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Robotic assembly of smartphone back shells with eye-in-hand visual servoing

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ABSTRACT

Research concerning smartphone assembly has attracted increasing attention from the manufacturing industry. This paper presents an automatic back shell assembly system using real-time visual servoing in an eye-in-hand configuration. Look-then-move and look-and-move control approaches are sequentially proposed to handle distal and proximal assembly tasks, respectively. During distal assembly, binocular vision is employed to assist a robotic manipulator to locate and reconstruct the positions and orientations of a cellular phone and its back shell in the work space. After lifting the back shell up and then reaching the top of the cellular phone, there is no binocular field of view. A seemingly novel way of 3-D reconstruction by two uniocular fields of view of the two cameras is proposed. With the pair of monocular vision sensors, two monocular visual servo control laws are employed sequentially to perform the proximal assembly task autonomously. Based on the experimental results, the robotic manipulator can be driven to hold the back shell by a vacuum absorption device and position it precisely onto the smartphone to accomplish the automatic assembly task even if the vision system is only roughly calibrated. The proposed control approach for distal and proximal assembly appears to be efficient, flexible, and reliable for potential applications in industrial manufacturing.

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1. Introduction

Robotic manipulators have been playing a crucial role in factory automation. Typically, they need to be trained to perform repetitive and dangerous tasks. They can help to reduce the cost of manufacturing, complete their tasks efficiently and productively, and standardize all goods to a high quality [1,2]. Dauting tasks causing strains and tiredness and dangerous tasks resulting in hazards can also be avoided with the aid of robots. However, the capability of robotic manipulation is somehow restricted due to its fixed and inherited nature. In order to allow robotic manipulators to handle autonomous and flexible tasks, sensors such as cameras are required. By using real-time visual feedback, robotic manipulators can possibly accomplish autonomous tasks flexibly, precisely, and robustly. Real-time vision has received much attention with the increasing demands for a variety of applications in robotics and automation. Two-camera vision systems have been widely employed but they do not always find the corresponding physical point in both cameras due to limited field of view. Hence, the 3-D reconstruction cannot be performed based on the triangulation principle. A variety of sensor configurations have been experimented for robotic applications.

In recent years, a lot of research about vision-based control of robotic manipulators has been conducted. Hutchinson et al. [3] provided an excellent introduction and tutorial for visual servoing. Corke and Good [4] made a distinction between visual kinematic and visual dynamic control. Specifically, the former approach deals with how a manipulator should move in response to the perceived visual information, while the latter focuses on the dynamic effects that usually occur in a robotic system. Espiau et al. [5] proposed image-based visual servoing control which involves the computation of image Jacobian or interaction matrix. Chang [6] proposed a strategy to precisely perform 3-D trajectory following without assuming pointwise binocular correspondence information. Quach and Liu [7] implemented tracking control of a robotic manipulator by employing a projection matrix design approach. These approaches require hand-eye coordination which can be established by calibrating the coordinate transformation between the cameras and the manipulator in either eye-to-hand [8] and eye-in-hand [9] configuration. Eye-to-hand approaches are often employed for applications that require manipulations in a large workspace not requiring precision in proximal range. Calibration of such hand-eye systems can be performed automatically with a novel method that simultaneously calibrates the intrinsic parameters of a camera and the hand-eye-workspace relations using a line laser module [10]. For the purpose of performing tasks with equal dexterity and precision, eye-in-hand configurations can be adopted in a variety of industrial applications [11,12]. Real-time visual servoing can also be applied to perform active tracking [13], grasping [14,15], and assembly tasks [16]. Li et al. [17] introduced a fast color information setup based on evolutionary programming like particles

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swarm optimization for manipulator grasping systems. Buttazzo et al. [18] proposed an eye-to-hand visual servo control system for ball capturing. Image sensing, planning, and feedback control were performed in real time to cope with possible unpredictable trajectory changes of the moving target. Lippiello et al. [19] proposed an eye-in-hand visual servo system for a robotic manipulator to grasp unknown objects. A fast iterative object surface reconstruction algorithm together with a local grasp planner were proposed to complete the grasping task effectively. Advances in mechanical design as well as sensor-based control make state-of-the-art manufacturing systems important tools in many research and industrial environments. As with the controller design methodology, Huang and Tsai [20] chose a fuzzy sliding-mode control approach to accomplish assembly tasks. The goal of this random robotic assembly operation was achieved by an appropriate integration of robotic motion control, machine vision, and force sensing techniques. Hao and Sun [21] introduced a state-space approach of uncalibrated model-free visual servoing providing a unified perspective, a standardized platform and much more flexibility for future improvement. Su et al. [22] proposed a nonlinear visual mapping model for an uncalibrated eye-in-hand robotic system with an artificial neural network implementation. Compared with the image Jacobian matrix formulation, this model is more powerful and general. Thus, more flexibilty for making full use of neural networks and taking advantage of prior knowledge from offline training could be provided. In design methodology, this scheme is a good solution for proper tradeoff between offline modeling and online control.

