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Eyes On the Ground: Path Forward Analysis

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Abstract

A previous report assesses our progress to date on the Eyes On the Ground project, and reviews lessons learned [1]. In this report, we address the implications of those lessons in defining the most productive path forward for the remainder of the project. We propose two main concepts: Interactive Diagnosis and Model-Driven Assistance. Among these, the Model-Driven Assistance concept appears the most promising. The Model-Driven Assistance concept is based on an approximate but useful model of a facility, which provides a unified representation for storing, viewing, and analyzing data that is known about the facility. This representation provides value to both inspectors and IAEA headquarters, and facilitates communication between the two. The concept further includes a lightweight, portable field tool to aid the inspector in executing a variety of inspection tasks, including capture of images and 3-d scan data. We develop a detailed description of this concept, including its system components, functionality, and example use cases. The envisioned tool would provide value by reducing inspector cognitive load, streamlining inspection tasks, and facilitating communication between the inspector and teams at IAEA headquarters. We conclude by enumerating the top implementation priorities to pursue in the remaining limited time of the project.

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1. RECAP OF INIITAL WORK

The Eyes On the Ground project seeks to develop tools to aid an IAEA inspector. The founding goal was to develop a tool that measures a site of interest, performs analysis of the measurement, and the presents the inspector with both geometric and semantic information to aid their understanding.

In the first half of this project we pursued a "What is this?" scenario, with a goal to aid the inspector in diagnosing the function of unknown equipment they encounter. We identified candidate solutions for the necessary data capture, data processing and segmentation, and semantic analysis algorithms.

This led to a number of key lessons learned, which are explained in detail in [1]. To sum up, our original "What is this?" vision seems infeasible, for these reasons, repeated from [1]:

1. Data will often be insufficient:
    - Access constraints limit what can be seen.
    - Large equipment may be split across several rooms.
    - Important features are hidden inside equipment.
    - Facility operators may forbid measurement of important information.
    - Scan resolution may be too coarse for small features.

2. Time will be insufficient:
    - Inspectors do not have spare time for complex scan operations.
    - Inspectors cannot afford to wait for long computations.
    - Facility operators may forbid removal of data for faster off-site processing.

Given the above constraints on data and time, automatic equipment diagnosis is will often be ambiguous, since different equipment types can have a similar outward appearance. This is compounded by the wide variation in configuration of equipment with a common functionality.

Yet our work up to this point has also identified several opportunities. These insights are outlined in [1], page 21.

The prior report addresses the question "What have we learned?" In this report, we address the question, "What are we going to do about it?"

2. DESIGN OPTIONS

So what can we do? Here are two top-level concepts:

A. *Interactive Diagnosis.* Bolster the original "What is this?" idea by adding significant manual input capabilities. For example, if the sensor resolution is too coarse to detect braided wire cable connected to a device, let the user manually note its presence. If the sensor can see the geometry of a feature but cannot distinguish, say, a network cable from ¼" stainless tubing, then let the user provide the answer. Meanwhile, build a semantic graph of all this input to support functionality analysis. This could be augmented by a decision tree, which generates a sequence of questions to identify an item, and questions are answered by a combination of user input and sensor measurements – possibly multi-modality measurements including laser scans, radiation measurements, mass measurements, etc. By playing a game of "20 Questions," such a system might be able to help an inspector diagnose a piece of unknown equipment.

B. *Model-Driven Assistance.* Develop an "inspector's aid" designed to assist an inspector and improve their productivity on site, while also maintaining and augmenting a model of the facility and its components. This idea centers around a model of the facility, which includes a functional representation of material flow and an approximate representation of plant geometry. The geometric representation may be very coarse in places where either data is sparse or intentionally limited by proprietary information restrictions. Yet the model provides a common backbone on which to associate a variety of useful data, ranging from inspector checklist instructions, spatial logging of radiation measurements, scans and measurements of specific equipment items, and so on. Since the model includes both functional and geometric representations, it has rich semantics. Since it can be built to hold multi-modality information, it could support both human cognitive understanding and automated system analysis. It might support a variety of questions of interest, detailed below.

Among these, the Interactive Diagnosis option is the closest to the original goal of the project. There is some concern that even if executed well, such a system would still exhibit a narrow range of utility. This is due to the fundamental difficulty of deducing a device's function by only viewing its outside surface. For example, a gamma-ray spectrometer, dental x-ray emitter, and mounted capacitive sensor all share the common features of a cylinder with a flat opaque face, mounted to a slightly larger box. All three are semantically similar in outward appearance, but very different in function. To fully diagnose the difference, you need to disassemble the devices and study their internal components. This diagnosis difficulty is compounded by the wide variation in the configuration of equipment with similar functions when sampled across a range of laboratory and industrial settings.

