ROBOTIC SYSTEMS for DEPLOYING SENSORS to DETECT CONTRABAND in CARGO

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We find all known contraband detection sensors and instruments to be in some important way imperfect. However, we find that some instruments that use penetrating radiation backscattering for bulk solids detection are viable *in the hands of an expert operator/inspector*. With this perspective we present a scenario for a staged program to expand and enhance existing detection capability: (1) deploying existing penetrating radiation backscattering instruments via robotic machines; (2) optimizing instrument sensitivities for deployment by robotic machines; (3) augmenting the penetrating radiation backscattering approaches with complementary sensing technologies; (4) providing a picture- and graphics-oriented human interface; (5) providing database and statistical tools to assist decision making. To illustrate concretely how this system concept might be implemented we describe the suction-cup-footed, eddy-current- and vision-sensor-carrying robot we are building and evaluating for attacking the problem of inspecting passenger aircraft for pressurization-depressurization induced radial cracks around rivets and corrosion induced delamination of lap joints.

INTRODUCTION

Methods for finding contraband narcotics in commercial shipping containers by directly detecting the narcotics fall into two categories, vapor or particulate detection and bulk detection. Vapor or particulate detection (for example, plasma chromatography) is inadequate because all such methods are child's play to evade by packaging the narcotics in plastic bags, metal cans, etc. In contrast, several bulk detection instruments, e.g., neutron and γ-ray backscattering, have been demonstrated to have enough sensitivity, selectivity, probing range, and immunity to evasion to be practical narcotics detectors. The most promising method is hand-carried γ-ray backscattering.

However, hand-carried γ-ray backscattering instruments fall short of the needs for radiation safety of inspectors, instrument portability, ease of operation, and clarity of interpretation. The radiation safety requirement limits the intensity of the source that can be used, forcing design compromises that reduce the sensitivity. Furthermore hand-carried instruments fundamentally suffer from functional problems such as low throughput, spotty coverage, and inconsistent interpretation. In this paper we outline a program whereby instruments based on a bulk detection method that uses penetrating radiation that is hazardous to enforcement personnel, in particular neutron and γ-ray backscattering, can nevertheless be used safely and effectively.

Several methods that use penetrating radiation are feasible in theory and in the laboratory, but hand held instrument designs sacrifice sensitivity to meet safety requirements. These degraded instruments have nevertheless been shown to be viable in the hands of some especially knowledgeable and enthusiastic inspectors who have developed and begun to use effective operating protocols.

In the context of these observations, we outline a five component program:

I Deploy existing neutron and/or γ-ray backscattering instruments via robotic machines that operate at the skill level of the most expert inspectors. Thus we improve the effectiveness of existing instruments by:

- applying a consistently high level of operating expertise equivalent to the level now practiced by the most capable human inspector now in the field
- improving throughput, inasmuch as robots work with unfailing consistency without taking off for meals, sleep, sickness or vacation
- increasing acceptability to the inspection work force by eliminating radiation exposure.

II Optimize neutron and/or γ-ray backscattering instrument sensitivity for deployment by robotic machines:

- remove instrument design compromises previously made to minimize radiation exposure to the operator of a hand held instrument
- design the instruments for maximum effectiveness in contraband detection

  Taking into account knowledge of container materials and construction, physical properties of the anticipated contraband types, and the operating methods employed by drug smugglers, we can select the instrument source radiation energy or spectrum, the instrument detector physical and electronic filtering, and other engineering parameters to maximize overall instrument effectiveness for the contraband detection application.
- safety interlocks ensure that the high source strength instruments would cease to emit radiation any time humans are in their vicinity.

