Robotic Inspection for Vehicle-Borne Contraband

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ABSTRACT

Vehicle-borne smuggling is widespread because of the availability, flexibility and capacity of the cars and trucks. Inspecting vehicles at border crossings and checkpoints are key security elements. At the present time, most vehicle security inspections at home and abroad are conducted manually. Remotely operated vehicle inspection robots could be integrated into the operating procedures to improve throughput while reducing the workload burden on security personnel. The robotic inspection must be effective at detecting contraband and efficient at clearing the "clean" vehicles that make up the bulk of the traffic stream, while limiting the workload burden on the operators.

In this paper, we present a systems engineering approach to robotic vehicle inspection. We review the tactics, techniques and procedures to interdict contraband. We present an operational concept for robotic vehicle inspection within this framework, and identify needed capabilities. We review the technologies currently available to meet these needs. Finally, we summarize the immediate potential and R&D challenges for effective contraband detection robots.

Keywords: contraband, mobile robots, physical security technology

1. INTRODUCTION

Vehicle-borne smuggling is widespread because of the availability, flexibility and capacity of the cars and trucks. The contraband can be hidden in a safe location prior to border or checkpoint crossing. Smugglers use inconspicuous passenger cars and light trucks in the hope of slipping through security by merging with the traffic stream. They use cargo trucks in hopes of large profits with single operation. The contraband may be concealed in a container and placed in a trunk or luggage compartment, or hidden within the body of the vehicle. Contraband items include illegal narcotics, weapons, explosives, illegal aliens, and legal but untaxed goods.

Figure 1: Contraband Found In Vehicles at Border Crossings

Inspecting vehicles at checkpoints and border crossings are key elements of physical security. At the present time, most vehicle security inspections, both at home and abroad, are conducted manually. Figure 2 shows a typical border crossing initial visual inspection.

Remotely operated vehicle inspection robots could be integrated into the operating procedures to improve safety of the security personnel. The robotic inspection systems must be effective at detecting contraband. They must be efficient at

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1. REPORT DATE **29 MAR 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**	
4. TITLE AND SUBTITLE **Robotic Inspection for Vehicle-Borne Contraband**		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) **Gary Witus; G. Gerhart; W. Smuda; H. Andrusz**		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA Turing Associates, 1392 Honey Run Drive, Ann Arbor, MI 48103**		8. PERFORMING ORGANIZATION REPORT NUMBER **15682RC**	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM/TARDEC**	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) **15682RC**	
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**			
13. SUPPLEMENTARY NOTES **The original document contains color images.**			
14. ABSTRACT			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **SAR**	18. NUMBER OF PAGES **9**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

clearing the "clean" vehicles that make up the bulk of the traffic stream. They must not impose excessive workload burden on the operators.

Figure 2: Visual Inspection At Border Crossing

Robots are being used on a limited scale in current military operations. A variety of different robots designed for explosive ordnance disposal (EOD) have been fielded. These sturdy robots are designed to drag or carry suspected IEDs, and to field disrupters destroy IEDs. These robots are assets of bomb disposal squads and are used primarily to dispose of IEDs once they have been found. Although not originally intended for vehicle inspection, they have sometimes used for this purpose.

The ODIS robot, fielded in 2003, was designed for vehicle underbody inspection as a dedicated physical security asset. ODIS is a highly maneuverable robot able to translate and rotate independently. This inherent maneuverability makes ODIS an easy-to-use platform for vehicle inspection. In its initial configuration, ODIS reduced the exposure of security personnel to the particularly onerous and hazardous job of underbody inspection (see figure 3). Modifications to ODIS to put the camera on an extensible mast to look in passenger compartments and truck beds (see figure 4) were requested.

Figure 3: Truck Underbody Inspection

Figure 4: ODIS Robot

In this paper, we present a systems engineering approach to robotic VBIED inspection. We review the tactics, techniques and procedures to interdict contraband. We describe an operational concept for robotic vehicle inspection within this framework, and identify needed capabilities. We review the technologies currently available to meet these needs. Finally, we summarize the immediate potential and R&D challenges for effective vehicle inspection robots.

