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Vision guided autonomous robotic assembly and as-built scanning on unstructured construction sites

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ABSTRACT

Unlike robotics in the manufacturing industry, on-site construction robotics has to consider and address two unique challenges: 1) the rugged, evolving, and unstructured environment of typical work sites; and 2) the reversed spatial relationship between the product and the manipulator, i.e., the manipulator has to travel to and localize itself at the work face, rather than a partially complete product arriving at an anchored manipulator. The presented research designed and implemented algorithms that address these challenges and enable autonomous robotic assembly of freeform modular structures on construction sites. Building on the authors' previous work in computer-vision-based pose estimation, the designed algorithms enable a mobile robotic manipulator to: 1) autonomously identify and grasp prismatic building components (e.g., bricks, blocks) that are typically non-unique and arbitrarily stored on-site; and 2) assemble these components into pre-designed modular structures. The algorithms use a single camera and a visual marker-based metrology to rapidly establish local reference frames and to detect staged building components. Based on the design of the structure being assembled, the algorithms automatically determine the assembly sequence. Furthermore, if a 3D camera is mounted on the manipulator, 3D point clouds can be readily captured and registered into a same reference frame through our marker-based metrology and the manipulator's internal encoders, either after construction to facilitate as-built Building Information Model (BIM) generation, or during construction to document details of the progress. Implemented using a 7-axis KUKA KR100 robotic manipulator, the presented robotic system has successfully assembled various structures and created as-built 3D point cloud models autonomously, demonstrating the designed algorithms' effectiveness in autonomous on-site construction robotics applications.

1. Introduction

Several studies have argued that among all industries, construction has seen a significant productivity decrease over the last several decades compared to other industries [30]. Construction has also been documented to have some of the highest rates of workspace injuries and fatalities [6]. Automation and robotics in construction (ARC) has the potential to relieve human workers from repetitive and dangerous tasks, and has been extensively promoted in the literature as a means of improving construction productivity and safety [3].

Compared to the tangible benefits of automation and robotics identified by the manufacturing industry, the construction industry is still exploring feasible and broadly deployable ARC applications [3]. This can be attributed to several commercial and technical challenges. From the commercial perspective, the fragmented and risk-averse nature of the construction industry leads to little investment in ARC research causing construction to lag behind other industries [31]. On the other hand, as described next, there are several technical complexities inherent in construction that have contributed to hindering the successful development and widespread use of field construction robots.

1.1. Technical challenges

1.1.1. Unstructured construction environments

Automated and robotized manufacturing facilities are typically considered as structured environments, since both the machines and evolving products either stay in their predefined locations or move on predesigned and typically fixed paths. In general, such environments do not change shape or configuration during the performance of manufacturing tasks, making the enforcement of tight tolerances possible [23]. In contrast, construction sites can typically be considered unstructured since they are constantly evolving, and dramatically changing shape and form in response to construction tasks. Building components are moved around without fixed paths or laydown/staging areas. Various physical connections are established through improvisation in response to in-situ conditions, making tight tolerances hard to maintain and enforce [24].

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1.1.2. Mobility of construction manipulators

In manufacturing, factory robotics typically involves robotic platforms that are generally stationary (or have limited linear mobility) and partially complete products that arrive at robot workstations and precisely localize themselves in the robots' base reference frames. Precision is achieved by controlling the pose of the moving (and evolving) product, and the robots themselves are programmed to manipulate the products through fixed trajectories. Thus, from a mobility and cognitive perspective, a factory robot has little responsibility and autonomy. Control is achieved by enforcing tight tolerances in moving and securing the product in the manipulator's vicinity. However, this spatial relationship is reversed in construction. A construction robot has to travel to its next workface (or be manually set up there), perceive its environment, account for the lack of tight tolerances, and then perform manipulation activities in that environment. This places a significant mobility and cognitive burden on a robot intended for construction tasks even if the task itself is repetitive.

This discussion highlights that factory-style automation on construction sites requires development of robots that are significantly more mobile and perceptive when compared to typical industrial robots. Such on-site construction robots have to be able to semantically sense and adjust to their unstructured surroundings and the resulting loose tolerances. This paper proposes a new high-accuracy 3D machine vision metrology for mobile construction robots. The developed method uses fiducial markers to rapidly establish a local high-accuracy control environment for autonomous robot manipulation on construction sites. Using this method, it is possible to rapidly convert a portion of a large unstructured environment into a high-accuracy, controllable reference frame that can allow a robot to operate autonomously.

The rest of the paper is organized as follows. Related work is reviewed in Section 1.2. The authors' technical approach is discussed next in detail in Section 2. The experimental results of both assembly and scanning are shown and discussed in Section 3. Finally, in Section 4, the conclusions are drawn and the authors' future work is summarized.