III Augment the neutron and/or γ-ray backscattering approach with complementary sensing technologies and sensor fusion data handling methods for disambiguation:

- add other bulk solid sensing modalities to reduce the false alarm rate, resolve borderline detections, etc

  If a dual neutron backscattering/γ-ray backscattering instrument is employed, sensor fusion methods allow synergistic operation wherein the whole becomes, effectively, greater than the sum of the parts.
- add vapor detecting sensor modalities for situations in which penetrating radiation based bulk detection is unsuitable, e.g., for endpoint searching by hand, for sniffing the garments of suspected offenders, etc
- add a suite of navigation, location, and manipulation sensors, coupled with machine vision systems to provide a multi-sensor modality image and interpretation of the container under inspection.

IV Provide a picture- and graphics-oriented interface through which the inspectors remotely supervise the robotic machines and instruments, thus improving detection *system* performance by:

- depicting the primary data in a natural form amenable to rapid and accurate interpretation by people and computers,
- providing an integrated representation of multiple data types synergistically contributing to a high detection rate and a low false alarm rate,
- taking optimum advantage of the respective unique strengths of people, machines, and people and machines working together.

V Develop and provide state-of-the-art database management and statistical analysis tools to aid inspection personnel in:

- making strategic and tactical decisions about deployment of finite human and machine resources,
- interpreting instrument responses,
- identifying the most suitable strategies and tactics for physical seizure of the contraband.

NEED FOR ROBOTICS AND AUTOMATION

The purpose of this paper is in part to advance the concept that the functional problems of existing methods can be overcome by using computer control of the machinery to automate the boring, uncomfortable, time consuming and error prone aspects of the inspector's job. We also suggest that at the same time the safety shortcoming of existing instrumentation can be overcome by using remotely operated machinery to separate the inspector from the instrument.

Mobile robots similar in mechanical complexity, remote controllability, and degree of local autonomy to those that will be needed for contraband detection are already in use in other applications. We will discuss one of these applications, aging aircraft inspection, in depth later.

The flexibility and extensibility of the robotic approach, illustrated by the ease with which these concepts can be transferred across applications, will permit systems built along the lines discussed here to keep up with evasive maneuvers that will emerge in narcotics smuggling technology as the detection technology improves.

Robotic approaches to deployment of established detection technology would wisely be the first step of a broad program to make systematic improvements in the effectiveness of a range of contraband import, export, and domestic shipping policing efforts. These might include, in addition to narcotics, substances such as explosives and ammunition, special nuclear materials, strategically important metals, as well as restricted agricultural products, electronic components and assemblies, etc.

The application of similar technology to a variety of problems that share the need to make "difficult measurements in difficult environments," each with unique features that can be individually addressed in a common framework, presents an opportunity for synergistic technical and economic improvement across the board. The last section of this paper concretely illustrates the system architecture by outlining its implementation in the aging aircraft inspection application, and by comparing and contrasting the aging aircraft inspection and the contraband detection applications.

SYSTEM FEATURES

Several mechanical design concepts for mobile teleoperated and semi-autonomous manipulators aimed specifically at the narcotics-in-cargo-container threat are sketched in Figure 1. The "side sucker" design, using suction cups to adhere to the exterior of a cargo container, is in the same spirit as the robot (described later) we are building for airplane skin inspection. However, unlike airplanes, cargo containers are often dirty and dented, making adhesion difficult. Thus the "rail rider" sketch, suggesting a mobile car wash, would probably be a preferable technology for an early contraband interception demonstration. With the "rail rider" design we would have the option to deploy at least three instruments simultaneously, one each for the left and right vertical walls and one for the top. If the top rail were to ride up and down on the two vertical rails then the top sensor package could inspect the front and back faces of the container as well. This implementation would easily also accommodate a variety of container sizes.

The mobile robots would be integrated with a suite of proven detection and sensing technologies, using established observation-plus-context based procedures for path planning, guidance, and world model building. A combined color TV and computer graphic human interface would report the instrument's findings via contour maps, special symbols marking suspicious areas, with printed numerical data and appropriate highlighting superimposed on live images of the actual container under inspection.

