# Robotic Systems for Deployment of Explosive Detection Sensors and Instruments

M. W. Siegel
The Robotics Institute
School of Computer Science

in cooperation with

A. M. Guzman and W. M. Kaufman
Carnegie Mellon Research Institute

Carnegie Mellon University
Pittsburgh, PA 15213 USA

There is no "silver bullet" sensor technology that will win the explosives interdiction war; rather, there is an arsenal of partial but complementary weapons, sensors and instruments that can be dynamically reconfigured, combined, and deployed against a fast evolving spectrum of terrorist threats to commercial air transport. The paper describes an integrated solution, implemented by a system of robots and computers, that relieves the human inspectors of the routine portions of their jobs, reserving their energies and uniquely human judgement skills for responding to the exceptions flagged by the machines.

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## 1. Summary

We have examined technologies for sensors and instruments to detect explosive vapor emissions, taggant vapor emissions, and explosives solids in bulk in cargo, in luggage, concealed on persons, etc. We find all known sensors and instruments to be imperfect. However we find that most of the sensors and instruments proposed could be valuable components contributing to the effectiveness of an integrated explosives interdiction system.

The utility of any measurement technology is enhanced when it is employed by *an expert operator/inspector* in contrast to an unskilled (and perhaps an unenthusiastic) user. A successful explosives interdiction program has to combine the best features of advanced detection technology with realistic provision for human factors.

With this background as context, we suggest a practical and economical five component systems integration program to bring existing detection technologies, human skills, and robotic manipulation and mobility capabilities rapidly to bear on the explosives detection problem:

1. Deploying existing vapor and bulk detection instruments with robotic machines that would acquire and eventually operate at the skill level of the most expert human inspectors.
2. Optimizing for deployment by robotic machines one or more instruments that employ ionizing radiation; instrument design compromises currently made to minimize radiation exposure to the operator of a "hand held" instrument would be removed while at the same time increasing the safety afforded the inspectors.
3. Augmenting the primary detection approaches with complementary sensing technologies that, via "sensor fusion" methods, increase overall system sensitivity and provide a high degree of disambiguation, thereby reducing the false alarm rate.
4. Providing a picture- and graphics-oriented interface through which inspectors would supervise the robotic machines and instruments; where appropriate for reasons of geography or safety, operation would be remote.
5. Providing database and statistical tools to advise and assist inspectors in making decisions about machine deployment, interpretation of instrument responses, and the most suitable strategies and tactics for physical seizure of the explosives.

This concept for inspection and interdiction aided by systems that integrate ***measurement***, ***manipulation***, ***mobility***, and ***monitoring*** has been applied to several difficult detection problems that have a remarkable degree of top level similarity. Detailed scenarios have been developed for application to interdiction of narcotics in cargo and to inspection of aging aircraft. A systems architecture for demonstrating the latter application is currently being developed via an FAA sponsored project. This paper describes the system concept and details pertaining to its application to explosives detection and interdiction.

## 2. Introduction

Methods for intercepting explosive devices in commercial aviation by directly detecting the explosives fall into two categories, vapor (or sometimes particulate) detection and bulk detection. Vapor (or particulate) detection (for example, gas or plasma chromatography) is inadequate because all such methods are child's play to evade by packaging the explosive component or the entire device in plastic bags, metal cans, etc. In contrast, several bulk detection instruments have been demonstrated to have enough sensitivity, selectivity, probing range, and immunity to evasion to be practical explosives detectors. The most promising methods appear to be neutron activation and x-ray backscattering. However radiation based methods are unsuitable for passenger screening, and the present generation of these instruments are neither portable nor flexible. Radiation safety requirements limit the intensity of the source that can be used, forcing design compromises that reduce the sensitivity. Hand carried instruments that might be envisioned 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, 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 nevertheless have been shown, in contexts such as contraband drug detection, 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 facts, we propose a five point program:

1. Deploying existing instruments via robotic machines that would operate at the skill level of the most expert inspectors. Thus we would 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 essentially eliminating exposing them to radiation.

2. Optimizing instrument sensitivity for deployment by robotic machines:

- instrument design compromises previously made to minimize radiation exposure to the operator of a "hand held" instrument would be removed
- the instruments would be designed for maximum effectiveness in explosives detection
- safety interlocks would ensure that these high dose instruments would cease to emit radiation any time humans were in their vicinity.

3. Augmenting the primary detection method with complementary sensing technologies and "sensor fusion" data handling methods for disambiguation:

- other bulk solid sensing modalities to reduce the false alarm rate, resolve borderline detections, etc, all in the general category of "disambiguation,"
- 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.,
- a suite of navigation, location, and manipulation sensors, coupled with machine vision systems to provide a multi-sensor modality image and interpretation of the baggage under inspection.

