INL/EXT-17-43264

Light Water Reactor Sustainability Program

Automated Work Packages: Radio Frequency Identification, Bluetooth Beacons, and Video Applications in the Nuclear Power Industry

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September 2017

U.S. Department of Energy

Office of Nuclear Energy

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SUMMARY

The need to move conventional paper-based work packages into an electronic state motivated the development of a large span of electronic work package forms that ranged from simple PDF files to adaptive and intelligent electronic forms.

In parallel to this development, the Department of Energy Light Water Reactor Sustainability Program initiated the automated work package as a pilot project to evaluate implementing state-of-the-art automation techniques into the work package process to improve the economic and safety of the work process.

Through a multiple-year effort, the automated work package project has developed a vision of the future work package that relies on automation in all critical, complex, and challenging tasks. The vision identified gaps in the work process; the means to automate them; and evaluated the implementation, feasibility, and benefits of these means. This was conducted through continuous engagement with the nuclear power industry.

The aim of this report is to study the potential of three automation technologies, which have been advancing in various industries, in the current work process of nuclear power plants. The study is to determine the feasibility and benefits of incorporating the technologies and determine potential gaps, if any, that need to be addressed to facilitate deployment of these technologies in nuclear power plants.

The three automation technologies identified for this effort are ultra-high frequency radio frequency identification, Bluetooth low energy beacons, and video monitoring and recording. As part of this effort, Idaho National Laboratory collaborated with Xcel Energy Inc. to evaluate these technologies. During the research and development scope of the effort, Idaho National Laboratory engaged Xcel Energy Inc. periodically and exchanged valuable insight on the means to implement these technologies in a nuclear power plant. Multiple pilot prototypes were developed and tested in a user study conducted at Xcel Energy Inc. in Minneapolis, Minnesota.

The outcome of this effort resulted in identifying significant findings that included the detailed means to customize the technologies to fit the nuclear power industry need, and identifying and evaluating several applications of high economic or safety potential. The limitations and obstacles that could impact deployment of the technologies were also identified, and the means of how to address these limitations and obstacles were studied.

ACKNOWLEDGEMENTS

The authors of this report would like to acknowledge and thank the Department of Energy Light Water Reactor Sustainability Program for funding this effort. The authors would also like to acknowledge and thank Xcel Energy Inc. for collaborating on this work under CRADA 17-CR-05.

In specific, the authors would like to acknowledge the significant contribution of Mr. John DeDomenico and James L Kennedy for leading the effort on the Xcel Energy Inc. side and the team of user study participants at Xcel Energy Inc.

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ACRONYMS

BLE	Bluetooth low energy
eWP	electronic work package
FMEZ	foreign materials exclusion zone
GATT	Generic Attribute
GUI	graphical user interface
ID	identification
INL	Idaho National Laboratory
IP	internet protocol
LWRS	Light Water Reactor Sustainability
MTE	Materials, tools, and equipment
RF	radio frequency
RFID	radio frequency identification
RSS	received signal strength
UHF	ultra-high frequency
USD	United States dollar

Automated Work Packages: Radio Frequency Identification, Bluetooth Beacons, and Video Applications in the Nuclear Power Industry

1. INTRODUCTION AND BACKGROUND

The plan for the nuclear power industry to extend its operating licenses to 80 years motivated exploring means to enhance the ability of the nuclear power industry to maintain safe and economic operation of the existing fleet. The Department of Energy Light Water Reactor Sustainability (LWRS) Program achieves this objective through four pathways. The Advanced Instrumentation, Information, and Control Systems Technologies pathway of the LWRS Program conducts research and development to address aging and reliability concerns with the legacy instrumentation and control and related information systems of the United States operating light-water reactor fleet. This includes developing novel technologies to enhance the performance of the current labor-intensive business model of nuclear power plants.

Work packages are the key element of the work process in a nuclear power plant. They directly impact the labor cost associated with operating nuclear power plants. A work package is a set of work orders, forms, and reference documents. A work order contains procedures that the craft follows to execute the work package in a systematic and safe manner. Forms are usually attached to ensure the craft conducts proper checks for executing the task such as required resources, hazard awareness, and safety precautions.

The means to improve the work package process was first realized by converting the work package to an electronic format referred to as an electronic work package (eWP) or mobile work package (Farris and Medema 2012). eWPs are work packages that rely, to various extents, on electronic data acquisition, processing, and presentation. They result in significant safety and economic benefit for the nuclear power industry (Thomas and Lawrie 2015), and therefore became one of the areas of focus in the LWRS Program plan (Hallbert and Thomas 2015).

The potential of eWPs was studied with respect to every step of the current work process by EPRI 2015. The means to convert the front end of the paper-based procedure of a work package into a human-factored electronic version was studied in Oxstrand and Le Blanc 2016 and Oxtstrand et al. 2015b. Automated work packages were introduced by the LWRS Program as an advanced version of eWPs that rely on automation methods to address work process deficiencies that cannot be resolved by just digitizing the work process, and require relying on supplemental automation methods or technologies.

The potential for automation technologies to replace costly and labor intensive tasks was surveyed and confirmed by the industry (Al Rashdan et al. 2016). A guideline to work packages data architecture was developed in Al Rashdan et al. 2016. To implement such an architecture, a digital architecture planning model needs to be developed to take into account the diverse infrastructure requirements (Oxstrand et al. 2016).

Al Rashdan et al. 2016 identified 50 promising functions to automate parts of the current work process. Some of these functions were researched in earlier and parallel projects. For example, the initial pilot prototype for acquisition of plant information into a procedure was conducted in Oxstrand et al. 2015a. The development of smart instruments to automatically report aging of plant components has been researched by Agarwal et al. 2014 and Agarwal et al. 2015. The automated work package was designed as a hub to integrate these efforts in one platform that drives the work process in an efficient manner, and to research and develop technologies for new automation functions that have a significant economic or safety potential.

In 2017, Idaho National Laboratory (INL) collaborated with Xcel Energy Inc. to evaluate the means to develop some of the most promising capabilities of the 50 identified functions. Three technologies were identified as promising technologies for the nuclear power industry. These are ultra-high frequency (UHF) radio frequency (RF) identification (RFID), Bluetooth low energy (BLE) beacons, and video monitoring and recording. The aim was to evaluate these technologies for the nuclear power industry from a feasibility and benefits perspective. The main scope of the technologies applications are:

- UHF RFID:
  - Tracking of materials, tools, and equipment (MTE) for foreign materials exclusion zone (FMEZ)
  - Verification of MTE proper use in terms of job fitness, condition, and calibration
  - Easily search for missing MTE in any location of the plant
- BLE beacon:
  - Location identification of craft with respect to critical equipment and locations
  - Location-driven checks and actions in a work package procedure or mobile device
- Video monitoring and recording:
  - Remote concurrence and approval of work steps
  - Just-in-time training
  - Peer review and quality assurance.

