Electromechanical Development of a Low-Cost End Effector Pose Estimation System for Articulated Excavators

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Abstract

Marker-based pose estimation, in which optical cameras monitor fiducial markers to determine the three-dimensional positioning and orientation of an articulated machine's end effector, has been identified as a potential low-cost alternative to currently available machine control and guidance systems. In an effort to develop such a marker-based pose estimation system for excavators, several iterations of prototypes were designed, fabricated, and tested. Performance was measured in terms of the system's ability to estimate bucket tooth position, with an acceptance criterion of 2.5 centimeters (1 inch) of absolute error. Although initial prototypes were found to possess practicality and performance issues, a fourth prototype offered encouraging experimental results suggesting the feasibility of marker-based sensor technology for excavator pose estimation. Further work needed to refine the technology for large-scale practical implementation was also identified.

Keywords: camera-marker network; pose estimation; machine control; equipment monitoring; construction equipment; articulated machines; excavator guidance; grade control

1 Introduction and Motivation

1.1 Motivation for Articulated Excavator Pose Estimation Systems

Excavation is a common construction activity wherein earth is removed to produce a desired ground contour or gain access to a buried object. Much of today's construction excavation is performed by excavators, or human-operated powered digging machines. In general, the operation of an excavator requires skill and experience, but even skilled operators may be susceptible to human error.

In US brownfield (i.e., urban) environments, the excavation process typically begins with a request of local utility providers to mark the location of underground utilities in a planned excavation area. Approximate utility locations are then marked on the ground's surface with flags or paint, and with little or no information indicating the depth of the utility. The uncertainty inherent in locating underground utilities is indicated by the fact that mechanized excavation is typically prohibited within a 0.9 meter (36 inch) wide band of the utility markings [1]. Additionally, the incidental disturbance of ground markings during construction processes can further exacerbate the uncertainty in actual utility location.

Not only does there exist uncertainty in the location of underground utilities, but the sheer number of utilities continues to grow with population, property development, and the advancement of technologies like telecommunications. According to the Common Ground Alliance, an organization which collects and reports data on underground utility strikes, the US contains more than 30 million kilometers (19 million miles) [2] [3] of underground utilities including gas, electric, water, sewer, cable television, fiber optic, phone, drainage, traffic signals, and street lighting circuits. Shown in Figure 1 are two examples of the congestion found

underground in some urban areas. Many of these utilities are now approaching the ends of their service lives and will need to be repaired or replaced in the near future. For example, the American Water Works Association reports that the majority of the US underground water supply infrastructure is at least fifty years old and will need to be replaced or expanded over the next twenty-five years [4].

Figure 1: Examples of Urban Underground Congestion

The increasing volume of underground utilities and the uncertainty in their location are factors contributing to the rate of excavation incidents. The 2013 Common Ground Alliance Annual Damage Information Reporting Tool Report estimates there were over 4 million [5] excavation incidents resulting in damaged underground utilities in the US during the ten year period between 2004 and 2013. Similarly, the US Department of Transportation Pipeline and Hazardous Materials Safety Administration reports there were 786 [6] incidents of excavation-related damage to natural gas and liquefied petroleum gas pipelines in the US during the same ten years. Those 786 gas pipeline incidents resulted in 39 fatalities, 127 injuries, and over 200 billion dollars in property damage [6]. As stated in the US Congressional Transportation Equity Act for the 21st Century, Title VII, Subtitle C, Section 7301, “...unintentional damage to underground

facilities during excavation is a significant cause of disruptions in telecommunications, water supply, electric power, and other vital public services, such as hospital and air traffic control operations, and is a leading cause of natural gas and hazardous liquid pipeline accidents” [7].

Thus, changes are needed to help reduce incidental utility strikes. One potential solution lies in the establishment of accurate as-built records of underground utilities [8] which could be used to provide better estimates of utility locations onsite. It is anticipated, however, that the existence of accurate ground markings alone may have a limited effect on the reduction of utility strikes, since operators would continue digging without direct sight of the bucket or buried utilities. A second solution involves combining accurate utility records with sensory feedback to provide operators with real-time estimates of their excavator’s pose (i.e., position and orientation) relative to the jobsite [9]. In such a system, sensors could be used to estimate the current pose of an excavator’s components, combine the information with a model of underground utilities, and relay the information back to the operator to permit a more informed judgment. Potentially, the inclusion of warning systems or more sophisticated measures could also be implemented to further reduce the risk of utility strikes.

