# Development and Demonstration of a Buddy-Tag Prototype

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**ABSTRACT.** Future nuclear arms-control agreements may place numerical limits on the total number of warheads in the nuclear arsenals of states. Verifying these limits may require inspectors to account for individual warheads, both deployed and non-deployed. Typically, this task can be accomplished with unique identifiers, but standard tagging techniques may be unacceptable in this case due to host concerns about safety and intrusiveness. First proposed by Sandia National Laboratories in the 1990s, the "Buddy Tag" concept seeks to address these concerns by separating the tag from the treaty accountable item itself. Verification of the pairings between tags and accountable items would take place during a short-notice inspection, where the host would be required to produce one buddy tag for each item. A buddy tag has two key elements: a tamper-indicating enclosure and a motion-detection system designed to detect illicit movements in a stand-down period. As part of this project, we have built a full-up buddy-tag prototype for demonstration and evaluation purposes. This paper reviews the design choices and functionalities of the different subsystems, both for the enclosure and for the motion-detection system. We pursue a modular approach for the tag's hardware, built around a *Raspberry Pi* and an ITAR-free high-precision inertial measurement unit, and use open-source algorithms for the motion-detection software. We also discuss the results of an experimental campaign assessing the performance of the tag under challenging ("noisy") environmental conditions and propose a set of standing-operating procedures for the buddy tag concept relevant for the arms-control and safeguards context.

## 1. Background

Procedures and techniques to confirm upper limits on the number of nuclear warheads would become a key verification objective should future arms-control agreements place limits on the *total* number of nuclear weapons in the arsenals. Verifying such agreements may then require the ability for inspectors to account for individual warheads rather than launchers. In principle, this can be accomplished by tagging treaty accountable items with unique identifiers (UIDs), which effectively transforms a numerical limit into a ban on untagged items [1,2]. Direct tagging may be difficult to implement in practice, however, because the host may have safety, performance, or other concerns, and inspections would necessarily be highly intrusive. Development of concepts to support verifying limits on non-deployed and nonstrategic warheads therefore faces important challenges. On the one hand, the capability to verify numerical limits on weapons in these categories could be useful in both bilateral and multilateral contexts. Indeed, General James Mattis, former Commander of U.S. Central Command and current U.S. Secretary of Defense, raised the question in a U.S. Senate Armed Services Committee hearing in January 2015 [3]: "Could we re-energize the arms control effort by only counting warheads vice launchers?" On the other hand, the locations and movements of warheads and weapons in these categories may be considered sensitive information, and robust verification measures to ensure the authenticity and integrity of a declared treaty accountable item could put such information at risk. To address this dilemma, we revisit the so-called "buddy tag" concept first proposed by Sandia National Laboratories in the early 1990s as an option to confirm numerical limits on missile systems (Figure 1, left). A buddy tag would act as a token, proving ownership of a treaty accountable item without having to present the item itself for close inspection [4]. This paper provides an update on a joint project between Princeton and Sandia seeking a "fresh look" at the concept and pursuing the development of a buddy-tag prototype using modern software and hardware concepts to examine the viability and potential value of the concept for verifying future arms control agreements [5].

