FLW), Missouri in cooperation with the FLW Directorate for Combat Developments (DCD) Military Police (MP), the DCD Robotics office and the Test and Evaluation Coordination Office. The primary LOE objective was to transition from TRL 6 to TRL 7.

A military standard safety release and Training Support Package (TSP) were generated prior to introducing ODIS robot to the soldiers and DoD guards. The TSP was successfully delivered to 5 MP’s and 9 DoD guards. Both the training and testing was conducted at Training Area 190 (TA-190). Training and testing were conducted at three stations in the TA-190 area: Current Operation (Inspection Mirror), line-of-sight (LOS) and non line-of-sight (NLOS) (Figure 8).

Figure 8. TA-190: (a) Inspection Mirror, (b) NLOS, (c) LOS

ODIS training was held at TA-190 August 6-8th. Topics covered in the TSP were: 1) Identify Components of the ODIS, 2) Develop an understanding to the safety issues of the ODIS, 3) Pre – Operations of the ODIS, Perform Inspection Operations with the ODIS, 4) Perform Battery Charging Operation with the ODIS, and 5) Identify Mission Packages with the ODIS (non-visual). Training time involved a 30 minute group presentation and at a minimum 1 hour hands-on ODIS operation. An hour of drive time per personnel was crucial--not for navigational comfort, but to acquire a new visualization from ODIS’s perspective. The conversion from the MOS to the ODIS camera seemed to be trainee’s biggest hurdle

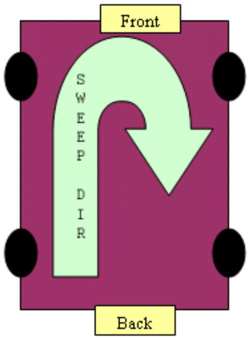

Figure 9.ODIS Vehicle Sweep Pattern

to overcome. Contributing other factors effecting the transition was: a lack of standard search procedure, operator age, and familiarity with vehicle's undercarriage. Establishing a standard search procedure tuned to the ODIS application was an on-going effort throughout the LOE. TACOM engineers attempted to show the operators a good search approach. The final resulting approach is an aft to fore sweep along the driver's side, followed by a fore to aft sweep under the passenger side of the vehicle (Figure 9)

The search initiates with ODIS driving from the staging area to the rear left bumper. Camera positioning is tilted about a 45° from the horizon. This establishes a sense of orientation of the searched vehicle and the four tires. The operator begins to drive to the front bumper and tilts the camera 90° to inspect the bumper crevasse. Continuing forward, the rocker panel is kept at the left side of the display. Each time a crevasse or suspicious area is located the operator will hover ODIS around the area until inspected. A sense of orientation must be established before beginning any detailed search. Neglecting a portion of the car was a common error before these procedures where setup and in the early stages of training. The front bumper crevasse is inspected, ODIS rotates 180°, and the same inspection is performed with the right rocker panel and the previous inspection area within the Field-of-View (FOV).

An objective of the LOE was to demonstrate ODIS's effectiveness over inspection mirrors. This task was accomplished by establishing the three testing stations mentioned above. Operators remained at their assigned test area for a complete iteration. Whether the vehicle was rigged with a stimulant was left undisclosed to the MPs and guards. The objective of the NLOS versus LOS was to understand the more effective approach. Initially, the NLOS and LOS seemed to each have pro's and con's. However, the thought of LOS having an advantage because orientation could be determined easier was proven invalid. This was probably due to the pleasant working conditions in NLOS: a large TV monitor over 4" LCD display, air-conditioning versus Missouri's August weather, and controlled ambient lighting. These external factors undoubtedly influenced the general consensus: Soldiers NLOS performance was superior as inspection time was lower, and the detection rate was greater. The only apparent advantage of the inspection mirror over ODIS was the inspection time—a factor overcome by increased ODIS usage.

ODIS demonstrated a clear-cut advantage over the inspection mirror at night and in rain. Both conditions diminish visibility of the inspection mirror to near blindness, as we experience in a torrential rain conditions on the night of August 13, 2002. Every inspection mirror inspection failed in the rain at night, while ODIS remained at its normal detection rate. Raindrops added to the problem by scattering the light source and reducing visibility (Figure 10).

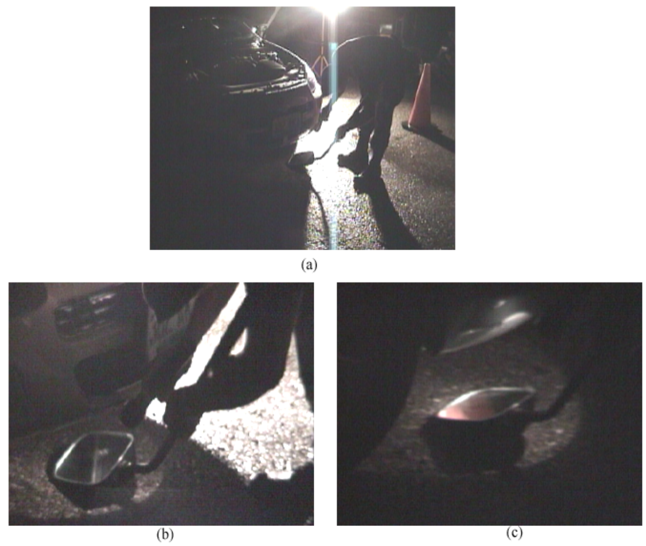

Figure 10. Inspection Mirror at Night. (a) Soldier using flashlight, (b) & (c) View of mirror with use of flashlight.

