Optimising a layered port security system

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Introduction

Today, there are many different security inspection technologies available. These technologies may be combined in an attempt to achieve a better result. How the systems are combined strongly affects the results achieved, and different applications may require different combinations. This paper will examine several examples.

There are three major applications for screening technology today: Revenue enhancement, contraband detection, and nuclear weapons of mass destruction detection (WMD). Several technologies that can be used are: Portal monitors, gamma ray imagers, high-energy X-ray imagers, and neutron systems. Matching the application and the technology correctly is critical.

Revenue enhancement

The goal of this application is to detect undeclared or misrepresented goods in the normal flow of commerce and recover unpaid duties. Over time, in many cases, the recovered duties exceed the cost of ownership, so the initial investment in this technology is recouped and exceeded. Because the mission is not safety critical, a missed detection is not a serious problem. Only an imaging system can yield the data required to compare the container contents to the cargo manifest. Therefore the appropriate technologies here are high-energy X-ray imaging and possibly gamma imaging. The choice will depend on the type of cargo traffic at a given port. Gamma systems are best at imaging empty or lightly loaded containers while high-energy X-rays are capable of imaging all containers. However the X-ray systems are typically 1.5 to 3 times more expensive than the gamma systems.

Assume for the moment that a gamma system can detect undeclared and/or misrepresented goods in containers with a detection efficiency of 100% in lightly loaded containers and 1% in very heavily loaded containers. Then the actual detection rate will depend on the distribution of container densities but in a typical cargo flow this might be less than 50%. If, however, a high-energy X-ray system can detect 100% of the undeclared or misrepresented goods it will clearly have a bigger payback. The optimal choice of technology in this case depends on the maximum enhancement dollars available.

When computing the cost of ownership of a system, it is important to compare the sum of the yearly operation plus the initial purchasing costs. Both types of systems have similar costs for manning and this turns out to be a large fraction of the cost of ownership. As an example, assume the gamma system costs $1million and the X-ray system costs $3million (these numbers are purely examples) and both require a three-person crew to operate. Although the acquisition costs differ by a factor of three, the yearly cost of ownership for the X-ray system is actually only about 50% more than the gamma system. Since the X-ray system will detect contraband or other prohibited cargo more than twice as often, the economics favour it.

Contraband detection

The goal here is to interdict goods deemed dangerous to society such as drugs or conventional weapons. The payback mechanism in this application is not easy to calculate. For drugs, interdiction increases the street prices of the drugs. If there is economic compliance it reduces drug usage and associated health and law enforcement costs. For conventional weapons, the payback is realised in terms of a reduction in the cost of fighting street crime and/or civil war. Screening for these purposes typically requires a government commitment ("war on drugs"). Often the costs of a missed detection are very high but limited in scope. The emphasis in this application depends on the political perception of the threat. In the United States' "war on drugs" officials realised that it was virtually impossible to completely stop the flow of drugs and only partially effective technologies were deployed. These slowed the flow of drugs at a modest cost.

Weapons of mass destruction

The goal of this application is to prevent the introduction of nuclear weapons into a country. Clearly, any use of such a weapon in a port environment would cause a serious disruption of worldwide trade, with immense economic and human consequences. Any process for detecting WMD's must accomplish two things: Prevent their ever reaching a target country, and do this successfully every time. If a WMD were actually to reach a target country, then the risk would be immense, requiring only detonation to cause unthinkable damage. This understanding is what informs the structure of the United States' Container Security Initiative (CSI). Under CSI, the intention is to discover any threat before it is shipped to US soil by inspection at the port of embarkation. Needless to say, a single incident is unacceptable. This means that any inspection regime must guarantee 100% detection.

Nevertheless, successful inspections for WMD's must occur in the normal stream of commerce, which cannot be disrupted. If inspection results in a significant reduction in the flow of commerce, then, like terrorism, it causes serious economic penalties. The remainder of this paper will look at how to optimise an inspection regime under these constraints.

Technologies available for layering

A layered inspection system combines two or more technologies either serially or in parallel to attempt to achieve a better result than would be possible using either one alone. There are four technologies that are usually discussed as having a significant role in WMD interdiction: Portal monitoring, gamma ray and high-energy X-ray imaging, and neutron interrogation.

Portal monitoring utilises a passive detector to identify radiation being emitted from a container. While useful for detecting and identifying an unshielded plutonium device, this technique will be limited in finding uranium or shielded plutonium devices, and suffers from a significant level of nuisance alarms. A nuisance alarm is a positive indication from a cargo container that does not contain a real threat. Since many types of cargo are radioactive, and given that the number of false positives rises with the short integration times normally available for cargo scanning, this kind of system will yield a fair number of false and nuisance alarms.