Due to the specific nature of the work process in nuclear power plants, an application-oriented customized prototype was needed for each technology that enables simple and efficient use, and excludes unnecessary and complex functions. The prototypes relied on in-house integrated and developed systems that interfaced the software with a spectrum of hardware products from multiple vendors.

The selected prototype development environment was identified in collaboration with Xcel Energy Inc. However, the prototypes can be easily migrated to other mobile device environments. The operating system selected was Microsoft Windows 10. The demonstration mobile devices included Windows Surface 3 and 3 Pro, and Xplorer XSlate industrial tablet. The hardware selected was driven by product evaluations, users' feedback, suitability to the application or research, and cost. However, the research developed findings that are independent of the product or vendor used.

2. ULTRA-HIGH FREQUENCY RADIO FREQUENCY IDENTIFICATION

An UHF RFID tag is a radio transceiver chip that operates at a frequency of 902 to 928 MHz in the United States. The chip uses the energy of the radio signal from an UHF RFID reader as its source of power, and responds back to a reader inquiry with its identification (ID) as a minimum. Depending on the tag, reader, and antenna design and capabilities, a typical tag can be read from a range of tens of feet. In its simple form, a UHF RFID tag would respond with a static ID to an inquiry by any UHF RFID reader. However, programmable tags do exist to perform more advanced functions such as changing the tag ID, storing data on the tags, and requiring authentication to respond back.

An UHF RFID reader is the device that transmits the signal to power the tags, requests data, receives the response back, and decodes it. The reader can be a fixed device with relatively high-power requirements or a portable device that is battery powered. The reader is connected to an antenna to transmit and receive the radio signal. The antenna can be integrated within the reader chip or connected externally.

In order to ensure unbiased and wide exposure to available UHF RFID technologies and the directions of the technology development, a large set of UHF RFID samples were acquired from the main

UHF RFID vendors. These included tags of different shapes and sizes and different bias angles and ranges of detection (Figure 1). The aim was to sample enough of available UHF RFID items to make valid conclusions. A selected set of UHF RFID readers were also acquired that would be a best fit for the targeted application (Figure 2). The readers selected were a portable reader that can be attached to a mobile device and that includes its own antenna, a portable reader that can be connected to an external antenna, and a fixed reader that can be attached to multiple antennas. Several antennas were acquired as well to enable evaluating the antenna impact on the system (Figure 3).

Figure 1. Sample of UHF RFID tags of various forms and designs.

(a) Fixed reader

(b) Mobile reader with intenral antenna

(c) Mobile reader with external antenna

Figure 2. Sample of UHF RFID readers.

Figure 3. Sample of UHF RFID antennas.

2.1 Benefits

The UHF RFID technology was found to provide promising improvement in the time, cost, human error, and safety aspects associated with several processes in the nuclear power industry. These can be summarized as:

- ***Challenge 1:*** The manual tracking of MTE in a nuclear power plant is manual and time consuming. In average, a craft takes 10 to 15 MTE items for a task in the FMEZ. For certain locations in the plant, 24 to 30 entries per shift are expected over 12 days of shutdown. Though the actual MTE logging process requires a few minutes to login and logout, it can take 30 minutes to 1 hour to log an MTE into a FMEZ, and 15 minutes to logout. This is because the majority of time is spent waiting in line to enter or exit the FMEZ, which is due to the slow nature of the manual process. The current tracking process fails when a discrepancy is found and results in a significant critical path loss, which is often the case in FMEZs. Reconciling the logs of an FMEZ is a stressful process that can take several hours to complete. If an item is deemed lost, a search party of several persons is sent in for hours to find it.

  Solution. The attachment of UHF RFID tags and use of UHF RFID readers (fixed or portable) to scan the tags as they go in or out of a FMEZ can be used to track the majority of MTE going in and out of a FMEZ. The logging time of one craft will drop from minutes to a few seconds. The lines of craft will disappear. Discrepancy logs will be instantaneously generated if needed, and can be generated per shift or day to keep an up-to-date look at the use of MTE in the FMEZ. If a discrepancy is found, a handheld reader with portable antenna can be used to scan the area to find the missing item. A missing item will take one person minutes to find instead of large teams searching for hours.

- ***Challenge 2:*** The current work process in nuclear power plants does not always specify the needed MTE for the job and often relies on the experience of the craft to identify the job's needs. This can result in the (1) acquisition or use of the wrong MTE, which affects the quality and safety of the job; (2) missing MTE, which results in time lost to return to acquire the missed MTE; and (3) excessive MTE use, which impacts the MTE availability for other jobs and overestimates the use of resources.

  Solution. If a database is established to link the procedures to the needed tools, and craft associated with UHF RFID tags that are attached to the craft mobile devices, helmets, or uniform, the UHF RFID reader can send the tags' data to the database to verify that the procedure's MTE are present during a scan prior to heading to the task. The system will notify the craft of wrong items (not associated with the procedure), missing items, and excessive items in the craft possession as the craft heads toward the job area. This can also include safety personal protective equipment checks for compliance.

- ***Challenge 3:*** Contaminated MTE are currently tagged through painting with a specific color (e.g., magenta) and remain in dedicated contaminations zones for repeated use in contamination areas. Once an item is marked as contaminated, it is not supposed to be removed from the dedicated zone by the craft. However, the potential lack of experience with contracted workforce could sometimes result in contracted staff unintentionally removing a contaminated item from the contamination zone, which is a critical safety violation.

  Solution. Attaching an UHF RFID tag to the contaminated equipment (by radiation control staff) and setting up powerful reader and antenna systems outside the contamination zone will detect the removal of contaminated items as soon as the removal occurs. With the proper UHF RFID tag size and antenna setup, it is possible to score 100% detection rate of any removal, therefore adding a powerful layer of defense against the spread of contamination.

- ***Challenge 4:*** Tools that require calibration are usually manually checked for its calibration status. It is sometimes the case that a tool is due for calibration but the tool cannot be found in the plant, which implies that a craft might be using an out-of-calibration tool.

Solution. The use of fixed portable readers and antennas to scan for a specific tool in the plant can easily detect a tool with an UHF RFID tag within tens of feet from the scanning location. If the tool is due for calibration, the scanning system can alarm the calibration staff with the tool location for its retrieval.

- ***Challenge 5:*** Tracking expensive MTE in the plant is very difficult during outages, due to the large amount of workforce going in and out of the plant on a daily basis. The share of resources between the plant and contractors sometimes result in lost expensive items that are never found.