4. Providing a picture- and graphics-oriented interface through which the inspectors would remotely supervise the robotic machines and instruments, thus improving interdiction *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 interdiction rate and a low false alarm rate,
- taking optimum advantage of the respective unique strengths of people, machines, and people and machines working together.

5. Development and provision of 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,
- in interpretation of instrument responses,
- in identifying the most suitable strategies and tactics for physical seizure of explosives and other contraband.

Taking into account knowledge of container materials and construction, physical properties of the anticipated explosives types, and the operating methods employed by terrorists, 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 in the context of the application. If a dual technology instrument is employed, "sensor fusion" methods allow synergistic operation wherein the whole becomes, effectively, greater than the sum of the parts.

## 3. Robotic Deployment

The purpose of this paper is to outline the concept that the functional and safety shortcoming of existing instrumentation can be overcome by using remotely operated machinery to separate the inspector from the instrument. We also suggest that at the same time the functional problems 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 believe that some supporting basic research will be required to accomplish these goals: mobile robots similar to those that will be required in this application (with respect to mechanical complexity, remote controllability, and degree of local autonomy) are already in use in other applications. The flexibility and extensibility of the robotic approach will permit systems built along these lines to keep up with evasive maneuvers that will emerge in terrorists' bomb construction and deployment technologies as the interdiction 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 counter-terrorism activities in commercial air transportation. These might include, in addition to explosives, substances such as chemical and biological weapons, guns and ammunition, special nuclear materials, and various forms of "currency" including narcotics, cash, and securities. The application of the same level of technology to a variety of similar problems, each with unique features that need to be individually addressed in a common context, presents an opportunity in breadth.

The machines would be integrated with a suite of proven detection and sensing technologies, using established observation and 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 our operational scenario a supervisor, working at the display, dispatches inspectors to suspicious pieces of baggage or passengers who may have explosives concealed on their persons. The inspectors carry color prints of the display, guiding them rapidly, by images and coordinates, to the suspicious artifacts or people. They proceed with their own familiar methods of inspection and interrogation. If they want more detail from the instrument, they request it. The immediate localization to a specific locality enhances by a hundred or more the throughputs and the seizure rates that are credited to the inspectors. The machines are doing what machines do best, the tedious, uncomfortable, and dangerous work. The inspectors are doing what intelligent people do best, flexibly exercising human judgments.

The unpredictable and open-ended jobs of final inspection, seizure, and apprehension of the terrorist 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 present perceived need to rapidly deploy a practical explosive devices interdiction system.

Practical constraints will also limit the number of instruments that can be deployed in a pilot program that must produce real results. The most technical/cost effective solution will therefore be achieved by the most intelligent deployment of a small number of machines. Intelligent deployment means being able to predict which objects and people are most likely to be concealing explosives, and concentrating the machines and the inspectors there. The inspection technology that we conceive incorporates electronic command, communications, and computing components that, for program evaluation, will automatically build a performance database. It would be useful, although not essential, 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.

## 4. Methods Selection

Contraband detection technologies that have been considered are divided, in some arenas, into *physical*, *chemical*, and *biological*, and in other arenas, including (at least recently) explosives detection, into *vapor (and particulate)* collection based means and *bulk interrogation*. The latter grouping is the most relevant in the deployment systems context.

The vapor (or particulate) based group, which includes techniques like mass spectrometry, ion mobility spectrometry (a.k.a. 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 under intense study. But these studies and debates aside, vapor barriers (plastic film, metal containers, etc) are just too cheap and too effective for any air sampling technology to be considered seriously as a sole interdiction technology against explosive-containing packages.

On the other hand vapor detection must continue to be pursued as it is one of the few available alternatives (along perhaps with magnetic resonance methods) for inspecting people; fortunately encapsulation of explosives carried on the person is more difficult than encapsulation of explosives in a package, and body temperature aids volatilization and thus detectability.

In contrast, potential bulk detection methods, which include x-rays, acoustics, neutron interrogation, neutron and $\gamma$-ray backscatter, nuclear magnetic resonance, microwave attenuation, and others, are applicable *in situ*. They are in some cases (especially neutron interrogation) difficult to shield, and they more than compensate for modestly 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 not destructive, to improve signal-to-noise by interrogating each molecule an arbitrarily large number of times. For these reasons we consider the bulk detection technologies to be the only serious contenders for screening of baggage, cargo, mail, galley supplies, etc.

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 (optimized for the new deployment method) detection instruments 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 weakness of these instruments, in a scenario where the threat is constantly evolving in evasion of detection apparatus, is their inflexibility because of their marginal suitability for deployment as hand held instruments. There are two essential reasons:

- they expose the inspectors to radiation, and
- to use these instruments effectively the inspector has to develop an unlikely "rapport" with the instrument, given the hazard it presents to his (or her) health.

