MULTI-SENSOR MONITORING FOR REAL-TIME 3D VISUALIZATION OF CONSTRUCTION EQUIPMENT

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ABSTRACT

Construction and mining worksites pose unique challenges to workers and equipment operators due to their dynamic and unstructured nature. Narrow haul roads, crowded work spaces and presence of workers and equipment in close proximity, combined with large blind spots and overall poor visibility afforded to operators lead to collisions and run-over-type accidents between equipment, workers, and other entities that may be present on the jobsite. Operations that involve machine-infrastructure interaction, particularly in the case of concealed infrastructure such as excavation and drilling lead to unintended strikes between the equipment's end-effector and the infrastructure. Such accident-prone scenarios can be avoided by providing operators with real-time feedback and warnings using 3D visualization and proximity monitoring of the entities present in the equipment's vicinity. Thus the jobsite in the real world is abstracted and represented in a 3D virtual world. However, this requires the ability to create a seamless link between real-world sensors present on the equipment and/or the jobsite and the virtual environment. This paper describes a non-restrictive acquisition allocation framework that allows position and orientation sensor streams from construction and mining job sites to be used for updating 3D virtual scenes in real-time for providing vital collision avoidance warnings to equipment operators.

KEYWORDS

Sensors, Visualization, Collision Detection, Excavation, Real-time

INTRODUCTION

In fields such as mining, quarrying, and construction, equipment monitoring plays a crucial role in accident prevention (MSHA 2012). Construction jobsites, in particular, are occupied by

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workers and equipment, often belonging to different sub-contractors (Castro-Lacoutere et al. 2007). The visibility available to an operator on a dynamic construction site can often be blocked by various obstacles such as materials, temporary or permanent facilities, other equipment, and even workers (Lu and Liang 2012). The importance of clear, unobstructed vision coupled with the inherent poor visibility that operators of equipment such as dump trucks, loaders and excavators deal with due to blind spots (Teizer et al. 2010a) and other issues suggests that equipment monitoring and active visual guidance can play a critical role in jobsite safety.

The type of equipment that can be monitored can vary from jobsite to jobsite, and even a single jobsite can have monitoring requirements that span different categories of equipment. The type of sensing mechanism used to record the position and orientation of equipment is also an operation- and equipment-dependant parameter. Thus, any monitoring framework intended for jobsite safety via active visual guidance must be scalable and generic in order to be capable of monitoring equipment and operations across a broad range of conditions and engineering activities.

In the presented research, the authors instrument a backhoe loader with orientation sensors that monitor the rotation of the boom, stick, and bucket, and track the articulation of the machine (and consequently the position of the bucket end-effector) in real-time. A generic and scalable framework for transmitting real world sensor data to update 3D equipment models inside a graphical virtual world for concurrent visualization is presented. The developed framework can be used to visualize any construction operation, as it occurs, inside a dynamic 3D world simply by outfitting the real equipment pieces with appropriate sensors and connecting them to their virtual counterparts.

REAL-TIME 3D VISUALIZATION

In this section the authors differentiate between real-time and post-processed visualization and why the former is of importance in the field of equipment and construction process monitoring. Post-processed visualization gets its input data from a simulation model or a pre-recorded data source such as trace simulation (Kamat and Martinez 2001). On the other hand, real-time visualization is used to represent an ongoing operation or process in the real world. Hence there is emphasis on maintaining low-time lag and high correlation between the real and virtual worlds. In such scenarios, data from on-site (on-board) equipment sensors is used to drive the real-time visualization engine.

Real-time visualization provides benefits over video from a conventional on-site camera by allowing views that would be impossible through physically mounted cameras. Such physical cameras can also limit the field of view for equipment operators on the jobsite (Huber et al. 2009). Finally, through real-time visualization it is possible to create and represent views of the real world jobsite that go beyond what is capable through conventional video. For example, a 3D virtual world can be used to present the location of buried utilities to an excavator operator and warn them against potential strikes. Thus real-time 3D visualization is an essential tool for improving safety and productivity on a construction jobsite.

LITERATURE REVIEW

An overview of existing research in the field of equipment tracking and monitoring is presented in this section. The authors differentiate equipment (asset) tracking as taking place at the macro- and micro-levels. Macro-level tracking refers to those techniques where the remote operator or fleet manager is interested in the location of the equipment (asset) in the global space. The user is not primarily concerned with the detailed configuration of equipment's articulated components such as their roll, pitch and yaw. Examples of this macro-level tracking seen in fleet tracking applications for trucks, cars and other assets (Derekenaris et al. 2001, Sterzbach and Halang 1996, Zarazaga-Soria et al. 2001).