We might succeed in constructing a diagnosis system that succeeds in a limited range of cases. But we should ask: Would that same set of cases also be easy for the inspector? For example, nuclear fuel rod assemblies have unique configuration properties that might support automatic recognition. But those same properties also make them easy for humans to recognize.

These difficulties draw our attention toward the Model-Driven Assistance option, which might conceivably support a fairly broad range of inspector needs. We will explore this concept in the following sections.

3. MODEL-DRIVEN ASSISTANCE CONCEPT

IAEA inspectors perform several types of inspections. These include standard material accountancy, design verification, special inspections, and complementary access inspections. The first three are examples where the IAEA has an advance declaration of the facility's function and primary components; in these cases, the IAEA already has a "model" of each facility, although the form of the model may vary widely. Here the IAEA's goal is to verify that the facility matches its declared function, and is operating without material diversion. As of 2015, there are over 709 facilities and 577 locations outside facilities subject to inspections, a significant opportunity [4].

In contrast, complementary access inspections are fundamentally different. Here the IAEA inspects an unknown site they suspect might be conducting undeclared proliferation activity. Unlike the other inspections, the IAEA has much less advance information describing the facility's function or its components.

Because the Model-Driven Assistance option assumes a model of the facility, it is mostly applicable to accountancy, design verification, and special inspections. For complementary access inspections, the Interactive Diagnosis option appears most relevant, because it does not require an up-front model. However, as we flesh out the Model-Driven Assistance concept, we will see that it could also contribute to complementary access inspections. For example, if the operator allows data to be removed from the site, the proposed system could aid in logging the location of material samples, or gathering detailed information about specific pieces of equipment that are encountered.

3.1. Assumptions

In designing the Model-Driven Assistance concept, we assume the following:

A1. IAEA Headquarters has a model of each facility, describing at minimum (a) the facility's functional material flow and (b) basic geometric layout. The detail of the model may vary, in some areas including precise attributes, and in others only rough approximate information. The form of current model information may also vary, from simple schematics to more detailed design drawings or CAD models.

A2. The inspector has limited time on-site, and a heavy workload.

A3. For current tasks, required inspector data entry is sparse. Sparse data entry is also necessary, due to inspector time constraints.

A4. Data quality from 3-d scanning will be mixed and incomplete. Data quality will typically trade off against time spent collecting data; if more time is spent scanning, data quality increases. However, tight limits on inspector time in turn imply that scan data quality will be limited.[1]

A5. In general, the operator won't allow a full detailed scan of the facility, instead restricting study to only those components related to nuclear material flow.

A6. In some cases the operator will allow removal of scan and other data, and in other cases they will not allow data removal.

A7. If data cannot be removed, the inspector can at least store acquired data on-site in a sealed locker, in a form that would allow reading the data during a subsequent inspection for comparison and change detection.

A8. If an operator forbids removing data, they might also forbid removing computer equipment, for fear that it might carry data with it. In such situations, the inspector can leave the computer equipment in a sealed locker for later re-use.

A9. If data and computer equipment cannot be removed, the inspector can at least print out a post-inspection report containing tables of measurements, photos, notes, etc.

A10. If data and computer equipment cannot be removed, the inspector may bring new software updates and data, and upon arrival upload these to the stored computer.

A11. If data and computer equipment cannot be removed, and storing computer equipment is also forbidden, then the inspector may arrive with a sheaf of pre-printed notes and diagrams, make hand-annotated notes, take photos, and either remove the resulting notes and photos or store them for reference during a later inspection.

A12. We can implement secure data connections between devices that do not allow the possibility of device tampering through firmware hacking, etc.

[1] Technology advances might improve this. For example, imagine an eyeglass-based device which captures a video of everywhere the inspector looks, coupled with photogrammetry software that constructs a resulting 3-d model. This would not be a radical departure from current industry trends. If this were to become available, possible data quality could improve, but issues of operator acceptance could still present challenges.

3.2. System View

The Model-Driven Assistance concept is based on the thesis that in order to produce an effective device for assisting an inspector, you have to understand the context in which they work.

The inspector's mission is to support the IAEA's effort to determine whether or not a state is complying with their NPT agreements. Inspectors contribute to this goal by routinely visiting sites and assessing whether material control and accountancy procedures are properly followed, and whether declared material quantities match what is seen on site. In DIV inspections, inspectors compare hardware against declared design functions, and in repeat inspections also assess whether equipment has changed. Inspectors report their findings to IAEA headquarters, where they contribute to a comprehensive state-level analysis. The state-level analysis considers information from a variety of sources, seeking to verify compliance or detect inconsistencies. Issues encountered in the state-level analysis might generate questions about specific facilities, which could potentially identify specific items for an inspector to check on the next inspection.