In addition to warning operators where they should not dig, excavator pose estimation systems can help operators identify where they should dig, as shown in Figure 2. In some applications, like drainage pipe installation, for example, both the height and slope of the excavated surface are often critical. In such situations, accurate grading is typically accomplished through an iterative process of digging and checking. Checking is usually performed by a human grade checker who manually measures the height of the ground’s surface and informs the operator whether more soil should be removed. In addition to being slow, the process can be dangerous as the grade checker is often subjected to the hazards of working near both trenches and heavy

88 machinery. Pose estimation systems may serve to relieve a grade checker of such duty, thus
89 potentially improving both safety and efficiency.

Grade Control (Where to Dig)

Utility Avoidance (Where Not to Dig)

91 *Figure 2: Benefits of Excavator Pose Estimation: Grade Control and Utility Avoidance*

92 **1.2 Motivation for a Low-Cost, Ubiquitous Pose Estimation System**

93 Excavator pose estimation systems are commercially available today [10] [11], but have not yet
94 been widely adopted by the construction industry. Various types are available, but all possess
95 shortcomings. Companies like Trimble and Leica offer packages that make use of Global
96 Navigation Satellite Systems (GNSS) to permit a full six-dimensional (three position and three
97 orientation) estimation of the machine's pose relative to the jobsite. These systems likely offer
98 the most potential to improve construction safety and productivity, but tend to be cost prohibitive
99 due to the expensive GNSS components. Additionally, the use of these systems is limited to
100 environments where GNSS communication is reliable, as GNSS-based systems are susceptible to
101 failure in areas with tall trees, in urban environments with tall buildings, and indoors [12].

Alternatively, pose estimation systems can make use of robotic total stations, rather than GNSS, to provide full six-dimensional pose estimation relative to the jobsite. Since these systems do not use GNSS, they are capable of functioning reliably in urban environments and indoors. However, as each excavator requires a dedicated robotic total station during operation, total-station-based systems also tend to suffer from high cost.

Lastly, an alternative to GNSS and total station systems are laser level pose estimation systems. Using a rotary laser level and a receiver mounted on the stick of the excavator, these systems are capable of accurately monitoring digging depth. However, these systems are incapable of determining an excavator's position within the jobsite. Additionally, their functional range is often limited by the length of the laser receiver. Although laser level systems offer an affordable option capable of functioning in GNSS-denied areas, their potential to improve construction safety and productivity is hindered by limitations in their position estimation and functional range. Thus, the development of a low-cost, ubiquitous, six-dimensional excavator pose estimation system may help to fill a market need.

1.3 Motivation for a Marker-Based Pose Estimation Prototype

One potential approach to developing a low-cost, ubiquitous, six-dimensional excavator pose estimation system is to use optical cameras and fiducial markers as sensors. A fiducial marker, as described here, refers to a two-dimensional visual object having a prescribed geometry and identification features to distinguish it from naturally occurring objects and other markers. Upon capturing video of such a marker, a camera's image can be analyzed to estimate the marker's pose relative to the camera, generally in the form of a homogeneous transformation, as illustrated in Figure 3. Given that the focus of this paper is prototype development, only an overview of

camera-marker pose estimation is provided here. Interested readers are referred to Feng and Kamat, 2013 [13] for more details.

Figure 3: Camera-Marker Pose Estimation

Such methods can be extended to the pose estimation of an object simply by attaching a marker to the object and viewing it with a camera. Thus, it follows that cameras and markers could hypothetically be used to estimate the pose of an excavator simply by attaching markers to the machine's components and viewing the markers with a camera, as described by Feng et al., 2015 [14]. A marker-based sensor system could potentially offer such benefits over traditional systems as requiring fewer and less expensive sensors, as well as providing functionality in urban environments and indoors. To evaluate the feasibility and capabilities of a marker-based excavator pose estimation system, a series of prototypes was developed and tested. The remainder of the paper is dedicated to describing the development of such a physical marker-based excavator pose estimation system.

2 Technical Approach Overview

Prior to the work described in this paper, preliminary studies were conducted in a simulated environment to evaluate whether cameras and markers could be used for excavator pose estimation. The studies offered encouraging results, but were limited in their ability to capture real-world effects. Interest in real-world performance and commercial application drove the need

to develop and test physical prototypes. As such, the building and testing of field prototypes emerged as the primary research objective of this work.

Rather than immediately delving into prototype development for excavation equipment, two experiments were first conducted to gain a better understanding of the pose estimation capabilities of cameras and markers. Section 3 is dedicated to the discussion of such experiments. The first experiment was conducted to determine whether the pose estimation capabilities of real cameras and markers were accurate enough to justify further prototype development, as well as to study the effects of marker yaw on pose estimation accuracy. Unexpected findings led to a second camera-marker experiment, which further explored the effects of marker yaw angle on pose estimation accuracy. The two experiments not only verified the system's accuracy and provided the confidence to move forward with prototype development, but also offered insights into camera-marker behavior and informed strategies for prototype design.