2. TACTICS, TECHNIQUES AND PROCEDURES

Vehicle inspection is a sequential process beginning with checking the vehicle's access decals and driver's ID, proceeding to simple visual observation of the passenger and cargo area, to basic invasive physical and visual search, and finally to comprehensive vehicle search. At each stage the inspector can clear the vehicle through the checkpoint, decide to initiate the next stage of inspection, or quarantine the vehicle. As a point of reference, the Army's checkpoint inspection time goals, as of 1993, can range from 10 to 20 seconds to 5 minutes for a comprehensive vehicle search [1].

In simple visual observation the inspector observes the behavior of the driver and passengers, examines the exterior of the vehicle, and looks in through the windows for indicators of contraband. In basic physical and visual search inspection, the driver is asked to perform certain operation functions and then exit the vehicle (see figure 5). Comprehensive inspection is a further stage of invasive inspection in which parcels, loose obstructions, interior barriers and components are moved or removed to search for contraband [2].

Figure5: Vehicle Internal Search

Driver reaction indicators are "flight or fight" manifestations including refusing to make eye contact, shaking and other observable physiological action. Vehicle indicators include evidence of new body work, new paint jobs or interior features.

In addition to direct visual inspection and inspection with canines (when available), inspectors use the "mirror on a stick technology" to look under vehicles and on top of trucks during basic physical and visual search (see figure 6).

If mobile robots, under remote operator control, are able to perform effective visual and physical inspection, and deploy advanced contraband detection technologies with capability approaching that of a canine team, this would reduce manpower by eliminating the specialty positions of dog handler and explosive detection technology equipment operator. Since canine detectors can only work two hours per day, mobile robots with effective detection technologies could significantly increase the availability of advanced detection capabilities.

Figure 6: External inspection with mirrors

3. OPERATIONAL CONCEPT AND DESIRED CAPABILITIES

This section describes a notional sequence of events in which a robot is used for remote inspection as an alternative to close-contact human and canine inspection. The scenario provides a basis to infer desired robotic capabilities. A robot that is able to perform some, but not all, of the actions described in this scenario could still make a significant contribution to physical security.

At fixed checkpoint operations, the robot operates out of a "dog house" off to the side near the checkpoint gate and is controlled by an inspector in a protective bunker 300 meters or more from the checkpoint. In roving security operations, the robot is deployed from a security vehicle that also serves as the inspector's base of operations. *The operator and robot need reliable high-bandwidth communications.*

The inspector performs several functions. The inspector examines images from the robot for contraband indicators. He also directs the robot in its maneuvering and sensor deployment around the vehicle. These two functions are closely interlinked: the inspector decides what he wants the robot to do based on what he sees in the images and in the output of the robot's other sensors. The inspector weighs the evidence and makes the decision to clear the vehicle or to declare

that contraband has been found. Visual inspection, weighing the non-visual evidence, and directing the robot need to be performed by one inspector, not fragmented between and operator and an inspector. *The interface and control procedures need to have a low workload burden so that the inspector can both control the robot and examine imagery.*

When an incoming vehicle pulls up to and stops at the checkpoint gate, the robot moves from its "dog house" to the front driver's side and positions its camera to view the vehicle ID tags on the windshield. The robot asks the driver to roll down the window and show his picture ID. The camera zooms and focuses on the picture ID, then on the driver's face. *The inspector needs to be able to talk and listen to the driver. The inspector should be able to read vehicle ID tags, read the driver's name on the ID, and compare the picture ID to the driver's face from the camera imagery.*

If the inspector decides to pass the vehicle, the robot thanks the driver for his cooperation, and then returns to its "dog house". Otherwise the inspector -robot team begins external visual inspection.

The robot focuses its camera on the license plate to cross-reference it with the vehicle ID and the driver's name. The robot positions its camera and microphone to observe the driver and passengers for behavioral indicators. The inspector directs the robot to maneuver and deploy the camera to look for external indicators of vehicle modification as previously noted. It looks through the windows into the passenger compartment for obvious explosives, for tarps or coverings or packages that could conceal explosives. *The robot should be able to see into the passenger compartment.*

If the inspector decides to pass the vehicle, the robot thanks the driver for his cooperation, and then returns to its "dog house". Otherwise the inspector -robot team begins basic physical and visual inspection.

The robot asks the driver to turn the headlights, brake lights and turn signals on and off. The robot asks the driver to turn off the engine, open all doors and hoods, and step out of the vehicle. If the vehicle is a truck with a ramp to access the cargo compartment, the robot asks the driver to extend and lower the ramp.

