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Eyes On the Ground: Final Report

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Abstract

This report summarizes the work performed under the Sandia LDRD project "Eyes on the Ground: Visual Verification for On-Site Inspection." The goal of the project was to develop methods and tools to assist an IAEA inspector in assessing visual and other information encountered during an inspection. Effective IAEA inspections are key to verifying states' compliance with nuclear non-proliferation treaties. In the course of this work we developed a taxonomy of candidate inspector assistance tasks, selected key tasks to focus on, identified hardware and software solution approaches, and made progress in implementing them. In particular, we demonstrated the use of multiple types of 3-d scanning technology applied to simulated inspection environments, and implemented a preliminary prototype of a novel inspector assistance tool. This report summarizes the project's major accomplishments, and gathers the abstracts and references for the publication and reports that were prepared as part of this work. We then describe work in progress that is not yet ready for publication.

ACKNOWLEDGMENTS

This work was funded by the Sandia National Laboratories Laboratory Directed Research and Development program. We thank George Baldwin, Dianna Blair, Sharon Deland, Zoe Gastelum, Tina Hernandez, Mark Schanfein, and Matt Sternat for many useful discussions and suggestions. This work was funded by the Sandia National Laboratories LDRD program. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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1. SUMMARY

1.1. Motivation

IAEA inspectors face a daunting task, and their challenge is growing. As of 2015, there are over 709 facilities and 577 locations outside facilities subject to inspections [14]. This number is growing as more facilities come on-line, and the task is also becoming more complex due to increases in technology sophistication and diversity. Ensuring IAEA inspector effectiveness in this ever more complex environment is critical to long-term nuclear security.

The goal of the Eyes On the Ground project is to develop tools to aid an IAEA inspector. In particular, the project's original goal was to develop a tool that measures an object seen at a site of interest, performs analysis of the measurement, and then presents the inspector with both geometric and semantic information to aid their understanding of the scene.

Our ultimate vision was to apply a representation called the *geospatial-temporal semantic graph* [5] to this problem, to develop a system to aid an inspector in the field. Imagine a device that could measure an unknown piece of equipment, and use graph search techniques to identify candidate explanations of equipment functionality. We refer to this as the "What is this?" scenario, where the goal is to aid the inspector in diagnosing the function of unknown equipment they encounter.

We pursued this problem by exploring solutions for the necessary data capture device and analysis algorithms, and we also studied a range of possible functional specifications that could serve as technology design targets. These are discussed in the following section.

1.2. Use Case Analysis

In addition to the "What is this?" scenario described above, there are other possible ways that a measurement and analysis system might help an inspector assess a facility. During the first phase of the project, we evaluated several potential use cases. These are summarized in Figure 1 and Table 1, which first appeared in [6].

The plot in Figure 1 shows a set of candidate use cases, plotted according to our estimate of their value and feasibility. Desirable concepts are both valuable and feasible; the plot axes are arranged so that desirability increases toward the upper right corner of the plot.

We considered the candidates shown with a red box to be the most promising. Among these, the pipe mapping candidate was the most promising, since solving this task would yield a general-purpose method of measuring and mapping cylinders. This would provide value for three other promising tasks: UF6 cylinder counting, static drum counting, and evaluating equipment functionality against a template. Thus we elected to pursue pipe mapping as a core technology.