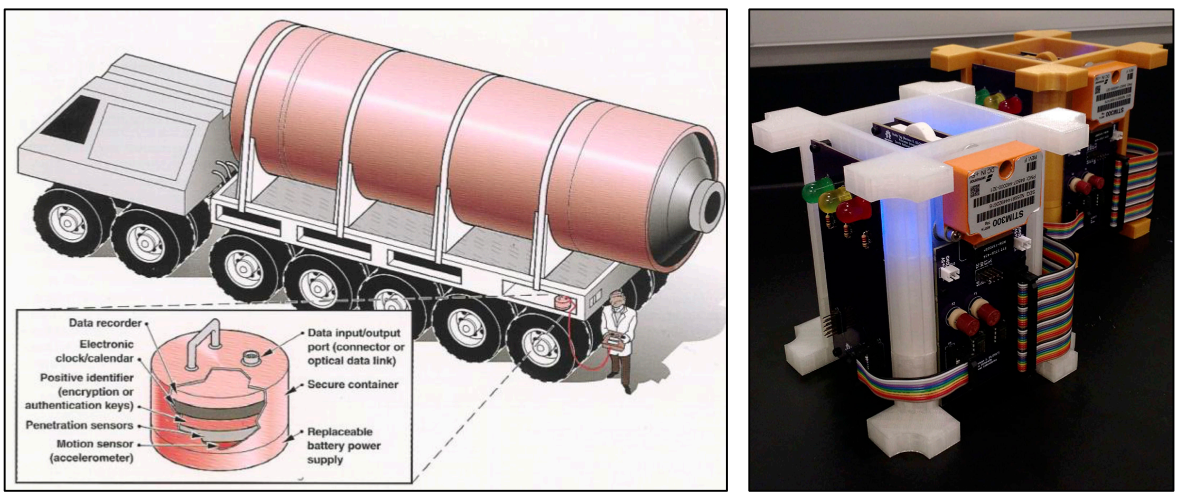


**Figure 1. Artist's conception of the original Buddy Tag for confirming limits on numbers of treaty-accountable missiles**. Shown on the right is the 2017 buddy-tag package (discussed further below) during field-testing. *Image credit, original concept (left): James Fuller [6].*

## 2. Concept of Operations

In a tagging regime using buddy tags, a party would declare a certain number of treaty accountable items and receive exactly one tag for each of these items. The basic idea is that, during a short-notice onsite inspection later on, the inspected party must be able to present one buddy tag for every declared treaty accountable item encountered at the site.

Between inspections, buddy tags would be stored "near" the treaty accountable items, on the same site, perhaps in a dedicated and lower-security display area to which inspectors would have relatively easy and quick access (Figure 2, right). If a treaty accountable item is moved between sites, the buddy tag must go with it. It is worth noting that buddy tags do not have to be associated with a particular treaty accountable item, which could help protect operational patterns that the host party may consider sensitive.

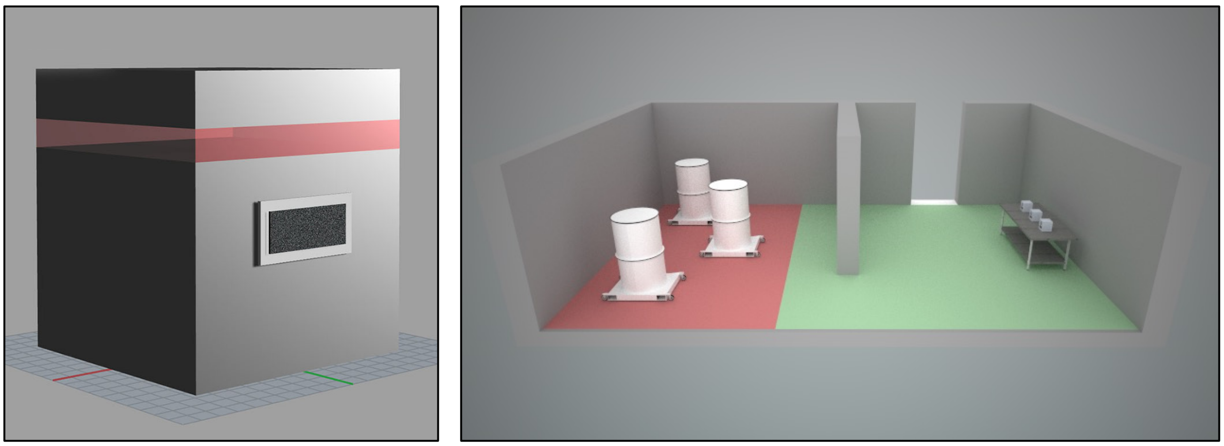

**Figure 2. Scenes from a notional Buddy Tag inspection**. A rendering of a Buddy Tag with a unique identifier and LED-indicator band in a tamper-indicating enclosure. During an onsite inspection, shown on the right, inspectors would access the Buddy Tags in the non-sensitive display area (green) to inspect them. Inspectors would then request to visually confirm the number of treaty-accountable items stored in the red area. *Image credit: Authors.*

