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# Minimally Intrusive Verification of Deep Nuclear Warhead Reductions: A Fresh Look at the Buddy-Tag Concept

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**ABSTRACT.** Next-generation nuclear disarmament treaties may place limits on the total number of nuclear weapons in some arsenals. Verifying such agreements would require the ability for inspectors to count individual warheads. Attaching unique identifiers directly to nuclear warheads could be problematic due to a range of concerns by the host related to safety, security, and intrusiveness. To resolve this dilemma, we revisit the so-called "Buddy Tag" concept first proposed by Sandia National Laboratories in the early 1990s. Buddy Tags are tokens that must accompany each treaty-accountable item and be produced without delay. In an arms-control context, each treaty partner would receive a number of Buddy Tags, one for each accountable item. Verification would rely on short notice inspections. Sensors on the Buddy Tag would show that it had not been moved to the inspected site after the inspection was declared (e.g., within the last 24–48 hours). If the inspector counted more (or fewer) TAIs than Buddy Tags at the inspected site, a treaty violation could be asserted. Using a number of single-site inspections, an inspecting party can hold the host at risk for discovery of violating the treaty at an enterprise level by possessing more TAIs than the treaty allows. This paper summarizes the performance requirements for an advanced Buddy Tag that is being developed as part of this project, reviews the proposed conduct of operations, and discusses initial results obtained for a first prototype.

## Background: Confirming Numerical Limits on Declared Treaty-Accountable Items

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 would then require the ability for inspectors to "count" individual warheads (rather than launchers). In principle, this can be accomplished by tagging treaty-accountable items with unique identifiers (UIDs), which 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 (Figure 1, Options 1–3).

Development of concepts to support verifying limits on non-deployed and nonstrategic warheads poses something of a dilemma. On the one hand, the capability to verify numerical limits on weapons in these categories could be useful in both bilateral and multilateral contexts. Note for example, that the US Senate Resolution of Ratification for the New START Treaty required the Obama Administration to engage Russia on limits on non-strategic weapons before seeking further reduction in strategic weapons. However, the locations and movements of warheads and weapons in these categories would generally be considered sensitive information. 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 [3]. Buddy Tags are tokens that must accompany each treaty-accountable item and be presented to the inspecting party without delay when requested. In an arms-control context, each treaty partner would receive a specified number of Buddy Tags, one for each accountable item. The treaty partner would be expected to keep the Buddy Tag "near" the accountable item so that the tag could be produced when requested. Verification would rely on short notice inspections. Sensors on the Buddy Tag would show that it had not been moved to the inspected site after the inspection was declared (e.g., within the last 24–48 hours). The ability to produce a Buddy Tag for each treaty accountable item declared and observed in an inspection provides confidence that treaty accountable items found at the site are part of the population of items allowed within the limits of the treaty.

Options 4–6 in Figure 1 illustrate possible variations on the Buddy Tag concept; for the remainder of the discussion, we focus on the most basic implementation (Option 4), where no direct connection or association exist between the treaty-accountable item and the Buddy Tag.