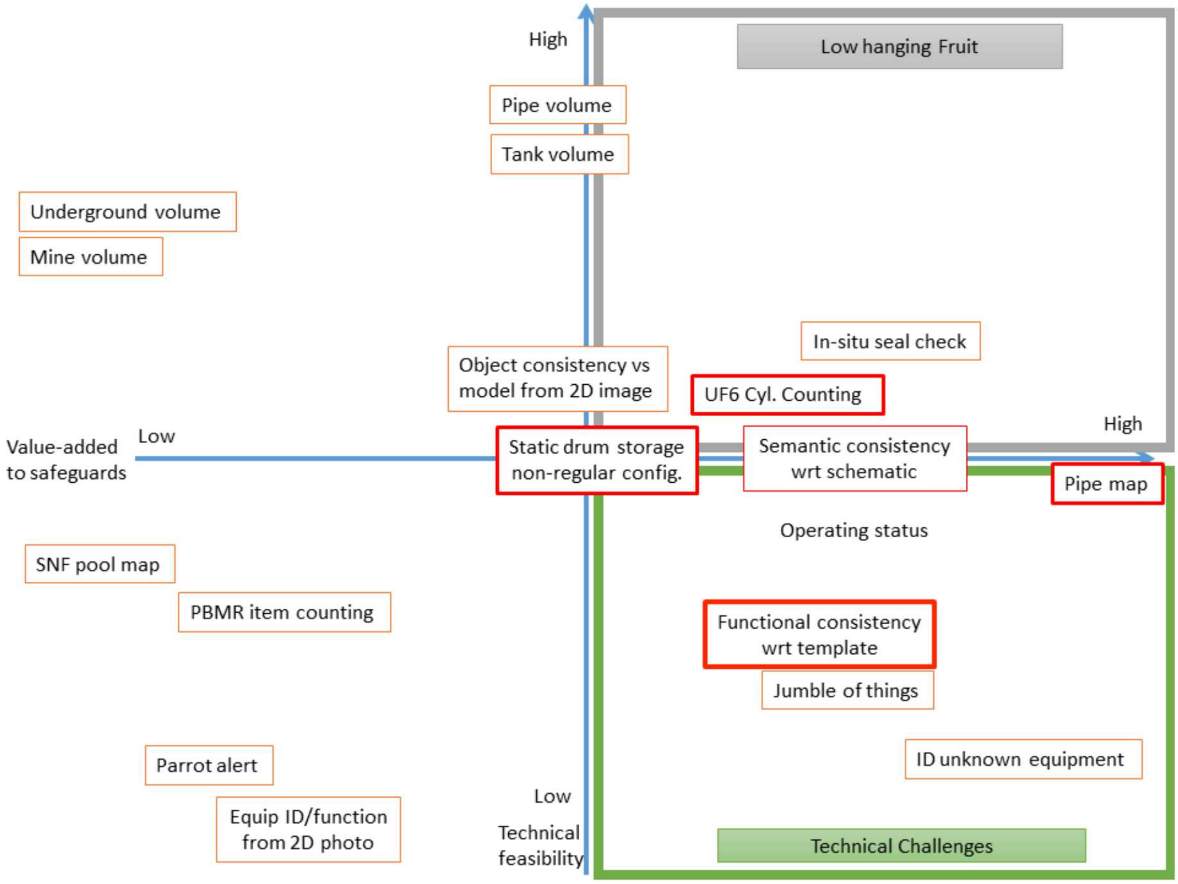

Figure 1. Analysis of potential use cases.

Pipe volume	Estimate the volume and flow capacity of pipes.
Tank volume	Estimate the capacity of tanks and reactor vessels.
Underground volume	Estimate the volume of an underground cavern.
Mine volume	Estimate the excavated volume of a mine.
Object consistency vs model from 2D image	Compare an observed 2-d image against an equipment functional specification.
In-situ seal check	Verify a seal has not been broken.
UF6 Cyl. Counting	Count UF_6 cylinders in a storage area.
Static drum storage non-regular config.	Count drums in a storage area, when not placed in regular order.
Semantic consistency wrt schematic	Compare observed equipment against a schematic functional description.
Operating status	Determine whether equipment is operable, and/or operating now.
Pipe map	Analyze pipe topology, verify expected connectvity, check for diversion.
Functional consistency wrt template	Compare equipment features against a template of expected components, to determine if it is consistent with its declared use.
Jumble of things	Count a set of haphazardly placed items. Shapes can be arbitrary.
ID unknown equipment	Identify function of an unknown piece of equipment: What is this?
SNF pool map	Map control rods within a spent nuclear fuel pool.
PBMR item counting	Count pebbles moving through a pebble bed modular reactor.
Parrot alert	A system that warns the inspector of items that merit attention.
Equip ID/function from 2D photo	Determine equipment function from a two-dimensional image.

Table 1. Explanation of use case labels in Figure 1.

1.3. Mid-Term Evaluation

We investigated a variety of technologies to support pipe mapping, including both measurement devices and analysis methods. We also studied the related safeguards inspection tasks in more detail. This study was quite informative, and is described in detail in [6].

A key finding of this study was that our original "What is this?" vision seems infeasible, for several reasons, reproduced from [6]:

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.

The full report [6] explains this in detail, but a concise summary is that we concluded that our original envisioned goal would be difficult to make practical, and even if we succeeded, the applicable scope of the resulting system would be narrow.

We also gained several basic insights about this problem space, which helped us contemplate an improved path forward. These are listed below, reproducing the summary provided in [6]:

- 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 led us to conceive a revised concept that we feel would produce a much more useful result. This revised concept is described in the next section.

1.4. Revised Concept

The lessons and insights reported in [6] led us to propose an improved concept for a tool to aid inspectors, derived from our original concept. This new concept and its requirements are explained in full detail in [7]; here we provide a brief excerpt summarizing the idea:

> *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.

We developed this concept into an early prototype, and presented the concept at INMM [9]. Figure 2 shows a photograph of the hardware platform we selected for the prototype. This is a small handheld scanner manufactured by DotProduct LLC, which supports easy, impromptu 3-d scan measurements, as well as digital photographs [11]. It contains an integral tablet computer for control and processing, and this tablet can be used to execute custom inspection-specific software as well. We have designed and begun implementation of our envisioned inspector's assistant software for this device. Figure 3 shows a screen shot from our prototype software, which is still in an early stage of development. For a concise summary of the inspector's assistant concept and a detailed description of our early prototype, see [9].