Once a short notice inspection is called, the designated site goes into a stand-down, and the buddy tags present at the site are activated by the inspected party, ideally within minutes of the call. From then on, the inspected party may not move any treaty accountable items or buddy tags on or off site until the inspectors arrive at the site and the inspection can be completed. The stand-down on movements of treaty accountable items could be monitored through a combination of national technical means such as satellite reconnaissance and possibly also through portal-perimeter monitoring. As further discussed below, illicit inter-site movements of buddy tags, which are much smaller and whose movements would be difficult to monitor otherwise, are to be detected by a motion-sensing subsystem in the tag.

During a typical inspection, inspectors would count the number of buddy tags present, verify that the tags have not been moved since they have been activated, check the integrity of the tags, and confirm their authenticity, e.g. through a unique identifier that is attached to the tag [7,8]. Inspectors would then be allowed to visually confirm that an equal number of treaty accountable items are present at the site and accept these declared items without further authentication. Inspectors might also be able to verify that additional items present at the site are in fact non-treaty-accountable and access other areas large enough to contain treaty accountable items to ensure the absence of such items in those areas. Over time, the numerical limit on accountable items could be gradually lowered, and a corresponding number of buddy tags would be jointly disabled or destroyed following specified procedures.

When implemented effectively, the buddy-tag approach makes it difficult for an inspected party to store undeclared treaty accountable items at a declared site. The party would be forced to hold such items at undeclared sites, which may be difficult to conceal from national technical means over time, especially when it is assumed that adequate security and a parallel support infrastructure would have to be maintained.

The motion-sensing functionality of the buddy tag is a unique characteristic of the tag and also presents the most significant technical challenge. Fundamentally, the buddy tag must be able to distinguish covert movement attempts from environmental noise with very small false-positive and false-negative rates. The motion-sensing system has therefore been the main focus of our study, and it is also the main focus of the results presented in this paper.

## 3. Prototyping Platform

We have designed and built a prototyping platform to facilitate the development of buddy tag components and to support software development and testing (Figure 1, right). For this purpose, we have pursued a modular design, with each tag-subsystem contained on its own PCB and mounted on one side of a 3D-printed support structure (Figure 3). This allows for quick design changes and swapping of components to compare performance. Computing power is provided by a *Raspberry Pi 3*, and motion detection is enabled by the *Sensonor STIM300*, an advanced inertial measurement unit (IMU) based on micro-machined electro-mechanical system (MEMS) technology [9]. The sensitivity of the STIM is about 2 μg for the least significant bit. In contrast to other packages with similar performance, the STIM is ITAR-free, i.e., it is not subject to export controls, which facilitates research, development, and testing of the tag. Power to the *Raspberry Pi* and the STIM are supplied by six 18650 lithium-ion battery cells with a total capacity of about 20,000 mAh, giving the system a battery life of more than 24 hours. The tag's current status is indicated to the inspector (or the developer) by three LEDs: Yellow indicates that the tag has not detected a displacement since activation but hasn't reached a pre-defined minimum uptime of, say, 24 or 48 hours yet; green indicates that the tag has not detected any illicit displacements in a time period exceeding the minimum uptime; red indicates a violation. This instantaneous feedback functionality also aids in the development and fine-tuning of the algorithm parameters.