We've all read articles that highlight false alarms triggered by a vehicle driver who recently underwent a Thalium scan. Although this is presented as an indication of the sensitivity of the passive screening system, it in fact highlights the weakness of the system in triggering nuisance alarms and becoming disruptive, or worse, ignored by the users due to frequency. It is possible that these alarms may be resolved with longer integration times. Therefore there will probably be two levels of portal monitor. The first will be a general screen and, if there is an alarm, the cargo will be moved out of the normal flow to an area for longer-term inspection by passive means.

Gamma ray imaging should be useful for detection of WMD's (either uranium or plutonium based) in empty or lightly loaded containers, even if shielding is present. With both gamma ray and high-energy X-ray screening, any attempt to shield a device from the portal monitors will make it even more easily seen in the image. It is possible to automate the detection by simply diverting every container with contents that exceed expected densities, and sending these containers to the next step of inspection. This makes the system very sensitive (high probability of diverting a container with a threat) but not very specific (high probability of diverting a container which does not contain a threat). These characteristics mean that gamma imaging is best used to clear empty or lightly loaded containers. The speed of this inspection is limited by the flux from normally available gamma ray sources. About 20 containers per hour can be processed using today's gamma ray systems. Since the average rate through a large port is several hundred containers per hour, this approach clearly can only inspect a small fraction of the containers. Since gamma systems are commonly used at US ports, this explains why such a small percentage of containers are screened currently.

High-energy X-ray screening is capable of penetrating containers of all densities. In articles published elsewhere, the author has proposed a technique whereby WMD's could be detected automatically with a very high detection efficiency and very low false alarm rates. The nuisance alarm rates for this technique have yet to be empirically determined, but it is expected that it will be low (in the order of 1% or less) and that examination of the images acquired using this technique will reduce the nuisance alarm rate by a factor of more than 10. Alarms from this type of system that cannot be cleared by visual inspection of the image and comparison with the shipping manifest should be taken very seriously. There are two possible additional techniques for clearance: Manual inspection or the use of neutrons to identify fissile material. It is even potentially possible to combine X-ray and neutron inspection by looking for neutrons emitted from the container during the short intervals that occur between the pulses from the X-ray source. The overall speed of inspection in this scenario would be limited by container handling capacities. Right now between 30 and 50 containers an hour could be inspected. Intrinsically, this type of inspection could accommodate up to 200 containers per hour with the design and use of sophisticated materials handling processes.

The idea of using neutrons to characterise any threat regions found using other inspection technologies is an intriguing one. However, at this time this technique is slow and very expensive. Speed may not be terribly critical, at this step because, ideally, the reject rate from the other inspection modalities would be very low. However, neutron-detection technology is expensive.

System integration

Let's consider how three different technologies could be combined in a layered approach. This section examines the strengths and weaknesses of various combinations. In the first example, each technology (green box) is used separately to clear cargo as shown in the simple diagram below (Figure 1). Cargo enters from the left and is inspected using the first technology, which might clear some as a "non-threat." The remainder goes on for inspection using technology two, which also may clear some cargo. The remainder is sent on to be inspected by technology three and if it is not cleared, it is finally called a threat and sent on to whatever form of threat resolution is available at the site. This could include hand inspection, some other more expensive technology, or rejection of the cargo. Assume that each of the technologies can be characterised by the probability of its finding a threat when presented and the probability of mischaracterising a non-threat as a threat. These probabilities are written P_{di} and P_{fai} for the detection and false alarm probabilities at each of the three systems (i=1, 2, or 3).

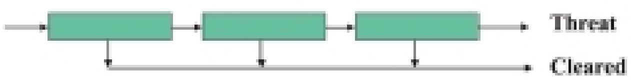

Figure 1. Each technology is used separately to clear cargo.

To calculate the performance of this layered system one can consider what would happen to a stream of cargo containing a number of containers with a threat, N_t, and a number of non-threat containers, N_n. Then the number of containers that will be cleared by the first technology will be:

$$N_c = N_t(1-P_{d1}) + N_n(1-P_{fa1})$$

If you follow this simple logic through the chain, you will find that the overall detection rate is given by the product of the detection rates for the three technologies, $P_{d1}*P_{d2}*P_{d3}$ and the false alarms also, $P_{fa1}*P_{fa2}*P_{fa3}$. Since the probability of detection is always less than one, the detection rate for three serial layers will not exceed that of the weakest link. As an example, if one coupled three systems with detection probabilities of 0.80, 0.90, and 0.99, the detection probability of the system would be 0.72. However, the false alarm rates are usually small numbers and when multiplied together yield an even smaller number. Assume these same three technologies had false alarm rates of 0.12, 0.08, and 0.01. The false alarm rate for the combination would be 0.0001. This type of system might be appropriate for an application where the cost of a missed detection is low, the cost of resolving a false alarm is high, and quick clearance of cargo is important. This is typical of a revenue enhancement type of application.

