BUDDY TAG'S MOTION SENSING AND ANALYSIS SUBSYSTEM

Sabina E. Jordan
Sandia National Laboratories*
Albuquerque, New Mexico USA

ABSTRACT

Buddy Tag is one of several types of tags being developed as a means of verifying arms control limitations on numbers of treaty limited items (TLIs). The TLIs being focused on for now are missile systems. Buddy Tag has the attractive feature that it does not have to be attached to the TLI, making it less intrusive than conventional tagging schemes. Key to Buddy Tag's capability is its motion sensing and analysis subsystem. Due to the nature of Buddy Tag's potential application, the motion sensing and analysis subsystem must be highly sensitive, extremely reliable, and capable of correctly distinguishing illegal movement of the Buddy Tag from inputs due to nearby cultural activity or low level seismic disturbances. This paper overviews the Buddy Tag concept and discusses its motion sensing and analysis subsystem.

INTRODUCTION AND BACKGROUND

Tagging has been proposed as a means of verifying arms control limitations on numbers of treaty limited items (TLIs). Counting all of the TLIs in a country in order to verify that the treaty limitations on their number is being observed, is not always a feasible approach. The advantage of using tagging is that it allows the verification of these treaty limitations by the inspection of only a percentage of the total allowed number of TLIs. The reasoning behind this is that if excess TLIs have been placed in the legal, inspectable infrastructure, then each inspection of a TLI has associated with it a finite probability of detecting one of the excess, non-tagged items.

Tagging would be used in conjunction with short notice on-site inspections. Each country would be allowed a certain number of short notice inspections of the other countries' declared sites, each year. For practicality and so as not to impose military disadvantage, a country could choose only one declared site of another country to inspect at a time. Declared sites would include production facilities, storage sites, and deployment sites. The reason tagging schemes would need to be used with short notice inspections, instead of, for example, just counting the number of TLIs at a site, is that the TLIs are generally moved around and a constant number does not remain at each site. When a short notice inspection were called at a chosen site, a stand-down would immediately become in effect there. The stand-down would require that the inspected party not alter the situation by moving TLIs in or out of the inspected area until the inspecting party arrives.

Tagging is one element of an entire treaty verification monitoring system. Other elements such as satellite reconnaissance or portal perimeter monitoring system are important to ensure that the inspected party does not change the situation during a stand-down, before the inspecting party arrives at the site.

The conventional approach to tagging involves the application of a tag to each TLI when it is declared by a country as an indication that the item is one allowed by the treaty. In subsequent inspections the tag could be read to verify that it is genuine, and therefore that the TLI to which the tag is permanently attached is one of the original tagged items.

One of the requirements of this implementation of tagging is that the tag cannot be removed from one TLI and transferred to another, undetectably. To prevent this, the tag must be attached to a part of the TLI which cannot be removed and replaced easily, and must be permanently attached in such a way that removal would result in irreparable damage to the tag. To ensure that the tags are applied properly and read properly during inspections would require direct access by the inspecting party to a major element of the TLI. Operationally, this can be very difficult for TLIs such as missiles in silos or in environmentally controlled canisters.

In addition to these operational difficulties, there are also other potential concerns with this implementation of tagging. For example, the direct contact with the TLIs that the inspecting party must be allowed may be considered too intrusive. There is some concern with the whole idea of a tag being attached to the TLI--that potentially the tag could somehow affect the TLI's operation or could somehow be used for targeting purposes. And also, there are concerns about the unique tag-TLI pairing, i.e., the association of a specific tag with a specific TLI, because it allows for collateral information to be derived from the inspections. For example, because of the unique tag-TLI pairing, a particular TLI could be identified at different inspections during its lifetime,

* This work was supported by the United States Department of Energy under Contract DE-AC04-76-DP00789.

revealing information about the military infrastructure or even reliability information, if the TLI were identified at a repair facility.

Whether or not these objections outweigh the benefits of using a conventional tagging implementation, is debatable, and in the final analysis, it is something that governments will have to decide. In the meantime, Sandia National Laboratories is looking into the development of a totally different type of tagging concept for the DOE Office of Arms Control, which addresses these concerns. Sandia is developing a tag that does not need to be attached to the TLI and does not have to have a unique tag-TLI pairing if it is not desired. The tag we are developing is called Buddy Tag.