Information is key to this process. On a routine inspection, the inspector needs to know what to expect in the facility, and what to check. They must record their findings and communicate them to IAEA Headquarters. Teams at headquarters must assimilate this and other information to build a picture of nuclear material flow throughout the country. Their study may identify information gaps generating questions, which in turn generate information describing desired inspection actions, informing the next inspection.

3.3. Annotated Facility Model

In order for this information to be meaningful, it must exist within a model. Here we mean "model" in the most general sense – a means for organizing and making sense of the relationships between various pieces of information. A purely mental model meets this criterion. Without a model, a scattering of discrete facts cannot be used to derive a conclusion.

In the Model-Driven Assistance concept, we make this model explicit, and use it as a means for describing, storing, and communicating packages of information relevant to a facility and IAEA's state-level analysis. The model serves as a backbone on which to attach information from various sources, within an organizing context.

For example, a model of a facility would have a functional block diagram expressing the processing steps performed in the facility, combined with annotations indicating material balance areas and key accountancy points. Links from these features would point to declarations of material content and historical inspection measurements.

The model would further include a geometric representation, including plant layout and links between the functional block diagram elements and facility items in the layout. The geometric description may vary in detail. At minimum it would include a floor plan, augmented by a schematic representation of material flow elements. We envision that it would usually also incorporate a 3-d representation showing room locations in 3-d space and CAD models of relevant equipment, albeit very coarse for items where either data is missing or the operator forbids explicit modeling.

The model would also include inspection-relevant information, in the form of either inspection measurement records or instructions for inspections to be done. These would be linked to corresponding elements in both the functional block diagram and the geometric model.

The model would support rendering with a variety of views. For example, one could simply view the functional block diagram. Or alternatively the geometric model. Either view would support adjusting focus by panning and zooming. In addition, either of these views could be augmented by graphics indicating links to inspection information, perhaps filtered by selection criteria. (Examples: Show the planned inspection stops with numeric labels. What locations have not yet been visited? Where have we observed radiation intensities exceeding X? Indicate where 3-d scan snippets have been taken; click on link to view them. Etc.) Yet another view would be a checklist view, displaying the planned inspection agenda, indicating what has been completed and not completed. Clicking on a task could show the functional or spatial context. Input fields would allow entry of required measured data. As tasks are completed, this becomes a transcript record of the inspection.

The model would allow input from either the inspector or an analyst at headquarters. An inspector could add results from planned measurements, or notes describing an unexpected observation. Locations could be selected on the geometric model, allowing logging of measurement locations, material sample locations, observation notes, etc. Input created in one view (e.g., geometric) would be automatically associated with the appropriate context in other views (e.g., functional). The time and user identity are associated with posted notes, enabling question-and-answer conversations to be logged in the model, associated with relevant facility features.

The model would include time information. This would include associating a time stamp with every entry – especially measurement observations – and also some method of capturing changes over time.

The model may also include a schematic piping and instrumentation (P&ID) diagram. These diagrams have more detail than a functional block diagram, but do not show accurate geometric layout. This can make it much easier to precisely depict function, without concern about geometric scale and interference.

The master copy of the model resides at IAEA. The inspector takes to the site a copy of the model suited to the inspection task, interacts with the model while on-site, and brings back the result, which is then used to update the master model at IAEA. In the preferred scenario, the inspector takes the model copy with them on an inspector tool (described below), uses it on-site to record results, and brings back the tool to electronically download the data and update the master model. In cases where facility operator restrictions prevent this ideal scenario, the model supports output and input to/from non-volatile media to support this process.

3.4. Inspector Tool

In this section, we present our vision of the proposed tool, after it is fully developed. Note that in the scope of the current project, there is not sufficient time to prototype all of these capabilities. Nonetheless, the benefit of articulating this long-term vision is that it provides a context for building components, so that they will ultimately fit together to produce a useful whole. This envisioned description of the full system also provides a concrete description to share with the stakeholder community, to solicit their feedback and comments.

We desire a system that an inspector can take on a site visit. Possible hardware:

Very light	Tango smart phone with 3-d sensing [3].
Light	Tablet-based solution, such as the DotProduct scanner.
Medium	A portable scanner feeding data to a laptop with a swivel screen.
Heavy	The FARO laser/optical scanner, with laptop data processing.

Of course, we desire the most capable, lightest weight solution. Selection among the above will be determined by technical feasibility, which we will learn through development.[2]

The tool's software should support several functions:

Fxn 1. Setup: Verify that the tool's internal software has not been tampered with, and load updated software, model data, and task updates.

Fxn 2. At any time, display the site model, supporting functional and geometric views, pan/zoom, overlay of CAD, point cloud, radiation, and annotation data.

Fxn 3. At any time, display inspection task status, including planned sequence, tasks accomplished, tasks remaining, etc.

Fxn 4. Provide a means for helping the inspector remain oriented in the plant, to allow the tool's model display to correspond to the inspector's local vicinity. This might be accomplished manually, using simple floor plans, location markers, etc.