Micro-level tracking is defined as that which occurs at a per-equipment level where the equipment position in global space is collected in addition to the detailed configuration of its sub-components through roll, pitch, and yaw angles. The rest of this paper is focused on micro-level equipment tracking through the use of sensor-based real-time 3D visualization. Lu and Liang (2012) used the Denavit-Hartenberg notation to develop a kinematic model for simulating the movement of a backhoe excavator, an example of articulated construction equipment. Zhang et al. (2012) demonstrated the use of ultra wideband (UWB) technology for tracking, monitoring, and estimating the pose of cranes. Teizer et al. (2010b) implemented Radio Frequency (RF) technology to provide real-time warnings to RF-tagged equipment operators and workers through alarms when the a safety threshold distance was breached. Lytle and Saidi (2007) of the National Institute of Standards and Technology developed a method to track the 3D position of a robotic crane using a laser-based 3D site measurement system.

Oloufa et al. (2002) demonstrated the feasibility of GPS technology for equipment tracking on a construction site for preventing collisions between two moving equipment through operator warnings. Commercial applications using orientation (rotation) sensors, Global Positioning System (GPS) and laser technology have been developed for equipment tracking in earthwork, grading and compaction operations (Leica Geosystems 2012, Trimble 2012). Equipment teleoperation through a 3D virtual system using GPS and orientation sensors data transmission over a wireless network has been demonstrated by Steffen et al. (2007). In addition, the use of computer vision technology has been explored for monitoring equipment to capture productivity rates (Azar and McCabe 2012).

The authors identify two primary limitations in the existing approaches: First, some of the existing approaches are limited by their narrow scope in being applicable to only a specific sensor-type and/or equipment type. Being applicable to any equipment type commonly found on a construction jobsite is a key requirement due to the number of different equipment pieces that may be present on any medium to large project. Second, monitoring of equipment without providing operators with concurrent 3D visualization and proximity monitoring information limits its effectiveness due to the limited information being presented to the operators.

OVERVIEW OF THE PROPOSED METHODOLOGY

Articulated equipment is one whose individual components are linked through joints that allow rotation about their pivot. Articulated equipment such as hydraulic excavators, scraper, backhoe loaders, motor graders, articulated trucks and dozers need to be monitored such the rotation and translation that the equipment and its sub-components undergo can be recorded and utilized in downstream analysis. The method of using real-time 3D visualization for equipment tracking recreates the real world jobsite inside a 3D virtual world using 3D CAD models, live sensor data and geometric proximity monitoring for collision prevention. The position and orientation data collected from on-board sensors ensure that the real and virtual worlds are correlated to each other. It is important to note that the entire downstream analysis and visualization must occur in real-time or near real-time in order for the output to be useful to the equipment operator.

The success of equipment tracking thus depends on the ability to create an effective link or mapping between the real and virtual worlds. Equipment position and the orientation of its sub-components can be recorded through a wide variety of sensors and/or technologies. Thus any methodology for creating a link between real and virtual world equipment must be generic enough to account for the various sensor types and technologies. A single jobsite may have different types of articulated equipment operating at any given instant and thus the mapping methodology of real to virtual must be flexible enough to allow any articulated equipment to be represented accurately in the virtual world through real-time sensor updates. Such a non-restrictive and flexible methodology is presented in Figure 1. The figure shows an excavator's sub-components i.e. track, cabin, boom, stick and bucket being linked to corresponding position and orientation sensors such that the excavator's motion in the real world can be successfully replicated in the virtual world.