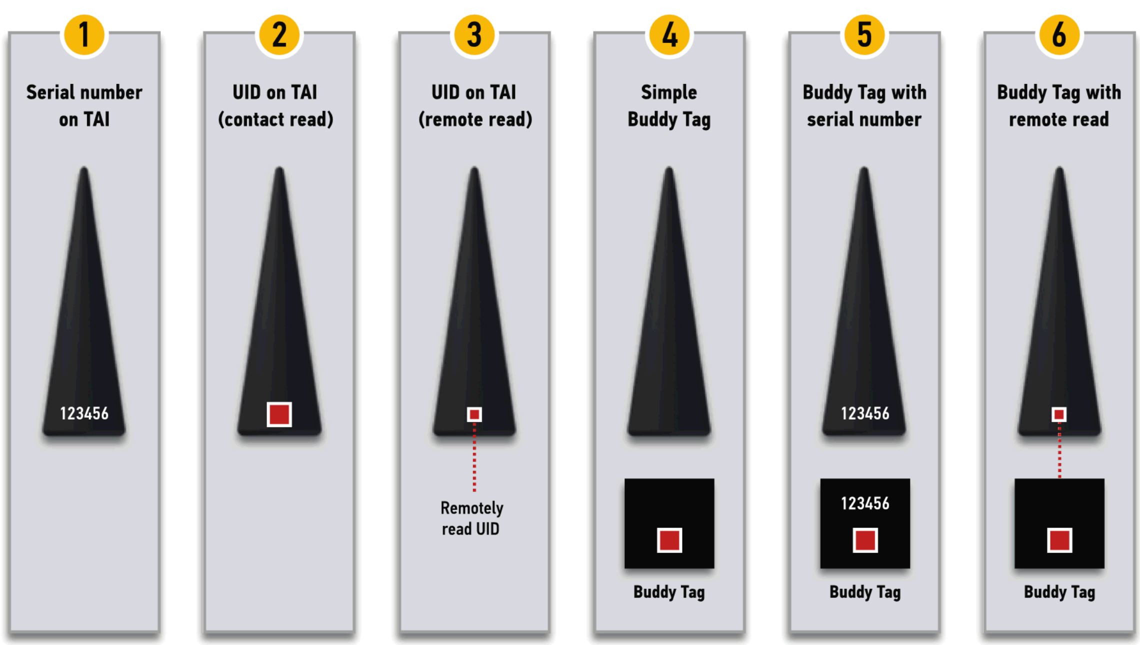


**Figure 1. Some tagging options for nuclear warheads.** Options 1–2 require direct access of the inspector to the treaty-accountable item, which is highly intrusive and may be unacceptable to the host. Options 2–3 envision attaching UIDs to the item itself, a requirement that the host might find equally objection-

able. Option 4 is the basic Buddy Tag concept discussed below. The concept could be further strengthened over time (Option 5–6), but would then face some of the same challenges as the other approaches do.

## Buddy Tag Inspection Scenarios

Figure 2 illustrates the basic procedure of a notional Buddy Tag based inspection. After inspectors arrive on site, they count and inspect the Buddy Tags presented for each treaty accountable item to confirm their authenticity and to verify that the tags have not been moved within the agreed upon time. Inspectors then visually confirm the number of treaty accountable items without directly accessing them.

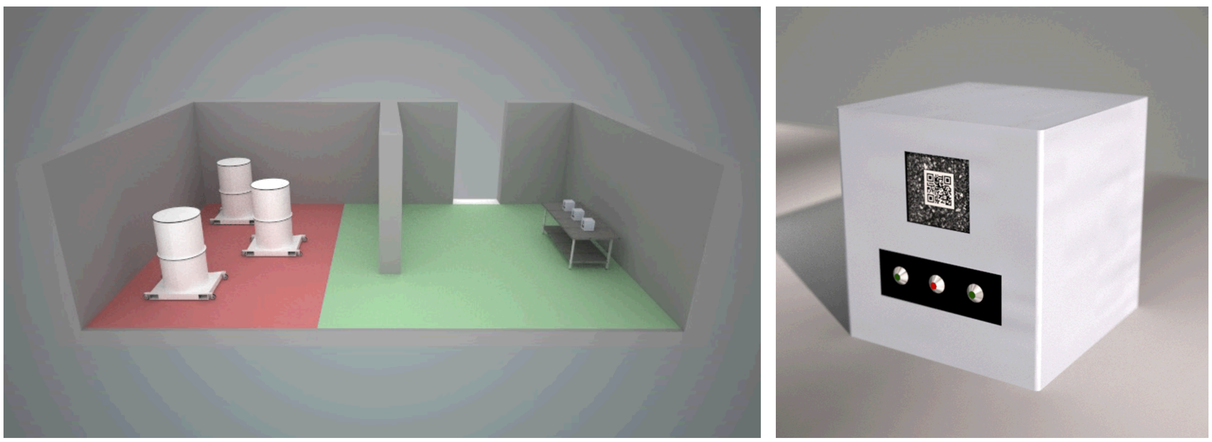

**Figure 2. Scenes from a notional Buddy Tag inspection**. During an onsite inspection, inspectors would access the Buddy Tags in the non-sensitive area (green) to inspect them. Inspectors would then request to visually confirmation of treaty-accountable items (stored in the red area). Shown on the right is a close-up of a Buddy Tag with a unique identifier (shown in the image as a Reflective Particle Tag [7]) and LED indicators in a tamper-indicating enclosure. *Image credit: Tamara Patton.*

Figure 3 illustrates two important scenarios that are effectively addressed with the Buddy Tag concept. Both scenarios assume that a future treaty places numerical limits on treaty-accountable items, i.e., on the number of warheads that each party possesses. States obtain the number of tags that corresponds to the number of items declared in their baseline declarations. In Scenario 1, non-compliance is detected because not enough Buddy Tags are present at the storage site and cannot be moved there in time. In Scenario 2, the state is compliant, but treaty-accountable items are observed by an inspector in an unexpected location; since these items are accompanied by an identical number of Buddy Tags, however, the inspector accepts them as part of the declared inventory.

