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Scene understanding for adaptive manipulation in robotized construction work

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ABSTRACT

Unlike manufacturing robots, whose kinematics are pre-programmed based on robust metrology, tight tolerances, and rigid workpieces, construction robots operate under conditions of imperfect metrology, loose tolerances, and large workpiece uncertainties. Despite having access to a designed Building Information Model (BIM), construction robots must sense and model their actual environment, and adapt their kinematic plan to compensate for deviations from the expected. This research investigates methods to enable the autonomous sensing and modeling of construction objects so construction robots can ultimately adapt to unexpected circumstances and perform quality work. To that end, two construction component model fitting techniques are presented, namely the Clustering and Iterative Closest Point (CICP) construction component model fitting technique and the Generalized Resolution Correlative Scan Matching (GRCSM) construction component model fitting technique. The GRCSM construction component model fitting technique employs the presented GRCSM search algorithm, which is a modified version of the existing Multi-Resolution Correlative Scan Matching (MRCSM) search algorithm. Three experiments are presented to evaluate the ability of the CICP and GRCSM construction component model fitting techniques to model construction features. It was found that the CICP and GRCSM construction component model fitting techniques are capable of estimating the pose and geometry of arbitrarily shaped objects and construction joints, but are susceptible to modeling error. Despite their limitations, the CICP and GRCSM construction component model fitting techniques appear to be promising tools for the geometric estimation of construction features, especially for situations involving full automation, detailed construction work, incomplete sensor data, and complex object geometry.

1. Introduction

The construction industry is often considered an industry of slow change, hazardous conditions, old technology, and stagnant productivity levels. Robotics offers the potential to change that by reducing construction project cost, shortening project lead time, improving construction quality, and improving worker safety [1]. However, the construction industry's adoption of robotics has proven slower than other industries, such as manufacturing. This is largely attributable to technological challenges arising from the unique characteristics of the construction industry [2]. One such challenge is the construction robot's need to perceive its workpieces and adapt its plan in order to reliably perform quality work. The objective of this research is to develop a means by which a construction robot can perceive and model the workpieces in its immediate environment so it can ultimately adapt its plan and autonomously perform detailed construction work.

The remainder of the paper is outlined as follows. Section 2 further expands upon the challenges confronting construction robots and the importance of scene understanding in robotized construction work. Section 3 describes the relevant prior work and the gaps addressed by this paper. Section 4 outlines the central contributions of this paper. Section 5 describes the technical approaches employed in this work. Section 6 describes the experiments and results used to evaluate the effectiveness of the technical approaches. Section 7 provides a discussion of the experimental results. Section 8 provides a summarizing conclusion and outline of future work.

2. Need for scene understanding and adaptive manipulation

To illustrate the construction robot's need to perceive its workpieces and adapt its plan to perform quality work, it is instructive to contrast the construction industry with the manufacturing industry. Although today's manufacturing robots possess a variety of sensing capabilities, many are able to perform work with little or no sensing of their

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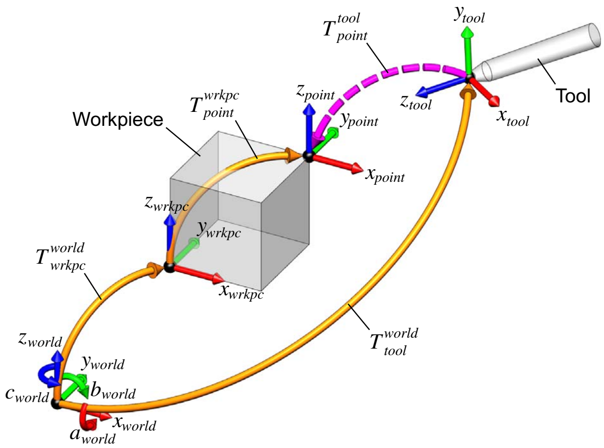

Fig. 1. Kinematic chain used to determine the relative pose (dashed magenta arrow) between a robot's tool and the point of interest on its workpiece. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

workpieces. This is typically made possible by reducing stochastic variation through tight process and environmental controls. As such, a manufacturing robot can neglect stochastic variation and simply estimate the relative pose (i.e., position and orientation) between its tool and the point of interest on its workpiece (hereafter referred to as *tool-to-point-of-interest pose*) from a kinematic chain, as illustrated in Fig. 1 and Eq. (1), where $T_b{}^a$ is a homogenous transformation matrix describing frame b in frame a.

$$\mathrm{T}^{\mathrm{tool}}_{\mathrm{point}} = (\mathrm{T}^{\mathrm{world}}_{\mathrm{tool}})^{-1}\mathrm{T}^{\mathrm{world}}_{\mathrm{wrkpc}}\mathrm{T}^{\mathrm{wrkpc}}_{\mathrm{point}} \tag{1}$$

In order for a robot to reliably perform value-added work, the uncertainty in tool-to-point-of-interest pose (in addition to other sources of uncertainty) must be less than the allowable process uncertainty [3]. This requirement is described by the law of propagation of uncertainty, as shown in Eq. (2), where the standard deviation is taken as the measure of uncertainty, Σ is the covariance matrix, and J is the Jacobian matrix which projects uncertainty into a common frame.

