TRAJECTORY MEASUREMENT OF MOVING OBJECTS FOR ROBOTIC ASSEMBLY

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Abstract: Automated robotic assembly on moving objects, called as assembly in motion, demands that the assembly robot is synchronised in all degrees of freedom to the moving workpiece, on which assembly parts are installed. Currently this requirement cannot be met due to the lack of robust measurement of the 3D position and the trajectory of the moving workpiece. In this paper, an assembly robot-guided monocular camera system approaching this problem of the trajectory measurement is introduced. The experimental results show the proposed method is able to measure arbitrary trajectories of the assembly point on the workpiece moving in 3D space. The limitation of the developed method of the trajectory measurement for robotic assembly in motion is also analysed.

Keywords: Optical measurement, machine vision, robotic assembly

1. INTRODUCTION

To achieve flexible robotic assembly in an unstructured and dynamic manufacturing environment, new robotic technologies are required to enable the installation of parts on a moving workpiece [1-2]. This technology, called as assembly in motion or synchronised assembly, combines the high and reproducible level of quality of the automated assembly and the flexibility of manual assembly lines and enables furthermore a flexible switching of work contents between consecutive assembling stations, which improves the degree of automation in assembly [1-2].

In the real production, the robotic assembly is executed according to an optimised robot program. Usually the robot assembly path is primarily programmed on the basis of the taught points and movements [1, 3]. The assembly on moving objects is different with respect to usual robot programs since a normal teach-in procedure is not possible. The automated assembly in motion is limited by the need for the synchronization of the assembly robot and the moving workpiece. For this purpose, sensors have to be used to continuously sense the dynamic assembly environment and moreover to determine the location and motion of the workpiece [1, 4].

In this paper, a measurement system, which is based on a monocular camera guided by the assembly robot, is presented that determines the 6 DoF (degrees of freedom) poses and the trajectory of the workpiece and enables the assembly of parts on the moving workpiece.

This paper is organised as follows. The related research work is introduced in Section 2. The problem of the trajectory measurement is introduced in Section 3, followed by the two main parts of this problem: the sensor fusion-based estimation of the absolute camera pose and the measurement of the motion trajectory of the workpiece (Section 4). The performance is demonstrated by experiments with the assembly of a cylinder block (Section 5). Thereby, Section 6 includes the analysis of the limitation of the trajectory measurement. Finally, Section 7 describes the conclusion and the future work.

2. RELATED WORK

Currently there are rare robotic assembly applications in the final assembly of a vehicle on a moving line [1, 4]. For example, wheel assembly is performed predominantly manually, while the car body is continuously moved by a conveyor. Considering this background, the most research works relating to assembly in motion focus on the problem of assembly on workpieces fed by conveyors. Recently new research works to automatically assembly automobile tires, wheels and windscreens on conveyed vehicle bodies have been undertaken in Europe [1-2], US [4] and Japan [5]. However, all applied synchronization of the assembly robot with the workpiece - e.g. using the conveyor tracking [1] - is enabled only in flow direction of the conveyor systems. In real production, workpieces may move randomly and the movements in 3D space are not considered.

For continuously sensing the 6 DoF poses of workpieces, different sensors can be applied. Besides the high investment, the disadvantage of the laser tracker systems and the indoor Global Positioning System (indoor-GPS) is that a pre-installation of signal receivers on the workpieces is required. For a stereo camera, during measurements in the near area of the camera system it is likely that the workpiece does not appear in both camera images at the same time. Furthermore, the space requirement of the stereo camera at the robot flange is high.

Compared to a stereo camera, a single camera system requires less space. With an appropriate arrangement (e.g. the camera is positioned in the middle of the gripper system of the assembly robot), the occlusion during measurements in the near area of the camera could be prevented. The camera system moved by the assembly robot could view the workpiece from different perspectives. For these reasons, this paper investigates the feasibility and the accuracy of the recovery of a moving workpiece trajectory in all 6 DoF by using a monocular camera system mounted on the robot.

3. PROBLEM FORMULATION

In this section the problem of the trajectory measurement is analysed and the central issues of this problem are defined. To simplify the explanation, a single moving point instead of the whole object will be observed.

This unknown 3D point $[X \quad Y \quad Z]$ is related to its detectable pixel position $[x \quad y]$ in a 2D image by the projection matrix. Each mapping of the 3D point on a 2D image generates two equations [6]

$$x = \frac{p^{11}X + p^{12}Y + p^{13}Z + p^{14}}{p^{31}X + p^{32}Y + p^{33}Z + p^{34}} \qquad (1)$$

$$y = \frac{p^{21}X + p^{22}Y + p^{23}Z + p^{24}}{p^{31}X + p^{32}Y + p^{33}Z + p^{34}} \qquad (2)$$

where elements of the projection matrix p^{ij} are determined by the camera calibration (intrinsic camera parameters) and the camera pose (extrinsic camera parameters).