  Solution. Setting UHF RFID tags at exit locations of the plant can detect the removal of any plant equipment and alarm the plant to the removal as it occurs.

- ***Challenge 6:*** Large containers of MTE are sometimes stored in dedicated outage hangers. The contents of these containers are unknown after an outage. Before an outage, dedicated craft has to go through the containers to develop an inventory of the items, or search for a certain item if it cannot be found.

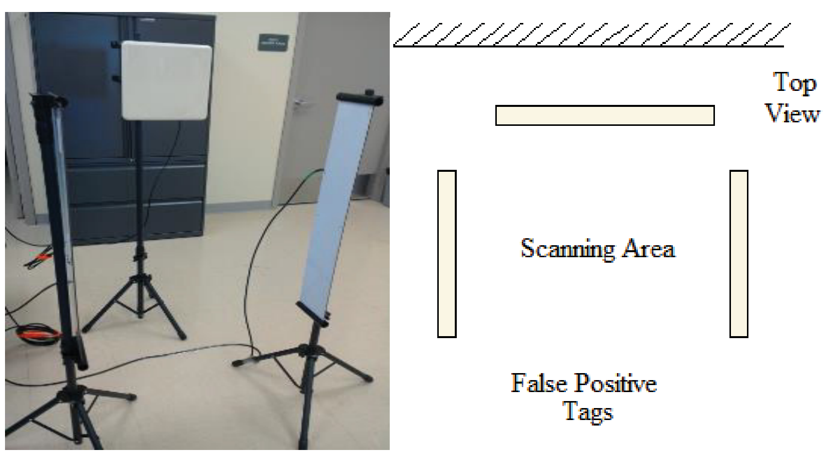
  Solution. Craft can use portable readers and antennas to scan a container all at once if the container MTE is tagged with UHF RFID. The inventory development process will occur instantaneously instead of the current several-days and multiple staff manual inventory process.

- ***Challenge 7:*** The location and removal of large assets in an area or from one area to another in the plant needs to be manually logged and is not always tracked.

  Solution. Large UHF RFID tags can be installed on large assets to track their movement in the plant. Large UHF RFID tags can be read from a long distance with powerful readers and antennas.

2.2 Prototype Development

The use of UHF RFID tags on a sample of MTE was evaluated through a system prototype and software that was developed in C# language at INL. The prototype used three antennas to create a scanning area (Figure 4), and tagged a selective set of tools and safety equipment with UHF RFID tags (Figure 5).



(a) Actual setup picture (b) Location of false positive tags

Figure 4. Layout of antenna setup.

(a) Tools tagging (b) Personal protective equipment tagging

Figure 5. Example UHF RFID tagging of MTE

The prototype contained a graphical user interface (GUI), an interface to the UHF RFID reader, and a database interface. The database was created to contain tables for the MTE, procedures, users, and their associations. The prototype operation consists of driving the reader to scan for UHF RFID tags for a certain period of time, using the scanned UHF RFIDs to collect information about the MTE from the database, and populating the GUI. The UHF RFID tags are also checked against staff IDs. If a tag is a staff ID tag, the procedure associated with the staff is pulled from the database, along with the associated MTE of the procedure. The MTE scanned are then verified against the MTE associated with the procedure to detect discrepancies. The database was placed on a network machine. Adding a new tag is achieved by adding an entry to the database.

The application was developed with the top part containing the GUI controls (Figure 6). The worker will have to click whether the items are going in or out of the zone and the lists shown in Figure 6 will be automatically populated with the scanned items as described. Automatic detection of direction was also evaluated using the detection of hits (replies) per time, but abandoned due to the lack of significant added value and potential impact of an error when compared to the manual process of the worker selecting to login or logout the MTE. The worker mobile device was equipped with an UHF RFID sticker, which is associated in the database (DB) with a procedure. The DB is requested to confirm the found tools are what is needed by the procedure. Any discrepancy is reported in the “Missing Items List” and “Unassociated Items List.”

2.3 Feasibility

The feasibility for UHF RFID in the nuclear power industry was evaluated with respect to several application specific requirements that are summarized in the following sections.

2.3.1 Tag Size

The size of the UHF RFID tag was the main element in increasing its range and probability of detection. Though a clear size cut was not possible to define when considering the tags, due to the technology and quality perspectives, the tags were split into three size ranges for the targeted applications:

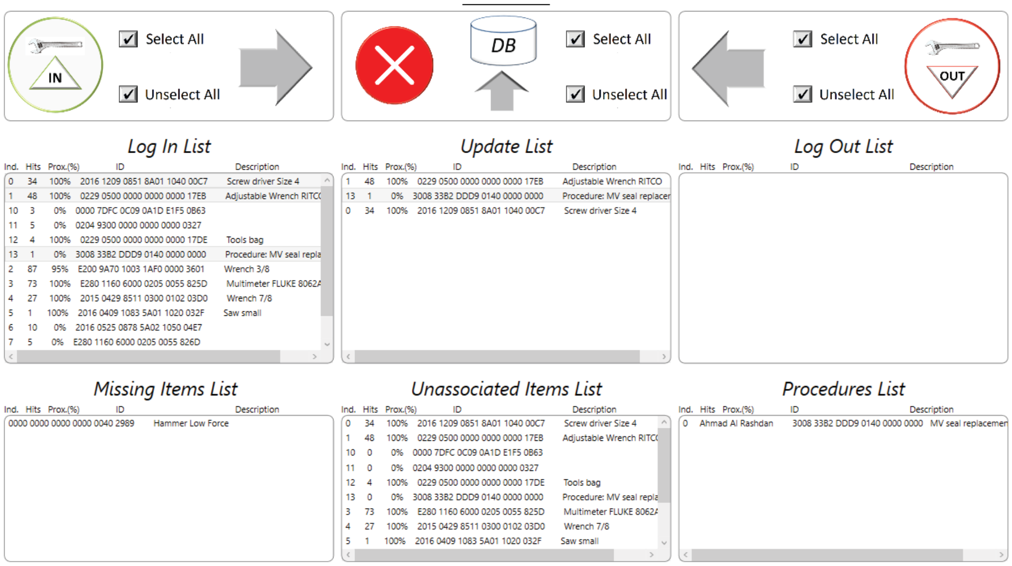


Figure 6. Advanced version of the MTE logging prototype.