In the most basic version of the Buddy Tag concept (Option 4 in Figure 1), there is no connection or association between the tag and the treaty-accountable item. This allows the host to use any tag to represent any TAI. This feature could allow the treaty partner to protect operational details (movements of specific items between specific sites) and was considered as an option in the original Buddy Tag concept. Of course, this might also allow the host to replace an authentic treaty-accountable item with a mockup. This non-compliance scenario requires the host to conceal the true item elsewhere with the associated risk of detection. Advanced Buddy Tag concepts (Options 5–6) could mitigate this scenario.

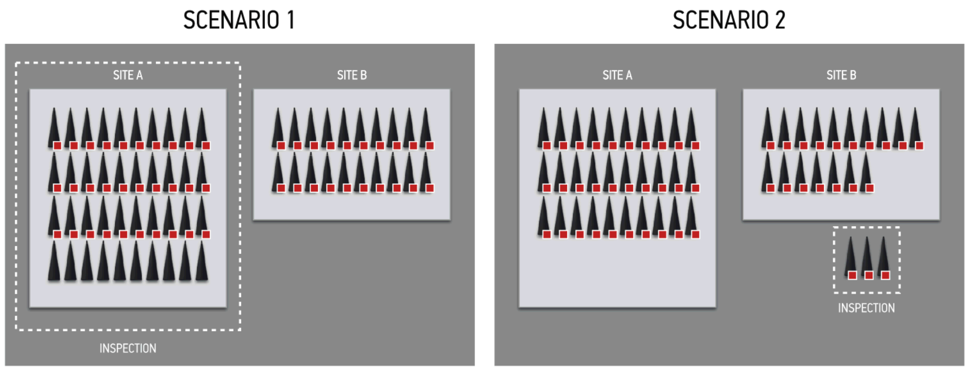


**Figure 3. Two scenarios that are addressed with the Buddy Tag concept.** In Scenario 1, a state stores treaty-accountable items at two storage sites (A and B), but declares fewer than actually exist; if the inspector randomly selects Site A for an inspection, non-compliance will be evident as not enough Buddy Tags are present at that site (and tags can't be moved there without detection). In Scenario 2, the state is compliant with the treaty, but the inspector observes treaty-accountable items in an unexpected location; since these items are accompanied by an identical number of Buddy Tags, however, the inspector accepts them as part of the declared inventory.

If Buddy Tags are used as part of a regime that also reduces the number of allowed treaty accountable items, then as reductions are undertaken, Buddy Tags will also need to be destroyed. Destruction of Buddy Tags could be evaluated as a transparency measure in such a regime.

**Considerations**

Buddy Tags would be part of a larger monitoring regime. As in all tagging-based approaches to verifying numerical limits, it is important to be able to detect the removal of treaty accountable items from a site before inspectors arrive. Additional measures (e.g., a portal perimeter monitoring system) are required to provide this capability.

An additional consideration for a larger monitoring regime is how much access inspectors have. The minimal Buddy Tag regime described here has a finite probability of identifying undeclared items in the declared enterprise. It does not address an undeclared enterprise. Additional access or measures would be required to address concerns that undeclared warheads may be stored in undeclared facilities.

There must be some way to determine if an observed object is a treaty accountable item and therefore should have an associated Buddy Tag. In the past, when dealing with missiles, distinguishing features have included physical measurements. Monitoring warheads could be more challenging. Warheads are typically stored in containers which then become a proxy for the warhead.