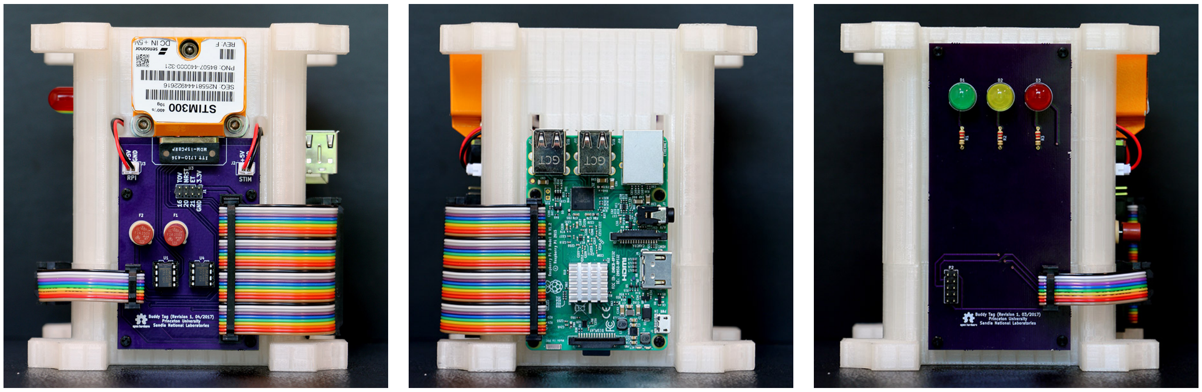

**Figure 3. Buddy Tag modules.** The module with the inertial measurement unit (left) forwards the incoming data to the GPIO pins of the *Raspberry Pi 3* located on a separate module (middle), where a dedicated algorithm processes the data in real-time. Results are displayed via the output module (right).

## 4. Motion Sensing and Analysis Algorithms

The viability of the buddy tag's motion-sensing subsystem depends on the ability to process and analyze the incoming accelerometer data in real-time. The prototyping platform offers a flexible tool to test, optimize, and benchmark a variety of algorithms, and we have so far examined two approaches for analyzing the data: the first algorithm directly estimates the tag's displacement by integrating the accelerometer data; the second algorithm uses a heuristic approach based on the autocovariance of the data to decide whether a movement has occurred. Both approaches are briefly discussed below.

*Integration method.* The first implementation is based on an estimate of the total displacement of the tag. To this end, the incoming accelerometer data is downsampled to an appropriate rate, on the order of 10–50 Hz, and then filtered using an infinite impulse response (IIR) filter to remove quasi constant components, such as gravity and other offsets, and to remove high-frequency components including noise. Figure 4 shows a range of IIR filters that have been considered for this purpose; the lower and higher cutoffs were set to 0.01 and 1 Hz, respectively—the same values Sandia had chosen in the 1990s. Figure 5 shows a sample dataset with movements in different directions. The acceleration data for all axes are then integrated twice to update the estimated total displacement of the tag since activation.

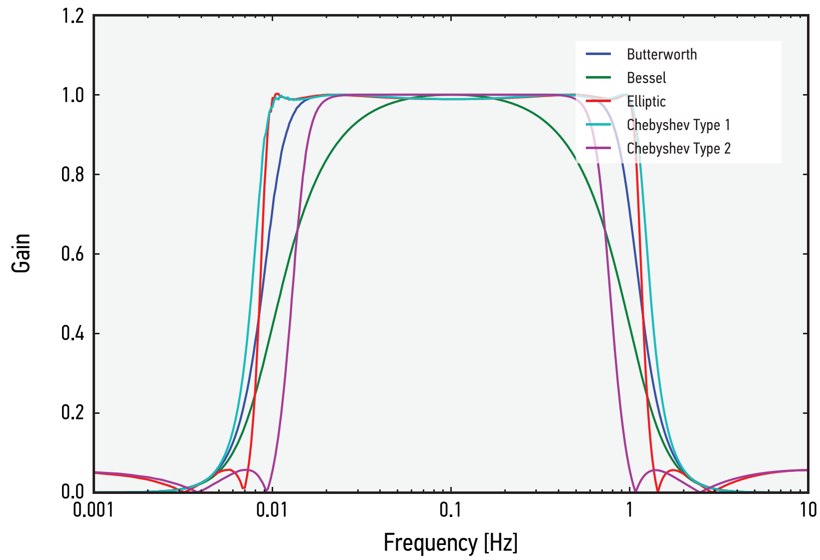


**Figure 4. Comparison of filters, as implemented in Python (SciPy, scipy.signal)**. The lower cut-off of 0.01 Hz removes quasi constant acceleration components including gravity or other off-sets due to the orientation of the IMU. The higher cutoff of 1 Hz removes high-frequency data (including noise) not of interest. In this example, all filter orders are set to 4.