1. Extremely small tags that have a maximum one surface area of less than 1 cm^2: These tags were often found ineffective to use for the targeted applications even with a powerful reader and antenna, mainly because of their very low response rate if any. The tags required very close proximity to the antenna for detection, which made them impractical for rapid automatic scanning. As a result, these tags operated poorly with the UHF RFID gates approach or with mobile readers.
2. Small tags that have a maximum one surface area of more than 1 cm^2 and a volume of less than 5 cm^3: These tags were often found effective to use with a powerful reader and antenna. They were read by the gates as long as they were not blocked by a thick surface. As a result, these tags operated reasonably with the gate approach (if surrounding gates are used) as well as the mobile readers if placed in proximity.
3. Large tags that have an approximate volume greater than 5 cm^3: These tags were often found to result in false positives, which mean that they were read even when they were not at the gate or in close proximity to the mobile reader. As a result, these tags are not favored for MTE tagging in FMEZ applications but are desired for detection of unauthorized removal of items from contamination zones or the plant, or for large items logistics.

2.3.2 Setup Layout

The power consumption and size of the antenna are directly proportional to the detection range of the UHF RFID tags. As a result, three setups were analyzed for the scope of the evaluated applications. The three evaluated setups are:

1. Fixed setup with antennas gate: This approach relied on a combination of orienting two antennas to face each other and create a limited space of exposure where the craft would stand when being scanned. The rear and sides of the enclosure would be made of a radio degrading surface (walls or metallic plates) to reduce the probability of detection of tags outside the scanning enclosure. Due to the antennas' wide range of detection, it was found that this setup would still read tags in close proximity to the scanning area (false positives). A new approach needed to be developed. In this approach, a third antenna was added with a scanning domain that is perpendicular to the two antennas (Figure 4). The third antenna is set up to face the source of the false positive. If a UHF RFID tag is present in the tag's scanning area, all antennas would have a large number of hits. If the tag is far from the working area, but facing the third antenna, the third antenna hits would be much higher than

the hits of the two other antennas. A proximity indicator was added using this approach with 100% indicating full confidence that the tag is in the scanning area. The number of hits received from each tag was also shown. A large number of hits, representing enough data points, is needed to be able to use the proximity indicator. This approach worked well when the three antennas are placed on a wall where the source of the tag's false positives is uni-directional (Figure 4). The approach reduced the probability of detecting false positives but did not completely resolve the false positives issue. Another issue associated with this approach is the need for a dedicated power source, due to the large power consumption of the reader. A power supply is not always feasible in some locations of the plant.

2. A portable reader with an integrated antenna: This is a device that connects to a mobile device through a USB or audio cable and is battery powered. To preserve the power consumption, these readers usually consume less power than the wall-powered fixed readers, and therefore have less range of detection than fixed readers. As a result, using a portable reader will not always detect all the tags in a bag of MTE if the scanner does not get close enough to some of the tags. Since UHF RFID antennas are orientation dependent, using this approach will require wandering the antenna around the UHF RFID tags to increase the probability of detection.

3. A portable reader with external antenna: This is similar to the aforementioned portable device but allows connecting external large antennas, and can sometimes be powered externally if needed. As a result, these readers have larger range of detection and are portable to some extent.

It was found from the user study that each of the three setups is suitable for some applications. The fixed setup is ideal for alarming the unauthorized removal of items from the plant. The portable reader with an integrated antenna setup is suitable for logging tags in and out of a FMEZ, especially if the FMEZ monitor will count the items scanned and compare them to the items in the bag. This was deemed easier than having to deal with a large set of false positive tags when the antenna is too powerful. The portable reader with external antenna setup was deemed most suitable for searching applications when an MTE is missing and a search is conducted that requires very strong but portable range of detection, or for outage containers inventory development. A fourth non-gated setup using one reader in the middle of a FMEZ with location detection ability was excluded early in the evaluation, due to the non-uniformity associated with FMEZ space. The use of any UHF RFID reader setup (portable or fixed) in the plant should not occur in radio exclusions zones, and should be in compliance with Nuclear Regulatory Commission Regulatory Guide 1.180 (NRC 2003).

2.3.3 Tag Mounting and Structure

Due to the nature of applications targeted, it was decided that the following are important feasibility considerations should be addressed:

1. The form factor of the tag should be considered when selecting the most suitable tag to use. The mounting of tags should be conducted in a manner that does not interfere with the operation of the MTE (through adhesive or zip ties). This can be done by using groves or areas that do not get in contact with the craft. This will reduce the odds of incidental removal and human hand interference when the tag is being scanned.

2. Tags are often biased towards certain orientation. This was found to play a significant role when scanning for tags in distance.

3. Some tags are more suitable for certain type of surfaces. Metals surfaces are usually more challenging since metal distorts the radio signal and affects the performance of some tags. Adding an insulation layer between the tag and metal was found to help. On the other hand, some tags use the metal surface to improve their range of detection. In summary, tag compatibility should be ensured when selecting the tag to use and a performance test must be conducted before massive deployment of a certain tag type.

4. Tags that have soft or rubber surfaces can be hard to decontaminate, potentially resulting in tag removal and disposal. This finding is not verified but such tags should be avoided in nuclear applications if possible, until a dedicated study is conducted.
5. Disposable items, such as duct tapes or disposable towels, are very challenging to log, and should be manually logged if a whole item is used. If a specific number of sheets is used, specific label UHF RFID tags do exist that can be attached to each sheet.
6. Radiation tolerance of UHF RFID tags is unknown. However, the expected exposure level is very low. Though not IP67 certified, tags are usually resistant to most of the normal natural conditions like wind and dust, due to their full enclosure. Their survivability under rough conditions, including radiation, remains a feasibility gap for future evaluation.
7. If a tag is detached from an MTE, this should be detected when the monitor counts the items and compares the count with the scanned number, or when the item is returned to storage and fails to be scanned by the store keeper. The search setup described in the previous section can be used to find the missing tag.

2.3.4 Front-End Application

Through studying the developed prototype application, several findings were generated on the best means to develop an UHF RFID application for the nuclear power industry. These can be summarized as:

1. Two version of the front-end application are needed. A simple version, which would only show the description of the scanned MTE, would be ideal for all users. An advanced version will be needed for the advanced users, developers, troubleshooters, and system administrators. The advanced version will include tag information such as ID, type, and model, in addition to the number of hits and resulting tag predicted proximity (Figure 6).
2. The application should incorporate an easy method to tag and add new tags in seconds when needed to allow easy integration of the system into the current MTE tracking system.
3. Since the monitor might not know the MTE to verify against the description, pictures of the tools should be incorporated in the application.
4. The instruments should be grouped so that the tool is not assigned to a procedure but the class of tools, representing the same tool specification, is.
5. The database should be located on a remote server for applications with multiple readers and for secure housekeeping of the data.
6. The application should be able to manually log MTE that are not UHF RFID tagged (such as spare parts or disposables).