The ODIS counterexample of improved visibility and lighting is shown in figure 11. The superiority of the

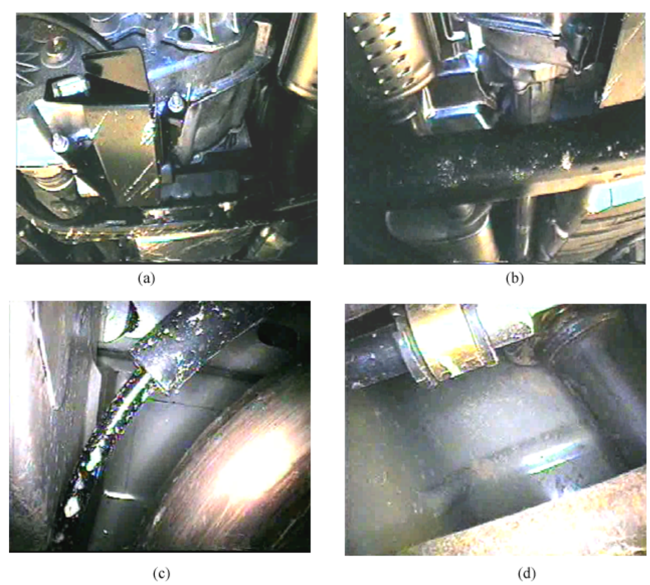

Figure 11. ODIS Under Vehicle View at Night.

ODIS lighting and maneuverability is demonstrated in this under vehicle compilation. The inspection mirror limits the searchable area by forcing the operator's viewpoint to be angular. The added flexibility of the ODV ensures all crevasses are searched. Having the active lighting of an ODIS is important especially when a bomb is concealed in the dark vastness of a vehicle. In this case the simulant is an example of a pipe bomb beckoning to be overlooked by the inspection mirror enclosed in an Army green pipe with a yellow igniter switch at the end (Figure 12).

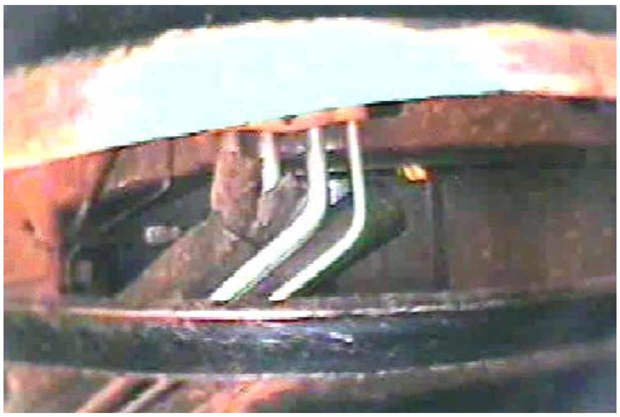

Figure 12. Pipe Bomb Simulant at Nightfall.

Two of ODIS's supplemental payloads were used in the experiment: infrared thermal imager (Raytheon 2000AS), and a radiological detector (Electronic Personal Dosemeter EPD Mk2 by Siemens). Of the three sensors, data collection could only be attained from the radiological detector using a CS-137 source at a detection level at 3 above background. The radiation source could be safely shielded, while a chemical source of G or H nerve gases (CW agents) couldn't be safely handled without exposure to personnel. Six iterations were conducted using two vehicles: a GOV van, and a POV mini-van. The concluding results were a 100% detection of the Cesium source. Figure 13 depicts the GOV van used in the radiation experiment with the source located in the back shielded by 6 inches of tin.

Figure 13. ODIS Exiting a Van Rigged with a CS-137 Source (located in rear).

Overall, the ODIS FLW LOE was a great success. The test was a reassurance ODIS could be implemented successfully at a state-of-the-art facility such as FLW. Valuable feedback from the soldiers and DoD guards was gathered. Desired enhancements (i.e. lighting and video reception) and aesthetics will be evaluated for future modifications. A compilation of the field data found two important conclusions: 1) average inspection time generally improved with operator experience and 2) ODIS detection was superior over inspection mirrors especially during night operations. Operator experience started the first day at a 7% detection rate and rose to an average of 55% the final days of testing. With the complexity of a vehicle and the limited search time these results were acceptable. The factor clearly demonstrated ODIS's superiority over the inspection mirror in the time-of-day calculations. Night inspection mirror calculations were at 13% for normal ops and well below for the added rain factor. ODIS's NLOS calculations were significantly higher at a 56% detection rate.

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CONCLUSION

Robotic technology research, previously focused on the Objective Force and Future Combat System (FCS), can and should be applied to current national priorities. Soldiers and civil authorities are in need of tools to help them safely complete their missions. Partial solutions are acceptable if they reduce risk, without significantly impacting manpower requirements. Incremental improvements to the technology should be prioritized with user input as a driving function. Aggressive development strategies, such as spiral development, lead to cost effective near-term tools that can reduce risk to first responders and force protection personnel. User involvement is critical. Researchers and developers must establish a relationship with the user community that facilitates frequently interchange of ideas.