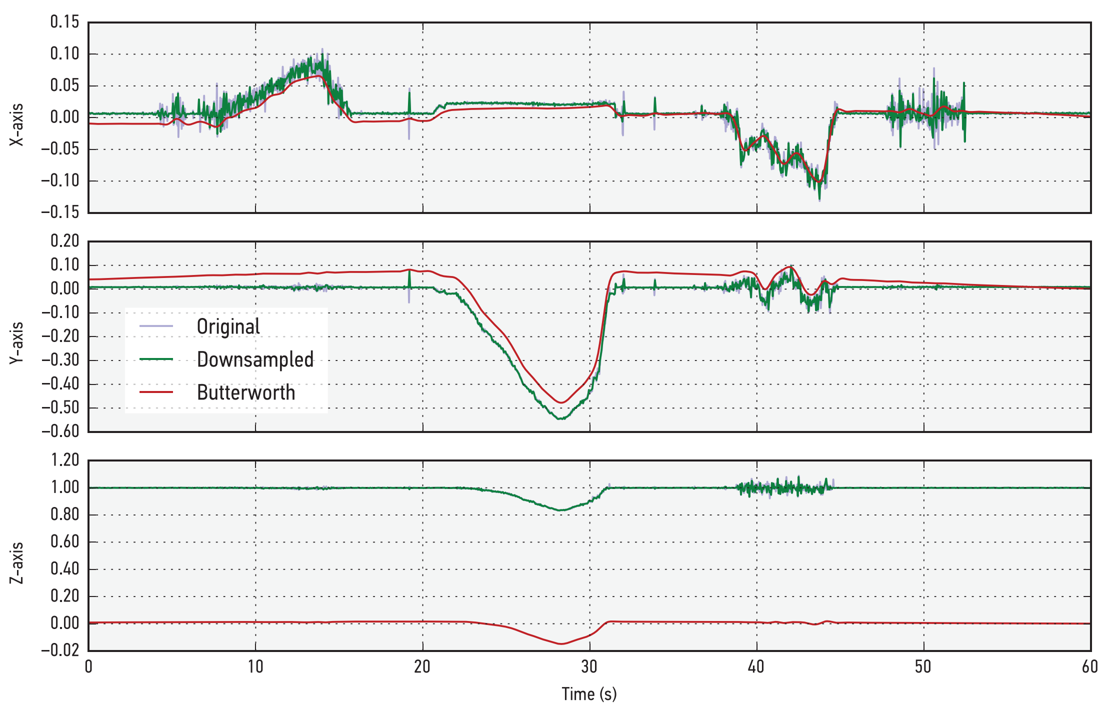


**Figure 5. Sample dataset, with movements in different directions and different noise levels.** The signal has to be downsampled before the infinite impulse response (IIR) filter can be ap-plied, in this case from 500 Hz to 20 Hz. Passed through a 4th-order Butterworth filter, the data

clearly reveals even small movements. Filtering also removes gravity (along the z-axis in this example) and small offsets, which may be due to the orientation of the tag/IMU. The filtered data can be integrated twice to estimate the absolute displacement of the tag.