The inspector conducts a more thorough visual inspection. The robot deploys the camera to visually examine the engine compartment, passenger compartment, and trunk or cargo area for exposed contraband, packaging that might contain contraband.   The robot examines the underbody for unusual packaging, and elevates the camera and look down into the bed of a trailer or pickup truck. *The robot needs the ability to maneuver and deploy its arm within the confines of vehicles with open doors. The robot should be able to look inside compartments, on the roof and under the vehicle. The robot arm needs to be able to move objects to expose potential contraband.*

The robot deploys an detector for traces of contraband that may have been transferred to the vehicle exterior. It inspects the handles of the door, hood and hatch and areas where someone might have placed their hand when closing the door or hood. It inspects steps or ramps where trace contraband may have been transferred on shoes during loading. *The robot needs a trace contraband sensor and arm control with depth perception to position sensor at the appropriate distance and orientation to the surface.*

The robot employs a density sensor to check for possible contraband in the door panels, bumpers, tires, roof, fuel tank, and other hollow areas where contraband could be packed. The robot sweeps the sensor exterior to detect variation in the density behind the surface that indicates concealed objects. Absolute readings for the tires are compared to readings for air-filled tires. *The robot needs a density variation sensor and arm control with depth perception to position the sensor at the appropriate distance and orientation to the surface.*

The robot deploys its density variation sensor check for anomalies in seats and backrests, floor, ceiling and sidewall of the passenger and cargo compartments. The robot moves the doors to check weight, and presses down on seats to check if they feel unusually solid. The robot deploys its explosive trace and vapor detector to inspect items that could conceal contraband and on powders or streaks that could be residue. *The robot arm needs sense mass by providing force-feedback.*

If the vehicle is a cargo truck or semi-trailer with an access ramp, the robot enters the cargo area to inspect the interior. It employs its various sensors on cargo packages and potential false compartments on the front, sides, ceiling and floor. *The robot needs to be able to enter and exit the cargo area via the access ramp.*

If the inspector does not expose contraband, but remains suspicious that contraband may be concealed in luggage, crates, etc., the robot asks the driver to open the suspect packaging. Then the robot examines the interior just as it examines the interior of any compartment.

If contraband is found at any point during the search, the vehicle is quarantined. If not is found, the vehicle is cleared to proceed and the robot returns to its "dog house". The robot should be able to recharge its batteries at its "dog house." The battery system has to be able to fully recharge from partial discharge, or the robot begins a recharge only when the batteries are low and only after completing a rapid discharge. Alternatively, when the battery charge is low, the robot alerts the operator to have its batteries swapped out.

4. TECHNOLOGIES AND CURRENT CAPABILITIES

4.1 Communications
Uninterrupted, high-bandwidth communications between the mobile robot and the remote operator is within current commercial capabilities. In fixed checkpoint operations, the operator can have a fiber-optic connection to a wireless relay station at the "dog house." Current 802.11n protocol provides sufficient bandwidth, at ranges up to one kilometer in open outdoor conditions, transmit medium resolution video (640x480) at 20 to 30 Hz, and high-resolution static images (e.g., 2048x1536). Short range wireless high-definition TV networks have been demonstrated and are an area of intense commercial R&D. Operations in and around vehicles could interfere with point-to-point communication. A mesh-network with stations at several locations around the checkpoint gate can provide redundant communication paths for communication between the robot and "dog house." In roving applications in which the inspector operates from a security vehicle, a second robot with a fiber-optic link to the security vehicle can serve as the repeater station. This second robot needs only limited capabilities since it only provides communication relay and possibly provides overwatch video. Maneuvers under and around the target vehicle prevent using a direct fiber-optic link to the robot.

4.2 Interface and control
Teleoperation requires real-time man-in-the-loop attention. At best, the inspector's attention is split between driving the robot and studying the visual input. Teleoperation is the current standard operating mode. Currently, there are various initiatives in simple semi-autonomous behaviors and supervisory control intended to allow the operator to direct the robot where to go or what to do without having to control every action and without having to explicitly define a complex set of goals and constraints. Further development and testing are needed. In particular, semi-autonomous methods are needed to direct complex robotic arm movements, such as sweeping a sensor over a surface.