The Buddy Tag concept coupled with visual inspections does not in itself address whether the presented treaty accountable item is in fact a real warhead. Instead it provides a mechanism for having some confidence that the number of items presented by the treaty partner and/or identified in an inspection does not exceed agreed treaty limits. If more confidence in the authenticity of the presented items is needed, other measurements would be required with appropriate chain of custody measures to assure that the measured item came from the inspected population. In addition, if an inspector finds items that look like they might be warheads but are not declared to be, measurements could be used to provide assurance that they are non-nuclear.

## Design Requirements

The Buddy Tag is an active device that includes a unique identifier, a motion detection subsystem, and a robust power management system in a tamper-indicating enclosure.The interface of the Buddy Tag can (and should) be very simple. As illustrated in Figure 3, for a basic tag, we envision three indicator LEDs. The main LED indicates whether the tag has detected a movement in a previously-agreed time period, e.g., within the last 48 hours. A second LED indicates the state-of-health of the tag and would signal (and remain lit for the remainder of the tag's lifetime), in particular, if a tampering-attempt has occurred since the last inspection. Finally, a third LED could indicate low battery level to avoid inadvertent shutdown of the tag, which would generally be considered a non-compliant status. Ideally, the tag would be fully autonomous with a battery lasting for months or years. Due to the power requirements of the motion-detection subsystem (discussed below), however, this appears currently infeasible and an external power supply for enduring operation and charging of the internal battery may be required.[*]

The Buddy Tag has a number of separate subsystems, most of them linked to a central microcontroller. These include standard systems such as a real-time clock, data storage, battery management, and the LED display. The tag also requires robust tamper-indicating capabilities and some of them may also be connected to the microcontroller. As a default unique identifier for confirmation of a tag's authenticity, we envision the Reflective Particle Tag (RPT), which has been under development at Sandia National Laboratories since the 1990s as a robust, low-cost, hard-to-counterfeit passive tagging system for treaty verification and international safeguards applications [7]. The RPT could be read out with a non-contact handheld tag reader if disturbance of the Buddy Tag is undesired [8]. The central (and most unique) subsystem, however, is the motion-detection subsystem, which is discussed in greater detail below.

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[*] We do not consider the use of radioisotope thermoelectric generators here. To reduce power consumption of the tag, the LEDs could be duty cycled at a very low rate; most of the power, however, is required by the accelerometers, gyroscopes, and the microcontroller continuously processing incoming data. Autonomous operation for 48–72 hours is possible even for tags with a compact enclosure (e.g., a cube with ~ 150-mm sides).

## Motion-detection Subsystem

As recognized in the original work on the Buddy Tag [3], the critical and most unique element of the Buddy Tag is the motion-detection subsystem. The Buddy Tag has to reliably distinguish stealthy motion from all relevant types of environmental noise in a variety of locations throughout the warhead lifecycle. The ambient vibrational noise may vary significantly from location to location, while false-alarm rates must remain extremely low under all circumstances. These requirements inform the choice of hardware and algorithm for the motion-detection subsystem.*

Various types of accelerometers can be used to detect movements along the axes of the device, and many compact modules are available. Most convenient are packaged triple-axis accelerometers and inertial measurement units (IMUs), which combine accelerometers with gyroscopes and possibly other sensors. Figure 4 shows a selection of candidate components. Recent years have seen the introduction of numerous new platforms for a variety of applications, in particular, for use in quadcopters and drones, with many new hardware and software developments (including open-source flight stacks). For this project, we pursue a two-pronged approach to examine the viability of both low-cost and high-end solutions using the ADXL362 and the STIM300, respectively.