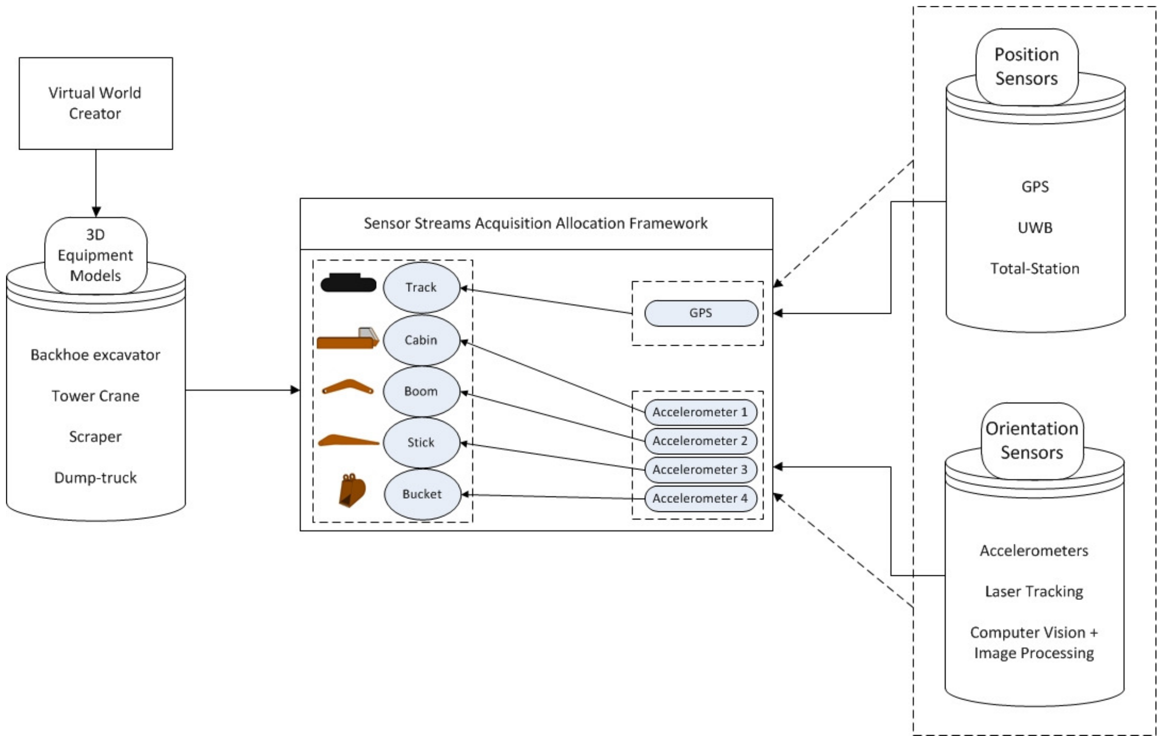
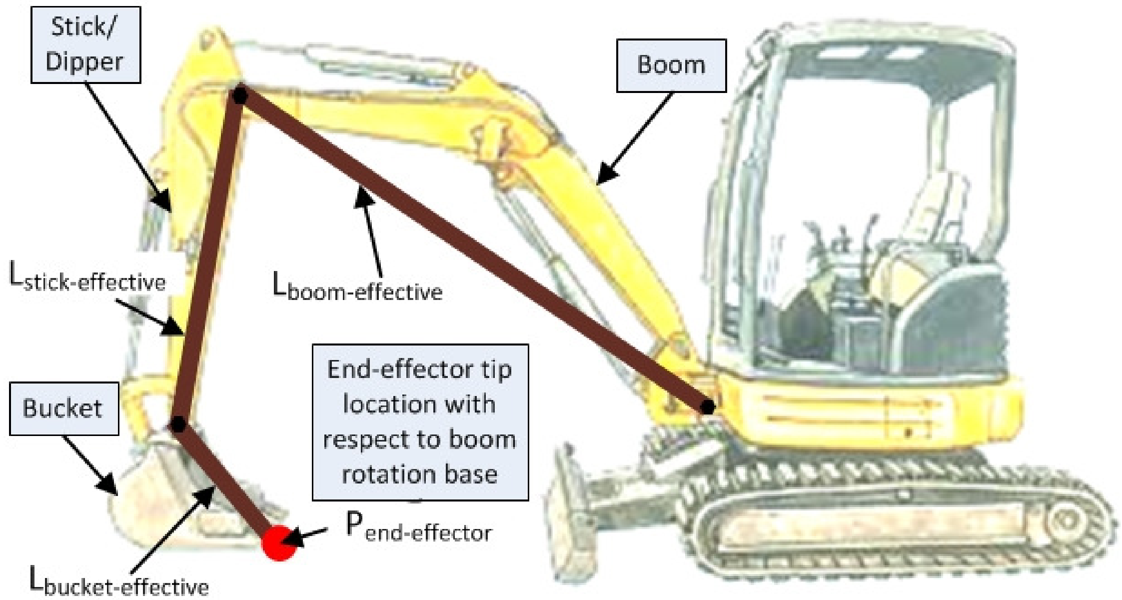


Fig. 1: Proposed methodology for creating a link between real world sensor data and 3D virtual equipment models

TECHNICAL APPROACH

In this section the authors describe the underlying concepts required to replicate real world motion of articulated equipment inside a 3D virtual world. In equipment such as excavators, the position and orientation of the end-effector cannot be obtained directly as sensors would be damaged when the bucket comes in contact with the ground during excavation. Thus an indirect method using the concept of kinematics is required. Kinematics is the branch of mechanics that deals with the study of motion of a singular object or a group of objects without considering their causes (Beggs 1983). Forward Kinematics is the subset of kinematics where equations and joint parameters (individual joint angles and link lengths) are used to compute the position of the end-effector (extremity). This concept is represented in Figure 2 where the position and orientation of the end effector is computed using the orientation angle and lengths of the boom, stick and bucket.



$$P_{end\text{-}effector} = f(\Theta, L)_{Boom} + f(\Theta, L)_{Stick} + f(\Theta, L)_{Bucket}$$

Fig. 2: Backhoe side view with schematic kinematic chain representing its boom, stick, and bucket articulation

Thus the determination of global position and orientation of an end-effector has two computations associated with it. The first is the position aspect of the equipment in the environment, i.e. on the jobsite. The second involves the articulated chain of linked elements associated with the equipment. Thus, in the case of the backhoe shown in Figure 2, a GPS receiver is placed on the top of the backhoe to provide the equipment position on a jobsite in terms of latitude, longitude and altitude. Data from tilt measuring sensors placed along the boom, stick and bucket arms in combination with lengths of the respective components can provide the distance of the end-effector tip, measured from the articulated chain base i.e. the pivot point of the boom.