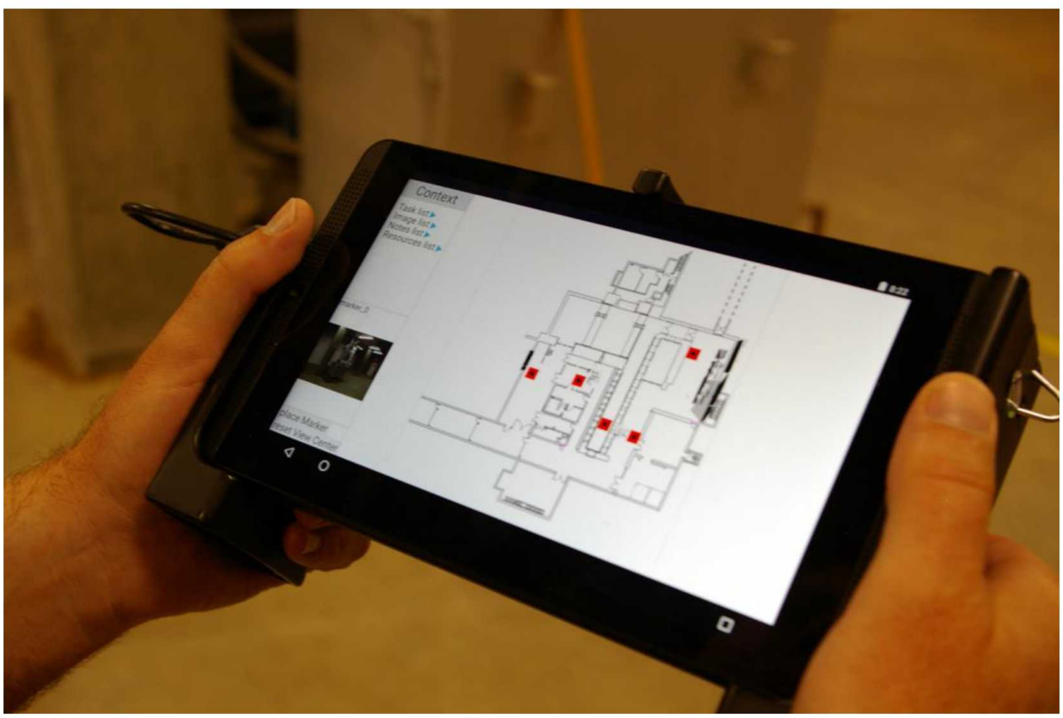

Figure 2. Our prototype inspector's assistant.

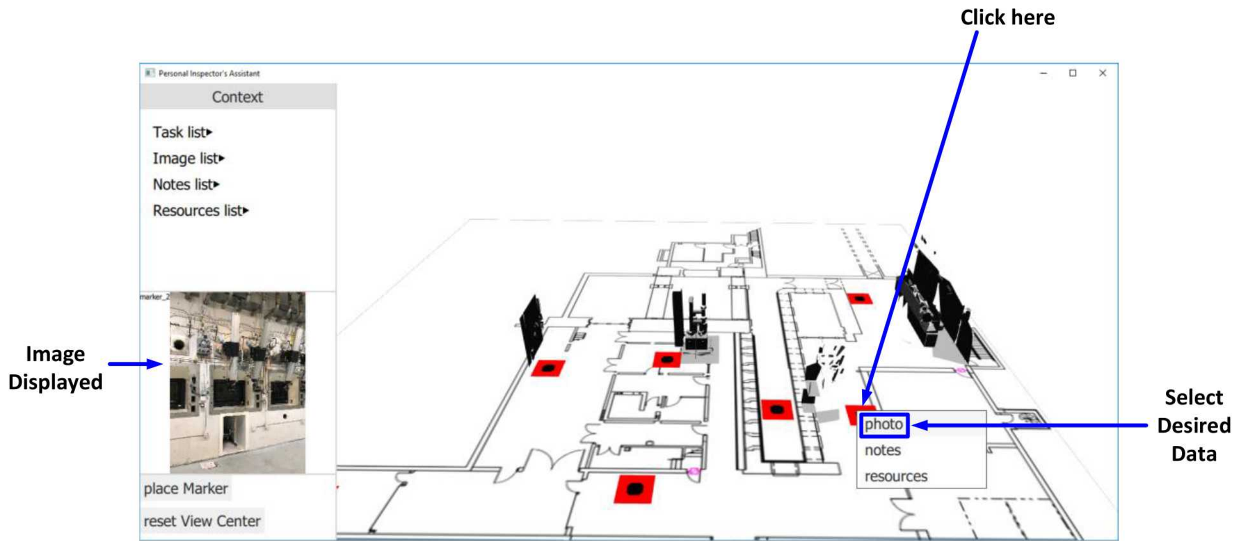

Figure 3. Inspector's assistant software prototype.

The above device selection was informed by our investigation into the capabilities of three different technology types: 3-d laser scanning, structured light scanning, and photogrammetry. All of these have potential for use in safeguards applications, and to our knowledge only one has been reported in the safeguards literature [3, 4, 15, 16]. Since we learned a lot about the strengths and weakness of each technology, we reported these in [8]. See the paper for details.

Our interest in the pipe mapping application led us to investigate the 3-d measurement accuracy of each technology. We made significant progress, but feel that further work is needed before our results are suitable for publication. Thus we report this work in progress in Section 3, to document what we accomplished.

1.5. Path Forward

This project has explored the notion of developing a tool to help IAEA inspectors, and has produced a concept and early prototype of a tool designed to assist inspectors not only in completing tasks and staying oriented, but also in communicating effectively with IAEA headquarters. We presented the concept at INMM [9], and received significant positive feedback.

Yet at this time, our prototype is still in the early implementation stage. Additional work could flesh this out and produce a tool that could be evaluated in user test trials. This seems worthwhile.

In addition, our investigation of 3-d measurement technology revealed significant insight into each technology's suitability for safeguards applications. Further investigation assessing the accuracy of measuring complex apparatus geometry and equipment typical of safeguards environments would be worthwhile. It would also significantly enhance the knowledge gained thus far, and provide practical and detailed feedback to the safeguards community.