Fxn 5. Present a step-by-step walk through of planned inspection tasks.

Fxn 6. For each task, provide easy entry fields for logging observed data.

Fxn 7. Support standard tasks such as NDA analysis and random sampling with simple calculation tools that generate the required random numbers for sample selection, computations of statistical confidence given measurements so far, etc. Use IAEA standard calculation techniques and present transparent calculations.

Fxn 8. Allow manual annotation, and manually assisted attachment of multi-modality data such as radiation scan results to model locations. Allow the inspector to click on a location and view associated data details.

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[2] We also considered a Hololens / augmented reality approach [5], but set this aside for now, due to concerns regarding safety while walking through a facility, and also the challenge of keeping the Hololens location registered while moving throughout the facility.

Fxn 9. Support easy 3-d scan data collection, viewing, editing, and conversion to geometric primitives.

Fxn 10. Allow manual correction of inferred model errors, connecting occluded things, etc.

Fxn 11. Allow manual connection of inferred pipes to existing CAD model pipes and features.

Fxn 12. For both large and small process equipment, display connected pipes, and allow inspector to click equipment and show pipe connections to other plant process components. Possibly color code to indicate connection certainty, which could help identify where to look further.

Fxn 13. Compare scans from opposite sides of a wall to assess pipe match, whether any pipes are missing, etc.

Fxn 14. Estimate the capacity of reactor vessels, storage containers, and pipes, along with uncertainty reporting.

Fxn 15. Allow easy, flexible logging of ad hoc impromptu inspector studies. Examples include swipes, radiation measurements, and photos. For each, capture the associated location:

a. Note the starting location marker, such as an entry to a known room number.
b. Scan portions of the room walls, etc. to establish context and register the scan against the model floor plan.
c. Scan the area where the swipe / radiation scan / photo was captured.
d. Allow the inspector to note the exact measurement location on the scan, with an associated bag number, numerical capacity estimate, comments, etc.

Fxn 16. Compare and evaluate the fit of point cloud data against expected or hypothesized models. This amounts to a modification of the semantic sequence previously shown in [1], Figure 2 to the revised design shown in Figure 1 below.

Fxn 17. If data is available from previous inspections, perform change detection. This could identify gross changes, such as the appearance of a new pipe.

Fxn 18. If data is available from previous inspections and precision is sufficient, perform micro-move detection to detect pipe or equipment removal and replacement. (Note: Tamper-indicating seals would work better, if available.)

Fxn 19. At the end of the inspection, prepare an inspection report. This could include a log of inspection tasks and results, informative plots, annotated photos, and 3-d information, all associated with the facility model. If the facility operator does not permit data removal, print a hardcopy report, containing details up to allowable limits.

Fxn 20. Upon return home to IAEA headquarters, the tool would communicate primary inspection results, and update the facility model to include information gained.

Fxn 21. For complementary access inspections, the tool could aid logging the locations where environment samples, photos etc. are captured, as described above. It could also capture detailed measurements of unknown equipment that might be encountered for later analysis. (These functions would be curtailed by operator data removal limits.)

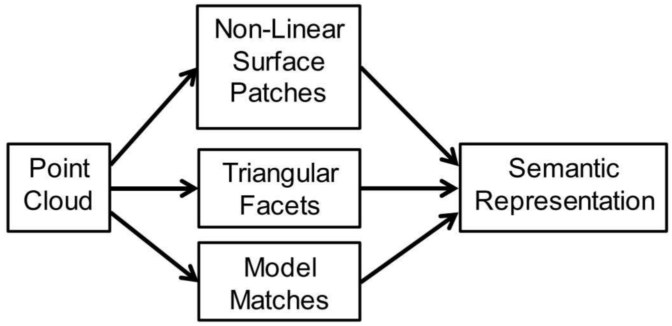

Figure 1. Revised view of representations.

3.5. Example Use Scenarios

In this section we present three scenarios envisioning how an inspector would use the proposed tool. The scenarios include example applications of the functionality described above.

<u>Scenario #1: Routine Inspections</u>

At IAEA Headquarters, the country team has completed the initial design information verification inspection for a particular facility (e.g., an operating power plant), and some number of material accountancy inspections. It is time for another accountancy inspection, and an updated design information verification inspection. Because initial design information verification has been completed, IAEA Headquarters has a site functional model, and a fairly well-developed site geometric model. The site geometric model is comprised of a 2-d model of the general floor layout, and rough approximate 3-d models of material flow components, with blanks or boxes for other potentially proprietary components. There are links between the site functional model and corresponding components in the site geometric model. The site functional model and site geometric model also indicate material balance areas and inventory store locations. Further, because this is ongoing, IAEA Headquarters also has a history of material inventory values, with records of declared values and inspector measurements.