4.3 Robot maneuverability and mobility
There is a tradeoff between platform maneuverability and the reach of the robotic arm. If the robot can not safely maneuver in close proximity to a vehicle with open doors, then it needs a strong, long-reach arm, which in turn requires a large and heavy base platform (see figure 7). Robotic arms are generally more expensive, less reliable, less durable, and harder to maintain than the base platforms. To the extent possible, we should exploit platform mobility and agility to minimize the requirements for robot arm reach, articulation, strength and dexterity.

Figure 7: Long robotic arm reaching into vehicle

During external inspection, the robot maneuvers in close proximity to the target vehicle. During internal inspection, the robot maneuvers in-between the open doors. The distance between the fully opened front and rear doors of a 4-door car is 24 inches for a compact car. Typical door opening is 30 inches, with the bottom of the doors 12 inches above the ground. If the robot is less than 10 inches high, it can safely maneuver under the open doors. Otherwise, it has to be able to maneuver in a rhomboid space 30 inches on a side with a width of 24 inches. Even with the arm or mast raised, a robot with body height 10 inches or less has considerably more room to maneuver than a robot whose body is more than 10 inches high. Smooth, omni-directional motion is highly desirable for these close-quarter maneuvers. Differential drive (skid-steer) robots run a greater risk of collisions. If the robot is too big to fit in this space, it has to reach into the car from a distance of at least 30 inches.

To inspect the underbody, the robot needs to either go under the vehicle or extend its arm under the vehicle. The height with the mast retracted needs to be 10 inches or less to maneuver under open doors and under vehicles built on a truck chassis (e.g., pickup trucks, cargo vans and SUVs). At 6 inches retracted height, ODIS can go under most passenger cars. To inspect the cargo areas of box trucks and trailers, the robot needs perception, control, traction, and uneven-surface mobility to use the cargo ramps.

4.4 Robotic arm
The robotic arm is used to deploy cameras, speaker systems, and other advanced technology sensors. The robot arm is also used to move objects that could be concealing IEDs or indicators of IEDs. It also functions as sensor with force-feedback to "feel" the mass of doors and the stiffness of cushions.

The robot needs to be able to elevate the camera to look for vehicle tags on the windshield and in the driver's window (4 feet for a passenger car, 5 feet for a light truck, and 6 feet for a semi-tractor cab). To inspect the roof, the robot arm or mast needs to elevate the camera to a height of 5 feet for a passenger car, 6 feet for a van or light truck, 8 to 12 feet for a moving van box truck, and 14 feet for a semi-tractor-trailer.

A simple variable-height mast with tilt actuation for the camera is sufficient for external visual inspection and limited internal visual inspection. Additional articulation is needed to position the camera to look around inside vehicle compartments, to deploy advanced sensors that have close tolerances on the distance and orientation relative to the object or surface to be inspected, to move objects that might be concealing contraband, to test if seat cushions are soft or solid, and to assess whether a door is unusually heavy.

To examine the interior, the robot needs to be able to reach into the back seat of a 2-door car, and from the backseat doorway into the third row of seats in an SUV. To reach over the hood and roof to position the density variation sensor, the arm needs to be able to extend vertically to the height of the vehicle, then horizontally half the width of the vehicle plus the horizontal distance from the robot to the vehicle. The half-width of typical vehicles is 3 feet for passenger cars and trucks and 4 feet for large trucks.

Current mobile robot arms have grippers are capable of moving tarps and other light objects that might conceal IEDs. Some mobile robot arms have 60 pound lift ability and can move cargo. Others have only 5 pounds of lift ability and can move tarps and blankets, but not cargo. It remains to be determined whether current robot arms can take out a spare tire to check that space.

Current perception and control systems for robot arms on military robots are suitable for a variety of tasks, but not for tasks requiring good depth perception or fine motor skills [3]. Sandia National Laboratory tested two robots with seven degree of freedom arms in a variety of tasks, e.g., sweep an area with a standard hand-held mine detector, defuse anti-tank and anti-personnel mines, remove trip wires using standard hand-held cutting tools, place an explosive charge, place an EFP charge, place a breaching frame, aim a gun-type weapon, emplace perimeter sensors, remove a tarp from a suspicious package, open the door to a building, open the door to a truck, scoop a soil sample into a vial, insert a temperature probe into the ground, replace a chemical trace sampling wheel, inspect an object with a handheld Chemical Agent Monitor, place and retrieve liquid sampling papers, and deploy a handheld radiological sensor.