After conducting the two camera-marker experiments, work continued with an iterative process of excavator-centric prototype development. Section 4 is dedicated to the discussion of such prototypes. Four prototypes in total were iteratively developed to evaluate the feasibility and performance of a marker-based pose estimation system on an actual excavator. The first iteration advanced through conceptualization stages into design stages, but was prematurely terminated due to the discovery of singularities in the mechanical system. The second design iteration provided much the same function as the first design, but utilized a different transmission mechanism free of singularities. The full prototype was found to perform satisfactorily, but was deemed impractical for use on actual excavators as it impeded normal operation. The third design iteration attempted to minimize interference with excavator operation by using different

marker placement locations on the machine. To facilitate such a design, a new mapping approach was adopted. When experimentally evaluated, however, the third iteration prototype was found to provide insufficient accuracy. Lastly, the fourth design iteration employed a hybrid sensor suite by combining an electromechanical sensor with camera-marker sensors. It also employed the mapping approach developed in the third design. Experimental evaluation of the fourth iteration prototype yielded satisfactory results.

3 Identification of Camera-Marker Performance Characteristics

After having identified cameras and markers as an alternative sensor system for excavator pose estimation, it was important to gain a better understanding of the system's performance capabilities. Interviews with more than a dozen professional excavator operators indicated that +/- 2.5 centimeters (1 inch) was a typical tolerance range for most excavation activities. As such, an experiment was conducted to identify the sensor system's pose estimation accuracy for comparison with customer requirements.

Since the relative pose between a camera and marker is defined by three components of translation (e.g. differential x , y , and z positions) and three components of orientation (e.g. differential roll, pitch, and yaw angles), a full characterization of pose error would require measurement of all six components. However, it was not feasible in the experiment to measure all six components quickly or accurately with the equipment available. Rather, a single component, vertical displacement, was chosen as an approximate measure of the system's pose error. Vertical displacement was selected because ground truth measurements could be quickly and accurately ascertained using a rotary laser level and tape measure, and because vertical displacement, or depth, is generally the component of greatest interest in most excavation

activities. Thus, the experiment involved estimating the vertical displacement between a camera and marker using the sensor system, and comparing the estimates with ground truth measurements.

While measuring the system's pose estimation accuracy, the effects of marker yaw were also studied by varying the marker's yaw angle. Marker yaw was defined as shown in Figure 4, with a zero yaw angle corresponding to the marker facing directly toward the camera. The experiment was comprised of 756 test combinations, which were equally divided between 0, -15, and +30 degree marker yaw angles.

Figure 4: Marker Yaw Illustration

The markers used in the experiment were made from AprilTags developed by Olson [15], and measured 57 centimeters (22.5 inches) between outermost black edges. The markers were leveled and affixed to a plumb surface, which was free to rotate about a plumb axis. The camera used was a 1.3 megapixel Firefly® MV optical camera by Point Grey with a Fujinon DF6HA-1B 6mm F/1.2 fixed focal lens. The camera was mounted at the same height as the center of the marker. Half of the experiment's test combinations were conducted at a distance of 4.0 meters (13 feet), and the other half at a distance of 7.6 meters (25 feet). A picture of the experimental setup is shown in Figure 5.

Figure 5: First Camera-Marker Experimental Setup

The experimental results are shown in Figure 6. The experimental results led to two interesting observations. First, the sensor system was found to exhibit considerably less error when the marker's yaw angle was nonzero (i.e., -15 or +30 degrees). Such results contradicted expectations, initiating a follow-up experiment to further explore the effects of marker yaw. Second, it was observed that the absolute error remained below 2.5 centimeters (1 inch) for 97% of nonzero marker yaw cases. For such nonzero marker yaw cases, the sensor system's accuracy appeared sufficiently close to the requirements of excavation to warrant further development.

Figure 6: First Camera-Marker Experimental Results

A second experiment was then conducted to further investigate the seeming correlation between marker yaw and error suggested by the first marker experiment. The experimental setup was

similar to that of the first experiment, as shown in Figure 7, but with a denser and wider range of marker yaw angles studied, namely -20, -10, 0, +5, +10, +15, +20, +30, +40, +50, +55, +60, +65, +70, and +80 degrees. Vertical displacement was again selected as the measure of error because ground truth measurements could be quickly and accurately ascertained using a rotary laser level and tape measure, and because vertical displacement, or depth, is generally the component of greatest interest in most excavation activities. The markers used in the experiment were made from AprilTags developed by Olson [15], and measured 57 centimeters (22.5 inches) between outermost black edges. The markers were leveled and affixed to a plumb surface, which was free to rotate about a plumb axis. The camera used was a 1.3 megapixel Firefly® MV optical camera by Point Grey with a Fujinon DF6HA-1B 6mm F/1.2 fixed focal lens. The camera was mounted at the same height as the center of the marker. The experiment was comprised of 120 test combinations, half at a distance of 4.6 meters (15 feet) and half at 9.1 meters (30 feet).