Prior to this inspection, information arrived from external sources which raised a question about the frobnitz portion of the plant. In response, the IAEA country team would like the inspector to check the frobnitz apparatus, collecting several environmental samples in the vicinity.

The inspector is an experienced inspector, but it is their first time to this particular site, because the previous inspector handling the site has rotated out.

Otherwise, this is an ordinary material accountancy inspection, followed by an ordinary follow-up design information verification inspection. The IAEA country team uses the headquarters "base system" to prepare an inspection plan for both the accountancy inspection and the design information verification inspection. The inspection plan is comprised of a series of task specifications, including:

- Accountancy inspection to verify the most recent state declaration of material inventories.
- Design information verification inspection to verify that key processes and equipment still match their stated function.
- Special inspection of the frobnitz apparatus.

The IAEA country team uses the headquarters "base system" to download the latest site functional model, site geometric model, state declaration data, and inspection plan into the field tool.

The inspector picks up the field tool and their other equipment and travels to the city nearest the site. They maintain physical control of the field tool tablet while in transit.

The night before the inspection, the inspector uses the field tool to review the inspection plan and site, viewing the floor plan, 3-d models of key areas, desired inspection tasks, any applicable notes or instructions, and prior measurement records.

The morning of the inspection, the inspector uses the field tool tablet's navigation app to follow the recommended route to the site.

After meeting with site personnel, the inspector views the task list on the field tool, and selects the first task, which is checking the inventory in a material balance area. This task has an associated location in the plant, shown highlighted in the 2-d floor layout. The inspector and their escort proceed to this location. Once there, the inspector uses the field tool's camera to record the scene, associating the resulting images with both the plant location and the task. The inspector could then compare the scene with previous images on the field tool if desired. The inspector then manually counts the drums in the area,[3] and the field tool computes (a) the number of random samples required to achieve the desired level of confidence, and (b) a sequence of random selections of drums to inspect.

The inspector then requests each drum to be pulled, and measures each drum, using the field tool to record the measurements. The field tool aids the recording of measured data. In the case of a simple instrument such as a digital scale, the inspector places the drum on the scale, and then uses the field tool camera to snap a photo of the digital scale's output display. The field tool uses OCR software to read the scale data value, and stores it in the accumulating inspection report, supporting automatic confidence estimation and later report generation. In the case of a more complex instrument such as the HM-5 radiation detector, the field tool records the time, "confirmation number," and key data from the measurement, again by analyzing a photo of the HM-5 display output. This data capture supports immediate inspector feedback, and also integration of the full HM-5 data set when it is downloaded from the instrument later.

[3] Automatically counting the drums would be desirable, but this may be difficult to accomplish reliably.

Once all of the random drums have been measured, the field tool computes a summary assessment of the material balance area and presents it to the inspector. The inspector compares this measurement result with the state declaration, which has been pre-loaded into the tool as part of the inspection plan preparation, and also views a plot of historical inventory measurements over time, with the new data added. The field tool displays a preview of the report page for this inspection step, and the inspector reviews it to (a) verify that no required items have been skipped, and (b) verify that the inspection report faithfully reports what has been observed. The inspector makes any desired notes and then acknowledges that the task is complete, and the field tool updates the task status in the inspection plan.

As part of a routine inspection, the inspector is also verifying the seals and the safeguards cameras located within the area of interest in the inspected facility. The field tool assists in the status documentation of each Containment and Surveillance instrument.

The inspector proceeds through the tasks in the inspection plan. At the beginning of each task, the inspector views the field tool's site geometric model and photo log for orientation, context, and quick verification that what is seen generally matches what was seen before. The inspector then accomplishes and logs accountancy tasks using the methods described above. As each task is completed, a comprehensive log of data is assembled, contributing to the final inspection report.

At some point, the inspector decides to perform the special inspection of the frobnitz apparatus. The field tool's 2-d map shows the frobnitz location highlighted. Once there, the inspector compares what they see against prior images and 3-d measurements, displayed in context associated with the location. Then they use the field tool's scanner to capture a 3-d measurement of the frobnitz apparatus, along with enough additional area to clarify the location within the surrounding room. The inspector then takes environmental samples. The inspector notes and precisely logs each sample location as follows: First the inspector selects the sample location, and uses the field tool's display to select the corresponding point on the 3-d scan. Then the inspector collects the sample, placing the swipe in a sample bag with a pre-printed serial number and bar code. The inspector then uses the field tool camera to take a photo of the bag label, and the field tool reads the bar code and automatically associates the sample serial number with the indicated sample location. The inspector can add manual notes as desired.