To employ chemical detectors, the perception and control system for the robotic arm needs to measure the distance to the surface and the orientation of the surface, and point the sensor tip or probe at the suspected trace or vapor source. The ability to measure range and estimate surface orientation are within the current state of the art using ultrasonic sensing, stereo vision, point laser range sensors, and miniature flash lidar cameras. Additional research and development is needed to integrate these systems with robotic arms to deploy the sensors effectively. Semi-autonomous closed loop control and/or augmented reality displays are needed to provide the necessary depth and orientation coordination.

4.5 Visual imaging
The camera should have variable zoom, autofocus, exposure control options. The camera system should provide lighting for night operations and help see into relatively dark interiors. The lighting should be diffuse and offset from the camera to minimize glare. The inspector should be able to switch between spot metering and center-weighted metering modes, or exercise manual exposure control. Center-weighted metering is used to obtain balanced exposure over the full field of view. However this can underexpose the center of the image when the central area is dark, e.g., the interior of a

passenger compartment or the underside of a vehicle when the outside is in the field of view. In these cases, spot metering is appropriate.

The minimum number of pixels on target to read a printed character (assuming standard 5:3 height-to-width aspect ratio and 5:1 height-to-stroke-thickness ratio) is 10-by-6 pixels. Below this resolution, aliasing and blur degrade legibility. At a resolution of 15-by-9 pixels, characters are well-resolved. For a camera zoomed to 0.05 degrees per pixel, 5mm by 1mm lettering (typical of ID tags) is legible at 57cm. An ID picture, 2cm from ear-to-ear, is barely recognizable at this distance and resolution, but is satisfactorily recognizable at twice the resolution.

Commercial digital cameras and camcorders provide all the needed imaging capabilities. Commercial software is readily available to operate the cameras and camcorders from a PC with a Firewire or USB-2 interface. Additional user interface software development is needed to give the inspector the control he needs, without burdening him with unnecessary complexity. Digital cameras and computer video are rapidly evolving commercial markets. It is possible that new products may soon be commercially available that are well suited to this application.

4.6 Talking and listening
Two-way speaker systems suitable to integrate onto a mobile robot's arm or mast are commercially available with directional microphones to listen to driver's breathing and speech patterns. Aside from visual observation, "listening" was rated in a survey-study as the function that would be performed most frequently [4].

4.7 Chemical trace and vapor detector
A number of different handheld chemical trace and vapor detection systems, exploiting different technologies, are currently commercially available. Other technologies are under development. Some of the systems are able to detect vapors as well as physical traces, although vapor detection is highly dependent on wind, rain and dust conditions. Anything more that a cursory mention of the various technologies is beyond the scope of this paper. References [5] and [6] published in 2004 provide relatively recent surveys. However, new technologies and new implementations have been developed since these papers were published, including handheld Raman spectroscopy, miniature mass spectrometry, and laser-induced breakdown spectroscopy.

Mass spectroscopy is the leading laboratory method for chemical analysis. Recent developments in miniaturized mass spectroscopy equipment and improvements in pre-concentrators may lead to a viable implementation for the mobile robot application. Handheld thermo-redox electrochemical analyzers for narcotic detection are commercially available. A variety of handheld chemical vapor classifiers based on ion mobility spectrometry (IMS), also known as plasma chromatography, are commercially available. A handheld Raman spectroscopy unit is now commercially available with high sensitivity and able to classify surface traces and packaged substances. Unlike the previously mentioned systems, Raman inspection can "see" through plastic to classify substances without collecting any molecules. This technology does not currently analyze vapors, although efforts to incorporate surface deposition techniques for surface enhanced Raman spectroscopy are in progress. Portable laser-induced breakdown spectroscopy units are now available, but they are bulky and cannot currently be applied in situ. Instead a sample must be collected and put in the analysis chamber.

