Digital Fabrication of a 3D Object using Fixtureless Assembly

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Abstract. Digital fabrication is the kind of the manufacturing process expected to be the next industrial revolution due to its capability converting a digital model into a physical object with fully-automated operation of manufacturing. Although the assembly operation of mass-produced components gives relatively higher cost effective, it is still unprepared for the digital fabrication in practise, unlike the subtractive or additive operation. This research proposes the minimal-required robotic system and process enabling the digital fabrication using the assembly operation done at fixtureless location. The robotic system comprises a SCARA robot, a vacuum gripper, a ram extruder, a USB camera, and MATLAB® on a personal computer. The calibrations giving the required kinematic correlations, and the pose estimation capacitating the fixtureless location operation, are also described in this paper. The necessary process are product designing, product cell-decomposition, and product assembly. In result, the fully-automated assembly of a 3D object is successfully done at fixtureless location in about three minutes and half which is short compared with using the subtractive or additive operation. This research gives promise of applying the digital fabrication using the assembly operation at fixtureless location for practical applications, such as building and repairing of furniture, constructive structure, and etc.

1. Introduction

Digital fabrication is a term describing the manufacturing process building a physical 3D object from the corresponding 3D digital model using various kinds of fully-automated manufacturing operation [1]. According to various aspects of its benefit, e.g., customization, automation, transportation, storage, and etc., the digital fabrication is expected to be the next industrial revolution [1,2]. Among many kinds of the fully-automated manufacturing operation, the assembly operation gives relatively high cost-effective, if the assembling components are massively produced. With low time consumption, the assembly operation also provides high productivity which is a great advantage, especially for the fabrication of a large product [3,4]. However, the assembly operation is still unprepared in practise for the digital fabrication [5,6], while the digital fabrication using the subtractive or additive operation are widely used [7]. Consequently, the digital fabrication of large product which is suitable for the assembly operation due to long-time consumption, is done using the operation of the subtractive and additive in some researches [8].

This research aims to propose the minimal-required robotic system and process for the digital fabrication using the assembly operation. Since the existing assembly system involves the guidance system [9], the machine vision enabling the assembly operation done at fixtureless location is also included in this research. In this paper, the proposed robotic system is described in Section 2, the necessary calibration of the kinematic correlations is explained in Section 3, the routine of the pose estimation done by the machine vision system is presented in Section 4, the proposed process of
digital fabrication is described in Section 5, the assembly operation done by the proposed is demonstrated in Section 6, and the conclusion is in Section 7.

2. Robotic system
The robotic system consists of a manipulator, a gripper, a system of joining component, a machine vision system, and a control system of assembly operation. First, the manipulator is a SCARA robot, Yamaha YK350XC connecting to its controller, Yamaha RCX142. Next, the gripper is a single cup vacuum gripper [10], while the pressure at the cup is controlled by two solenoid-valves whose the logic is switched by the digital signal from the robot controller. In this case, the type of joining is adhesive bounding [11]. The system of joining component consequently comprises a ram extruder [12], and its control unit. including an Arduino MEGA board, a Ramp 1.4 3D printing shield, and a Polulu A4988 driver. The extruder is actuated by a NEMA 11 stepper motor through a lightweight ball-screw drive. For the machine vision system used to estimate the pose of assembling base and components, the sensing device is a USB camera [13], and the sensed result is inspected by image processing and analysis programs on MATLAB® running on a personal computer. To control the assembly operation, an operation-control program developed and run on MATLAB® is used. Thus, MATLAB® transfers the operation information with the robot controller, the extruder controller, and the USB camera via serial communication [14]. The layout of the entire robotic system is demonstrated in Figure 1, while the gripper, the extruder, and the USB camera are all equipped to the robot tip as the assembling head shown in Figure 2.