In one operational scenario a supervisor, working at the display, dispatches inspectors to suspicious

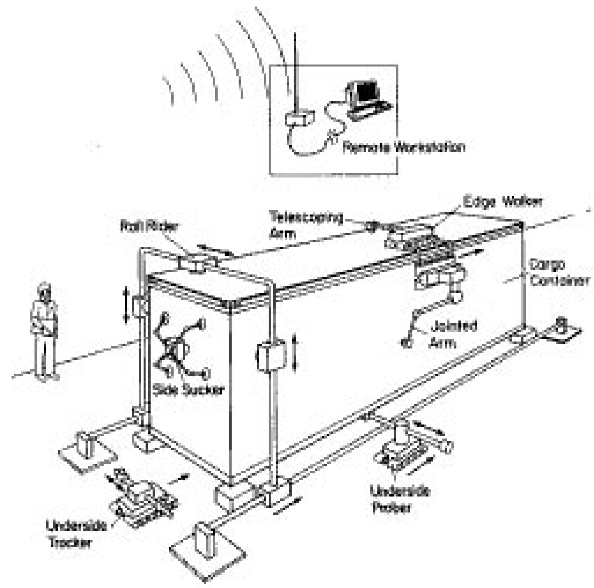

Figure 1. DESIGN CONCEPTS

Several design concepts for robotic manipulators using sensors to inspect cargo containers for contraband narcotics.

containers. The inspectors carry color prints of the display, rapidly guiding them, by images and coordinates, to the suspicious areas of the suspicious containers. They proceed with their own familiar methods of tapping, drilling, unloading, etc, and also have the option of obtaining additional data from the instrument. The immediate localization to a specific area of a specific container might enhance by a hundred or more the throughputs and the seizure rates that are credited to the inspectors. The machines do what machines do best, the tedious, uncomfortable, and dangerous work. The inspectors do what intelligent people do best, flexibly exercising human judgments.

> *The unpredictable and open-ended jobs of final inspection and seizure cannot be automated with off-the-shelf technology. To automate these tasks would take large scale, expensive, risk-laden research programs outside the pragmatic boundaries dictated by the urgent need to rapidly deploy a practical narcotics interception system.*

Cost effective deployment requires being able to predict which containers are most likely to be carrying narcotics, and concentrating the machines and the people on those containers. The inspection technology that we conceive incorporates electronic command, communications, and computing components that will automatically build a performance database. It will be natural to combine this program with research toward improving the statistical and heuristic (artificial intelligence) methods available for using the database to guide resource deployment decision making.

DIFFICULT MEASUREMENTS IN DIFFICULT ENVIRONMENTS

Common concealment strategies in commercial shipping containers include false walls, false fronts, and utilization of structural members designed with enclosed empty space. These common methods are of particular interest because they typically place the contraband in proximity to an outside surface of the container, making single-sided interrogation methods more attractive than they might seem *a priori*.

Detection technologies that have been considered are divided by the government into physical, chemical, and biological means [1]. We find an alternative grouping into vapor or particulate collection based means and bulk interrogation based means more useful for thinking about *interception systems*.

The vapor (or particulate) based group, which includes techniques like mass spectrometry, ion mobility spectrometry or plasma chromatography, gas and liquid chromatography, chemiluminescence, antibodies, and others, require the evaporation or removal of a portion of the contraband material from its hiding place, and its introduction into the instrument. There is generally at most one opportunity to interrogate each molecule before it is buried in the walls of the instrument, dissolved in the vacuum pump oil, or otherwise lost. Vapor and particulate techniques have generally been demonstrated on the relatively large quantities of material found in particulate suspensions, e.g., airborne dust. Whether any of them have adequate sensitivity to detect and discriminate dilute vapors in real world environments is still being debated.

But this debate aside, vapor barriers such as plastic bags and metal cans are just too cheap and too effective for any air sampling technology to be considered seriously. Finding narcotics in cargo containers differs in this respect from sniffing explosives on the persons of terrorists passing through airports: explosives and their carriers are not so easily encapsulated, and body temperature helps to volatilize the contraband.

