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Optical marker-based end effector pose estimation 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 cm (1 in.) 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.

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 m (36 in.) 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 km (19 million mi) [2,3] of underground utilities including gas, electric, water, sewer, cable television, fiber optic, phone, drainage, traffic signals, and street lighting circuits. Shown in Fig. 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].

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

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Fig. 1. Examples of urban underground congestion.

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

1.2. Motivation for a low-cost, ubiquitous pose estimation system

Excavator pose estimation systems are commercially available today [10,11], but have not yet been widely adopted by the construction industry. Various types of pose estimation systems are available, but all possess shortcomings. Companies like Trimble and Leica offer packages that make use of Global Navigation Satellite Systems (GNSS) to permit a full six-dimensional (three position and three orientation) estimation of the machine's pose relative to the jobsite. These systems likely offer the

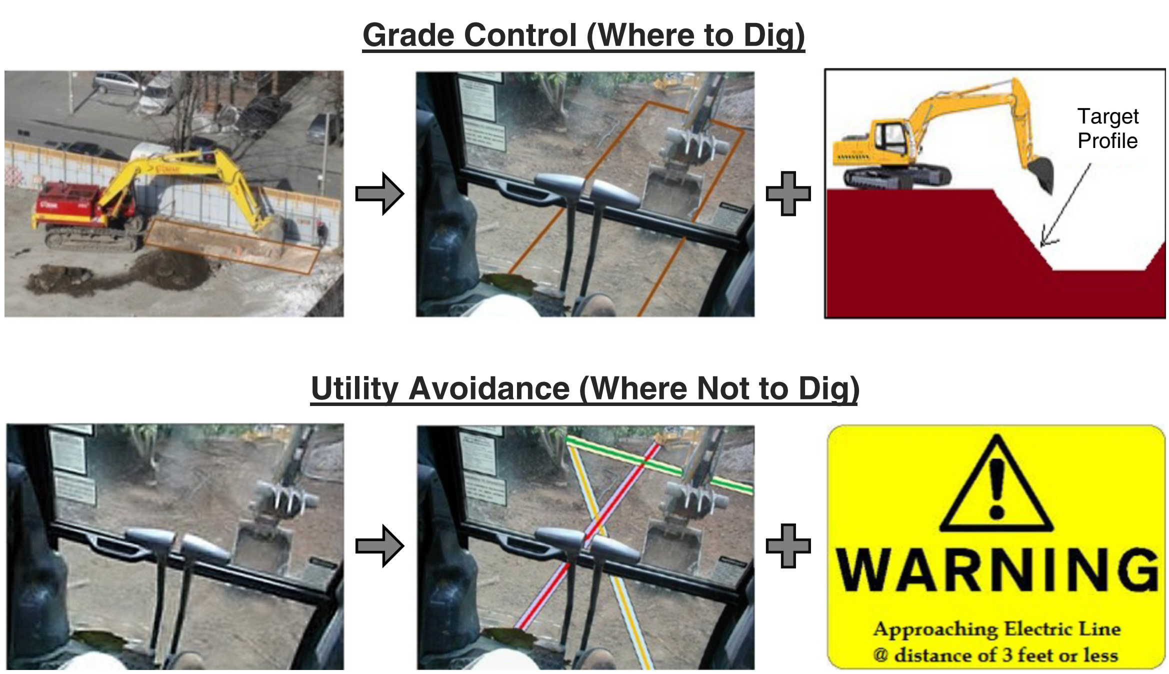

Fig. 2. Benefits of excavator pose estimation: grade control and utility avoidance.