2.4 Deployment Cost

The cost to implement a UHF RFID system depends on the approach of deployment. Most of UHF RFID readers provide interface capabilities to enable users to develop their own product. In addition, several vendors offer generic products or can develop application-specific products if needed. The normal cost of one multi-channel UHF RFID reader is on the order of a few thousand United States dollars (USDs). A portable reader is usually in the order of hundreds of USDs. The antennas to externally connect to a UHF reader are usually in the order of hundreds of USDs. The tags cost depends on the tags technology, size, and range of detection. When ordered in industrial quantities, it is estimated that tags can cost in the order of tens of cents per tag for relay-type tags and a fraction of one USD to a few USDs for other tags. This cost is expected to drop as the technology further matures. The majority of the cost of implementing the UHF RFID is associated with the software solution and product development.

Considering the benefits of using UHF RFID versus the cost of implementation, it is concluded that the cost is virtually negligible when compared to the operations cost of nuclear power plants.

3. BLUETOOTH LOW ENERGY BEACONS

BLE is a communication technology that is designed to limit the power consumption and is therefore common in devices that are usually battery powered. BLE beacons are microchips that communicate using the industrial, scientific, and medical radio band of 2.4 GHZ frequency with packets containing a unique identification for the beacon. The beacon is installed in locations of interest. As a mobile device equipped with Bluetooth Version 4.0 (as a minimum) approaches the beacon, the mobile device will identify the beacon by its unique name.

BLE devices operate with a standard protocol that relies on standard and customized characteristics and services. As a result, BLE beacons are a subcategory of BLE devices. A wide variety of designs exist for BLE devices and beacons. For this effort, the criteria to select a suitable beacon were the power consumption, type of enclosure of the device, and ease of installation. The BLE microcontroller or beacon evaluated in this effort is shown in Figure 7.

3.1 Benefits

The use of BLE beacons was found to provide a promising improvement in regulatory compliance and safety aspects and reduction of human error associated with the work process in the nuclear power industry. These can be summarized as:

- ***Challenge 1:*** As eWPs become the core of the work process in the nuclear power industry, the craft attention will often be focused towards the mobile device, and the probability of missing a posted warning sign increases. This is especially of importance for radiation area warnings.

  Solution. Using BLE beacons, the mobile device can be set to generate a visual and audio alarm when the worker is crossing into a certain warning zone where the BLE beacon is installed. The volume and tone of the audio alarm can be associated with the type of alarm and the criticality of craft awareness. The visual warning can block the craft view to ensure the craft is aware of the warning.

- ***Challenge 2:*** Nuclear power plants have zones where the use of any radio transmitters poses a safety risk to some radio-sensitive plant equipment. The means to enforce these exclusion zones is associated with administrative controls, such as signs and training. With the increasing use of mobile devices in the plant, the probability of a human error resulting in use of RF signal transmitters in these zones increases. Despite uncertainties about the effect of RF signals on relays (Keebler 2011), the regulatory aspect remains of high importance since the regulations stand did not change. The radio protection of these zones remains a requirement due to the safety concern.

  Solution. The mobile devices can be configured to automatically switch off all RF transceivers when certain BLE beacons are detected. The beacons can be installed at the gate to these zones. Adding a large number of beacons at the gate will reduce the odds of missing a detection. The beacons can be also installed at locations leading to the radio exclusion zones to alert the craft of their proximity and allow the craft to manually switch off the RF transceiver before the automatic action is taken at the gate to these zones.

- ***Challenge 3:*** The dynamics of radiation/dose maps in a plant require manual survey and map updates. This process is time consuming, due to the size of the radiation zones in the plant and need for the maps to be frequently updated.

  Solution. Attaching the BLE microcontroller-based beacon to a radiation detector through an analog input/output can directly transmit the current radiation measurement to the craft's mobile device long before approaching the radiation zone. Using this method, the maps get updated dynamically as workers move in the plant. A central DB can be used to track the updates through the whole plant, which is then populated to all plant mobile devices.

3.2 Prototype Development

The beacon shown in Figure 7 is capable of communicating with a computer through the java script language, in addition to the standard BLE Generic Attribute (GATT) Profile services. Java script is used to configure the microcontroller including the communication configurations, such as the contents of the periodic transmitted broadcast of the BLE beacon. This broadcast was configured to contain the battery level of the beacon, in addition to the beacon ID. This meant that an actual connection or pairing between the mobile device and the beacon was not needed. The broadcast is detected and read by any receiver in range, which enabled any mobile device within the range of the beacon to detect the beacon. This was found as a more suitable approach than peer-to-peer communication that relies on a cyclic connection and disconnection utilizing the BLE GATT characteristics and services due to:

1. Using GATT characteristics and services require pairing the beacon ahead of its use. This means that adding one beacon to the plant would require pairing the beacon with all mobile devices in the plant, which is not practical.
2. Using GATT characteristics and services requires some communication and processing time. If multiple mobile devices are present in the range of one beacon, the beacon will have to talk to each one at a time, which means the rest will wait and a mobile device might move out of the detection range before getting its turn.
3. Using GATT characteristics and services requires more energy than the broadcasting approach due to the dedicated messages to every mobile device. This reduces the battery life of the beacon.
4. If a connection is lost between the beacon and mobile device, due to the move of the mobile device to an out-of-range region, before a proper disconnection, the beacon could get stuck waiting for the mobile device to terminate the connection and not respond to other future requests.

Figure 7. BLE microcontrollers used as beacons.

The broadcast approach allowed the mobile device to estimate the received signal strength (RSS), which was used as a proximity indicator. Since the RSS is not stable in its nature, the feasibility of using the RSS for location identification was extensively researched in literature for accurate location identification applications (e.g., Goldoni et al. 2010). This was not the case for the applications of this research. Only a trigger was needed, which required a calibrated threshold to trigger the desired action. Since mobile device receivers affect the RSS indication, the calibration should be done for each mobile device model.

The compatibility to read BLE broadcasts favored the use of Windows 10 from a development perspective in comparison to older Windows versions. The application was developed in C# at INL to read and display the broadcast from a beacon; determine its ID, power level, and RSS; and display them

(Figure 8(a)). The application runs in the top middle end of the screen (Figure 8(b)). A configuration text file is used by the system administrator to correlate beacon IDs to certain actions and the associated RSS thresholds for each action. In the prototype developed, the actions were to (1) generate a battery low alarm when the battery level of the beacon drops below a certain threshold, (2) generate a radiation or electric shock warning (Figure 8(b)), or (3) switch off all RF transmitters on the mobile device when the mobile device crosses a certain RSS threshold value. The switch off of RF is done through disabling the drivers of the RF devices using applications such as the Windows Device Console. Once a warning is activated, it is blocked from reactivation until the mobile device moves away from the beacon for a certain period of time. Once this time has passed, a return to the beacon area would trigger the warning message again. The text file can be populated to all mobile devices through a network as beacons are added, so the system is easily updated.