2. OUTCOMES

In this section we list the publications and reports that were produced in this project. These provide detailed descriptions of the work performed and results achieved.

- R. Brost, C. Little, M. McDaniel, W. McLendon, and J. Wade. Eyes On the Ground: Year 2 Assessment. Sandia National Laboratories Report SAND2018-3211, 32 pages, March 2018 [6].

  Abstract:

  The goal of the Eyes On the Ground project is to develop tools to aid IAEA inspectors. Our original vision was to produce a tool that would take three-dimensional measurements of an unknown piece of equipment, construct a semantic representation of the measured object, and then use the resulting data to infer possible explanations of equipment function. We report our tests of a 3-d laser scanner to obtain 3-d point cloud data, and subsequent tests of software to convert the resulting point clouds into primitive geometric objects such as planes and cylinders. These tests successfully identified pipes of moderate diameter and planar surfaces, but also incurred significant noise. We also investigated the IAEA inspector task context, and learned that task constraints may present significant obstacles to using 3-d laser scanners. We further learned that equipment scale and enclosing cases may confound our original goal of equipment diagnosis. Meanwhile, we also surveyed the rapidly evolving field of 3-d measurement technology, and identified alternative sensor modalities that may prove more suitable for inspector use in a safeguards context. We conclude with a detailed discussion of lessons learned and the resulting implications for project goals.

- R. Brost, C. Little, N. Peter-Stein, and J. Wade. Eyes On the Ground: Path Forward Analysis. Sandia National Laboratories Report SAND2018-3210, 27 pages, March 2018 [7].

  Abstract:

  A previous report assesses our progress to date on the Eyes On the Ground project, and reviews lessons learned [6]. 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.

- R. C. Brost, C. Q. Little, and J. R. Wade. Comparison of 3-d Capture Technologies for Safeguards Applications. In *Proceedings of the 59th Annual Meeting of the Institute for Nuclear Materials Management,* Baltimore, Maryland, July 2018 [8].

  Abstract:

  Devices for recording a 3-d snapshot of a scene are commercially available, and evolving rapidly. These devices can simultaneously collect surface shape and color information, enabling subsequent analysis of a variety of questions. As recognized in both prior and ongoing work, these devices have the potential to make significant contributions to international safeguards. Applications include analysis of facility equipment, 3-d change detection, and documentation of critical measurement locations. However, multiple technologies are available, which employ different principles of sensor operation. These sensor differences may have a significant effect on their usefulness for safeguards applications. This paper compares three distinct sensor technologies: laser scanning, structured light, and photogrammetry, with a specific focus on safeguards applications. We use an instrument of each type to measure equipment representative of what might be encountered in a nuclear facility, and compare the robustness, clarity, and accuracy of the resulting data. We summarize these results, comment on their implications for safeguards applications, and then discuss the conditions and application domains for which each sensor is well-suited.

- R. C. Brost, C. Q. Little, M. D. McDaniel, N. L. Peter-Stein, and J. R. Wade. Eyes On the Ground: Toward a Portable Inspector's Assistant. In *Proceedings of the 59th Annual Meeting of the Institute for Nuclear Materials Management,* Baltimore, Maryland, July 2018 [9].

  Abstract:

  IAEA inspectors face a rapidly widening challenge. Working within an already small budget, the number of inspection sites is increasing, and the inspection complexity also rises as new technology and new reactor types are introduced. Despite this, inspectors must perform complex inspection tasks with multiple objectives, all within a limited time on site. This paper describes a concept of an Inspector's Assistant, a mobile device designed to aid the inspector in completing site inspection tasks, collecting and logging required data, and communicating the results to colleagues at IAEA. The device includes both a camera and hand-held 3-d scanning capability, to support direct assessment and documentation of observations. The envisioned tool would include a 3-d site model, supporting orientation, situational awareness, logging of data, observations, and environmental samples in context, and interactive analysis of current observed equipment compared to both design intent and what was observed in the past. The envisioned system would include task support, to integrate smoothly with the inspector's overall work flow. It would also operate in conjunction with models and data at IAEA headquarters, to support analysis and coordination of inspection activities over time. In this presentation, we will describe our progress pursuing prototypes of key functionality and work in exploring the use of 3-d measurement technology to enable an inspector's assistant tool.

3. WORK IN PROGRESS

For safeguards inspection applications such as Design Information Verification inspections, accurate measurements will be required. Because we are interested in pipe mapping (see Section 1.2), we asked: How accurately does each 3-d measurement technology measure pipes? In this section we will describe our preliminary investigation into this question, assessing each technology's ability to measure the diameter of a given pipe in a scene.

The three different 3-d measurement technologies we studied are shown below. Figure 4 shows a 3-d laser scanner from FARO [12], Figure 5 shows a structured light sensor from DotProduct [11], and Figure 6 shows a photogrammetry example from Bentley Systems [13]. In our photogrammetry experiments, we captured images with a Sony RX100M3 camera, and used the photogrammetry software package 3DF Zephyr Free, from 3DFLOW [1].