BUDDY TAG CONCEPT

Buddy Tag is comprised of the following components:

- motion sensing and analysis subsystem
- tamper protection/detection subsystem
- positive identifier
- real-time clock/calender
- memory for data logging
- power subsystem
- I/O communications port for communicating with Interrogator Unit

A block diagram is shown in Figure 1. Buddy Tag is internally powered and each Buddy Tag is stand-alone. When development of all of the subsystems is complete, Buddy Tag will probably be about the size of a briefcase.

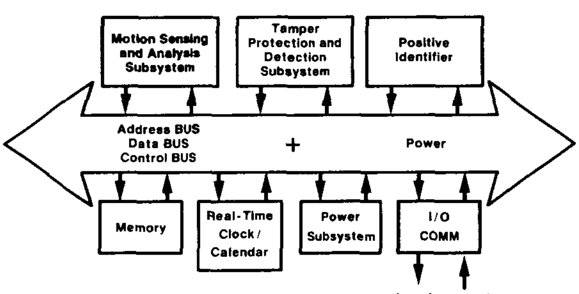

Figure 1. Buddy Tag Block Diagram

In the implementation of the Buddy Tag concept, each country is given a number of Buddy Tags equal to the number of TLIs that the country is allowed by the treaty. A Buddy Tag is to be kept in proximity of each TLI at all times. Each country is allowed a certain number of short notice inspections of the other countries' declared sites, each year. When a short notice inspection is called at a chosen site an immediate stand-down becomes in effect there, during which the inspected party is not allowed to move any of the TLIs or any of the Buddy Tags. The motion sensing and analysis subsystem along with the real-time clock/calendar in a sense "freezes" the tagging situation at the site at the time of the inspection call. Thereafter, the Buddy Tags cannot be moved undetectably.

As soon as the inspectors arrive at the site, they make sure that there is a Buddy Tag for each TLI present. If there isn't an equal number, it constitutes a non-compliance. The inspectors then interrogate each Buddy Tag with the Interrogator Unit. (Unauthorized interrogation of the Buddy Tags is prevented by means such as a one-time pad). In the interrogation, it is verified that the Buddy Tag is genuine, i.e., the positive identifier is read to determine if the Buddy Tag is one of the originals issued by the inspecting party, and also data from the tamper protection/detection subsystem is read to verify that neither the Buddy Tag nor its data have been tampered with. During the interrogation, data is also read from the Buddy Tag's motion sensing and analysis subsystem to verify that the Buddy Tag has not been moved since the time the inspection was called. This ensures that no Buddy Tags could have been brought in from other locations not being inspected, to be paired with excess TLIs located at the site, after the time the inspection was called there.

It is critical to prevent the removal of excess TLIs from the site before the inspectors arrive. To accomplish this, the use of Buddy Tag must be supplemented by other treaty verification means, as is the case with conventional tagging schemes. If a site has a portal perimeter monitoring system (PPMS) installed, it should be activated during the stand-down to make sure none of the excess TLIs can be transported out of the facility. At sites without a PPMS, satellite reconnaissance could accomplish this. Inspections could be announced immediately after the area to be inspected had been satellite imaged. The inspection team would then determine if the number and location of the TLIs are the same as they are on the image.

If desired, Buddy Tag can be made even more unimposing. As described earlier, Buddy Tag is not attached to the TLI and there is no association of a specific Buddy Tag with a specific TLI. Because of these characteristics, there is actually no need to keep the Buddy Tags and TLIs associated during normal operations, which would make things much more convenient. The Buddy Tags could potentially all reside in a single storage area located at the site and only be paired up with the TLIs for inspections. A very short period of time would be allowed to set up the pairing after the inspection call. The storage area could even be shielded to allay any fears of the Buddy Tags possibly providing targeting information.

In fact, the placement of the Buddy Tags next to the TLIs even during the inspection could be eliminated. When the inspection were announced, the Buddy Tags could just be set up in their shielded storage area. When the inspectors arrive they could count the Buddy Tags there to make sure their total number equals the total number of TLIs present at the facility, and they could also inspect them there at the storage area, in the same manner described before, making sure that all of the Buddy Tags are genuine, have not been tampered with, and have not been moved since the time of the inspection call. If so inclined, this would totally eliminate TLI exposure to tags and yet still accomplish the objectives of tagging.