Figure 7: Second Camera-Marker Experimental Setup

The marker yaw behavior observed in the first experiment was again produced in the second experiment, as can be seen in Figure 8. The system's ability to measure vertical displacement appeared to suffer considerable error in the vicinity of zero marker yaw, and appeared to improve as marker yaw approached 70 degrees. However, at 65 degrees and beyond, the camera began to

lose detection of the marker, as might be expected for any two-dimensional image turned nearly perpendicular to a viewer's line of sight. Thus, it appeared advisable to avoid marker yaws near the vicinities of 0 and 90 degrees in pose estimation applications.

Figure 8: Second Camera-Marker Experimental Results

The results of the two experiments suggested that camera-marker sensor systems might be sufficiently accurate for excavator pose estimation applications provided marker yaw angles near 0 and 90 degrees are avoided. After gaining insight into the performance characteristics of marker-based sensors, it was possible to consider their physical implementation on excavation equipment.

4 Electromechanical Prototype Development

4.1 System Implementation Overview

To begin the development of a functional prototype for excavators, it was first noted that the teeth of the excavator bucket represent the cutting edge of the machine, making bucket tooth location and orientation the primary points of interest in most excavation activities. As previously stated, it is conceptually possible to determine the pose of a bucket's teeth by attaching a marker to the bucket and observing the marker with a camera. In the simplest case, tooth pose can be determined by placing a marker directly on the side of the bucket in alignment with the teeth, as shown in Figure 9. Additionally, a camera can be aimed toward the setup with a known relationship to the jobsite, for example, facing north on a level tripod one meter above a benchmark. Here, the term *benchmark* refers to a known jobsite reference point, sometimes denoted by a point marked on a stable and pervasive jobsite feature like a sewer manhole rim. In such a manner, a kinematic chain can be established to relate tooth pose to the rest of the jobsite. If a model of the jobsite includes underground utility information, the bucket's pose can also be determined relative to the underground utilities.

Figure 9: Conceptual Marker-Based Sensor Setup

However, there may exist benefits to mounting the camera on the excavator cabin since it is a likely location for the occurrence of data processing and interfacing with the operator. In such

close proximity to the marker, a second camera, with known relation to the first camera, can be added to help expand the sensor's vertical range. As shown in Figure 10, this cabin-mounted camera setup may be accomplished through the use of one or more site-fixed markers called sentinel markers. Sentinel markers, as defined here, are markers stationed nearby with a known or measured relationship to the jobsite. Lastly, a third camera, having known relationships to the other two cameras, may be added to view the sentinel marker. With such a setup, the camera cluster is free to move with the excavator, provided at least one sentinel marker is within view of at least one camera.

Figure 10: Cabin-mounted Camera Setup with Sentinel Marker

However, since the bucket penetrates the ground's surface while digging, it may be impractical to place a marker near the bucket teeth, as the ground would likely occlude the line of sight between the camera and marker. In fact, placement of a marker anywhere on the bucket may be impractical due to the likelihood of occlusion or damage during digging. Thus, an alternative method is needed to estimate tooth pose without placement of a marker directly on the bucket.

4.2 Four-Bar Linkage Design

One solution for implementing marker-based tooth pose estimation without placing a marker directly on the bucket is to form a short kinematic chain involving the last two links of the excavator: the stick and the bucket. One marker can be used to provide an estimate of the stick's pose, and another to estimate the bucket's rotation relative to the stick, as shown in Figure 11. The first marker, termed stick marker, is rigidly attached to the stick with a known relationship to the bucket's axis of rotation. The second marker, termed rotary marker, is attached at a location removed from the vicinity of the bucket. The rotary marker is constrained with one degree of rotational freedom and a known angular relationship to the bucket. If the bucket's geometry is also known, or measured onsite, then all necessary information is available to deduce tooth pose.

Figure 11: Marker-based Kinematic Chain Setup

The four-bar linkage was one mechanism briefly explored for implementing such a system. An initial design for an experimental prototype was developed, as shown in Figure 12. The primary design objective involved transmitting the bucket's angle to a removed location and outputting the angle through the pose of a marker, all without permanently modifying the excavator. The design features a parallelogram four-bar linkage with strong magnets for attachment to the stick and bucket.