Figure 4. FARO laser scanner.[1]

Figure 5. DotProduct structured light sensor.[2]

[1] https://knowledge.faro.com/Hardware/Laser_Scanner/Focus/Laser_Scanner_Focus3D_X30-130-330_and_X130-330_HDR_News-Downloads-Quick_Start_Guides-Manuals_and_Technical_Resources
[2] https://www.dotproduct3d.com/industrial.html

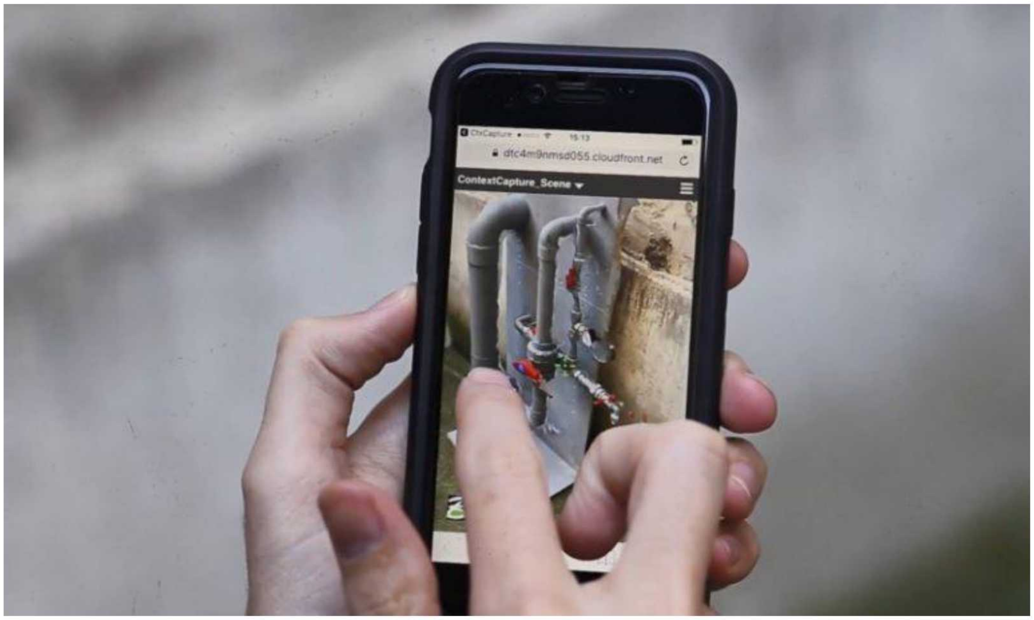

Figure 6. Bentley mobile photogrammetry.[3]

To evaluate pipe recognition accuracy, our basic procedure was to scan an arrangement of pipes, and then use the EdgeWise software by ClearEdge to recognize cylinders in the resulting point cloud [10]. The resulting cylinder features were then loaded into AutoCAD to determine each cylinder diameter [2]. These were then compared against the true ground truth pipe diameters to assess measured accuracy.

The following paragraphs will describe this procedure and our results in detail.

We established a pipe configuration within our test facility (see Figure 7). This facility allows us to establish pipe configurations desired for testing, and to obtain measurement scans under controlled conditions.

Figure 8 shows our first arrangement of pipes. Six pipes are arranged vertically, with their bases placed in a rough circle. Pipe materials are white and black PVC. Diameters are 2.375”, 3.5”, and 4.5”, with one pipe of each size and color. Calibration targets are in the scene to aid registration of multiple scans of the 3-d laser. Pipes are placed far enough apart that they will not interfere with other during scanning.

[3] Courtesy Bentley Systems. See press release at http://www.spar3d.com/sponsored/sponsored-software/bentley-launches-major-reality-modeling-update-new-mobile-app-photogrammetry-capture-planner-cloud-services/

Figure 7. Test facility for sensor characterization.

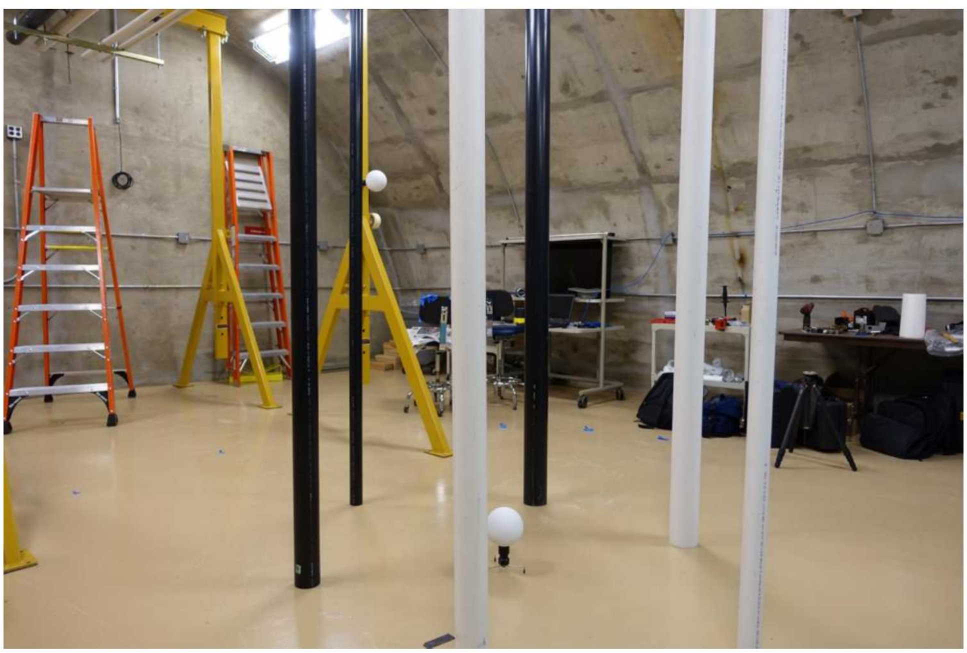

Figure 8. Vertical arrangement of white and black pipes.