1.2. Previous work

1.2.1. Robotic manipulators in construction

The construction community has pursued research on robotic manipulators for several decades: for example, Slocum and Schena [33] proposed the Blockbot for automatic cement block wall construction; Pritschow et al. [29] identified the needs and requirements of a bricklaying robot for masonry construction and developed a control system for such robots.

A large portion of the construction robotic manipulator research focused on mechanics and control of specific construction activities. Fukuda et al. [13] discussed the mechanism and the control method of a robotic manipulator in construction based on human–robot cooperation. Yu et al. [37] proposed an optimal brick laying pattern and trajectory planning algorithm for a mobile manipulator system, with computer simulation to test its efficiency. Hansson and Servin [17] developed a semi-autonomous shared control system of a large-scale manipulator in unstructured environments, with a forwarder crane prototype to test its performance. Chung et al. [7] proposed a new spatial 3 degree-of-freedom (DOF) parallel type master device for glass window panel fitting task. Gambao et al. [15] developed a modular flexible collaborative robot prototype for material handling, although without any perception sensors for capturing the working environment.

Another important aspect of construction robotic manipulators lies in sensing and perception. Kahane and Rosenfeld [20] proposed a “sense-and-act” operation concept enabling an indoor mobile robot to position itself with approximately 10 cm accuracy, using a CCD camera and several laser projectors. Kim and Haas [21] proposed automatic infrastructure inspection and maintenance using machine vision for crack mapping. Gambao et al. [14] developed a robot assembly system based on laser telemeter sensors of 6 to 15 mm positional precision. During these research studies, it was generally realized that increasing the level of autonomy for construction robots requires high accuracy localization of the robot: from 3–5 cm indoor positional accuracy for contactless construction tasks such as spray-painting, to 2–3 mm accuracy for more precise tasks demanding direct contact between manipulator and building components [32]. This requirement has posed a significant challenge for ARC because even by using current state-of-the-art simultaneous localization and mapping (SLAM) techniques, such accuracy is hard to achieve at large scales [22]. In order to address this issue, the authors of this study chose to pursue computer-vision-based pose estimation algorithms that can achieve high accuracy locally around a visual marker [10,26].

1.2.2. 3D as-built modeling in construction

3D as-built modeling (e.g., BIM) plays an important role in a wide range of civil engineering applications. This modeling process usually starts with collecting 3D point clouds of sites of interest. Paul et al. [27] utilized a 6DOF anthropomorphic robotic arm to get the 3D mapping of a complex steel bridge with a laser range scanner. Brilakis et al. [5] outlined the technical approach for automated as-built modeling based on point clouds generated from hybrid video and laser scanning data. Akula et al. [2] explored different 3D imaging technologies, e.g., 3D image system, image based 3D reconstruction and Coherent Laser Radar scanner, to map the locations of rebar within a section of a railway bridge deck in order to assist a future drill operator in making real-time decisions with visual feedback. Zhu and Donia [39] investigated the advantages and drawbacks of RGBD cameras in as-built indoor environments modeling, with evaluation on the accuracy of collected data, the difficulty of automatic scan registration and the recognition of building elements, demonstrating RGBD camera's potential in as-built BIM modeling. In this research, the automatic planning, scanning and registration of point clouds obtained from a 3D camera mounted on the manipulator are achieved with the visual marker-based metrology and the manipulator's internal encoders.

Once 3D point clouds are obtained, CAD-like geometric models can be generated. For example, Son et al. [34] automatically extracted 3D pipeline models from laser scanning data based on the curvature and normal of point clouds; Han et al. [16] proposed an automated and efficient method to extract tunnel cross sections from terrestrial laser scan (TLS) data. While this research focuses more on the automatic registration of different frames of point clouds, the resulting registered point clouds could be input into such algorithms to generate semantically meaningful CAD-like geometric entities for as-built BIM.

1.2.3. Robotic manipulators in architecture

Recently the architectural design community has also shown an increased interest in industrial robotics, with many academic programs investing in their own robotic work cells.[1] Capitalizing on the machines' inherent flexibility, they have leveraged the industrial robot as a development platform for the exploration and refinement of novel production techniques in which material behavior is intrinsically linked to fabrication and assembly logics. As part of the general ecosystem of industrial robotics, computer vision systems have begun to play an increasingly important role in these research initiatives, with a number of architectural research groups developing interfaces for accessible hardware such as the Microsoft Kinect.

Initially the majority of architectural robotic research utilizing computer vision has revolved around its application at the *micro* scale, using a vision feedback system to make incremental adjustments to a robotic strategy based upon local variations. Examples of this include Dierichs et al.'s [8] research into poured aggregate structures at the Institute for Computational Design at University of Stuttgart and Dubor and Diaz's [9] project Magnetic Architecture from the Institute for Advanced

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[1] http://www.robotsinarchitecture.org/map-of-robots-in-architecture.