Figure 1. Robotic system
Figure 2. Assembling head

3. Kinematic calibration
The kinematic correlations between the robot tip and all the devices of the assembling head, are constant and necessary, but unknown. The frames for kinematic analysis are attached of the robot base ([B]), the robot tip ([T]), the gripper ([G]), the extruder ([E]), the camera ([C]), and the pose-estimating objects ([O]) which are the assembling base and components. The frames of the robot and the assembling head are shown in Figure 3(a) and Figure 3(b) respectively. First, the camera calibration is done to determine the lens-distortion coefficients and the intrinsic parameters of the camera. The lens-distortion calibration of Heikkila and Silven [15], and the intrinsic parameters calibration of Zhang Z. [16] are used in order. Next, the correlation between the robot tip frame ([T]) and the camera frame ([C]) is calibrated following the approach of Zhang H. [17]. Then, the pure-translation correlation of the robot tip frame ([T]) and the gripper frame ([G]) locating at the center of gripping, is calibrated by gripping and releasing a sample object of same shape and size with the gripper, in the robot workspace, then estimating the object pose with respect to the robot tip frame ([T]) as the representative. Lastly, the pure-translation correlation of the robot tip frame ([T]) and the extruder
frame (\{E\}) locating at the tip of the extruder, is determined by extruding the adhesive in the robot workspace, then estimating the pose of the extruded adhesive with respect to the robot tip frame (\{T\}) to represent the extruder pose.

4. Pose estimation
The machine vision system provides the pose estimation of the assembling base and components, so the assembly operation can be done at a fixtureless location. There are five steps done for this purpose. The input and result of the pose estimation are shown in Figure 4. First, image acquisition captures an image of the workspace by the USB camera, and acquired the image into MATLAB®. Next, image undistortion correct the imperfection caused by the camera lens-distortion of the image using the coefficients obtained from the camera calibration. Then, image segmentation distinguishes the assembling base and components from the background in the undistorted image using the color thresholding [18]. So, the binary image representing the assembling base and components with white regions, and the background with the black region, is given. After that, features extraction is done on the binary image to obtain the position with respect to the image coordinate, of the concerned features. In this case, blob analysis [19] and the corners detection approach of Shi and Tomasi [20] are used, so the area, the centroid position, and the corners positions, of each white region are determined. Finally, the pose estimation project the extracted positions into the real world using the inverse calibration projection [21]. With known extrinsic parameters of the projection frame, these positions can be mapped into the robot tip frame (\{T\}) and the robot base frame (\{B\}) respectively. Consequently, the position and orientation of the assembling base and components are obtained.
5. Process
The process of the digital fabrication starts with product designing in which a 3D digital model of a product is built using CAD. Unlike the subtractive and additive which are the processing operation [11], the assembly operation joins discrete items together as the assembling components. Therefore, the cell decomposition [22] have to be applied to the designed model before the operation-control program is generated. In the decomposed model, the pose of each cell represents the pose of the corresponding assembling component. These poses are used to inform the poses of the assembling components relative to the assembling base in the operation-control program, while the pose of the assembling base and components are specified as the variables obtained by the pose estimation during the assembly operation. After the operation-control program is generated, the program is run on MATLAB® until the program end, meanwhile the assembly operation is fully-automated performed.

![Figure 5. Digital fabrication process](image)

6. Assembly demonstration
The curved-bridge model demonstrated in Figure 5, is fabricated using the proposed system and process. So, the performance of the proposed is observed. The physical model is successfully fabricated, while the fully-automated assembly operation is smoothly completed in about three minutes and half. Since the assembling base and components are placed at unknown location in the workspace, the assembly operation is exactly done at the fixtureless location. Furthermore, all four degrees of freedom of the robot are used to manipulate the assembling components. Together with the machine vision system, the robot can move the gripper and the extruder to their operating locations correctly. Lastly, the gripper grips and releases the assembling components firmly, while the extruder deposit the adhesive with the amount slightly deviated from the desirable.

7. Conclusion
The digital fabrication using the assembly operation at fixtureless location, can be practically done with the proposed robotic system and process. Lacking any part of the system or process, cause the failure. In the aspect of the product quality, the critical issues are the quality of the assembled joints, and the pose estimation noised by the surrounding light. Compared to the digital fabrication using the operation of the subtractive or additive, the presented digital fabrication gives lower time consumption. For the calibration approaches, all of them provides the accurate correlations of satisfying. Finally, this research gives the promise of applying the digital fabrication using the assembly operation at fixtureless location for the practical applications of building or repairing large product which cannot be moved easily, such as furniture, constructive structure, and etc.

8. References
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