$$\Sigma^{world}_{tool} + \Sigma^{world}_{wrkpc} + J^{world}_{wrkpc}\Sigma^{wrkpc}_{point}\, J^{world\top}_{wrkpc} < \Sigma^{world}_{process,allow} \tag{2}$$

The manufacturing robot, its workpieces, and its environment are all tightly controlled, which translates to low variation and low uncertainty. Low uncertainty in tool pose, workpiece pose, and workpiece geometry results in low uncertainty in tool-to-point-of-interest pose. Since the uncertainty in tool-to-point-of-interest pose is less than that allowed by the process, the manufacturing robot is able to estimate tool-to-point-of-interest pose directly from the kinematic chain and still perform work of sufficient quality and reliability.

A closer inspection reveals how such sources of uncertainty are managed in manufacturing. Uncertainty in world-to-tool pose is often managed through such means as rigid robot anchoring, precise robot installation or calibration, rigid robot links, and high precision joint sensors. Uncertainty in world-to-workpiece pose is managed through the controlled delivery of the workpiece to the robot. Fine control can often be achieved through the positioning, orienting, and holding of the workpiece via mechanical constraints such as stops, clamps, and jigs. Uncertainty in workpiece geometry (i.e., workpiece-to-point-of-interest pose) is managed through tight design tolerances and tight process controls. This allows the workpiece's geometric errors to be neglected when it arrives at the robot, despite the accumulation of errors from previous manufacturing steps. Additionally, the manufacturing workpiece is typically rigid enough that material deflections remain small and the workpiece's designed geometry remains sufficiently representative of its true geometry. Lastly, uncertainty in workpiece geometry is also managed through definition. Albeit a different form of uncertainty, the standard practice of fully defining the manufacturing product helps to reduce ambiguity about workpiece geometry.

A look at the construction industry, on the other hand, reveals that large uncertainties in the robot, its workpieces, and its environment generally preclude the use of the kinematic chain in Eq. (1) for estimating tool-to-point-of-interest pose. Estimating tool-to-point-of-interest pose from a kinematic chain is likely to prove ineffective for a construction robot due to large stochastic variation in the construction process and environment. If the construction robot were to estimate its tool-to-point-of-interest pose from the kinematic chain, then the combined uncertainty of the chain's components would generally exceed the allowable process uncertainty, and the construction process would be in violation of Eq. (2). Violation of Eq. (2) implies insufficient reliability in the construction process, or the inability to perform quality work reliably [3].

A closer inspection of the construction robot sheds light on the uncertainty present in its kinematic chain. Uncertainty in the world-to-tool pose arises from several sources. First, the sheer scale and nature of the typical construction project suggest that the construction robot will most likely need to be mobile. Although the pose uncertainty of a mobile robot's base varies depending on the sensors and estimation method used, such uncertainty is generally much larger than that of an anchored robot. A second consequence of the robot's mobility is that its base is likely to be less rigid than that of an anchored robot. Some uncertainty might be reduced through such means as outriggers, but the rigidity of a mobile robot's base is generally less than that of an anchored robot base. Third, since the construction robot must go to the workpiece to perform work, as opposed to having the workpiece brought to it, it is expected that the construction robot will generally require a longer reach than the manufacturing robot. Thus, the need to reach long distances and exert large forces, combined with size restrictions imposed by the need to access tight spaces, suggests that the construction robot will likely have greater deflection and uncertainty in its links.

Uncertainty is also present in the world-to-workpiece pose estimate. Although construction tolerances and manufacturing tolerances both vary widely, construction tolerances are generally looser [4]. As a result, there tends to be greater variation in the placement of construction components. In addition to uncertainty caused by loose tolerances, many construction details are not explicitly defined during the conventional design process, which has the potential to contribute considerably to uncertainty in the world-to-workpiece pose estimate. For example, consider the location of a stud in a wall. Although it is common practice to define the spacing between studs in construction plans, it is not common practice to define where the stud spacing begins, so a typical stud may actually be found up to 20 cm (8 in.) in either direction from its expected location.

Lastly, uncertainty is also present in the workpiece's geometry (i.e., workpiece-to-point-of-interest pose). It is common for some construction components to deviate from their designed geometry as a result of deflection, often due to their material properties and considerable length. Similarly, uncertainty arises from geometric variation in construction materials. For example, lumber often has such natural defects as knots and wanes, such warpages as bows and cups, and such manufacturing defects as skip marks and raised grain [5]. Workpiece uncertainty also arises from the accumulation of errors produced during previous construction processes. That is, the construction industry's loose tolerances often result in large process errors, and the product of one process often becomes the workpiece of a later process. So although a construction feature (e.g., window opening) may have been constructed in the correct location, its geometric errors (e.g., width, height, perpendicularity) can still be critical to subsequent construction processes (e.g., window installation).

Thus, given the large uncertainties faced by robots in the construction industry, it is expected that construction robots will need to employ different tool-to-point-of-interest pose estimation approaches