To measure the position and furthermore the trajectory of the point, namely the unknowns X, Y and Z for one and each time instant, the knowledge of projection matrix - besides the known pixel position - is required. Assuming that the robot-guided camera is already calibrated, the first central issue of the trajectory measurement is that the absolute camera pose, namely its position and orientation with respect to the world coordinate system, should be estimated. In our work, the absolute camera pose is achieved by fusion of measurements from inertial sensors (accelerometers and gyroscopes) and robot control data (3D position and 3D orientation) [7].

To measure a static point, since there are three unknowns (X, Y and Z), at least two views, which generate four equations, are required, so that the triangulation is enabled. If the object is moving, there are always three unknowns in respect of two equations for each time instant and this system is under-determined. Thus the task of the trajectory measurement of the moving point is not feasible, unless further constraints on its trajectory are imposed [8]. Considering that the 3D trajectories of real object motions are various and arbitrary, the second central issue of the trajectory measurement is how to measure objects moving along general trajectories (Section 4).

4. TRAJECTORY MEASUREMENT

In real production, a workpiece is physically moved by feeding machines. This limitation implies that the temporal trajectory of the workpiece is continuous and smooth in nature. As shown in Fig. 1, the smooth signals can be approximated compactly as a linear combination of trajectory bases, such as Discrete Cosine Transform (DCT) bases [9], which are defined as a set of k one dimensional sequences of length F

$$\theta_{F \times 1}^u = \cos\left(\frac{\pi(2x+1)(u-1)}{2F}\right) \quad for \quad x = 0, \ \cdots, \ F-1 \qquad (3)$$

for $u = 1, \ 2, \ \cdots, \ k$.

Mathematically the linear combination is formulated as $T_{3F \times 1} = \theta_{3F \times 3k}\beta_{3k \times 1}$, where $T_{3F \times 1}$ is the trajectory of the 3D point and $\beta_{3k \times 1}$ are the coefficients of the basis vectors. The principal benefit of using the trajectory space representation is that trajectory bases can be predefined and this results in a significant reduction in number of unknowns to be estimated.

Equations (1) and (2) can be rewritten in a matrix form

$$\underbrace{\begin{bmatrix} p^{11} - xp^{31} & p^{12} - xp^{32} & p^{13} - xp^{33} \\ p^{21} - yp^{31} & p^{22} - yp^{32} & p^{23} - yp^{33} \end{bmatrix}}_{Q_{2 \times 3}^i} \underbrace{\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}}_{T_{3 \times 1}^i} = \underbrace{\begin{bmatrix} xp^{34} - p^{14} \\ yp^{34} - p^{24} \end{bmatrix}}_{q_{2 \times 1}^i} \qquad (4)$$

where $T_{3 \times 1}^i$ are coordinates of the 3D point at time instant i.

The complete time varying point trajectory $T_{3F \times 1}$ is represented by concatenating the 3D locations of the point at each time instant. Considering all time instants, we have

$$\underbrace{\begin{bmatrix} Q_{2 \times 3}^1 & & \\ & \ddots & \\ & & Q_{2 \times 3}^F \end{bmatrix}}_{Q_{2F \times 3F}} \underbrace{\begin{bmatrix} T_{3 \times 1}^1 \\ \vdots \\ T_{3 \times 1}^F \end{bmatrix}}_{T_{3F \times 1}} = \underbrace{\begin{bmatrix} q_{2 \times 1}^1 \\ \vdots \\ q_{2 \times 1}^F \end{bmatrix}}_{q_{2F \times 1}} \qquad (5)$$

Since the trajectory is a linear combination of trajectory bases ($T_{3F \times 1} = \theta_{3F \times 3k}\beta_{3k \times 1}$), a linear equation system for the point trajectory is derived

$$Q_{2F \times 3F}\theta_{3F \times 3k}\beta_{3k \times 1} = q_{2F \times 1} \qquad (6)$$

which is an over-constrained system for $\beta_{3k \times 1}$ - which should be estimated - by setting k so that $2F \geq 3k$. Based on the known camera poses and pixel positions embedded in $Q_{2F \times 3F}$, $q_{2F \times 1}$ and the predefined trajectory bases $\theta_{3F \times 3k}$, the coefficients of the trajectory $\beta_{3k \times 1}$ can be estimated using a recursive linear least squares method. Using these determined coefficients, the point trajectory $T_{3F \times 1}$ is measured. In order to estimate the object orientation, multiple reference points are selected, which determine the object coordinate system. Position measurements of these reference points with the developed method enable to estimate the 6 DoF object pose.