Equipment components in an articulated chain have a parent-child hierarchical relationship. Hence, in the case of an excavator, the track component is the parent of the cabin, boom, stick and bucket elements. Similarly, the cabin component is the parent of the boom, stick and bucket components. In such a parent-child relationship, any rotation or translation experienced by the parent is implicitly transferred to the child entities. Due to such rotation and translation of individual components, the position and orientation of the local origin of the coordinate axes gets altered. This results in change in direction of local X, Y and Z axes. For example, rotation of the boom component in an anti-clockwise direction results in corresponding rotation of the stick and bucket components by the same magnitude. Due to this, the local axes direction of X, Y and Z differ from their global directions, i.e. directions corresponding to zero translation and rotation. This is represented in Figure 3, through side and top views of an excavator. Hence the angles need to be transformed from local to global rotation axes in order to correlate to the real world.

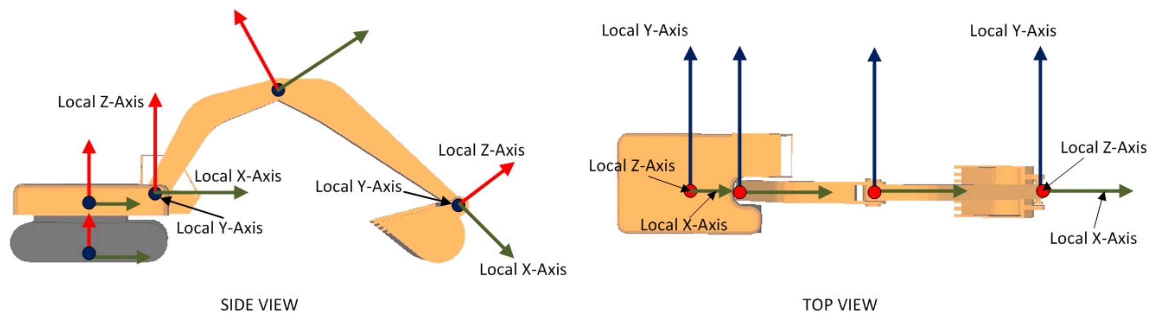


Fig. 3: Local rotation axes for equipment components

A 3D model used to represent equipment inside a virtual world must represent the real world adequately so that the down stream analysis provides meaningful output to the equipment operator. The authors refer to this concept as Kinematic Equivalence. When a 3D equipment model is kinematically equivalent to its real world counterpart, the end-effector global position and orientation would be identical in the real and virtual worlds. The effect of kinematic non-equivalence is most evident in the case of objects having curved bodies or objects having bends in their physical makeup such as booms and sticks/dippers. In such objects, the physical characteristics result in difference between the axis corresponding to a certain edge and the pivot-to-pivot rotation axis. For most equipment components, the sensors are often placed along an edge of the body, as shown in Figure 4, to ensure its position remains fixed during the course of operations and the sensors record the angle of a known edge in the real world.

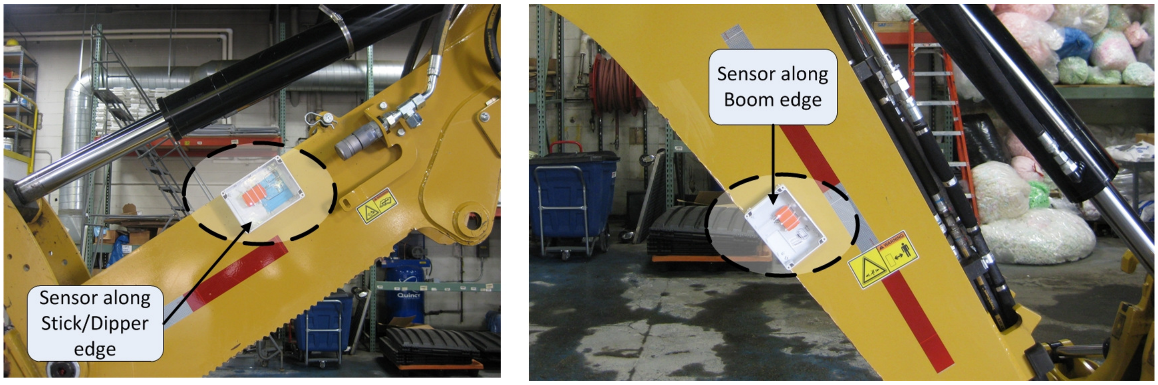


Fig. 4: Orientation sensors placed along the upper edge of the stick/dipper (left) and lower edge of the boom (right)