MOTION SENSING AND ANALYSIS SUBSYSTEM

It could be said that the other major subsystems, the tamper protection/detection and the positive identifier, maintain Buddy Tag's integrity but that the motion sensing and analysis subsystem provides Buddy Tag's capability. Considering this, we decided to first concentrate on development of the motion sensing and analysis subsystem.

The motion sensing and analysis subsystem has some challenging requirements. Because of the fact that the adversary has national level assets, and that there could be a high incentive to cheat since even a single TLI concerned can have impact on strategic balance, the subsystem must be highly sensitive so it can withstand even very sophisticated defeat attempts. Since the possibility of negotiating rigorous constraints on the use of Buddy Tag to confine the noise environment it is subjected to is very unlikely, the subsystem must be able to correctly distinguish illegal movement of the Buddy Tag from inputs due to cultural activity or low level seismic disturbances. And because the accusation of non-compliance is a very serious one, the subsystem must be extremely reliable, with a false alarm rate of practically zero. Since Buddy Tag might be used in many different places, the subsystem must be able to operate under a wide range of environmental conditions. The subsystem must also be relatively low power because it is battery powered, and reasonably priced considering its capability and application.

The subsystem prototype appears in Figure 2. The subsystem uses a three-axis accelerometer package comprised of three Sundstrand RBA-500 quartz resonating beam accelerometers, calibrated and mounted orthogonally on a block. One of the three RBA-500 accelerometers can be seen in Figure 2. Within each accelerometer, two crystals are in a push-pull orientation. For a given acceleration, this orientation places one crystal in tension and the other crystal in compression, resulting in one frequency going up while the other goes down. Custom LSI logic gate arrays are used to derive the acceleration signal from the difference in the two frequencies. The two custom gate arrays needed for the three accelerometers are also pictured in Figure 2.

In its final form, the subsystem will use an embedded microprocessor. However for this proof of-concept phase of the project, a portable computer was a much better choice for data acquisition, algorithm development, and

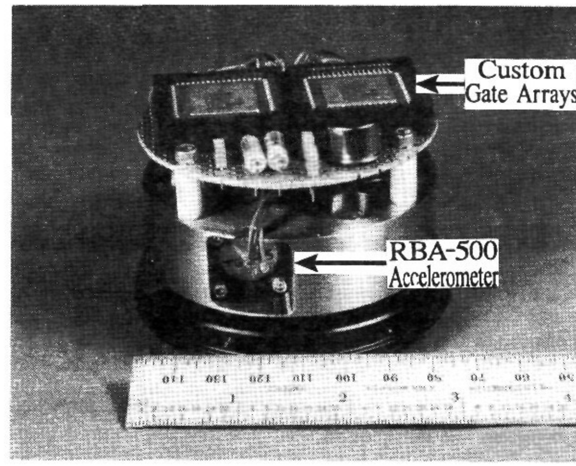

Figure 2. Motion Sensing and Analysis Subsystem

testing. Figure 3 shows the subsystem in its enclosure and connected to the portable computer. The bottom plate is for added stability.

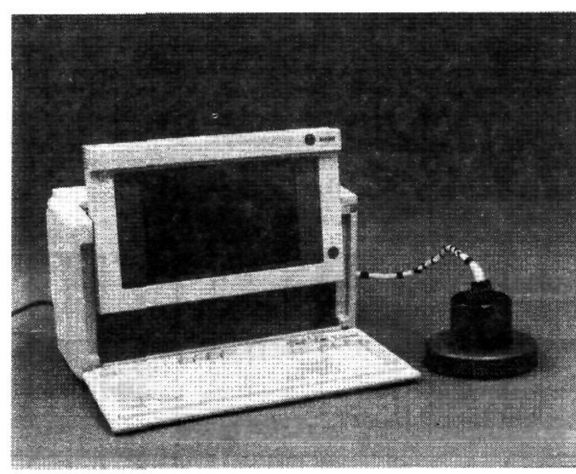

Figure 3. Motion Sensing and Analysis Subsystem Connected to Portable Computer

It must be emphasized that the subsystem does not perform navigation. The subsystem is not able to track Buddy Tag's movements or calculate exactly how much Buddy Tag has displaced. The objective of the subsystem is to be able to distinguish even extremely stealthy movement from cultural noise. From extensive laboratory experimentation, the sensitivity of the subsystem was found to be all the way down to 10μGs--beyond the capability of even national level assets to impart stealthy motion. The subsystem has the ability to be set to this extreme sensitivity and yet not false alarm to cultural noise. With the sensors and approaches traditionally used for motion sensing in security applications, it is very difficult, if not impossible, to achieve this high sensitivity without frequent false alarms.