Figure 12: Four-Bar Linkage Design

During the design process, it was realized that the operational range of an excavator bucket commonly exceeds 180 degrees, while the singularities inherent in a parallelogram four-bar linkage limit its functional range to less than 180 degrees. Although it may have been possible to avoid singularities through the use of a non-parallelogram four-bar linkage, such a mechanism would have introduced a nonlinear relationship between the bucket and marker. To avoid the complexities associated with nonlinear mapping, the non-parallelogram four-bar linkage was avoided. Thus, the four-bar linkage design was discarded for an alternative free of singularities and nonlinearities.

4.3 Synchronous Belt Design

The synchronous belt and pulley, sometimes referred to as toothed belt and pulley, was identified as an alternative mechanism for transmitting bucket angle to a removed location without singularities or nonlinearities. In addition to providing continuous rotation, the belt and pulley system offers the benefits of low maintenance and gearing capabilities through the employment of different sized pulleys. A belt-driven prototype was designed and fabricated for the purpose of marker-based sensor experimentation, as shown in Figure 13. As with the four-bar linkage, the primary design objective involved accurately transmitting bucket angle to a marker at a removed location without permanently modifying the excavator. In order to accurately transmit bucket angle through the device, alignment between components was critical.

Figure 13: Synchronous Belt Design

At the base of the device is a bracket which clamps to the bucket through the use of set screws, as shown in Figure 14, thus providing sufficient anchoring for experimentation without permanently modifying or damaging the excavator. Before clamping, the bracket is aligned with the bucket's teeth and axis of rotation. A cylindrical pocket in the rear of the bracket is fitted

over the bucket's pin for alignment with the bucket's axis of rotation. The bracket is aligned with the bucket's teeth through the use of an alignment tool.

Figure 14: Alignment and Clamping of Synchronous Belt Device to Excavator Bucket

Attached to the bracket is a synchronous pulley. During fabrication, the pulley is aligned with the bracket using dowel pins and accurately located holes, as shown in Figure 15. The pulley drives a synchronous belt, which transmits bucket angle to an upper pulley. The upper pulley is attached to a belt tensioning system which helps maintain accurate alignment between pulleys.

Figure 15: Pulley Alignment Methods

The upper pulley then attaches to a shaft, which drives the rotation of the marker, as shown in Figure 16. Cone point set screws are used to connect the upper pulley to the marker shaft. During installation, the cones press into the conical recesses in the shaft, thereby aligning and securing the two parts. This also provides a detachment point, allowing the prototype to be disassembled into two parts for easy installation and removal. Lastly, the rotary marker shaft is clamped to the excavator stick with set screws to provide sufficient anchoring for experimentation without permanently modifying the machine.

Figure 16: Alignment and Attachment of Upper Pulley and Rotary marker Shaft

The synchronous belt prototype was fabricated, installed, and tested on a Caterpillar 430E IT Backhoe Loader, as shown in Figure 17. The experiment served three primary purposes: to determine whether the prototype functioned mechanically as intended, to measure the accuracy of the entire pose estimation system, and to obtain open-ended feedback from a professional excavator operator about the prototype. The primary function of the sensor system is to provide an estimate of bucket tooth pose, which is defined by three components of position (e.g. x , y , and z) and three components of orientation (e.g. roll, pitch, and yaw) relative to a jobsite coordinate frame. In order to obtain an approximation of the system's pose estimation accuracy, a single component of bucket tooth pose was measured: tooth height. Tooth height was selected because

ground truth measurements could be quickly and accurately ascertained using a rotary laser level and tape measure, and because tooth height, or digging depth, is generally the component of greatest interest in most excavation activities.

The experiment involved placing the backhoe in random poses, using the sensor system to estimate bucket tooth height, and comparing sensor estimates with ground truth measurements to obtain a measure of error. The experiment's pass/fail criterion was set at 2.5 centimeters (1 inch) of absolute error. The markers used in the experiment were made from AprilTags, as developed by Olson [15], and measured 43.2 centimeters (17.0 inches) between outermost black edges. The cameras used were 1.3 megapixel Firefly® MV optical cameras by Point Grey with Fujinon DF6HA-1B 6mm F/1.2 fixed focal lenses. The cameras were mounted on a tripod near the operator's cabin, at approximately 1.5 meters (5 feet) above the ground. The experiment involved a total of 30 test combinations which were divided equally into three sets of horizontal distances between the camera and bucket teeth: 3.7 meters (12 feet), 4.9 meters (16 feet), and 6.1 meters (20 feet). These distances were chosen because they appeared fairly representative of the excavator's typical operational range. The experimental setup is shown in Figure 17.