The chemical trace and vapor detectors require that the detector be pointed at the suspected area, be positioned close to the surface, and be approximately normal to the surface. The commercial units are designed for handheld use, and may require modification for robotic employment

4.8 Density variation sensor
Density variation sensors are intended to detect objects hidden in hollow compartments, e.g., door panels, or hidden inside other objects, e.g., seats and fuel tanks. Three different sensor technologies are currently available as handheld systems: gamma ray backscatter sensors, millimeter wave near-field ground penetrating radar sensors, and ultrasonic sensors. Gamma ray backscatter sensors can penetrate thin metal but have limited range, and require a radioactive source with lead shielding. Millimeter wave sensors are blocked by metal, but have long range and good sensitivity through non-metalic substances such as seat cushions, bales of fabric, etc. Millimeter wave sensors are not effective for external inspection of the car body because the metal blocks the electromagnetic waves, but the can examine the door panels, sidewalls, ceiling, etc. effectively from the inside of the vehicle during invasive inspection. They are also effective at examining wooded cargo crates. Ultrasonic sensors are particularly effective at detecting objects hidden in fuel tanks, a situation in which the other two technologies fail. Reference [7] provides a review of these and related technologies as of 2001.

These methods work by sweeping the sensor across an area and detecting variation in a signal. In most cases the sensor output is an audible tone that changes frequency. A new implementation of the millimeter wave technology uses a more focused beam and synthetic aperture processing to produce an image of the hidden object. The commercial units are designed for handheld use, and may require modification for robotic employment.

5 CONCLUSIONS AND RECOMMENDATIONS

Visual inspection is the primary means of detecting contraband. The essential requirement for a robot is to deploy a capable camera system on an arm or mast so that the operator can examine vehicle decals, drivers' ID, driver's behavior, and contents of the passenger and cargo compartments. In addition, the robot needs a 2-way speaker system with a good microphone to talk to the driver and listen to his speech and breathing patterns. The technology is well within the current state-of-the-art.

An ODIS robot with a capable camera system (tilt actuation, zoom actuation, exposure control and active lighting) mounted on a capable arm or mast, would be able to perform most of the external visual inspection. The arm or mast would need to elevate to 4 feet to view passenger car interiors, 6 feet for truck cab interiors and passenger car roofs, 8 to 12 feet for van and medium truck roof, and 14 feet for all truck roofs. The height with the mast retracted needs to be 10 inches or less to maneuver under open doors and under vehicles built on a truck chassis (e.g., pickup trucks, cargo vans and SUVs). At 6 inches retracted height, ODIS can go under most passenger cars.

A simple camera on a mast can look into open doors and cargo areas during invasive vehicle search, but cannot insert the camera into the passenger or cargo compartment to look around. The camera could be inserted into the compartments if it were mounted an arm. A pan-tilt head camera mount on a 24 inch horizontal boom attached to a vertical mast would be adequate to insert the camera into vehicle compartments, but would not provide the benefits of a robotic arm.

Effective robotic arms capable of positioning a camera for exterior and interior inspection, with a gripper to move obstructions for better viewing have been fielded. The seven degree of freedom arms have the mechanical ability to deploy the advanced technology sensors, but, as currently integrated, lack the necessary depth perception and control. R&D is needed to integrate distance and surface orientation sensing with automatic robot arm control to deploy surface sensors without overburdening the operator.

At the current time, there is no "magic bullet" contraband detection technology. Most chemical trace detectors only work if traces of the substance have been transferred to some accessible surface and they are pointed at the trace (the exception is Raman spectroscopy which can detect through translucent packaging). Vapor detection sensors only work if the packaging is such that vapors are leaking, and if they are close enough to the source. Technologies to "see" into hidden compartments all have different limitations. A collection of different advanced sensors is needed for comprehensive inspection. Cumulative cost and the burden of fielding a robot with a multitude of sensors are logistical concerns.

Currently available advanced sensors are packaged for handheld use. We need to either re-package the sensors for robotic use, or develop robotic "hands" capable of employing systems designed for human hands. Improvements in robot arm technology are needed to reduce cost and improve maintainability, without sacrificing reach, strength and articulation. Haptic force-feedback to the operator needs to be integrated into the arm control systems.

There are a variety of advance sensing technologies that could be of benefit in contraband detection. There are two fundamental unanswered questions for all of these technologies:
    (1) Are they effective in operational conditions?
    (2) Can they be effectively employed remotely via a robotic arm?

Independent field testing of the various chemical trace/vapor detection systems, of density variation sensors, and detonation electronics sensors are needed to assess effectiveness in operational conditions with realistic contraband concealment. Field conditions and operational performance requirements are not well defined. At the present time, we lack standards for developmental and operational testing.

DISCLAIMER

Publication of this paper does not constitute endorsement by an agency or official of the U.S. Government.

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