Smartphone assembly is now an important and ongoing research for extensive industrial needs. Research concerning smartphone assembly can be found for camera module assembly [23,24]. The camera module is composed of small components and machine vision is employed to perform alignment for assembly purpose. A special assembly machine is required to attach a camera module to a printed circuit board. However, research concerning automatic back shell assembly cannot be seen in recent literature although it has attracted significant attention from the manufacturing industry. An intuitive approach to perform automatic back shell assembly is to employ an *open-loop look-then-move* control approach with calibrated cameras. However, the positioning accuracy is affected by the calibration error of the cameras and the kinematic parameter error of the manipulator system. If one demands a positioning task to be achieved by a manipulator with accuracy less than its repetitive positioning accuracy but higher than the positioning resolution, one cannot guarantee precision with an open-loop control approach. That is, it is possible for an open-loop control approach to perform tasks with specified precision only when the manipulator has the required repetitive positioning accuracy and the cameras are *properly calibrated*. In the case of properly-calibrated cameras, an offline calibration procedure must have been performed to provide an optimal estimate of the camera parameters. But, to come up with such optimal estimates of calibration parameters for cameras [25,26], offline time-consuming calibration algorithms must be employed. Moreover, any uncertainty during the manufacturing process could result in immediate failure in assembly tasks.

The purpose of the proposed research is to develop an effective and practical control strategy of automatic back shell assembly for smartphones. This study proposes a closed-loop look-and-move approach for proximal assembly that has been integrated with look-then-move distal assembly for efficient and reliable performance. Since look-and-move proximal assembly allows calibration errors and thus only roughly-calibrated hand-eye system is required to accomplish the proximal assembly task with precision. The resultant two-stage, distal assembly followed by proximal assembly, approach can perform back shell assembly tasks efficiently and reliably. Specifically, to perform such an assembly task with equal dexterity and precision, two-camera vision system is mounted on the end-effector of a six-degree-of-freedom manipulator.

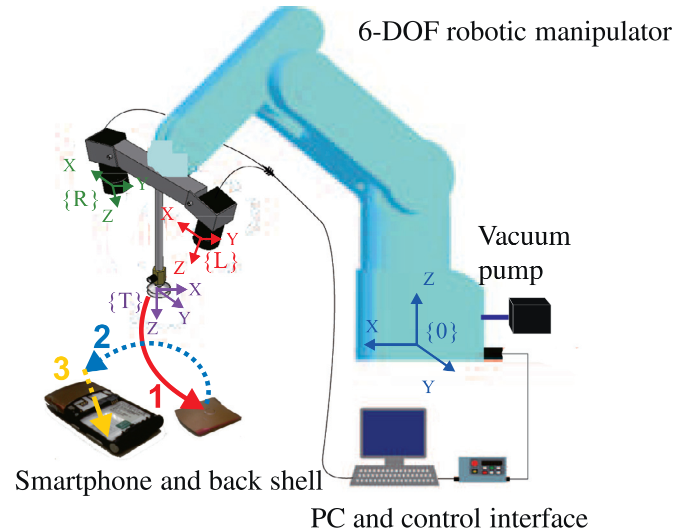

Fig. 1. Configuration of the proposed automatic back shell assembly system.

Thus, the binocular field of view of the two cameras may not cover the work space where the back shell and the smartphone are placed since they can be a distance away from each other. Hence, eye-in-hand binocular vision is used for *distal assembly* including back shell holding and positioning with an open-loop *look-then-move* control approach to speed up the control action. When the back shell is positioned near the smartphone, one does not have a binocular field of view any more. Thus, typical binocular visual servoing cannot be applied. In stead, a seemingly novel way of 3-D reconstruction by two uniocular fields of view of the two cameras is proposed based on which a monocular *look-and-move* visual servo control law is employed using the two monocular cameras for *proximal assembly*. The proposed closed-loop image-based controller has been validated to guarantee task precision even when the hand-eye system is only *roughly calibrated* . By roughly calibrated we mean calibration parameters are approximately or nearly calibrated with some deviation from optimal values. Moreover, the proposed approach provides not only a flexible and precision approach for autonomous assembly but also a robust way to tackle possible variations in manufacturing processes. In this research, a vacuum absorption device is chosen as the robotic tool instead of commonly-used grippers or fingers due to its applicability to hold a variety of phone components.

The proposed system configuration is explained in Section 2. Section 3 introduces 3-D reconstruction with two cameras, hand-eye transformation, and distal vision-assisted assembly in an open-loop fashion. In Section 4, the proposed proximal visual servo control approach employing two monocular cameras is presented. Section 5 demonstrates the experimental results of the proposed visual servo control system when compared with the all open-loop control system. Section 6 reports the concluding remarks.

2. System description

The configuration of the proposed automatic back shell assembly system for smartphones is illustrated in Fig. 1. The system is composed of an industrial six-degree-of-freedom robotic manipulator with two color CCD cameras mounted on the end-effector, a vacuum absorption tool, and a personal computer together with a control interface.

To perform the automatic back shell assembly task, one needs to calibrate each camera, and then establish the coordinate transformation matrix between the tool and the cameras referred to as hand-eye calibration. Observed images of the two cameras are processed to detect corner features. Based on the extracted features, 3-D position and orientation of the back shell and the smartphone can be reconstructed. Hence,

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