5. EXPERIMENTAL RESULT

A number of experiments, in which the robotic assembly of cylinder block in motion is tested, are conducted at an indoor-GPS based robot cell. The smart camera NI 1742 of National Instruments and the MTi IMU of Xsens are moved by a 6 DoF Kuka KR16 industrial robot (Fig. 2, left). The camera pose is determined up to 250 Hz by fusing measurements from inertial sensors and robot control data. The KR16 is also used as assembly robot which guides and assembles the cylinder into the cylinder block. In this way, the measurement und assembly tasks are combined.

A cylinder block is driven by another cooperating robot Kuka KR60 (Fig. 2, right). The advantage of this configuration is that it provides real motion trajectories for the camera, cylinder and the cylinder block which allows for an objective performance evaluation.

A set of 150 images of the cylinder block, which is moved along an arbitrary curve by KR60, is taken discontinuously with the smart camera driven by KR16. The measured trajectory of the assembly point is shown in Fig. 3. Comparisons of the trajectory measured with the DCT bases and the real trajectory of the assembly point confirm that the reconstructed positions are close to the real trajectory of the assembly point.
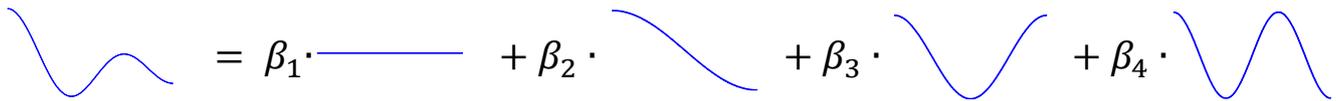
Fig. 1. Each smooth arbitrary trajectory can be approximated as a linear combination of predefined trajectory bases (Here the first four DCT bases in order of increasing frequency are used and $\beta_1 = 1$, $\beta_2 = 2$, $\beta_3 = 3$, $\beta_4 = 4$) [9].

Fig. 2. Test scene of robotic assembly of cylinder block in motion (1: robot KR16, 2: indoor-GPS, 3: IMU and camera, 4: cylinder, 5: cylinder block, 6: robot KR60)

Fig. 3. Measured trajectory (red +) and the real motion trajectory (blue curve) of the assembly point on the cylinder block

Fig. 4 shows the difference between the real and measured positions of the assembly point on the cylinder block for each axis and the Euclidean difference of the point position. The average of the Euclidean position difference is less than 6 mm.

For the other trajectories, which are not shown here, the similar performance is achieved. These experimental results show that the proposed method enables the positioning of the workpieces moving in 3D space.

6. LIMITATION OF 3D TRAJECTORY MEASUREMENT

As introduced in Section 5, for the assembly tasks both of the camera and the part to be assembled, e.g. the cylinder, are mounted on the assembly robot. With this construction the trajectory measurement and the assembly operation are performed jointly and along the same robot trajectory. It means the camera trajectory and the trajectory of the part to be assembled are correlated. Since the trajectory of the part to be assembled decides whether the assembly process is to succeed, it must be explained - for given trajectory bases - how the camera trajectory, namely the (correlated) trajectory of the part to be assembled, influences the result of the measured trajectory of the assembly point.

Since the perspective camera model enforces the measured position to lie on the ray connecting the camera centre and the real 3D point in space, the estimated point trajectory $\hat{T}$ can be formed as [6]

$$\hat{T} = AT + (I - A)C \qquad (7)$$

where T and C is the real trajectory of the assembly point on the cylinder block and camera trajectory respectively, I is an identity matrix and A is a diagonal matrix whose entries are arbitrary scalars.
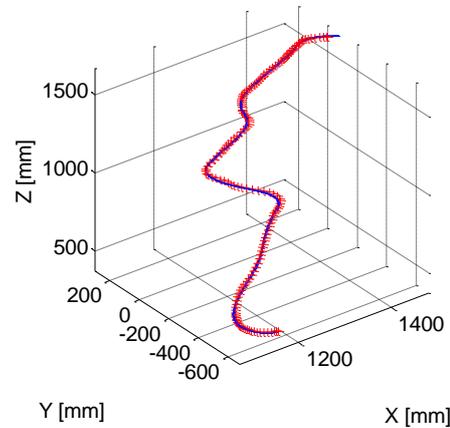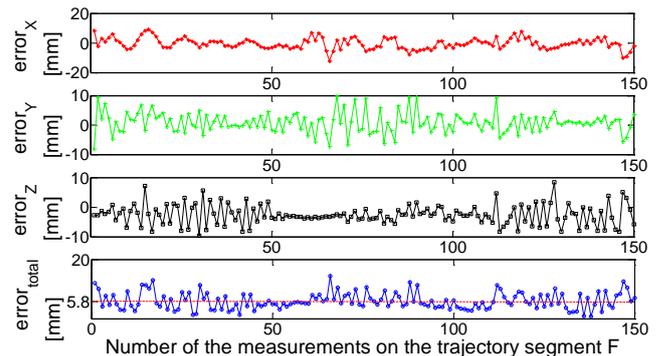