(a) BLE application front end

(b) Electric shock warning due to detection of BLE tag that is associated with this type of hazard

Figure 8. BLE prototype front end.

A second threshold was also incorporated to trigger an action when it is crossed by the average of several RSS readings. This can be used as an alternative approach if the RSS is too unstable, and the average provides a more reliable value for triggering. The disadvantage of the average threshold approach is that it requires multiple reading, which requires more time to trigger. As a result, this is more suitable for long-range BLE beacon applications, where multiple readings can be acquired as the craft approaches the beacon.

3.3 Feasibility

The feasibility for BLE beacons use in the nuclear power industry was evaluated with respect to several application-specific requirements that are summarized in the following sections.

3.3.1 Power Consumption

Since the BLE beacons are battery powered, power consumption is critical to its applicability. The factors affecting the power consumption are the frequency of broadcasts, length of the broadcast message, and strength of broadcasted signal. As a result, the means to reduce power consumption can be achieved by:

1. Reducing the frequency of broadcasts. If the frequency is too low, it can result in the beacon detection being missed if a craft passes by a beacon at a rush, especially since mobile devices are also configured to scan in certain intervals. Adding more beacons per location to improve the detection probability can improve the detection probability. In this case, the multiple beacons are associated with the same action, and the battery replacement will take place once per year for all beacons at the same time. This was concluded to be less maintenance demanding than having to replace fewer beacons every month or two when using high broadcast frequencies.

2. Reducing the range of the RF signal to the minimum acceptable range, which would be reflected in lower signal strength, thus saving power. The BLE beacon selected should allow the transmission power to be adjustable.
3. Keeping the broadcast message as short as possible. Only needed information should be transmitted. Ideally, the ID of the beacon and the battery level are the main information broadcasted.

In addition to the above measures, the application developed should facilitate reading the battery level of the beacon and alarming the craft if a beacon's battery crossed a certain battery level threshold.

3.3.2 Signal Range

The BLE beacon desired range of detection depends on the location of deployment. For example, if the control room area is a radio exclusion zone, BLE beacons would be installed at the entrance with a short range of detection that is oriented towards the area outside the control room by means of the walls or barriers. On the other hand, if there is long hall that leads to a radio exclusion zone, or when the BLE beacon is used for warnings, the range can be longer. It is important to always optimize the range keeping in mind two rules: (1) range is proportional to power consumption, and (2) range is proportional to detection probability. The second rule can affect the application in a positive or negative manner. If the range is too long, spurious warnings can occur to craft that are not really entering the area of enforced warning or action. If the range is too short, the craft might pass by the beacon without detection, and techniques like the ones mentioned in the previous section can be used. An optimization needs to be performed for each location of implementation when the BLE beacons are deployed.

3.3.3 Maintenance

Since the BLE beacon will require periodic maintenance (annual was targeted), the structure of the beacon should be modular to allow battery or controller replacement in a flexible and rapid manner. The in-site reconfiguration of the BLE beacon should be also facilitated through wired or wireless means.

The radiation tolerance of the BLE beacon is another factor that should be considered. Since the BLE beacons are not designed to tolerate significant radiation fields, the beacons should not be placed inside radiation zones unless a radiation tolerance study is conducted. Due to the low cost of the beacons, it is possible to replace both the controller and battery during the annual maintenance to reset the life expectancy of the beacon to its maximum.

3.3.4 Front-End Application

The front-end application should ideally be virtually invisible. It should not block the view of the craft, and run in the background to trigger the warnings and actions when a BLE beacon is in the threshold range. The application should run when the machine starts, and should not be stoppable by the craft. For warning implementation, the warning screen should cover the whole mobile device screen, and should require an acknowledgment button to close. It should be accompanied by an audio alarm, in case the craft is not looking at the mobile device. If the application is used for radio exclusion zone enforcement, the application should switch off the radio transmitting capabilities of the mobile device when it is stopped or killed by any means. The only means to restart the radio transmitting capabilities should be if the application is started again. Therefore, the craft's only access to start and stop RF transmitting capabilities is through the application. For system administrators, a version of the application should show the RSS, ID, and power level of all BLE beacons detected.

3.4 Deployment Cost

The typical cost of a BLE beacon or microcontroller is in the order of tens of USDs. The majority of cost for implementing this technology is associated with the software or product development that will be installed on the mobile devices. For the application of critical warnings or radio exclusion zones, a high number of beacons should be installed to ensure that the instability of the wireless signal does not significantly degrade the detection probability. The cost of implementing multiple tags per location is insignificant. If 10 BLE beacons are installed at every radio exclusion zone, and assuming 12 to 15 radio exclusion zones are present in one plant, the cost of implanting BLE beacons for radio exclusion zones in the whole plant (excluding the software cost) is a few thousand USDs. This cost is negligible when compared to the operating cost of a nuclear power plant and considering the fact that this technology provides another layer of safety defense in the plant.

4. VIDEO MONITORING AND RECORDING

Video monitoring or surveillance refers to the remote viewing of a video stream through a local network or over the Worldwide Web. In the context of this effort, video monitoring is focused on local network applications. The most common type of cameras used for video monitoring is a fixed dedicated camera referred to as an internet protocol (IP) camera (Figure 9(a)). Unlike web-cameras, IP cameras can be configured within a local network in matter of seconds, and do not require a wired connection to a device. They are designed to connect to any network, acquire their own IP address, and can be accessed by any device on the network with proper authentication. IP cameras are typically powered through a wall power outlet, but can sometimes be powered through a power bank. Their size is typically not suitable to be used on a human body, but is ideal for placement on a horizontal flat surface.

Video recording usually refers to storing the video stream into a local or remote device for later view. This is usually achieved by battery-powered cameras, such as action or body cameras (Figure 9(b)), and is often not optimized for real-time streaming. Both technologies found several new applications in various industries and markets, and have their own advantages and disadvantages (Table 1). However, the nuclear power industry has been reluctant in significantly adopting either technology due to unclear reasons. Camera applications in the nuclear power industry are mostly limited to using high–end cameras for in-pool fuel serial number acquisition, and borescopes for inspection of hard to reach areas.

(a) Fixed camera

(b) Action cameras

Figure 9. Sample of used cameras

4.1 Benefits

The use of video monitoring and recording was found to provide promising improvement in time and cost associated with several work processes in the nuclear power industry. These can be summarized as:

Table 1. The typical characteristics of the mobile versus fixed cameras.