Figure 17: Synchronous Belt Prototype Installed on Backhoe

The experiment was initiated, but inferior camera calibration methods, software bugs, and lack of tag redundancy in the markers led to poor sensor performance, and the experiment was quickly terminated. After months of further camera and software development, the experiment was repeated. The results of the repeated experiment are shown in Figure 18, where it can be seen that all thirty estimates of tooth height fell within the maximum allowable 2.5 centimeters (1 inch) of absolute error.

Figure 18: Synchronous Belt Experimental Results

Despite the system's demonstrated ability to estimate tooth height, it was ultimately determined that the synchronous belt design was not practical for use on excavators. The professional excavator operator assisting with the experiment expressed several concerns about the design. The first concern pertained to the hindrance of the bucket's clamping functionality by the presence of the device. Specifically, operators sometimes clamp objects between the bucket and stick for gripping purposes, but the locations of the markers in the synchronous belt design interfered with such action. Additional concerns included the device's lack of compatibility across different excavators, its need to be removed to change buckets, and its susceptibility to damage as a consequence of its high profile. Thus, an alternative design was sought to circumvent such issues.

4.4 Bucket Linkage Generalized Mapping Design

One design alternative having the potential for a low mechanical profile and high compatibility across platforms was termed *generalized mapping*. Generalized mapping, as described here, involves the use of a calibration process to map relationships between various components and bucket tooth pose. After establishing such a relationship, tooth pose can be inferred through measurement of the mapped components.

One implementation of generalized mapping is bucket linkage generalized mapping. Bucket linkage generalized mapping entails placing a stick marker on the stick and a key marker on a bucket transmission linkage, as shown in Figure 19. A third marker is also placed on the side of the bucket and aligned with the bucket teeth for the duration of a calibration process. The system is then calibrated by moving the bucket through its range of motion and recording intermediate marker poses obtained by the camera system. The intermediate pose measurements provide a mapping which relates the transformation between stick marker and key marker to the transformation between stick marker and tooth pose. After the calibration process, the bucket marker is removed. The sensor system then functions by observing the stick and key markers, and mapping their relative pose to that of the bucket teeth.

Figure 19: Calibration Process and Implementation of Bucket Linkage Generalized Mapping

One advantage of bucket linkage generalized mapping is that the placement of the stick and key markers is made nearly arbitrary by the calibration process. The markers can be placed on their respective components with little regard for alignment and location, as long as they are attached rigidly and with a clear line of sight from the cameras. Another advantage of the system is that its mechanical components are relatively flat, providing the potential for a low profile. In general, the less the prototype protrudes from the excavator's components, the less likely it will be to interfere with operation or get damaged. Although the markers used for experimental testing were of considerable surface area, it is not unreasonable to presume the markers could be made smaller through further sensor development. Lastly, the use of a calibration process allows

for high compatibility between excavators. Effectively, the only criterion for compatibility is that the markers are able to be mounted on the machine.

A prototype of the bucket linkage generalized mapping system was installed and tested on a Caterpillar 430E IT Backhoe Loader, as shown in Figure 20. The purpose of the experiment was to measure the system's pose estimation accuracy. As with the synchronous belt prototype experiment, the system's accuracy was approximated by measuring one of the six components of bucket tooth pose: tooth height. The markers used in the experiment were made from AprilTags developed by Olson [15], and measured 58.4 centimeters (23.0 inches) between outermost black edges. The cameras used were 1.3 megapixel Firefly® MV optical cameras by Point Grey with Fujinon DF6HA-1B 6mm F/1.2 fixed focal lenses. The cameras were mounted on a tripod near the operator's cabin, approximately 1.5 meters (5 feet) above the ground. The experiment involved calibrating the sensor system, placing the backhoe in random poses, using the sensors to estimate bucket tooth height, and comparing estimates with ground truth measurements obtained using a total station. The experiment's pass/fail criterion was set at 2.5 centimeters (1 inch) of absolute error.