To prevent integration over sensor noise not associated with translation, the code processing the data from the IMU consists of two operational modes: a sleep mode and a tracking mode. The buddy tag enters sleep mode when the IMU does not detect any accelerations above a specified threshold for an extended time period (on the order of a second or less). In this mode, the tag assumes that it is not moving, i.e., all velocity components are set to zero even if these were nonzero when it last exited the tracking mode. This method avoids accumulating very small errors over extended periods of time. Once an acceleration above a specified threshold is detected, the tag wakes up and starts processing and integrating the incoming data to determine if it is being translated. If a specified threshold value for the net displacement is exceeded, the tag indicates a movement.

*Autocovariance method.* Since buddy tag is concerned with simply detecting if forbidden motion has occurred, a heuristic real-time event detection algorithm can be built by monitoring statistical properties of the acceleration data. Using autocovariance of incoming accelerometer data has been previously proposed for event detection in a different context, where it was shown to be able to detect events even if measurements have poor signal-to-noise ratio [10,11]. In contrast to algorithms using FIR or IIR filtering, an autocovariance-based signal-processing algorithm has low computational needs and is suitable for real-time implementation on low-power devices. Autocovariance measures the degree of linear relationship between two time-shifted samples of the same signal. A negative autocovariance value indicates that the samples are inversely linearly related; a positive value denotes that the samples are positively linearly related. An autocovariance value of zero indicates no linear relationship. By monitoring the signs of the autocovariance values for different shift sizes, a heuristic can be built which determines the type of motion causing a sensed acceleration event.

In this method, the accelerometer data are passed through a 16 Hz low-pass Cascaded Integrator–Comb filter to remove high frequency noise not caused by movement. Then, a buffer is constructed to allow the signal and its time-shifted versions to be referenced by the autocovariance function, implemented in Python. Autocovariance values are computed for the input signal and time-shifted signals of progressively larger shift sizes. This autocovariance vector is the input to a decision function, which establishes a voting scheme based on heuristic criteria for determining whether a movement has occurred. The algorithm progression is displayed for a sample dataset containing shocks and 1 centimeter translations in Figure 6 below.