The problems associated with kinematic equivalency are graphically represented in Figure 5. In order to ensure that the 3D model in the virtual world has kinematic equivalence to its real world counterpart, the angular offset between the actual rotation axis (represented by dashed line in Figure 5) and rotation axis corresponding to the sensor and boom edge (represented by solid line in Figure 5) needs to be accounted for while transmitting orientation values from the real to the virtual world. In addition to kinematic equivalence, the authors also introduce the concept of dimensional equivalence. This refers to the characteristic of a 3D model and its sub-components to represent the real world equipment's constituent components in size and placement. Length of sub-components and location of base pivot joints and their height with respect to ground surface are identified as key dimensional equivalence requirements.

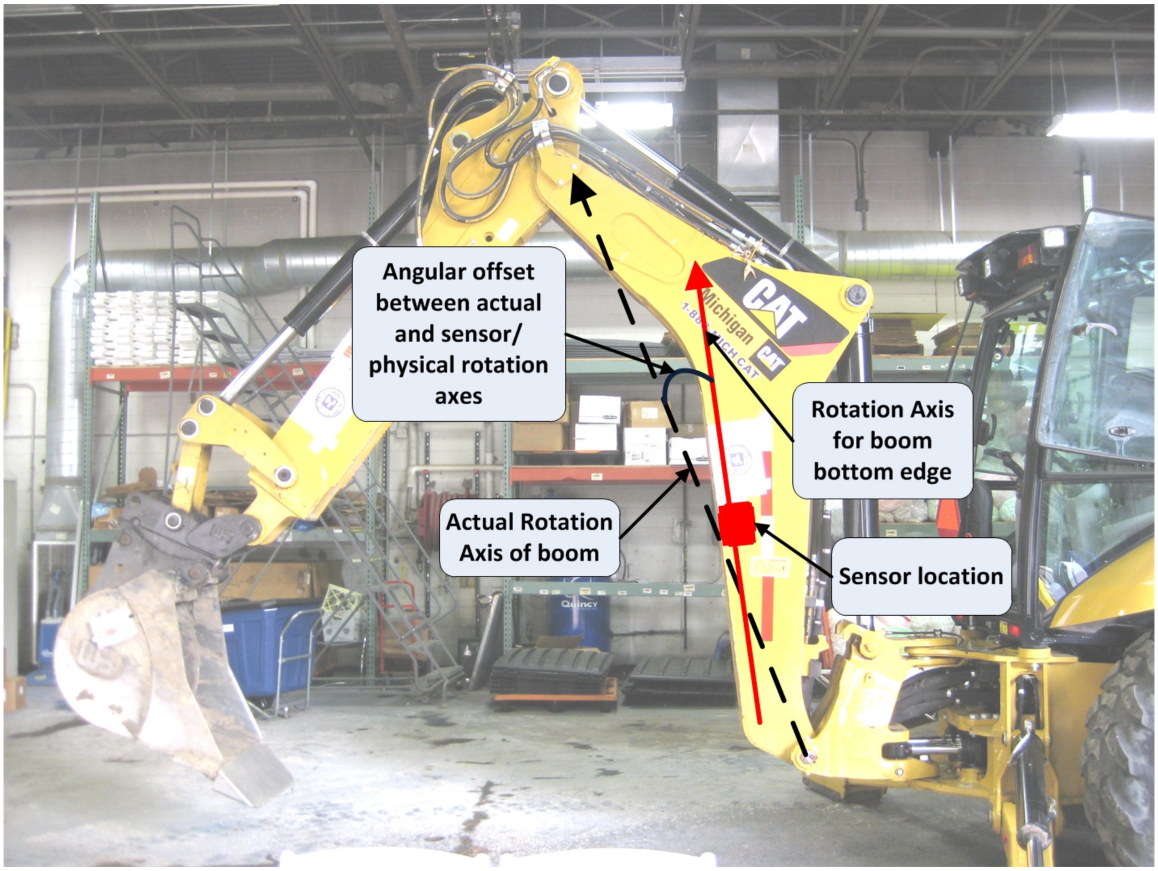


Fig. 5: Difference in actual rotation axis and rotation axis corresponding to physical edge of object (boom)

Construction equipment is represented in the virtual world through the use of scene graphs due to their articulated nature. For example, a crane consists of a cabin, boom, cable and hook; Thus, it can be seen that equipment of such type consists of more than a solitary sub-component, each of which is capable of translation, and/or rotation. The components in turn are linked to each other through a parent-child hierarchy, where translation or rotation of a parent component results in corresponding movement in a child component. This parent-child hierarchical representation is captured in a data representation structure called scene graphs through their layout and structure (Cunningham and Bailey 2001).