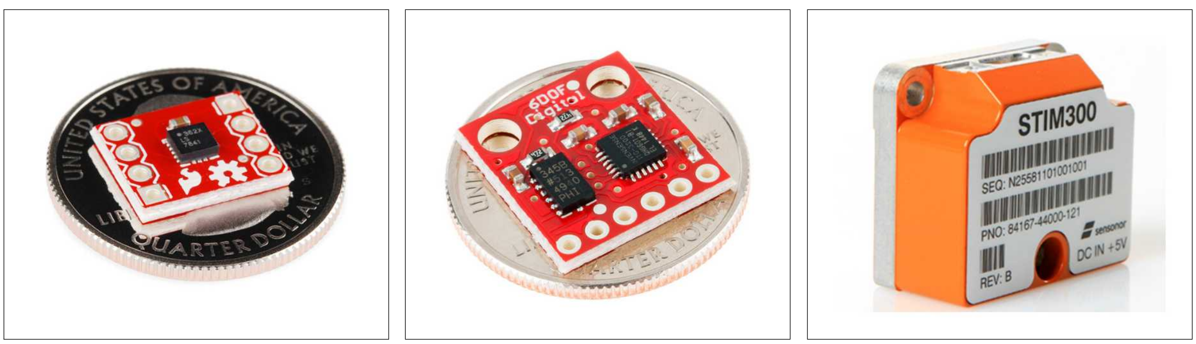


**Figure 4. Candidate components for use in the motion-detection subsystem** Triple-axis accelerometer (left) and two inertial measurement units (center and right). *Image credit: Sparkfun and Sensonor.*

At the high end, the STIM is an inertial measurement unit consisting of three high-stability accelerometers, three high-accuracy gyroscopes, and three inclinometers. The unit uses a 5 V power supply and a 32-bit RISC ARM microcontroller and communicates via a standard RS422 interface [9]. In contrast to other packages with similar performance, the STIM300 is ITAR-free, i.e., it is not subject to export controls, which facilitates research, development, and testing of Buddy Tag prototypes. The sensitivity of the STIM is about 2 μg for the least significant bit (LSB), and some representative results are briefly discussed further below.

* Already, by the late 1970s, Sandia National Laboratories had developed *an "incredibly sensitive motion sensor,"* which was considered at the time for a similar application in the context of a possible SALT 2 verification [5].

| | ADXL362 | ITG3200/ADXL345 | STIM300 |
|---|---|---|---|
| **Type** | Accelerometer | IMU | IMU |
| **Technology** | MEMS | MEMS | MEMS |
| **Range** | ±2 g | ±2 g | ±10 g |
| **Sensitivity** | 1 mg/LSB | 4 mg/LSB | 1.9 µg/LSB |
| **Maximum sampling rate** | 400 Hz | 3200 Hz | 2000 Hz |
| **Power consumption** | 0.1 W | check | 1.5 W |
| **Price** | $15 | $40 | $8600 |

**Table 1.** Main specifications of candidate components for the motion-detection system.

For development and testing, data is recorded for a fixed period of interest (e.g., 30 seconds, during which the system can be exposed to shocks and movements) and analyzed at a later point. For deployment of the Buddy Tag, data processing would have to take place in real time. In both cases, algorithms are only allowed to "look back in time" to decide if a violation has occurred. The code processing the data from the IMU* distinguishes two operational modes: a watchdog (or "sleep") mode and a tracking mode.

*Sleep mode:* The Buddy Tag enters watchdog or sleep mode when the IMU does not detect any accelerations above a specified threshold for an extended time period (on the order of [200–300] milliseconds). 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. While in this mode, the tag also determines the current direction and local magnitude of gravity, which is needed for correct operation of the tag in tracking mode. One can expect that a typical tag would be in sleep mode a dominant fraction of the time. Note that the tag does not signal (e.g., via LED) whether it is in sleep or in tracking mode to make attacks more difficult to execute.

*Tracking mode:* Once an acceleration above a specified threshold is detected, the tag wakes up and starts analyzing the incoming data to determine if it is being translated. The present algorithm first applies a low-pass filter (moving average) to the data to remove mechanical and electrical noise from the accelerometer. The algorithm then integrates the acceleration data to determine velocities and displacements along all three axes. If a specified threshold value for the net displacement is exceeded, the tag indicates a movement. Figure 6 shows a sample dataset, indicating sleep mode, tracking mode, and detected movements. Gravity poses a particular challenge for the analysis of the data because it introduces an offset in the Z-direction that is much larger than the expected accelerations of a

* In the following, the term IMU (Inertial Measurement Unit) is used to refer to the device. An IMU includes accelerometers as well as gyroscopes and, potentially, inclinometers. In practice, even when working with the STIM, we currently rely only on the accelerometer data. Further performance improvements of the motion-detection subsystem are possible with the use of the gyroscope data.

stealthy translation in the XY-plane. Tilting the tag from its straight-up position will therefore lead to significant accelerations due to gravity that have to be filtered out correctly.