In contrast, the bulk detection methods, which include x-rays, acoustics, neutron interrogation, neutron and γ-ray backscatter, nuclear magnetic resonance, microwave attenuation, and others, are applicable *in situ*. Neutron based methods are especially difficult to thwart by shielding, and all bulk methods more than compensate for relatively low sensitivity by being able to work with the order of 10^{12} times the number density of molecules that are available in vapor sniffing. They provide the opportunity, because they are generally non-destructive, to improve signal-to-noise by interrogating each molecule many times. For these reasons we consider the bulk detection technologies to be the only serious contenders for general screening applications.

Both single-sided and through-the-container implementations, both with and without imaging, are more-or-less feasible for most of the identified bulk interrogation technologies. Our advocated methodology, the combination of existing detection instruments, optimized for the new deployment method, with robotic mobility, is flexible and extensible with respect to these choices. The five component program we have outlined describes a pragmatic evolutionary path.

The government reports [2] that previous R&D efforts aimed at detection of contraband on or in people, conveyances, mail, baggage, and cargo show no immediate promise of finding specific drugs such as cocaine and heroin in the cargo of full containers. Still it seems clear that some of the backscattering techniques, especially neutron backscattering, and to a lesser but still real extent γ- and x-ray backscattering, show substantial technical promise for *single sided* interrogation to find contraband near the surface of containers. As we have discussed, the weakness of these instruments, even in the restricted scenario of single sided interrogation, is their marginal suitability for deployment as hand held instruments for two essential reasons: *they expose the inspectors to radiation*, and *the inspector has to develop a "rapport" with the instrument* that is improbable given its perceived health hazard.

The possibility of robotic deployment opens up several areas of dramatic improvement:

- the existing instruments, remotely deployed in a computer aided and partially automated scenario, become much more attractive because the perceived health hazard is eliminated;
- the instruments can be optimized, e.g., source strengths increased, and therefore signal-to-noise ratio improved, once mobile robots let the inspectors and the radiation sources stay far apart;
- whether or not the instruments actually are optimized for robotic deployment, the systematic nature of the automated robotic inspection process decreases both the miss rate and the false alarm rate.

In addition, throughput will be substantially improved:

- automated or semi-automated machines operate steadily and continuously;
- one inspector can simultaneously supervise multiple robots;
- inspectors will work primarily in an endpoint search mode, with a very high hit rate per person-hour, in contrast to the present situation where they spend most of their time looking for suspicious containers.

There are numerous additional technical possibilities, for example, some of the robotic machines could be designed for volume inspection (through the container) as well as surface inspection:

- by two sided inspection, by placing source(s) and receiver(s) on two limbs of one machine;
- by coordinated motion of two or more robotic machines working different faces of the container.

CONTRABAND DETECTION SYSTEM REQUIREMENTS

The semi-automated robotic deployment scenario makes a positive contribution to the generally acknowledged requirements for *sensitivity, specificity, portability and transportability, low false alarm rate, safety, simplicity of operation, "in the flow" operation,* and *reliability*