SENSOR STREAM ACQUISITION ALLOCATION (S2A2) FRAMEWORK

In this section, the authors introduce a computational framework developed to enable transmission of real world sensor data to a 3D virtual world. The framework is called the Sensor Stream Acquisition Allocation (S2A2) framework. The S2A2 framework is designed as an interface to an existing real-time 3D visualization system, SeePlusPlus that has been developed by the authors for improving safety in excavation operations through monitoring of excavators and providing visual guidance and warnings against impending collisions with buried utilities. The S2A2 framework is a link between articulated 3D equipment models present in the virtual world (SeePlusPlus) and sensor data streams from the real world. Figure 6 shows a schematic overview of the proposed equipment monitoring approach through real-time 3D visualization and proximity monitoring.

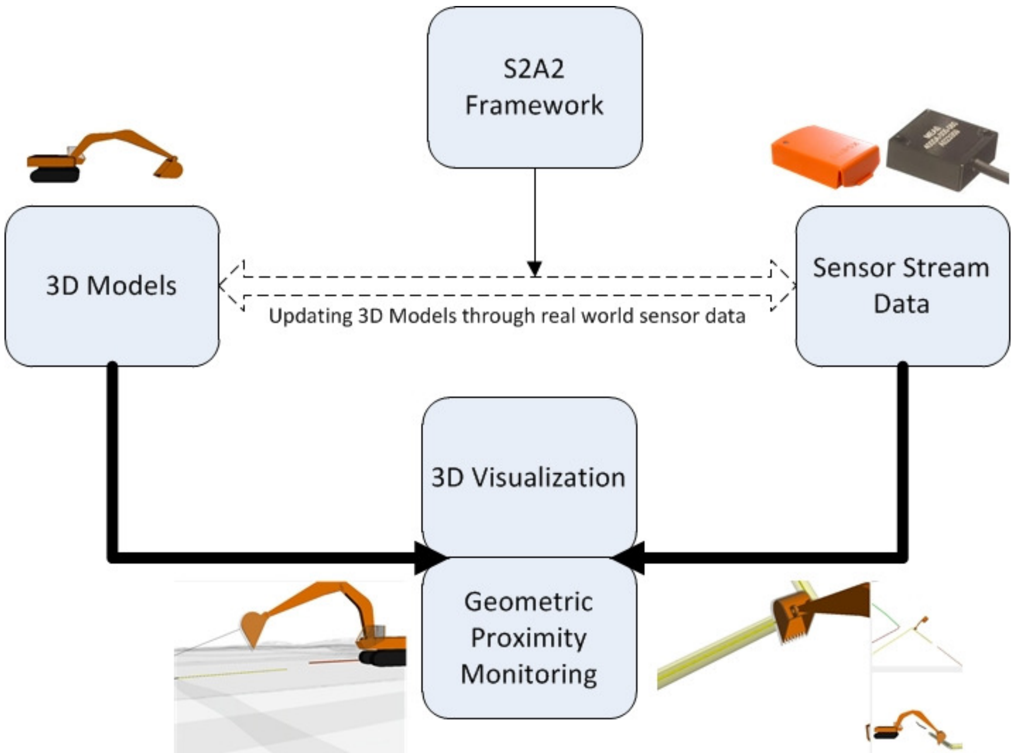


Fig. 6: Schematic representation of S2A2 framework for integration with real-time 3D visualization and geometric proximity monitoring

When a sensor from the real world needs to be made available to an equipment component in the virtual world, a socket-based server-client approach is used to make a connection between S2A2 and the sensor stream. The command to initiate a client-side connection to the server-side application provides the user with an interface as shown in Figure 7. Once the connection is successful, the sensor stream is displayed in the list of available sensors in the S2A2 interface as shown in Figure 8.

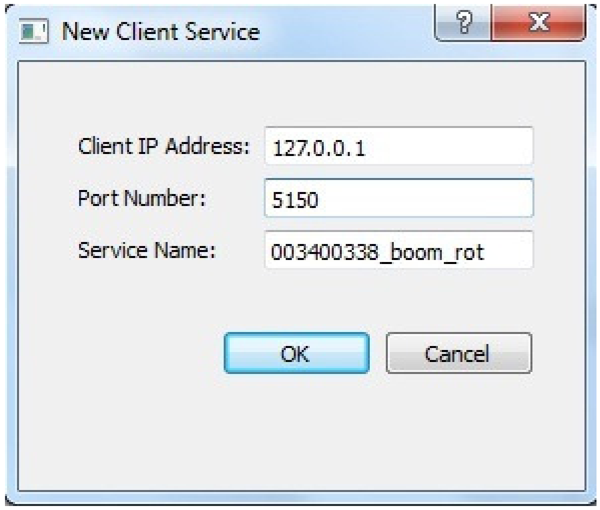


Fig. 7: Input dialog interface for creating new client service for connecting to a server-side data stream

As the S2A2 name suggests, the interface is also used to allocate sensor streams to individual equipment components. The allocation is specified through a set of checkboxes that allows users to select what component of the sensor data stream may be used to update the selected equipment component. For example, selection of only Translate X, Translate Y and Translate Z options of a sensor stream ensures that only its position aspect would be used to update the selected equipment component.