Figure 20: Bucket Linkage Generalized Mapping Prototype Installed on Backhoe

The experiment was conducted, but the prototype's poor accuracy led to unsatisfactory initial results. Due to discouraging initial results, the experiment was quickly abandoned and the data went unrecorded. It was concluded that the resolution of the relationship between key marker pose and bucket tooth pose was insufficient to accurately estimate tooth pose with the camera sensor system being used. It can be seen in Figure 21 that the key marker's radius of motion is considerably less than that of the bucket teeth. Thus, a small change in translation of the key marker corresponds to a large change in translation of the bucket teeth. Additionally, the resolution is further degraded by the nonlinear transmission of angle through the non-parallel four-bar linkage, which is evident in the total angles swept out by each marker. As a result, the error inherent in the sensor system was magnified by the low-resolution relationship between key marker pose input and bucket tooth pose output. Mounting the key marker further from the linkage's axis of rotation may have helped alleviate the resolution issue, but would likely have caused the marker to extend an impractical distance from the excavator. Thus, an alternative sensor was sought to provide a measure of bucket angle with higher resolution.

Figure 21: Smaller Radius and Swept Angle of the Key Marker

4.5 Cable Potentiometer Generalized Mapping Design

The cable-driven rotary potentiometer, sometimes referred to as *string potentiometer*, was identified as an alternative sensor capable of measuring bucket angle with sufficient resolution. In addition to its resolution, the cable potentiometer was identified as an economical, robust sensor that could easily be installed on an excavator without permanently modifying the machine. Specifically, the cable potentiometer could be mounted on the bucket's hydraulic cylinder to provide a measure of stroke length, which could then be used to determine tooth pose through the generalized mapping approach.

Cable potentiometer generalized mapping is accomplished much the same as bucket linkage generalized mapping. A calibration process is performed in which the bucket is moved through its range of motion and measurements of stroke length are mapped to the relative transformation between the stick marker and bucket teeth, as shown in Figure 22. After the calibration process, the marker is removed from the bucket. The system then functions by measuring stick marker pose and cylinder stroke length, and mapping such measurements to bucket tooth pose.

Figure 22: Calibration and Implementation of Cable Potentiometer Generalized Mapping

A prototype was designed for the purpose of testing the cable potentiometer generalized mapping concept, as shown in Figure 23. The prototype attaches to the bucket's hydraulic cylinder through the use of clamps to avoid permanent modification of the machine. The device includes a cable potentiometer for measuring linear displacement, a microcontroller for signal conversion, a radio for wireless transmission, and a battery for power, all mounted inside an enclosure for protection.

Figure 23: Cable Potentiometer Generalized Mapping Design

The sensor's cable is connected to a fiberglass rod, which telescopes through a rigid pipe lined with plastic to reduce abrasion. If brought into contact with a foreign object, the rod's compliant properties allow it to temporarily deflect and return to its natural shape. In the case of failure, however, the rod is expected to shear at the pipe and prevent the cable from being extracted beyond its physical limit. In this way, the fiberglass rod protects the cable potentiometer by acting as a sacrificial component. Additionally, the rod's low strength also prevents damage to the hydraulic cylinder by limiting the forces transferred to the clamps.

A cable potentiometer generalized mapping prototype was built, installed, and tested on a Caterpillar 430E IT Backhoe Loader, as shown in Figure 24. The experiment served three primary purposes: to determine whether the prototype functioned mechanically as intended, to measure the accuracy of the entire pose estimation system, and to obtain open-ended feedback from a professional excavator operator about the prototype. The system's accuracy was approximated by measuring three of the six components of bucket tooth pose: x -, y -, and z -position. The markers used in the experiment were made from AprilTags developed by Olson [15], and measured 58.4 centimeters (23.0 inches) between outermost black edges. The cameras used were 1.3 megapixel Firefly® MV optical cameras by Point Grey with Fujinon DF6HA-1B 6mm F/1.2 fixed focal lenses. The cameras were mounted on a tripod near the operator's cabin, approximately 1.5 meters (5 feet) above the ground. The experiment involved calibrating the sensor system, placing the backhoe in random poses, using the system to estimate bucket tooth position, and comparing estimates with ground truth measurements obtained using a total station. The experiment's pass/fail criterion was set at 2.5 centimeters (1 inch) of absolute error.

Figure 24: Cable Potentiometer Generalized Mapping Prototype Installed on Backhoe

A total of eight trials were conducted. For each trial, three components of tooth position (x , y , and z) were measured and compared with ground truth measurements. The three components of position were defined by a local orthogonal coordinate system, with y corresponding to the zenith direction, and x and z arbitrarily oriented in the level plane. Nearly all the data collected satisfied the pass/fail criterion of 2.5 centimeters (1 inch) of absolute error, as shown in Figure 25. Although x - and z -position estimates only marginally met the requirements, performance as a whole was deemed satisfactory since the system exhibited exceptional accuracy in the zenith direction (y -position), which is typically the most critical in excavation applications.

Figure 25: Cable Potentiometer Experimental Results

The cable potentiometer generalized mapping prototype was also tested on a PC138USLC Komatsu Excavator operating on an active construction site, as shown in Figure 26. A computer screen was mounted in the operator's cabin, providing a display of bucket height relative to a desired trench grade. The system was used to assist the operator in trenching operations.