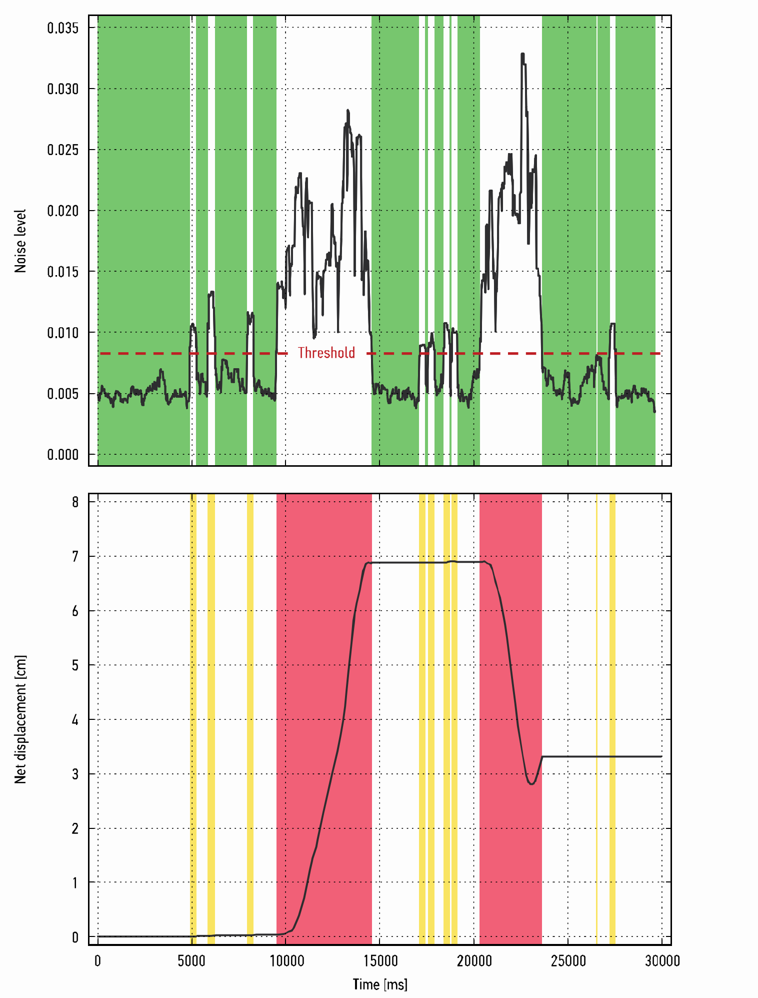


**Figure 6. Sample dataset and Buddy Tag's response.** The currently proposed algorithm constantly monitors the incoming data from the accelerometers. If the values remain below a specified threshold level, the tag remains in "sleep mode" (green). If the threshold is exceeded, the tag switches to "tracking mode" and starts analyzing the data, i.e., estimating velocity components and net displacements. Environmental noise (shocks, vibrations; in this case, hammer strokes) is recognized as such, and the tag remains in compliant status (yellow) before falling back into sleep mode; in the case of a translation, the tag indicates a non-compliant status (red). A video showing the events for this dataset is available at youtu.be/p0WykyNK6XA. [TO BE REPLACED WITH TRIMMED VIDEO AND/OR OTHER DATASET]

## 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 separating the treaty-accountable item and its tag from each other. As part of this project, we are examining the opportunities that this technology would offer and the challenges it would face for the verification of next-generation nuclear arms control treaties.

On the conceptual level, we find that the Buddy Tag concept does indeed enable more flexible and much less intrusive verification approaches. Moreover, the concept offers the possibility for gradual enhancements as parties to a treaty become more comfortable with the verification provisions. Preliminary results also indicate that the performance of the Buddy Tag could benefit enormously from a number of technological advances that have been made since the concept was first considered 25 years ago.

As part of this project, we are planning to complete the design and construction of a small number of prototypes by late 2016. These will then undergo technical review to assess the selected technical features and potential vulnerabilities. Numerous longer-term opportunities for advanced features exist. Specifically, on the hardware level, the best tradeoff between power consumption and sensitivity of the device has to be determined. On the software level, perhaps the most significant potential may be available in the area of supervised machine learning to replace deterministic algorithms to indicate violations.

Finally, and perhaps equally importantly, the Buddy Tag 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. Research in this area would not involve sensitive information of any kind and may therefore also offer opportunities for international collaboration. 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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