The discrimination algorithm involves integrating each of the three accelerometer signals two times and passing them through a bandpass Infinite Impulse Response (IIR) filter. The filter's lower cutoff frequency is about .01 Hz and its upper cutoff frequency is about 1 Hz. The purpose of the lower cutoff frequency is to filter out the components of gravity on all three axes. It also is very effective in filtering out bias and scale factor drift of the accelerometers due to temperature change. We have therefore not yet added any thermal compensation calculations to the algorithm. The upper cutoff frequency is to filter out data not of interest. The square root of the sum of the squares is then taken and only this one signal needs to be monitored.

The discrimination function has proved very effective in distinguishing illegal movement from cultural noise. For example, Figures 4 and 5 are screen dumps from the portable computer. They are from a demo showing a real-time graphical display of the discrimination function and the raw acceleration outputs. When the discrimination function reaches the level of the dashed line, it indicates an alarm. Figure 4 shows the results of actually tapping on the subsystem enclosure. It is apparent from the plot that a lot of accelerations were sensed but that the discrimination function was relatively unaffected by this type of input. But as shown in Figure 5, when the attempt is made to move the subsystem very slightly, the discrimination function goes into alarm right away.

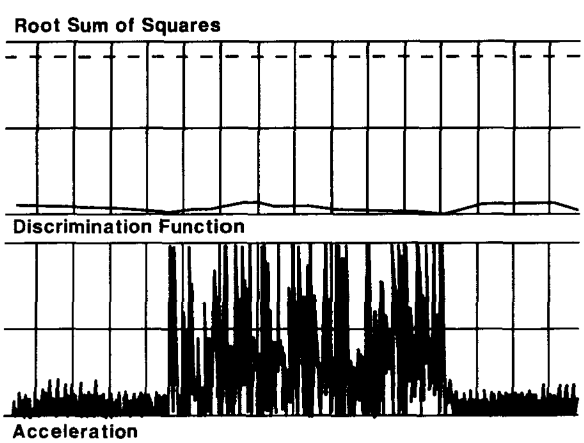

Figure 4. Real-Time Graphical Display of Tapping on Subsystem

An extensive cultural noise database was needed to test and fine-tune the discrimination algorithm. Much experimental data was gathered from tractor-trailer rigs loaded to different weights and from various types of rail traffic passing by the subsystem. Runs were made at several distances from the subsystem and for different traveling velocities. Data was also obtained of various military airplanes and military helicopters flying overhead. Also,

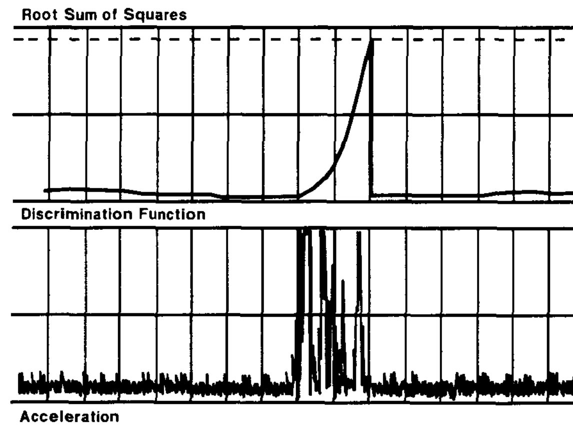

Figure 5. Real-Time Graphical Display of Trying to Move Subsystem

data from some low level seismic occurrences was obtained from a seismic monitoring station. Except for the seismic data, all of the data was gathered in the field, using the actual system.

Some examples of the data gathered appear in Figures 6 and 7. Figure 6 shows data from the tractor-trailer rig loaded to 60,000 lbs., traveling over a speed bump at 10 miles per hour, at a distance of 4 feet away from the subsystem, and also data from a 10 μG acceleration, both processed through the discrimination algorithm. As previously mentioned, 10 μGs is an extremely small acceleration and it is representative of extremely stealthy illegal movement, beyond the capability of even national level assets. The tractor-trailer produces a significant level of cultural noise which has quite a bit of low frequency content. This situation is sort of a worst case for the subsystem. It is apparent from Figure 6, though, that the 10μGs is very distinguishable due to the difference in amplitude between the two signals after they have been processed through the algorithm. Figure 7 shows similar data for a locomotive traveling at 45 miles per hour where the subsystem is located 12 feet from the track. Here again, after the locomotive data and the 10μG acceleration data have been processed through the discrimination algorithm, the 10μG acceleration is clearly distinguishable in amplitude.