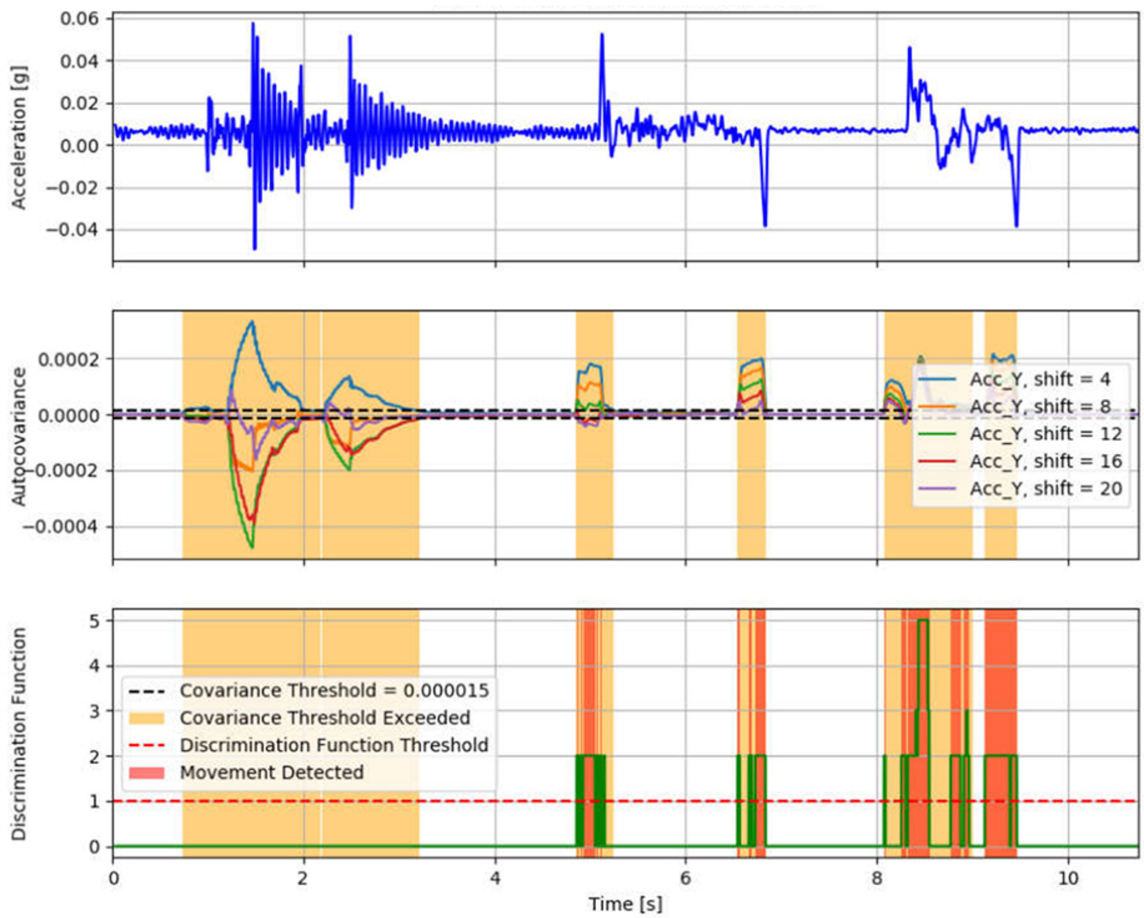


**Figure 6. Sample results obtained with the real-time autocovariance motion-detection algorithm.** This dataset begins with two shocks at roughly t = 1.5 s and t = 2.5 s, then contains two translations at t = 5 s and t = 8.5 s. In both translation events, the positive initial acceleration and negative deceleration at the end of the motion can be clearly seen. The autocovariance signals calculated from these acceleration data are displayed in the center plot. These values are compared to a threshold, and if any signal exceeds the threshold, the discrimination function is activated (yellow regions). In the regions where it is active, the discrimination function examines the sum of the signs of the autocovariance signals, and if this sum exceeds the discrimination function threshold, the algorithm flags the event as movement (red regions). In the central plot of Figure 6, the distinct behavior of the autocovariance signal can be clearly seen. Response to shocks is symmetrical depending on the size of the shift, whereas response to movement shows a positive relationship regardless of shift size. This allows the algorithm to distinguish between environmental noise and small covert motions and flag violations in real-time.

## 5. Conclusion and Outlook

There are currently no established methods for an inspecting party to independently confirm a numerical limit on treaty accountable items if the items themselves are highly sensitive in nature. In the case of nuclear warheads in particular, affixing unique identifiers directly to these items may be considered unacceptable by the host, and inspections may also reveal sensitive operational information. The buddy tag concept offers a radical solution to this dilemma by physically separating the treaty accountable item and its tag, while retaining robustness. As part of this project, we examine the opportunities that this technology would offer and the challenges it would face for the verification of next-generation nuclear arms-control treaties.

The buddy tag is fundamentally based on a motion-detection subsystem in the tag that is designed to distinguish covert movements of the tag from environmental noise. We have so far implemented two different approaches to process acquisition and analysis of the accelerometer data, one based on integration of filtered data and one based on analyzing the autocovariance of the time-shifted versions of the data in real-time. A third implementation based on a supervised machine-learning algorithm is now underway. Integration of the electronics package into a tamper-indicating enclosure is planned for the final states of this project.

The buddy tag prototype described here offers a platform to demonstrate a wide range of relevant technologies without involving sensitive nuclear information. In particular, the buddy tag concept can be used to develop and benchmark the performance of unique identifier technologies, tamper-indicating enclosures, secure electronics, secure software, and advanced algorithms for motion detection. Since the buddy tag concept offers particularly simple and non-intrusive implementations, it might be appealing to a number of weapon states and could facilitate early consideration of a verification regime that tracks treaty-accountable items. Taken together, the buddy tag concept may therefore help chart a path toward multilateral nuclear arms-control agreements.

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## Endnotes

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