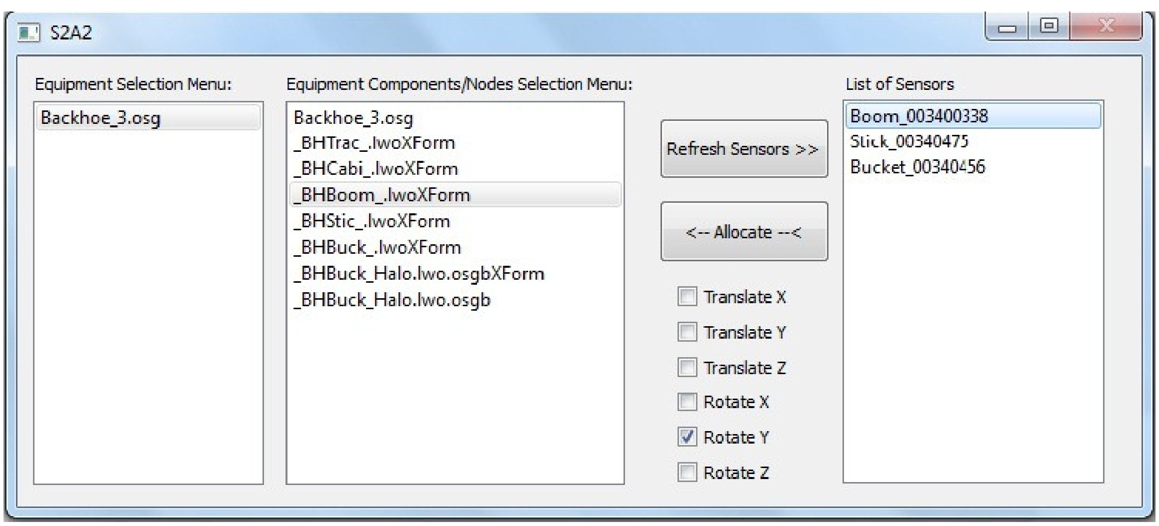


Fig. 8: Graphical interface for user-defined connections between real world sensors and virtual equipment components

In a similar manner, the rotation can also be specified by choosing one or more of roll (Rotate X), pitch (Rotate Y) and yaw (Rotate Z). Once an equipment component has been allocated a sensor stream, its position and/or orientation is updated in real-time as long as the sensor in the real world is active and transmitting data. The 3D visualization is provided through the SeePlusPlus application developed by the authors as shown in Figure 9.