- sensitivity of *any* instrument deployed robotically is enhanced by the systematic and untiring nature of the process, which improves signal-to-noise ratio by decreasing the noise associated with procedural inconsistency and increases the signal by permitting uniform scans at rates that are automatically adapted to the situation pertaining at any moment
- sensitivity is further enhanced if the opportunity is used to optimize the instrument for machine deployment, e.g., relaxation of neutron source strength restrictions
- specificity is enhanced by improved signal-to-noise, facilitating signature analysis, as well as by the ease of incorporation of auxiliary sensors and sensor fusion approaches to disambiguation
- portability and transportability become fundamental features of the approach, i.e., in the robotic deployment scenario the instrument is inherently and integrally part of a mobile machine designed at every level to bring the instrument to the cargo container, and most effectively to scan the cargo container with the instrument
- a low false alarm rate is assured both by the improvements to the physical detection process *per se*, and even more by the filtering, reliability checking, consistency and context cross checking, disambiguation, etc, provided by the computer modeling, analysis, and reporting system
- safety is assured by the physical separation of man and machine, and by conservative programming of the man-machine interaction with numerous software implemented interlocks and limit switches
- simplicity of operation is inherent in the semi-autonomous nature of the system
- all the interactions with the humans are at a natural language communication level, and are thus, from the human perspective, inherently simple
- throughput is enhanced, not because robots are necessarily fast, but because of the robot's perseverance and untiring obedience to the inspection protocol
- reliability is assured by conservative design, and by the relatively low cost of redundancy.

SYSTEM ARCHITECTURE

Our concept is not an instrument but rather a method of deploying existing and future instruments to maximize interception rate and minimize interception cost. We take it as given that one or more existing instruments is at least marginally suitable for detecting anomalies located within a foot or so of the container surface. The design phase for a practical system would include assessment of sensitivity, selectivity, false positive rate, false negative rate, and related technical parameters, in a realistic context subject to the constraints of cargo container inspection more-or-less as it is presently practiced. By using automatic and semi-automatic robotic machines to transport and operate one or more instruments, system functionality, throughput, and safety will raise one or more detection technologies to the realm of practical feasibility.

The system we envision is comprised of four subsystems: *measurement*, *manipulation*, *mobility*, and *monitoring*, integrated in a system that delivers adequate sensitivity, discrimination, reliability and throughput:

measurement: *primary* sensing technologies, e.g., neutron backscattering, interact with the container *per se*, the cargo, and any contraband that may be present; *secondary* sensing technologies, e.g., vision systems, eddy current sensors, etc, discriminate effects relating to the container from effects relating to cargo and contraband; *knowledge based interpretation* integrates sensor data into the contraband detection context

manipulation: precise navigation and motion control relative to the dimensions of the cargo container are essential to localization of suspect regions; scanning of the container surface is generally autonomous, but an inspector or supervisor can intercede to target suspect areas; a knowledge base of container types will aid navigation by facilitating landmark recognition, and it aids discrimination by maintaining sensitivity to anomalies, e.g., backscattering from structural regions that should be empty

mobility: it is crucial that the inspection equipment move to the container, wherever its location; the alternative of bringing containers to a central inspection station is unacceptably disruptive to the normal flow of activities; however there is little impetus to make this activity autonomous, and there would be much technological risk in attempting to do so; mobility is thus directed by inspection personnel, either locally or by teleoperation

monitoring: high level control and command, including dispatch of inspectors to suspect containers, is effected via a high quality visual interface; interaction between a supervisor, the robotic inspection equipment, and the human inspection staff is based on color TV images of containers under inspection with automatic overlaid mapping of sensory data, computer highlighting of automatically detected suspect areas, and the option of the supervisor designating other areas as suspect based on his or her interpretation of the data in context

This system partitioning is illustrated by Figure 2. Additional details of the sensor functions that are required, and the strongest candidate technologies for implementation, are tabulated in Figure 3.

DEPLOYMENT STRATEGY ANALYSIS

We believe that in contraband interception it is a more valuable skill to be expert about when and where to inspect than it is to be expert, with or without "high tech" instruments, at conducting the inspection *per se*. Present inspection target selection methods rely on heuristics whose effectiveness are unmeasured. Were inspection resources unlimited, targeting effectiveness would not be an issue. But the real situation is that there are too few inspectors to physically examine more than a small fraction of the targets. Under these circumstances, *flawed heuristics may be worse than no heuristics*. Powerful statistical and analytical methods could be brought to bear on at least two components of the contraband interception problem: verifying and improving existing heuristics, and systematizing inspection