Now consider the layered system shown schematically in Figure 2. Here, once any of the three technologies declares a container a threat, it is removed from the stream. To be cleared, a container must pass through all three technologies. It is very similar to the first layered system discussed except that the clear and threat channels are reversed. Using a similar analysis as discussed above,

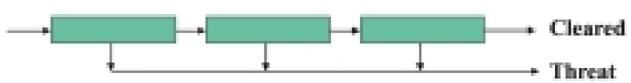

Figure 2. To be cleared a container must pass through all three technologies.

we find that the probability of detection and false alarms of this layered system is given by more complex functions:

$$P_{d123}=P_{d1}+P_{d2}+P_{d3}-P_{d1}*P_{d2}-P_{d1}*P_{d3}-P_{d2}*P_{d3}+P_{d1}*P_{d2}*P_{d3}$$

and

$$P_{fa123}=P_{fa1}+P_{fa2}+P_{fa3}-P_{fa1}*P_{fa2}-P_{fa1}*P_{fa3}-P_{fa2}*P_{fa3}+P_{fa1}*P_{fa2}*P_{fa3}$$

Using the examples of detection rates (as in the earlier example) of 0.80, 0.90, and 0.99, this layered system yields a detection rate of 100%. Using the false alarm rates of 0.12, 0.08, and 0.01, the system false alarm rate is 20% – nearly the sum of the false alarm rates of the component technologies. This type of system can be used only when there is a very high penalty for non-detection and when a very high number of false alarms can be tolerated or resolved. Even if the individual technologies have a false alarm rate of one percent, the layered system will have a false alarm rate of three percent. This may still be too high for stream of commerce systems.

There is another way of combining three technologies as shown here (Figure 3).

This is very similar to the second layered system example except that the third technology is removed from the serial path and is used only to resolve threats found by the first two technologies. In this case the detection and false alarm rates are given by:

$$P_{d123}=P_{d3}*(P_{d1}+P_{d2}-P_{d1}*P_{d2})$$

$$P_{fa123}=P_{fa3}*(P_{fa1}+P_{fa2}-P_{fa1}*P_{fa2})$$

Using the rates from our earlier examples, in this case the detection rate is 97% with a false alarm rate of 0.2%. This type of a system would be appropriate when very high detection rates are required and the penalty for false alarms is unacceptably high.

Let's look at a real example: Assume technology 1 consists of portal screening using radiation detectors. Generally this technology is considered very sensitive to plutonium devices but not very sensitive to shielded or uranium devices. Therefore, let's assume a detection rate of 50% and a false alarm rate of 1%. Assume technology 2 is a gamma imager. It can easily clear all empty containers and is set so that it rejects all containers that it cannot clearly penetrate. It therefore will have a high detection rate, say 98%, but an unacceptably large false alarm rate (including containers it could not penetrate) of 30%. Let technology three be a dual high-energy X-ray imager with an automatic detection algorithm. The author has simulated this kind of system and found that a detection rate of 99% with a false alarm rate of 0.1% is obtainable.

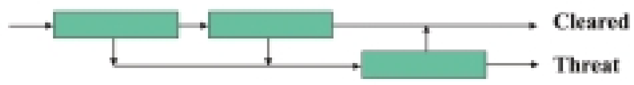

Figure 3. This type of a system would be appropriate when very high detection rates are required.

Using these rates to compute the detection and false alarm rates of each of these layered system approaches, we find the following:

Type 1: $P_{d123}=48.5\%$
$P_{fa123}=0.0003\%$

Type 2: $P_{d123}=100\%$
$P_{fa123}=31\%$

Type 3: $P_{d123}=98\%$
$P_{fa123}=0.03\%$

Clearly, if one were looking for WMD's, the type 1 layering would be inappropriate due to its low detection rate. The type 2 layering would be difficult to utilise because of the high rate of false alarms unless the cost of resolving these were negligible. The type 3 layering, while not perfect, would represent a reasonable compromise yielding very high detection rates and modest to low false alarms rates.

Conclusions

Layering of different technologies can improve the overall results in cargo inspection, but careful consideration should be given to questions of how the systems are combined and used. The detection and false alarm rates achieved for a layered system can vary dramatically, depending on the specific layering rules.

ABOUT THE AUTHOR

Paul Bjorkholm, Varian Security & Inspection Products' Senior Scientist, has spent his career designing and building X-ray imaging equipment of all types. He has created images using X-rays from 250 eV to 15 MeV with size scales from parsecs to microns. Recently he has concentrated on the application of high energy X-ray imaging of cargo containers for security, contraband interdiction and manifest verification. He invented backscatter imaging, helped develop 9 MeV inspection systems for Schiphol airport, and was essential in the development of 2.5 MeV mobile scanners. Dr. Bjorkholm has 16 patents to his name.

Dr. Bjorkholm graduated from Princeton University and received a PhD from the University of Wisconsin, Madison.

ABOUT THE COMPANY

Varian Medical Systems is a world leader in the design and manufacture of equipment and software for treating cancer and other medical conditions with radiation therapy, as well as a premier supplier of X-ray tubes and flat-panel digital technology for imaging in medical, scientific, and industrial applications. The company is also a market leader in high-energy X-ray devices for non-destructive testing and cargo screening.

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