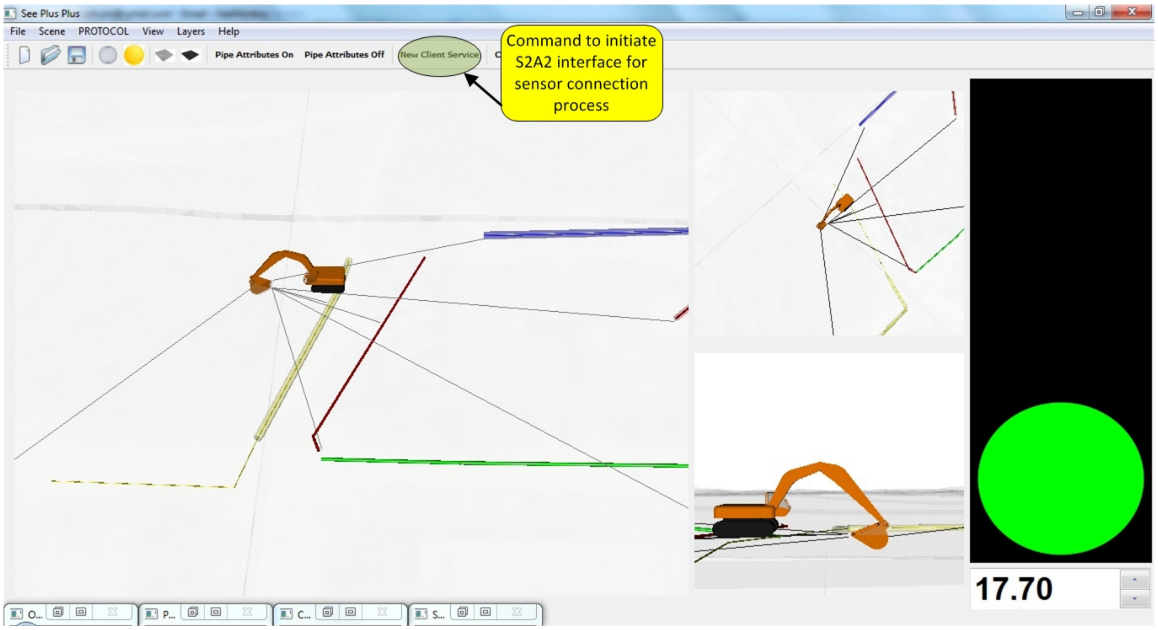


Fig. 9: Screenshot of SeePlusPlus showing a real-time scene containing an excavator and buried utilities and associated proximity monitoring between bucket and utilities, and S2A2 initiation command highlighted

VALIDATION EXPERIMENTS

In this section, the authors describe the procedure and setup used for carrying out validation experiments. The experiments are designed to demonstrate the functioning of the S2A2 framework and the accompanying 3D visualization when used to monitor and track a backhoe. The backhoe used in these experiments was a Caterpillar 430 E IT (Caterpillar 2012). Screenshots from a simultaneous video recording of the real and virtual worlds is shown in Figure 10. The articulation of the equipment's arm and end-effector was captured through a series of orientation sensors placed along its boom, stick and bucket. The orientation sensors used in the experiment were XSens MTw (XSens 2012). Bluetooth wireless technology was used to transfer pose data from individual sensors to the device running the 3D visualization.

Fig. 10: Images captured from a simultaneous video recording of the validation experiment showing backhoe in the real world and the 3D visualization

During the test, the equipment's boom, stick and bucket was manipulated by the operator similar to regular operations. As the validation required distance values from both the virtual and real worlds, the operator was instructed to stop motion of the equipment's arm whenever a distance measurement was to be made in the real world. After the equipment had come to a complete halt, the distance between the end-effector (bucket) and the ground surface beneath it was measured using a measuring tape. This process was repeated for several different configurations of the boom, stick and bucket. In total, 15 distance measurements were made in the real world. Corresponding distances displayed by the proximity monitoring framework in the virtual world were also recorded simultaneously. The values obtained from real and virtual world measurements are shown in Table 1.

Table 1: Comparison of distance measurements made in the real and virtual world for varying configurations of boom, stick and bucket

Iteration No.	Distance in Real World (meters)	Distance in Virtual World (meters)	Real World – Virtual World (meters)
1	3.07	3.12	0.05
2	1.54	1.52	-0.02
3	1.14	1.16	0.02
4	0.63	0.66	0.03
5	0.00	0.17	0.17
6	0.66	0.68	0.02
7	1.62	1.62	0.00
8	2.18	2.08	-0.10
9	2.48	2.39	-0.09
10	2.84	2.71	-0.13
11	1.82	1.87	0.05
12	0.99	0.99	0.00
13	0.61	0.67	0.06
14	2.66	2.74	0.08
15	2.54	2.59	0.05

DISCUSSION OF RESULTS

The difference between end-effector to ground surface distance in the real and virtual worlds as shown in Table 1 can be attributed to the following factors – 1) Sloping ground surface in the real world modeled as a perfectly flat surface in the virtual world due to non-availability of data; 2) Geometric difference between 3D virtual bucket and real world equipment bucket. Hence dimensional equivalence is stated as being a key requirement for effective monitoring; 3) Accuracy of orientation sensors. The MTw sensors used in the experiment have a static accuracy of 0.5 degrees (XSens 2012). Thus, for a boom length of 2.75 m as in the case of the Caterpillar 430 E IT, a 0.5 degrees error results in a vertical deviation of 0.09 m.

CONCLUSION AND FUTURE WORK

In this paper, the authors investigated the types of equipment monitoring that occurs on construction and mining jobsites as well as in other commercial settings. The need for detailed or micro-level equipment monitoring was presented and the areas where its use can help reduce accidents and improve overall safety were described. The authors also presented a framework for equipment monitoring based on concurrent 3D visualization and real-time proximity monitoring using sensor-based input for updating 3D equipment components. The principles developed in the proposed methodology and technical approach were demonstrated through an interface for mapping sensor data streams to specific equipment elements. This interface was presented in context of a real-time 3D visualization application for assisting excavator operators in preventing unintended strikes with underground utilities.

The paper also describes a validation experiment to demonstrate the ability to simulate the real world motion of equipment concurrently in a 3D virtual world. The experiments simulate the motion of a backhoe loader's articulated arm through orientation sensors installed on its boom, stick/dipper and bucket. The results comparing accuracies in the real and virtual worlds are presented.

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