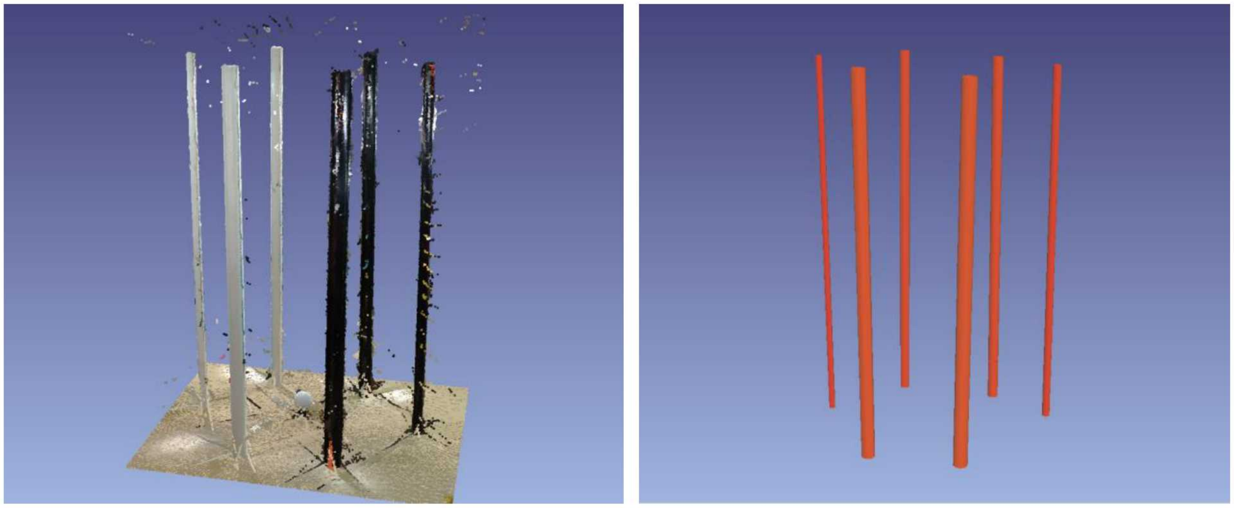

Figure 9. Cylinders fit to laser scan data.

Figure 9 shows the results from the 3-d laser scanner. On the left is the point cloud, rendered with color captured by the scanner's digital camera, and also with the fit cylinders rendered. Note occasional "hairs" extending from the point cloud; we believe these occur when the laser just grazes tangent to the pipe, causing some reflections to return from the pipe's surface, and some to return from whatever surface is behind the pipe. Note that in this sample, there are far fewer of these noise points than were observed in [6, Figure 12]. This is perhaps due to the greater distance between the pipes and the background surface.

On the right side of Figure 9 are cylinders fit to the point cloud by the EdgeWise software. All six pipes were found. The measured diameters showed good accuracy; we discuss this in detail below when presenting Table 2.

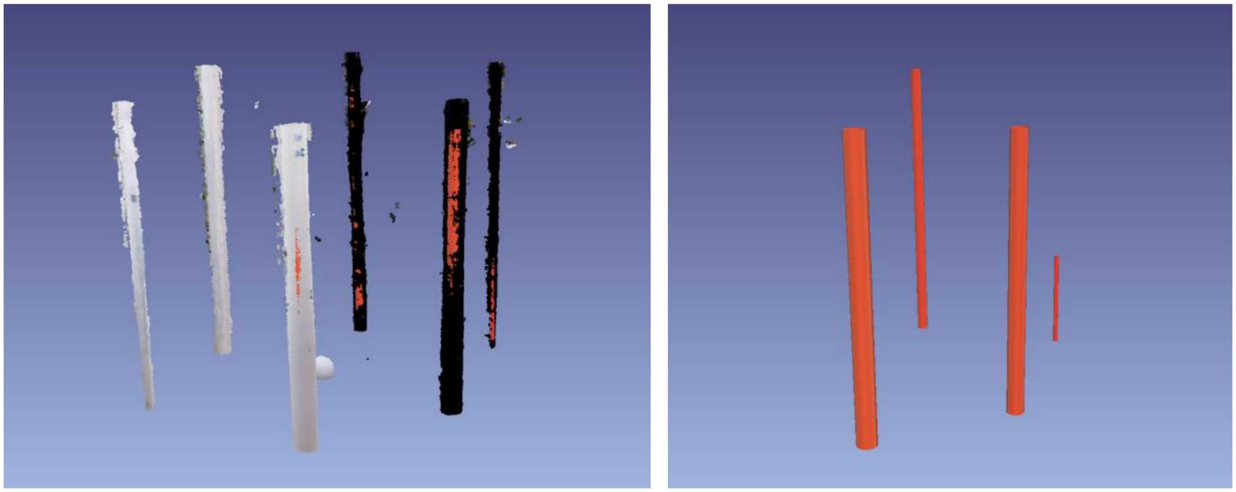

Figure 10. Cylinders fit to structured light sensor data.