Figure 26: Cable Potentiometer Prototype Installed on Komatsu Excavator

Shown in Figure 27 is a short section of trench in which the operator conducted a side-by-side comparison of traditional human-guided grading versus grading guided by the sensor system. After performing the excavation, the operator visually compared the depths of the two surfaces and judged the sensor-guided grading satisfactory in their expert opinion. After several days of function, the prototype incurred an impact to the fiberglass rod. The rod sheared off at the pipe opening as intended, and was thus considered a controlled failure. The failure, however, marked the end of the experiment.

Figure 27: Comparison of Sensor Guided Grading Versus Traditional Grading

5 Discussion

The experiments described here led to several major findings. First, it was suggested plausible by the camera-marker experiments that cameras and markers could be capable of providing sufficient accuracy for excavator pose estimation applications. Second, it was indicated by the camera-marker experiments that marker yaw angles near 0 and 90 degrees should be avoided in pose estimation applications. Third, it was found that although purely marker-based sensor systems may be sufficiently accurate for excavator pose estimation, it may be more practical to employ a combination of marker-based sensors and traditional sensors so as to exploit the strengths of each type. Lastly, it was demonstrated through physical experiments that cameras and markers have the capability to provide actual utility in the monitoring and guidance of construction equipment, especially in terms of reducing cost and providing functionality in GPS-denied areas.

This work is significant because it serves as a guide for the development of future marker-based pose estimation systems for excavators and other construction equipment. For example, this work describes several fundamental configurations for mounting cameras and markers on a machine and a jobsite, it describes lessons learned with regard to implementation, and it identifies future work needed. Most importantly, this work is significant because it demonstrates the feasibility of using marker-based sensors for the pose estimation of excavators and other equipment in real-world construction applications.

6 Conclusions and Future Work

Excavator pose estimation systems offer the potential to improve excavation safety and performance, but their widespread adoption is impeded by the high cost and limitations of

542 traditional excavator pose estimation systems. A marker-based sensor system, comprised of
543 fiducial markers and optical cameras, offers a potential low-cost and ubiquitous alternative.
544 However, because markers cannot be placed directly on an excavator's bucket for occlusion and
545 durability reasons, a device is needed to transmit bucket motion and provide information
546 necessary to deduce tooth pose.

547 Several design iterations were developed to address this problem, including a four-bar linkage
548 design, a synchronous belt design, a bucket linkage generalized mapping design, and a cable
549 potentiometer generalized mapping design. Prototypes were fabricated, installed, and tested.
550 Promising experimental results suggest the feasibility of marker-based sensor technology for
551 excavator pose estimation.

552 Marker-based sensors appear to offer a potential solution for the economical localization and
553 pose estimation of articulated construction equipment, especially in environments with limited
554 GNSS capabilities, but their specific application and implementation remain unclear. Although
555 several variations of marker-based pose estimation systems were demonstrated with reasonable
556 success, a robust system has yet to be developed for use on actual construction sites.

557 Future work is needed to identify the proper implementation of marker-based sensors in
558 excavator pose estimation systems. For example, it is still unclear whether it is best to place
559 cameras on an excavator in view of a jobsite, or on a jobsite in view of an excavator. One
560 potential advantage of the former is the centralization of power, sensors, processors, and
561 interface, while a potential advantage of the latter is the possibility of viewing multiple machines
562 with the same camera. Also regarding implementation, experiments have indicated that it may be

advantageous to employ a combination of marker-based sensors and traditional sensors, but the best combination and specific role of each sensor type remains unclear.

Another challenge needing to be addressed is camera-marker occlusion. Considering the busy nature of a construction site, it is not unreasonable to expect that a person, machine, or object could occasionally block the line of sight between a camera and marker. Thus, it may be necessary to evaluate the severity of the concern and address it, possibly through the incorporation of redundancies. Similarly, as an excavator moves, it may prove challenging to keep markers in the cameras' field of view. Again, one solution might exist in the use of multiple site-based cameras or multiple site-based markers for redundancy.

Lighting conditions may also pose a challenge, as low light levels can lead to marker detection loss. Thus, some form of active lighting may prove necessary for nighttime operation, and possibly even during dawn and dusk or in poorly lit indoor environments. Lastly, the harsh environment of the typical jobsite may present challenges for the sensor system's components. Thus, a fully functional system will likely require considerable design efforts to ensure electrical and mechanical robustness. Such efforts are currently being pursued by the authors' research group.

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Graphical Abstract