Parameter	Mobile Cameras (action and body cameras)	Fixed Cameras
Power source	Battery	Outlet
Power consumption	Low/medium	High
Resolution	High	Low/medium
Application	Recording	Monitoring
Local storage capacity	High	None
Direct network connectivity	No	Yes
Size	Small	Medium/large
Cost	Medium/high	Low
Compatibility	Limited to certain operating systems	Open

- ***Challenge 1:*** Decades ago, most of the tasks in a nuclear power plant were single-person tasks. Only ultra-high risk tasks required two crafts. As the work processes became more safety demanding, craft very often required verification and peer checks during the execution of the work package. This forced the nuclear power industry to rely on two-craft teams to execute a large portion of work packages, therefore doubling the time, cost, and dose associated with executing some tasks.

  Solution. Using remote video monitoring, it is possible to enable craft in the plant to view and concur the task execution almost instantaneously, without the need for the second craft physical presence. This could apply to all type of concurrences except for independent verification, which requires the worker to leave the area for another to come in, tag the equipment checked, and then leave.

- ***Challenge 2:*** A supervisor typically oversees 6 to 8 craft, and ideally is supposed to check on them regularly. The walk to a work location can take up to 1 hour. Due to other responsibilities and the time required to check on each craft, this is not always feasible. If an issue arises during off-duty hours, the supervisor could be called into the plant, which delays the response to the issue, and requires significant time for the supervisor to arrive.

  Solution. If the craft is using a helmet-held camera, and broadcasts the video stream over the network, the supervisor can remotely log into the worker camera and check on them without the need for the supervisor's presence at the work location.

- ***Challenge 3:*** The craft often require help conducting a new task that the craft is not experienced in. The lack of experience could impact the job quality and require a significant amount of time to complete in comparison to an experienced craft.

  Solution. The craft can use video recording (helmet or fixed) of previous execution of the job as a just-in-time training tool for the new task to ensure satisfactory job quality, and reduce the amount of time needed from other craft.

- ***Challenge 4:*** It is not always feasible for the supervisor or craft to explain a certain issue or concern with a certain work package during the job briefing without detailed illustration.

  Solution. Video recording of previous execution of the job can be used in pre-job briefing for illustration of potential job concerns and how to address them.

- ***Challenge 5:*** Operations are sometimes required to verify certain precautions or task completion in the field.

Solution. The craft can broadcast the video stream to the control room for operations verification without the need for a field operator's travel to the work site, which eliminates the wait time of the craft in addition to the travel time of the operator.

4.2 Prototype Development

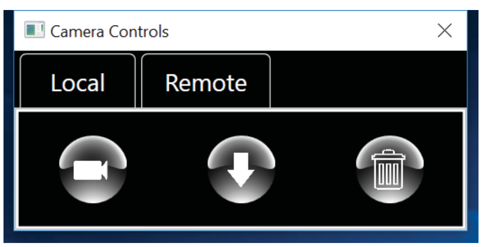
The cameras evaluated in this effort were selected from popular action and fixed cameras. The action camera accessories were procured to fix the camera on a helmet, human body, and wall or surface. The aim of the prototype is to develop a system that combines the advantages of the two types of cameras in Table 1 in one camera setup. This required a custom-developed system and software, which was developed at INL.

Instead of using the generic software provided by the cameras vendors, which contain several functions that would not be useful for the targeted applications, custom-designed software was developed in C# language at INL. The requirements for the application were set as:

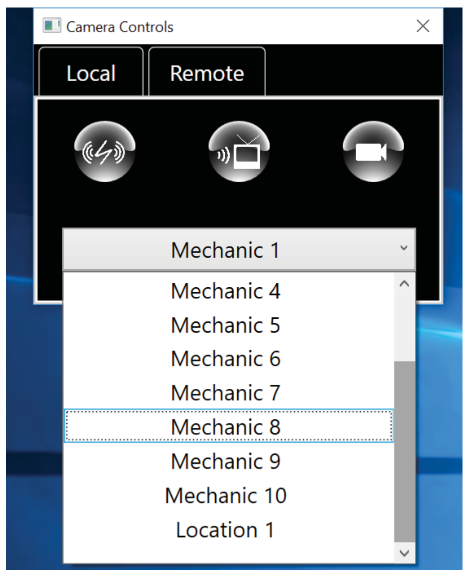
1. Modular to allow interfacing to different types of cameras (mobile or fixed).
2. Simple to use by having the core required functions only.
3. Easy to configure (to add new cameras or users to the network).
4. Optimize between video quality and latency.

The prototype developed was made up of two tabs:

1. Local functions to record to the camera memory or to a mobile device, download the recorded files from the camera, and delete the files from the camera (Figure 10(a)).
2. Remote functions to stream-out the video stream to the network, or to stream-in another user's video stream using a dropdown menu of all other users that are accessible by this craft's mobile device (Figure 10(b)).



(a) Video recording tab



(b) Video monitoring tab

Figure 10. Video recording and monitoring prototype.

The addition of the users to the dropdown menu is performed by editing a text file. The administrator will mainly list the name, IP address, and port of the local camera, and all other cameras that the application can access. If the camera is an IP camera, it is accessed directly through its IP. If the camera is an action camera, the port is used to link the mobile device to the camera. The video stream is then streamed out by the mobile device to other mobile devices. As a result, every mobile device is acting as a streaming server. Another setup could be for mobile devices to stream to a dedicated server, before another mobile device connects to the server for the stream. A third-party open source video manipulation tool was used for re-streaming the video through the mobile device, and for remote access and decoding of video streams. The video manipulation tool is the hidden video engine behind the developed prototype.

Control commands of the action camera were passed using code-incorporated and code-generated web requests. A keep-alive command was needed to stop the camera from automatically switching off when not in use. This command is camera-specific. A network wakeup command was also needed to switch on a camera remotely, if the camera supports this type of command. Each type of camera (fixed or mobile) was interfaced to support both monitoring and recording applications in the prototype.

4.3 Feasibility

The feasibility for video monitoring and recording in the nuclear power industry was evaluated with respect to specific implementation requirements that are summarized in the following sections.

4.3.1 Power Consumption

Due to the network communication aspect of IP cameras, they are usually designed to produce a stronger radio signal in comparison to action cameras that usually provide a weak radio signal to preserve the battery. Whether streaming or recording videos, the expected use of a camera will not need to exceed a couple of hours of total use per shift. As a result, an external battery is not needed when considering action cameras, because these applications would not consume much battery or bandwidth. If a fixed IP camera is used, an external power bank can be used to power the camera to last for the needed duration of operation.

4.3.2 Cybersecurity

Cybersecurity concerns are common in the nuclear industry when wireless data exchange is considered. Since the applications considered for this technology are for training or instant streaming, the risk and impact of a cyber-attack is not directly significant to the operation of the plant. The indirect impact remains for future evaluation.