Figure 10 shows the results for the structured light sensor. On the left we again show the point clouds with point color rendered, together with the fit cylinders. A visual comparison of Figure 9 and Figure 10 reveals that the data from the structured light sensor seems to exhibit more noise, especially near the top of the pipes. On the right side of Figure 10 we see the cylinders fit by the EdgeWise software. Only four of the six pipes were found, and one of the found pipes was only recognized over a portion of its length. The measured pipe diameters found from the structured light data were much less accurate than the laser scan; see Table 2 below for details.

We have made progress in understanding why these failures occurred, examining the data and considering the operating principles of the structured light scanner and its data processing. However, our work here is preliminary, and we may find that improved results can be achieved by simply adjusting our operating procedure with the instrument. So the above results should be viewed as a first test, subject to potential improvement. This investigation is ongoing.

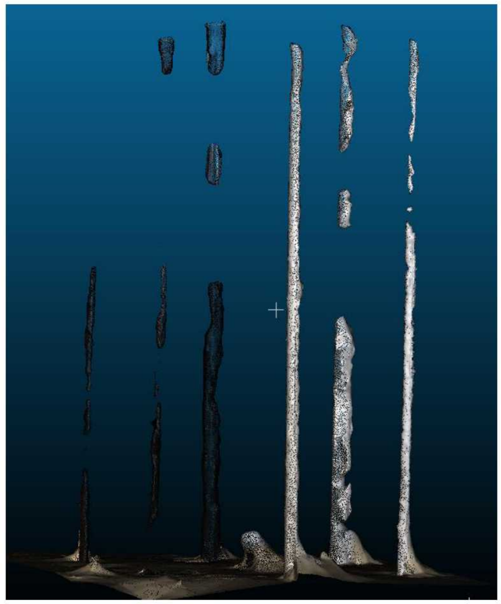

Figure 11. Point cloud obtained by photogrammetry.

Figure 11 shows the point cloud found using photogrammetry. The technique failed to find almost all of the pipe surfaces, even though 101 images were captured from a variety of view directions with significant overlap between adjacent images, both up and down along the pipes, and about every 18 degrees around the pipe structure. The EdgeWise software found no cylinders in this data set.

Photogrammetry works by finding features that are common to two or more images, and using the correspondence of these features to deduce 3-d location of each feature in space, and the camera positions. It relies on a large number of these features to produce dense point clouds. In the case of our example, the pipes are a uniform color, smooth, and have almost no features along their full length. Thus there are very few features available for photogrammetry processing, and it is not surprising that photogrammetry performed poorly in finding the pipe surfaces.

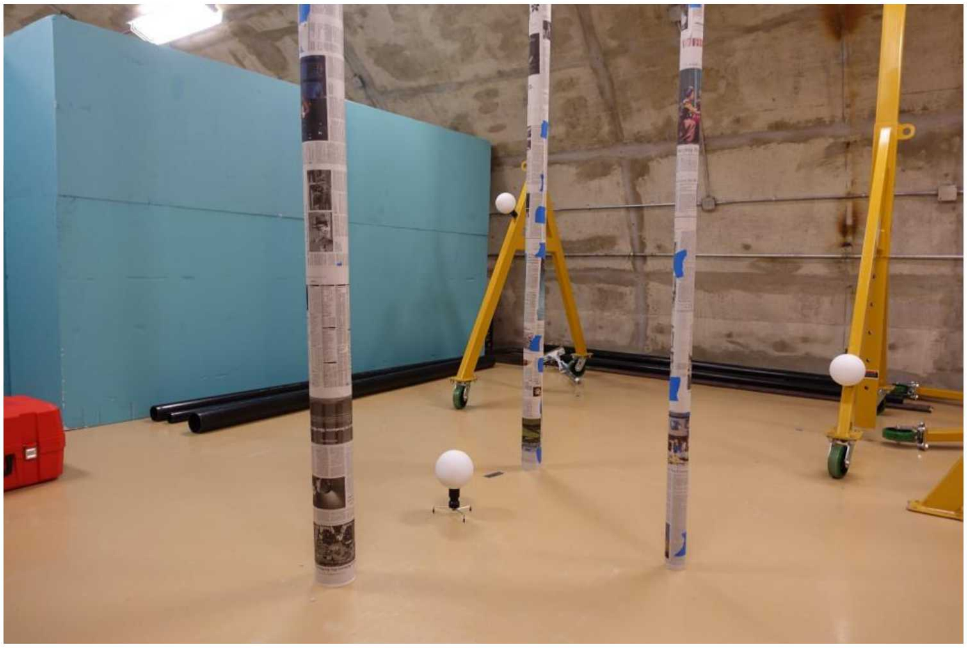

Figure 12. Pipes with artificial texture added.

Understanding the cause of failure in photogrammetry enables us to identify a solution. The problem is that the pipes have no recognizable texture, either along their length or across their diameter. So, we can solve the problem by adding texture. This may be accomplished by a variety of techniques:

1. Applying small adhesive patches over the surface.
2. Spraying color or texture onto the surface, using something either permanent (e.g., paint) or temporary (e.g., mud).
3. Projecting a fixed light pattern onto the surface.
4. Applying a textured surface covering.

Note that the applied texture should avoid repeating patterns (such as stripes), because a consistent repeating pattern could lead to ambiguities in the photogrammetry feature matching process.