Upon return to IAEA Headquarters, the sample location/serial number data will allow the lab results of the samples to be coordinated in the database when they become available. Then the resulting record of sample locations will be visible to the IAEA country team, who will upload all the data to the master site geometric model, allowing visualization of the full historical data set within the 2-d and 3-d spatiotemporal context. Then prior to the next inspection, these and other results may be downloaded to the field tool, enabling future inspectors to view the results, rendered in context with the 3-d scan. This would support follow-on inspectors in a number of ways, including enabling them to capture repeat samples in exactly the same location.[4] Finally, the 3-d scan of the frobnitz apparatus may also be used to update or augment the site geometric model back at IAEA Headquarters, supporting retrospective analysis and later change detection.

[4] If the site operator prohibits all this fancy electronic hardware and data removal, a similar capability could be achieved using instant-print photographic cameras and a Sharpie pen to indicate sample locations. Then the master site geometric model could still be updated back at IAEA Headquarters, yielding similar visualization capability.

The inspector then finishes the accountancy inspection, completing and documenting each task using the methods described above. The field tool then generates the inspection report, which the inspector reviews and edits as needed.

After completing accountancy inspection, the inspector proceeds to the design information verification inspection. In this phase of the inspection, the goal is to visit equipment and assess whether it has changed. This is accomplished in real time, as explained in the following paragraphs.

Recall that this is a follow-up design information verification inspection. In this scenario, an initial design information verification inspection was performed earlier, which included construction of an approximate 3-d model of the equipment related to material flow. This 3-d model could have resulted from scans performed during the initial design information verification inspection, or it could have been manually constructed from available information. Regardless, the pre-loaded nominal CAD model will be used for real-time change detection.

Returning to the inspector and the current follow-up design information verification inspection, the inspector visits each piece of material flow equipment, and takes a 3-d scan using the field tool. The resulting point cloud is then rendered on the field tool display, allowing pan, rotation, and zoom in 3-d. In addition, the inspector can toggle display of the pre-loaded models, registered in the same location as the newly scanned point cloud.

At this point, change detection is possible, using the geometry information of the before and after scan/model data, by analyzing where parts of the scene are missing, added, or changed. Ideally this processing would be available on the field tool, and take place in near real time. This may be constrained by time or processing power available, but if not possible on-site, the data would enable this to be done at the IAEA headquarters. Note that additional data editing may be needed to clean up the data, to remove temporary items that were captured or to remove noise.

The inspector uses this method to evaluate change for all of the equipment subject to the design information verification inspection, making notes along the way. The inspector also collects radiation measurements and environmental samples as indicated in the inspection plan, logging the data using the field tool as described above.

Upon completion of all tasks, and when the inspector is satisfied with the visit, a summary report is created and the inspector returns to headquarters. Once there, the field tool data is uploaded to the base station, enabling analysis and update of the master site database; including reports, notes, images, sensor data, and geometric model.

The above scenario described how an inspector would perform an inspection by completing planned inspection tasks. The pre-planned task list does not limit inspector activities; based on what they observe at the site, they can create new *ad hoc* inspection tasks at any time.

Scenario #2: Initial Design Information Verification Inspection

In this scenario, the inspector visits a facility during the initial design information verification inspection. Much (if not all) of the equipment is being seen for the first time. Prior to the inspection, the site operator has provided a functional description of the facility operation, schematics of the process, and a floor plan layout. The inspector is performing this type of inspection to verify that nuclear facilities are being constructed and operated as declared and to detect safeguards relevant changes.

To the degree possible, the inspection team enters the provided data into the inspection plan. What follows presumes the field tool has an interactive process schematic model that has been constructed prior to the visit, and also a functional model.

The inspector follows a process similar to the previous scenario, obtaining data to fulfill two goals: (1) real-time evaluation of whether the facility matches the declared design, and (2) gathering data that will enable the country team at IAEA Headquarters to perform more detailed post-inspection analysis and to construct the initial site geometric model.

For each process component on the schematic, the inspector visits the corresponding equipment. The inspector uses the field tool to mark the location on the floor plan, and then uses the field tool to capture both photographs and 3-d scans of the equipment. This information is then associated with the corresponding process component on the process schematic.

The process schematic is an active data object. Once a component is selected and supporting image/scan data loaded, then the schematic highlights the adjacent material flows into and out of the component. The corresponding physical geometry might be found automatically by software that finds cylinders in the point cloud, or manually by user interaction. Either way, material input/output mechanical features are identified and noted.

This process is repeated for each process component. This results in a process schematic with each component accounted for, along with its inputs and outputs. The next step is to verify that the connectivity between components matches the declared schematic. To aid this process, the field tool shows the schematic with each unverified component-to-component connection highlighted in a bright color. The inspector then selects a component to investigate, and verifies the component-to-component connection using a combination of manual and automated methods. The connection is annotated with scans, photographs, and supporting documentation notes, all linked to the schematic. Once the inspector verifies the connection, its highlight is turned off on the schematic display. Each unverified connection is then investigated and noted, eventually turning off all the highlighted connections on the schematic. Once all connections are resolved, the declared connections have been verified.[5]

The above description presented a specific order of finding components: First the components, then their inputs and outputs, then finally the inter-component connections. This is a reasonable sequence, but the tool will allow the inspector to verify elements in any order. Imagine the schematic broken up into component icons, short lines entering and exiting, and then longer inter-component lines. Initially all are highlighted as unverified, and the inspector can verify and unhighlight any of them, in whatever order is desired.