The 4 M's of Contraband Detection

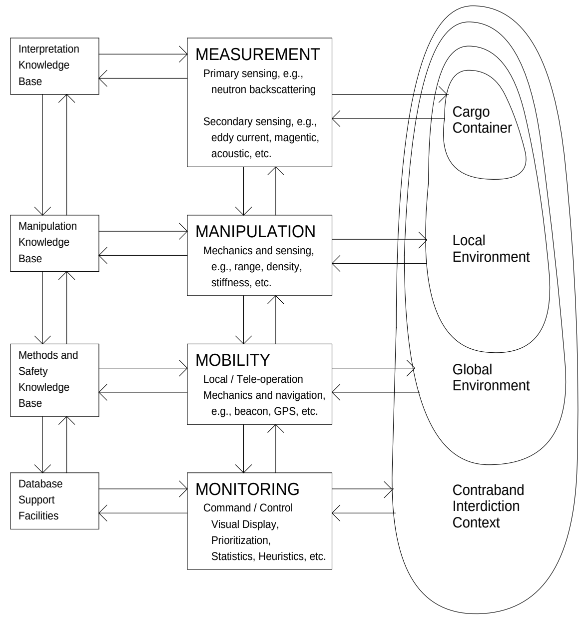

Figure 2. SYSTEM REQUIREMENTS

Hierarchy of Requirements for Contraband Detection System

targeting practice in the context of knowledge of the heuristics. We thus suggest several strategic deployment opportunities:

SAMPLING PROGRAM TO IMPROVE HEURISTICS

Responsible agencies in the short run optimize limited inspection resources (available manpower, essentially) by applying experience and intuition to decide where and how hard to look. Taking a longer term perspective, it might be productive to divert a small fraction of the manpower to *random* inspection, in order to improve heuristics used in the decision process for directed inspection.

APPLYING OPERATIONS RESEARCH METHODS

Mathematical methods for allocation of finite resources, e.g., finding enemy submarines given a limited number of search vessels, or making product mix decisions given a variety of economic constraints would substantially multiply the effectiveness of whatever technological aids, sensors, instruments, or systems, are used for contraband interception.

TECHNIQUES	APPLICATIONS
neutron backscattering γ-ray backscattering x-ray backscattering neutron activation microwave absorption nuclear magnetic resonance	bulk narcotics detection, gross anomaly detection
ion mobility spectrometry gas, liquid, scf chromatography electron capture detection quadrupole mass spectrometry tandem/hybrid techniques biosensors	narcotics vapor and particulate detection, solvent detection, chemical taggant detection
eddy current sensors magnetic sensors acoustic velocity	container wall thickness, structural features
inductive proximity sensors capacitive proximity sensors acoustic proximity sensors optical proximity sensors	instrument standoff, close-in navigation
radio beacons optical (infrared) beacons inertial guidance global positioning system	location, navigation, path planning, world modeling
vision (TV) sound force-torque sensing tactile arrays sensing	teleoperation, visual anomalies, container identification, paperwork verification
optical communication link radio link wire link	communication and control

Figure 3. TECHNOLOGIES AND APPLICATIONS

Sensor Technologies and Applications for Robotic Detecting Drugs in Cargo

KNOWLEDGE ENGINEERING

Close interaction with responsible agency personnel naturally launches an informal knowledge engineering program, whereby the academic and commercial participants acquire practical expertise they then incorporate into the decision making machinery of the robotic inspection tools. A formal expert system building program component might emerge later.

INTERFACES TO EXISTING DATABASES

Integrating the data gathering and decision making machinery of a robotic inspection system with the existing databases of responsible agencies would doubtless increase the immediate and ultimate effectiveness of deployment.