We tested this approach using option 4 above, applying a textured surface covering. By selecting full-page newspaper sheets with bold graphics, we were able to quickly apply an artificial texture with few repeating patterns. Figure 12 shows the result. Since the pipes were completely covered, there was no need to replicate the covering for the white and black pipes, since their white or black surfaces could not be seen.

Figure 13. Point cloud obtained by photogrammetry (with artificial texture).

Figure 13 shows the resulting point cloud, with the points rendered with color (left) and as plain points (right). As can be seen, the addition of texture enabled the photogrammetry processing to find a very high density of points.

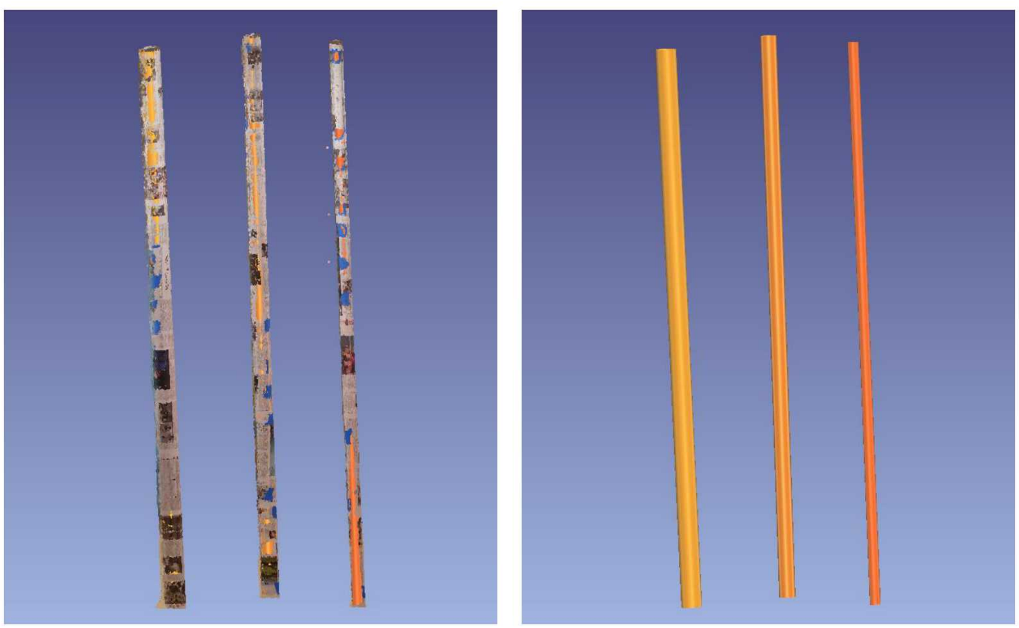

Figure 14. Cylinders fit to photogrammetry data (with artificial texture).

Figure 14 shows the results in a form analogous to Figure 9 and Figure 10. The left side shows the point clouds with point color rendered, together with the fit cylinders. It is immediately visually apparent that these results have the least noise of the three techniques. The right side shows the cylinders found by EdgeWise; all three cylinders were found, over their full length. The resulting pipe diameters were measured with high accuracy, explained below.

		Diameter Error (inch)		
		Laser Scan	Structured Light	Photogrammetry
White	4.5" OD pipe	-0.22	-0.75	X
	3.5" OD pipe	-0.26	X	X
	2.375" OD pipe	-0.33	X	X
Black	4.5" OD pipe	0.05	-1.25	X
	3.5" OD pipe	0.01	-1.32	X
	2.375" OD pipe	0.07	-1.37	X
Texture	4.5" OD pipe	-	-	0.03
	3.5" OD pipe	-	-	0.02
	2.375" OD pipe	-	-	0.01

Table 2. Pipe diameter measurement results.

Table 2 summarizes the results of our experiment. Each column lists the diameter error in inches, computed as (measured diameter – true diameter). An "X" indicates that the process failed to recognize the cylinder. A "-" entry indicates that the case was not reported.

For the laser scan data, all six pipes were found. The measured diameters showed good accuracy, with the worst-case error occurring for the smallest 2.375" white pipe, with an error magnitude of -0.33" or -14%. The accuracy of the black pipes was significantly better than the white pipes, with a worst-case error of +0.07 or +3%, again for the smallest pipe diameter.

For the structured light data, noise caused recognition failures for two of the pipes. The black pipes were more reliably found, but with a larger diameter error. The worst-case error again occurs for the smallest diameter pipe: –1.37", or –58%. All diameter errors for the structured light data were worse than for the laser scan data. Once again, note that these are preliminary results, and might be improved through better operational procedures.

For the photogrammetry data with plain surfaces, lack of features caused recognition failures for all of the pipes.

For the photogrammetry data with artificial texture (newspaper), all of the pipes were successfully found, and the diameter accuracy was the best of all of the techniques tested. Note that photogrammetry inherently measures only up to a scale factor, so we determined the scale factor by measuring the length of the pipes and comparing that to the length of the fit cylinders. After applying the resulting scale factor, the measured diameters were very close to the true diameters, with a worst-case error of +0.03", or +0.6%. Further this positive error might be accounted for by the thickness of the newspaper or its imperfect fit, which we did not measure.

In future work, we plan to further study the devices' performance in measuring more complex pipe geometry, and to explore whether structured light measurement precision may be improved by adjusting operating procedure.

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