The above process verifies all expected material flow elements. There is also the possibility of unexpected elements. The field tool helps the inspector recognize these by the presence of scan data that is not yet associated with any element. These can then be investigated manually, with the inspector adding explanatory notes.

In some cases, important pipes pass through walls. The field tool can be used to analyze whether the pipes entering the wall have the same configuration as the pipes exiting the other side. The field tool takes a 3-d scan of both sides, and then compares the geometric arrangement to determine whether there is a correct match. Dislocations are highlighted for further inspection.

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[5] If the site prohibits digital equipment and scanning, and equivalent process could be performed using a large hardcopy of the schematic, an instant camera, and a pen, using a systematic note-taking approach.

The field tool's 3-d scanner can also be used to obtain rough capacity measurements. Given a vessel or pipe of interest, the field tool captures a 3-d scan, and then finds primitive geometric features in the resulting point cloud. These are then used in an interactive process to produce capacity estimates. Note that these capacity estimates will be approximate, due to both noise and incomplete information.[6]

Note that given sufficient data capture, much of this work can be done at headquarters, eliminating time and processing constraints in the field.

The field tool we envision includes a 3-d measurement capability. Past work has explored the use of 3-d laser scanning devices for safeguards applications. Applications of the envisioned field tool would have some overlap with 3-d laser scanners, but would be characterized by more rapid, easy scans, that are more focused on particular items of interest. In contrast, 3-d laser scans require complex setup, longer scan and processing times, and produce comprehensive models of an entire space. Thus while there is some overlap, both fill complementary niches in safeguards applications.

Scenario #3: Complementary Access Inspection

In a complementary access inspection, we assume that there is no *a priori* information available, except perhaps a floor plan. The goal is to leave the inspection with some level of documentation about what was seen, a large number of environmental samples, and documentation noting the precise location each sample was taken.

If no floor plan is available, then the field tool can be used to sketch one during the inspection, using software such as the FloorPlan Drawing Pad [2]. When environmental samples are taken, their location is documented using the same process as explained above in the description of the special inspection of the frobnitz process.

The field tool's ability to capture notes, drawings, photos, 3-d scans, and to annotate all of this within a spatial location context could be used to document what is seen within the complementary access inspection, up to the limits of the inspection agreement. These data may be returned to IAEA Headquarters for post-inspection analysis and model construction if desired.

[6] Information will be incomplete for a variety of reasons. For example, the scan may not view all sides of the object. Or, the object may be obscured by a pipe manifold, or surrounded by another container. Even if the full object is scanned, precise capacity estimation will be confounded by unknown insulation thickness, wall thickness, etc.

3.6. Value Assessment

Once fully implemented, the envisioned system supports an enterprise workflow, where IAEA Headquarters reviews a wide range of data from multiple sources to assemble a state-level view of nuclear material flow, maintaining a model for each facility. This analysis generates questions to be resolved through inspection.

These questions may be standard inquiries or special questions motivated by issues found in the state-level analysis. The tool supports the inspector in resolving these questions and communicating the answers back to headquarters. For questions that are standard inquiries, the tool helps streamline the inspection and reporting process, and places measured observations and samples within a precise location context. For special questions, the tool helps the operator stay oriented within the plant, capture detailed information, and analyze it both on-site and at home. The tool also assists the inspector in recording ad hoc impromptu observations.

Crucially, the tool is designed to assist the inspector in mentally engaging the task of assessing a facility. It is not designed to automatically make decisions, or automate understanding of the facility. Instead, it is designed to reduce the time and cognitive overhead of documenting tasks, registering and comparing multi-modality data, and performing complex 3-d analysis. A successful implementation would keep the inspector fully engaged in the evaluation task, while freeing up cognitive resources for thinking about facility issues. In addition, the tool is designed to facilitate precise, comprehensive communication of inspection results back to headquarters, thus improving the information available to analysts there.

The envisioned system is designed to flexibly support a range of scenarios with varying permissions allowed by the facility operator. The basic theme is to take data into and out of the facility "electronically if you can, on paper if you can't." If the operator does not allow electronic data removal, they may also not allow electronic device removal. In these situations, the tool is left on site in the inspector's locker, and the inspector loads software, data, and task updates when they arrive. This is another reason why light weight, low cost hardware solutions are preferred. If the operator forbids bringing or storing instrumentation, then detailed paper communication materials would provide some of the functions provided by the tool, and hand-written data values and annotations could be used to update the model back at headquarters.