ROBOTICS FOR AGING AIRCRAFT

To illustrate the potential value of robotics for making "difficult measurements in difficult environments" in general, and as a tool for contraband detection in cargo containers specifically, we describe the issues, development, and progress in our FAA sponsored aging aircraft inspection project [3]. A system architecture that integrates *measurement*, *manipulation*, *mobility*, and *monitoring* is essential to both applications, and potentially to numerous others as well. In the case of these two specific applications it is also apparent that many critical hardware and software technologies could be effectively and economically shared.

SYNOPSIS OF THE AGING AIRCRAFT PROGRAM

Aircraft skins inflate and deflate with each cycle of pressurization on takeoff and depressurization on landing. The resulting stress causes several kinds of damage, primarily radial cracks around rivets and delamination of adhesive bonded lap joints. The tendency to delaminate is exacerbated by corrosion. The combination of sea-air corrosion and cycling-induced skin failure resulted in the newsworthy near-loss of an Aloha Airlines flight in 1988.

The problem is addressed by airlines, with the assistance of aircraft manufacturers and the FAA, through periodic inspection of known problem areas on each aircraft type. Close to 90% of skin inspection activity is visual, by inspectors trained for the task, and most of the remaining (instrumented) inspection uses eddy current probes.

Our program, under FAA sponsorship since mid-1991, focuses initially on mobile robots as an inspector’s aid to rivet and lap joint inspection using existing eddy current probes and methods. The robot will carry several (at present four) TV cameras that will be used both for automating manipulation and mobility and for providing the human inspector high quality visual images to assist his or her decision making. Machine vision for flaw detection is planned only in later program phases.

MECHANICAL DESIGN ALTERNATIVES

We considered many approaches to automation assisted eddy current probe deployment, with three main variants: the "car wash", the "cherry picker", and the "window washer". The same considerations, resulting in the same decision, apply to the contraband detection problem. The "car wash" approach envisages a permanent structure through which the airplane or cargo container is towed for inspection; it is too disruptive of other routine activities to be acceptable. The "cherry picker" approach envisages a vehicle with a crane that brings an inspection robot the airplane or cargo container; it too seems unworkable in the crowded hangar environment commercial aviation and the crowded warehouse or parking lot environment of commercial shipping. The "window washer" approach, small mobile robots that maneuver on the outer surface of the airplane or the cargo container, are the only viable alternative in the context of the constraints and priorities. Furthermore small mobile robots may be the only approach that will be acceptable to the human inspectors, who can view them as tools that they control rather than as monsters that compete for their jobs. Thus we adopt the "window washer" approach, illustrated by the cruciform robot sketched in Figure 4.

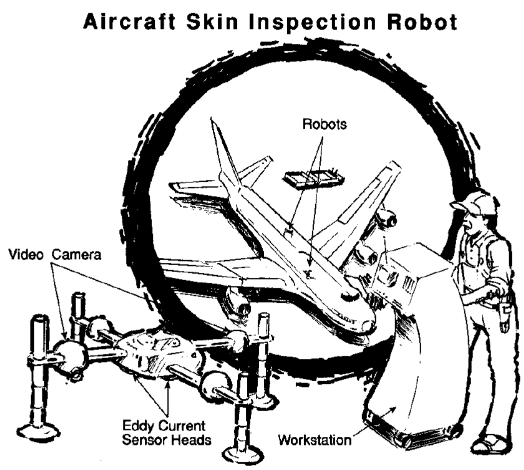

Figure 4. ROBOTIC AIRCRAFT INSPECTION CONCEPT

The design of the robot shown under construction in Figure 5 is tailored to the aircraft inspection application, characterized by the need to move very efficiently along the length of the (more-or-less cylindrical) airplane fuselage, only moderately efficiently around the circumference, and only occasionally skew to these two directions. As suggested in Figure 1, specialized small robots are envisioned for different applications, and different facets of each application. Because the robots are small they can be built with mostly off-the-shelf components, making them relatively inexpensive to design and assemble for specialized applications. The common underlying system architecture for navigation, inspection, operator interface, and database access and entry is the key to flexibility and reasonable cost over the spectrum of envisioned applications.