4.3.3 Resolution

While tracking the work process is not resolution demanding, peer checks such as component verification require the ability to read text with a font size in the order of fractions of an inch in height. Some means to improve the resolution include increasing the latency by creating a streaming buffer, or reducing the frames per second. If a satisfactory resolution cannot be achieved for peer checks, because of the action camera originating low streaming quality (due to the low signal strength) or the IP camera distance from the work environment, the mobile device camera can be used as a suitable option to view the targeted item for this specific application.

4.3.4 Infrastructure

The User Datagram Protocol often used as the backbone for streaming applications is an error-tolerant protocol, which means that the protocol discards messages with errors without requiring a retransmit. This is done to increase the communication speed (reduce latency). As a result, the video quality streaming drops if the network bandwidth suffers. Due to the significant bandwidth needed for streaming video, it is necessary to ensure the network has the required bandwidth infrastructure to support implementing the monitoring applications if high streaming quality is needed, and that wireless interference is addressed to ensure lower packets loss. Due to the size of power plants, and the fact that wireless access points will typically be sparsely placed, network interference is not expected to be significant in the site of a nuclear power plant.

4.3.5 View and Mounting

A camera mounted on a helmet was found to provide the best work area view for all the considered applications. Modern action cameras have wide view angles that cover the whole work area. Shaking was not found to significantly affect the view of the camera, but did sometimes impact the resolution if the decoding algorithm is sensitive to rapid changing frames. Body-held cameras were found to provide an angle that is more suitable for distant view. Glass cameras have limited power storage capacity. Handheld cameras were too close to the work area, and fixed cameras were too far, and therefore suitable for monitoring progress rather than training or quality review.

One important factor to consider when deciding on the means to mount a camera, is the impact of the mounting on the signal strength and the video quality. For example, the signal strength was found to suffer when the camera is placed on the top of a helmet in certain cases and resulted in poor video streaming quality. This is because of the action camera's low transmission power to preserve the battery power.

4.3.6 Size

The size of action cameras was better suited for the applications of interest. The weight of the camera allowed it to be attached to a helmet without significant discomfort to the craft. If the job requires long-time and continuous monitoring, or a distant view provides better status of the job, a fixed arrangement for the action camera can be used (in addition to the IP cameras option).

4.3.7 Audio

For plants that do not allow the use of radio handheld transceiver, it was found that there is a need to incorporate a notification system such as audio calling or instant messaging to request remote monitoring when needed.

For recording applications, the action camera microphone was found to provide satisfactory quality if the craft is in proximity of the camera, but did not perform as well if the action or IP camera is fixed at a distance from the job location, due to limited microphones sensitivity, and the impact of background noise. In these cases, it is possible to use the mobile device's microphone if audio is needed, due to the mobile device proximity to the craft.

4.3.8 Night Vision

If night vision is needed, a decision needs to be made whether a light source will be used or whether the camera should have dedicated night vision capabilities, which is more common in IP cameras than action cameras. The decision to switch on and off the night vision mode should be automated based on the level of light in the picture.

4.3.9 Perception

Due to privacy concerns, the access to video monitoring or recording should be controlled by the actual craft being monitored or recorded. The craft should enable the broadcast of the video when needed and notify the other party of the video availability for monitoring or recording. The craft should be able to record the video locally if needed.

4.3.10 Front-End Application

Through studying the developed prototype application, several findings were generated on the best means to develop a video application for the nuclear power industry applications. These can be summarized as:

1. The front end should only contain the needed functions. The application should be designed while acknowledging that the majority of the nuclear power craft is not aware of the functions or meaning of several video options. As a result, the setting of these options should be automated in the software and invisible to the user. Ideally, a front end that can be learned in a few minutes should be targeted.
2. The front end should isolate the different applications from a visual point of view for simplicity. This can be accomplished by isolating the recording from the monitoring functions, or more comprehensively by separating every single application in a dedicated tab if some application-specific functions are needed.
3. The front end should have two versions, one for staff with cameras and another for staff that do not have any cameras but monitor the ones who do. The staff with cameras should also be able to monitor other staff with cameras.
4. The application should allow easy update of the list of users that a craft has access to. This can be through setting the permissions in a database for large-scale implementation or a simple text file for small-scale implementation.

For the recording application, a prototype was developed to enable PDF files to trigger recording when the procedure reaches a certain step. This was soon replaced by the dedicated application mentioned above, due to potential licensing requirements, which resulted in significant cost addition that did not justify the added value.

4.4 Deployment Cost

The cost of an action camera is usually in the order of hundreds of USDs, while an IP camera is typically in the order of tens to few hundreds of USDs. As a result, the cost to deploy 100 cameras per plant is on the order of tens of thousands of USDs, if the software is available. This cost is insignificant when compared to the resulting cost saving due to the technology. The main indirect cost associated with deployment of video monitoring and recording is the wireless network infrastructure that needs to be incorporated to support high bandwidth use, which is dependent on the plant layout and current infrastructure condition.

5. CONCLUSIONS

The incorporation of automation methods into the work process is in full alignment with the objective of the Department of Energy's LWRS Program to enhance the performance of the current labor-intensive business model of nuclear power plants, and the nuclear power plant's plan for delivering the nuclear promise by assuring future viability through efficiency improvements. The fact that the vast majority of the current work process is manual indicates a significant potential for automation technologies. The cost of implementing these technologies is negligible, when compared to the cost of nuclear power plant operations. The cost savings, however, are potentially tremendous.

The technologies addressed in this effort have been explored to various extents in various industries. However, the nuclear power industry has been behind in utilizing them. The study performed as part of this effort determined that the need for the evaluated technologies does exist, the potential is significant, and deployment is feasible.

The use of UHF RFID was found to provide solutions to several severe challenges in the nuclear power industry, some of which have significant time, cost, human error, and safety impacts. The feasibility of implementing the technology is associated with using an optimal tag size, designing proper system layout to reduce false positives, determining the proper tags to use for every tool, and designing an efficient application, including the GUI.

The use of BLE beacons was found to provide an economic solution to any location tracking requirement of mobile devices. Whether for warnings or actions, this technology was found to offer a lot of safety and regulatory compliance improvement. The feasibility of implementing the technology is associated with optimizing the power consumption for reduced maintenance by means of communication configuration, calibration of signal strength per location of installation, and development of a suitable application to enable the needed functions.

Video monitoring and recording were found to result in time and cost improvements in the work process. Several applications were identified to benefit from mobile and fixed cameras. The feasibility of implementing the technology is associated with general aspects including consideration of the power consumption, resolution, means of mounting, size, night vision capability, and a suitable front-end application, and plant-specific aspects such as cybersecurity, wireless infrastructure, and staff perception.

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