However 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 health hazard is immediately and virtually completely removed;
- the instruments can be optimized, e.g., source

strengths increased, and therefore signal-to-noise ratio improved, once the operational scenario has the inspector at a remote location;

- whether or not the instruments actually are optimized for robotic deployment, the systematic nature of the automated robotic inspection process will decrease 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 direct 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 looking passengers and baggage.

There are numerous additional technical possibilities, for example, differentiation of robotic deployment machines into those specializing in volume inspection through the container and those specializing in single-sided or outside surface inspection. In particular, volume inspection could be facilitated by

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

## 5. Detection Requirements

The required, or at least the desired, attributes of a contraband explosives detection system include:

- sensitivity -- the ability to detect quantities well under 1 kilogram on a person or in baggage and perhaps just a few kilograms in cargo
- specificity -- the ability to discriminate explosives from legitimate baggage or cargo contents
- portability and transportability -- we regard it as essential, against an ever changing threat, that the instrument can be carried to the suspected baggage or cargo, not vice versa
- low false alarm rate -- despite some evidence that a modest level of false alarms keeps inspectors "on their toes," the high cost of manual inspection dictates a requirement for a very small false alarm rate
- safety -- e.g., both ionizing and laser radiation present personnel problems
- simple to operate -- inspectors are not trained in instrumentation
- "in the flow" -- the instrument must not introduce additional delays into the already objectionably slow inspection process, nor can it significantly disrupt current procedures
- reliable -- down times must be short and infrequent.

The semi-automated robotic deployment scenario makes a positive contribution to each of these requirements:

- 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 taken to optimize the instrument for machine deployment, e.g., relaxation of radiation 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 baggage, cargo container, or passenger, and most effectively to scan the subject 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, for detection modalities involving penetrating radiation, 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 fast (in fact, in the short run they are usually slower than skilled people), but because the competition almost always turns out to be a tortoise-and-hare story in which the robot's perseverance and untiringly systematic methods win out, statistically, over the human's "sprints" of wisdom or intuition
- reliability is assured by conservative design, and by the relatively low cost of redundancy.

## 6. System Architecture

Our approach is not an instrument but rather a method of deploying existing and future instruments to maximize interdiction rate and minimize interdiction cost. We take it as given that there are several existing instruments that, with specifiable constraints, can detect explosives. 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 the commercial air travel scenario. 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 activation, interact with the baggage *per se*, cargo containers, and any suspected contraband; *secondary* sensing technologies, e.g., magnetometers, discriminate effects relating to the container from effects relating to its content; *knowledge based interpretation* integrates sensor data into the explosives interdiction context
- ***manipulation***: precise navigation and motion control relative to the dimensions of the baggage piece or cargo container are essential to localization of suspect regions; scanning is generally autonomous, but an inspector or supervisor can intercede to target suspect pieces or areas; a knowledge base of baggage and 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 subject person, piece of luggage, or cargo container wherever its location; the alternative of bringing these 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 data-driven dispatch of inspectors, 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 subjects 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

## 7. Deployment Strategy

We suggest that in contraband interdiction 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 interdiction deployment problem: verifying and improving existing heuristics (a sampling program), and systematizing inspection targeting practice in the context of knowledge of the heuristics (an operations research program).

## 8. Conclusion

We have described a concept for using robotic systems to deploy and to evaluate objectively the effectiveness of sensors and instruments for detection of contraband explosives, particularly as they might be employed by terrorists against commercial aviation. The system architecture divides the problem into four levels: ***measurement***, ***manipulation***, ***mobility***, and ***monitoring***.

The ***measurement*** level is a suite of existing or adapted sensors and instruments that report the presence of material with chemical or physical properties that suggest the presence of explosives.

The ***manipulation*** level is a family of fine motion devices that, with the aid of secondary sensors, automatically deploys the explosive detecting sensors and instruments.

The ***mobility*** level is a family of virtually unlimited motion platforms that transport the manipulators and their sensor suites to appropriate inspection locations.

The ***monitoring*** level is the computer, interface, and display that, in response to strategic requirements articulated by the human operator, carries out an appropriate sequence of inspection, interpretation, and sensor fusion tasks, and notifies the operator of exceptions that require human attention.

The monitoring function particularly benefits from access to a variety of sensor inputs and a historical database. These in concert substantially enhance the abilities of the monitoring system to discern and call to the operator’s attention small but potentially significant departures from nominal, and to resolve ambiguities due to sensors with high sensitivity but imperfect selectivity.

We developed this model as a flexible approach to the general problem of making "difficult observations in difficult environments." In commercial aviation, our concept is now being instantiated via an FAA sponsored program thorough which we are applying it to aging aircraft inspection. The systems integration concepts and technology we are developing in the aging aircraft program have direct counterparts in the explosive detection program. We look forward to being able to apply what we learn in the first context to the problems of the second context.