NAVIGATION

In the aircraft inspection application we plan to achieve the required positional accuracy, the order of 25 µm (0.001") by high precision dead-reckoning over short distances from multiple landmarks, primarily the rivets themselves, each of which will be individually identifiable in the aircraft database. In the contraband detection application the positional accuracy needed is centimeters rather than micrometers (inches rather than mils), and displacement based dead-reckoning augmented by simple sensors or simple edge detecting computer vision algorithms will be entirely adequate.

SIGNAL ANALYSIS AND DATA ARCHIVING

Aircraft skin inspections are now pass/fail. We believe we will be able to make a significant contribution airplane inspection quality and economy by integrating the inspection system with a database system that uses trend analysis to detect incipient problems early, and at the same time decreases the required frequency of inspections by employing crack growth models. Contraband detection only needs to be pass/fail, i.e., whether a given container does or does not contain contraband is at first glance independent of whether or not it contained contraband on any earlier occasion. On the other hand, examining this assumption in more detail, it becomes apparent that database and analysis software that signaled changes in the appearance (in either visual or instrumentation domains) of individual containers could be a powerful tool for alerting inspectors to container modifications that suggest that a false wall, a hidden compartment, etc, has been added since this container last passed through the system.

IMPLICATIONS FOR CONTRABAND INTERCEPTION

There are clearly substantial parallels between our now architecturally well developed, physically under construction, robotic system to improve aging aircraft inspection and the robotic systems we hypothesize here as potential aids to contraband interception programs. The unifying theme of developing technologies for *making difficult measurements in difficult environments* applies to numerous domains, of which aging aircraft inspection is at the moment — and perhaps only at the moment — in the forefront. Composing robotic systems for deployment of anomaly detecting instruments out of modules for *measurement*, *manipulation*, *mobility*, and *monitoring* appears to be useful both conceptually and practically. This decomposition guides us in thinking systematically about new application

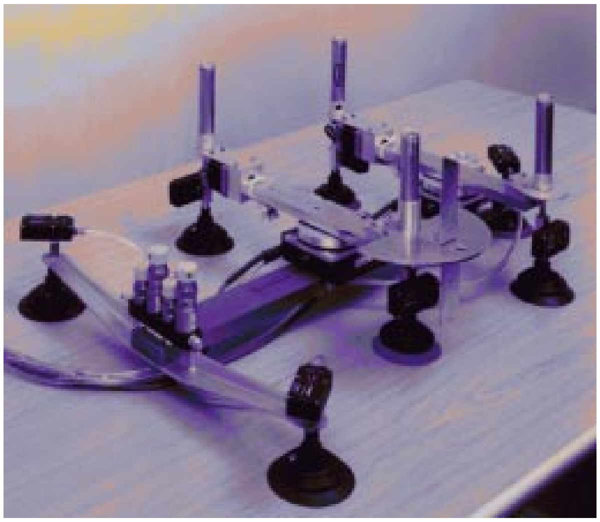

Figure 5. PHOTO OF ROBOT UNDER CONSTRUCTION

domains, and effectively facilitates exchanging demonstrated implementations between diverse domains. This upbeat conclusion notwithstanding, we caution that it would be misguided indeed for the contraband interception community to believe that it can now close its purse (or, more accurately, keep it closed) and wait for the airplane inspection community to hand over tools that it can apply directly to its problems.

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REFERENCES

1. J. Bowden, C. Cassapakis, R. Hancock, V. Verbinski, ‘‘Contraband Detection Technologies’’, Contract Report TC 81-4, Department of the Treasury, U.S. Customs Service, R&D Office, April 1984.

2. A. Brandenstein et al, ‘‘BAA #90-04’’, DARPA Broad Agency Announcement.

3. ‘‘Feasibility of Navigation (Guidance) of a Measurement Unit Over the Surface of an Aircraft’’, Final Report of Contract G03190014.