Value Added Specifically by the Field Tool

The envisioned tool's display of functional, CAD, point cloud, and multi-modality data together would increase the inspector's situational awareness while on-site, and the task management features would improve their efficiency in completing routine tasks. The multi-modality data capture and visualization including both 3-d scans and radiation measurements was previously reported [6, 7]; our envisioned system could include a similar visualization capability, while also including simpler radiation measurements obtained with non-imaging radiation sensors. The logging of precise locations for environmental samples and other observations would enhance understanding back at headquarters, and enable future inspectors to precisely identify prior sample locations during subsequent inspections.

The tool would also enable the inspector to pursue new questions of interest:

- Where does this pipe go?
- Does pipe connectivity through walls match expectations?
- What is topological connectivity among these processing units?
- Are there any unexpected pipes? (E.g., not in the design, or changed since last time?)
- Does pipe topology match the schematic?
- Do we see radiation? Where? Associate scan with precise location.
- Is capacity consistent with the declaration?
- How much diversion could occur within measured capacity uncertainty?
  (Note: Measurement uncertainty may make this infeasible.)

This project was conceived around the notion of supporting inspector semantic analysis given various data observations. The envisioned tool provides several forms of semantic support, including functional context, facility location context, relationships between functional, geometric, and multi-modality data measurements, pipe topology analysis and connectivity between processing components, and associated capacity analysis (precision TBD), all within an integrated model supporting visualization and analysis of multi-modality data.

It is tempting to assert that the existence of such a tool would improve our chance of building a successful "What is this?" capability, as originally conceived in the proposal. (See the Interactive Diagnosis concept A described in Section 2 above.) One might argue that the model context and organizing information infrastructure might support such a tool. While reasonable, this argument would overlook the more fundamental challenges that result from key differentiating equipment features being hidden by machine casings, and data limitations resulting from inspector time and permission constraints.

4. PATH FORWARD

Assessment of our progress to date has suggested that one of the original project concepts – a tool that would allow an inspector to scan a piece of unknown equipment and automatically suggest possible function explanations – will be challenging and of questionable value. In light of this, we have proposed two alternatives: Interactive Diagnosis and Model-Driven Assistance. Among these, the Interactive Diagnosis option is closest to the original concept, but may result in very narrow utility and limited value. The Model-Driven Assistance concept seems more promising, and could form the basis for follow-on proposals.

For the remaining year of the project, we plan to focus on the Model-Driven Assistance concept. This system-level concept includes both field and headquarters components, both of which are envisioned to support multiple functions. The time remaining under this project's funding is not sufficient to implement all of this functionality. So in order to produce a compelling demonstration to communicate the idea, we will focus on the inspector's field tool, and prioritize the following functionality:

1. The facility context model, including spatial representations in 2-d and 3-d, with interactive viewing and ability to attach data observations, notes, and other metadata to facility features. (All scenarios).
2. Documenting the 2D/3D location of environmental sample swipes, using photos and 3-d scans, with associated notes (Scenario #1).
3. Assess consistency of observed components with respect to the declared design schematic (Scenario #2).
4. Real-time change detection (Scenario #1).
5. Pipe matching through walls (Scenario #2).
6. Capacity estimation (Scenario #2).
7. Documenting previously unseen equipment (Scenario #3).

These functions were selected due to their importance, and because they include significant 3-d measurement and analysis, which is a focus of the original proposal. As time permits, we may implement other features, such as the functional model, inventory assessment logging, and the task sequence representation, either partially or with dummy façade interfaces to illustrate expected workflow.

The above capabilities will be very challenging to implement in the available time. Thus we envision a scrum-based development cycle, ala Jamie Coram's superb management of an earlier user interface development project, to ensure that the highest priority functions receive the earliest attention.

We aim to present our work in progress at INMM and the IAEA Safeguards Symposium, to gain feedback from the community about our ideas.

5. SUMMARY

Our work thus far in the Eyes On the Ground project has yielded several key insights [1]:

- There is not enough time or facility permission to build a full model.
- Semantic "What is this?" analysis is difficult because of ambiguity, hidden internal features, and overall view of large equipment obscured by the surrounding building.
- Analysis of 3-d measurements with no model produces little.
- It is more productive to start within the context of a model, and support finding answers to questions of interest.

These insights and other lessons learned drove the Interactive Diagnosis and Model-Driven Assistance concepts, described here. We believe that the Model-Driven Assistance approach is the more productive path forward. This document provides a detailed concept description of this approach, including specific functionality envisioned for the field tool component and example use cases. We have also identified a prioritized list of key features to implement in the time remaining in the project, and a plan for obtaining feedback from the safeguards community to share and improve these ideas.

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