The military airplanes and helicopters flying over did not produce much effect on the subsystem. Although there were low frequencies present, there apparently was not much coupling to the ground.

All of the low level seismic disturbance data we were able to obtain from a monitoring station was very much smaller in amplitude than the 10 μG signal when processed through the algorithm. The disturbances we looked at were around 140 Km away with a body wave magnitude of 5. Response to seismic occurrences, of course, depend on distance to the epicenter and

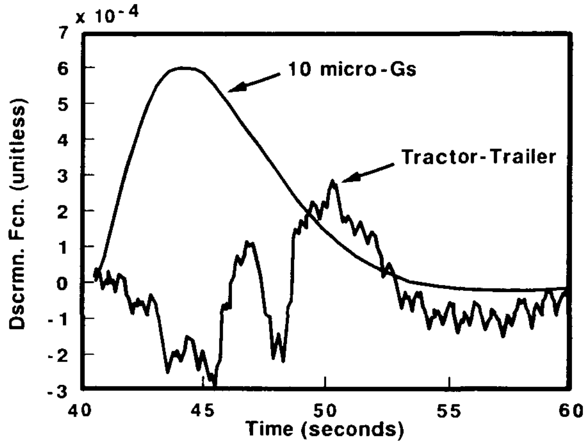

Figure 6. Tractor-Trailer and 10μG Data Processed Through Algorithm

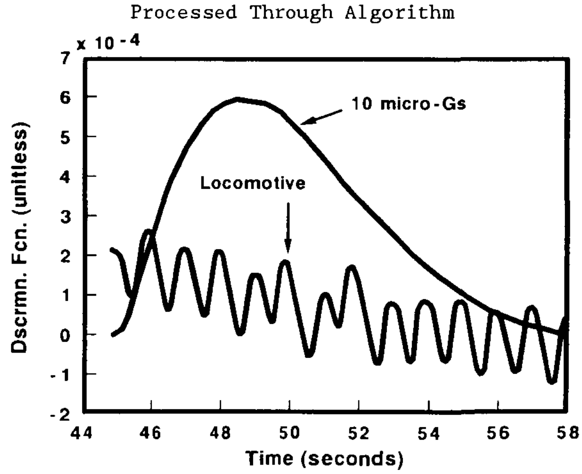

Figure 7. Locomotive and 10μG Data Processed Through Algorithm

the size of the disturbance (body wave magnitude). If a seismic disturbance actually displaced Buddy Tag, the subsystem would alarm. The occurrence of seismic disturbances, however, could always be confirmed by other means.

BUDDY TAG PROJECT FUTURE PLANS

We plan to implement the motion sensing and analysis subsystem as a microprocessor-embedded subsystem, develop all of the remaining subsystems of Buddy Tag, integrate the subsystems producing a Buddy Tag prototype, and finally, test, black-hat, and red-team the Buddy Tag prototype.

SUMMARY

Buddy Tag is a unique tagging concept which provides an attractive option to conventional tagging methods. Some reservations have been voiced about conventional tagging concerning attachment of tags to TLIs, operational difficulties and intrusiveness in applying and reading attached tags, and being able to identify specific TLIs due to the unique tag-TLI pairing. Buddy Tag addresses all of these issues and still accomplishes the goal of enhancing verification.

The motion sensing and analysis subsystem is key to Buddy Tag's capability. The subsystem correctly distinguishes illegal movement of Buddy Tag from cultural noise. The subsystem design allows it to be extremely sensitive and yet not false alarm to cultural noise. Besides Buddy Tag, the subsystem (or a modification of it) also has potential applications to other problems, such as in the area of safeguards and security.

ACKNOWLEDGEMENTS

The author wishes to gratefully acknowledge the guidance and support of Stan Fraley and Don Bauder, and the invaluable contributions of Stewart Kohler and Randy Rosenthal to the hardware development effort.