Fig. 4. The position difference between the measured and the real trajectory of the assembly point on the moving cylinder block (from top to bottom: difference for x-, y-, z-axis and the Euclidean position difference)

It can be seen from (7) that the measurement is limited due to the correlation between the trajectory of the assembly point and the camera trajectory. For example, when a camera trajectory is identical to the trajectory of the assembly point, it is not possible to measure the trajectory of the assembly point because the sequence of 2D projections is stationary. Based on this fact, a mathematical measure η, called as reconstructibility, is defined to characterise the cases when the measurement is possible and how accurate it can be [10].

For given trajectory bases, different camera trajectories which consist of 20, 50, 100 and 150 measurements respectively, are used to measure the trajectory of the assembly point on the cylinder block. In Fig. 5 (left), it is shown that as the local correlation between the camera trajectory and the trajectory of the assembly point becomes lower (inversely proportional to the correlation, the

reconstructibility η increases), the measured point positions are coming more closely to the real trajectory of assembly point on the cylinder block (Fig. 5, right).
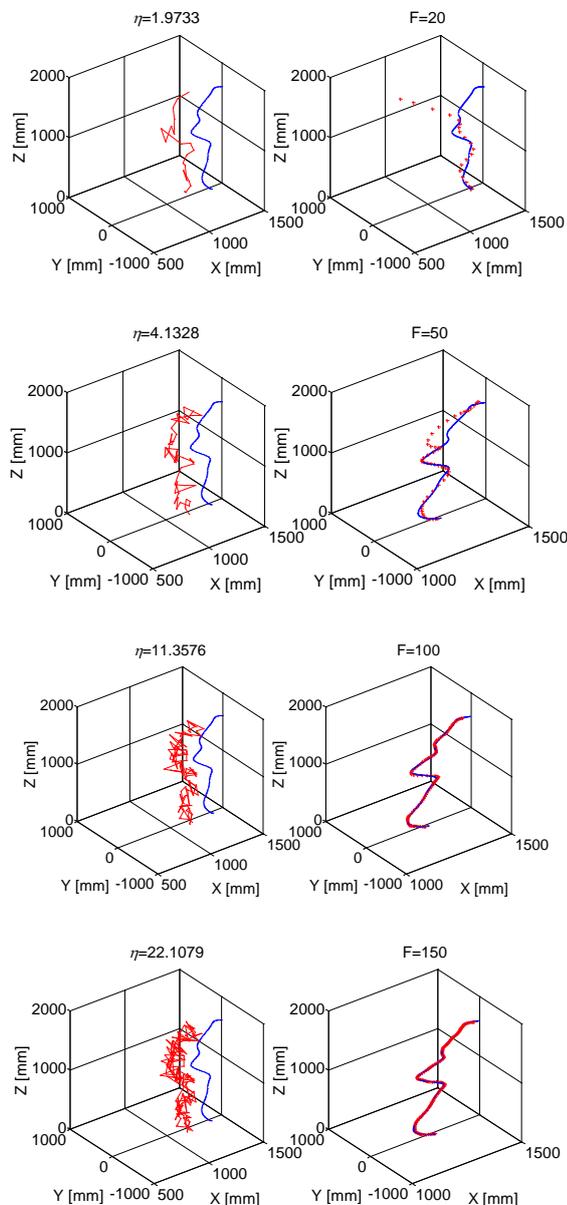

Fig. 5. The accuracy of 3D trajectory measurement is generally limited by the correlation between the trajectory of the camera and the trajectory of the assembly point (left: camera trajectory (red curve), real trajectory of the assembly point (blue curve); right: measured point position (red +), real trajectory of the assembly point (blue curve)).

This result states that it is possible to measure the trajectory of the assembly point, if the camera moves randomly and discontinuously. This condition restricts the application of the proposed method of the trajectory measurement with assembly robot-guided monocular camera for such tasks in which the part to be assembled could not be moved arbitrarily.

7. CONCLUSION AND FUTURE WORK

The proposed assembly robot–guided camera system realises robust trajectory estimation by measuring arbitrary trajectories of the assembly point on the moving workpiece. This system is used to synchronise the assembly robot with the moving workpiece in all 6 DoF. This approach enables the robotic assembly in motion, which is one of the key factors for flexible automation in assembly processes.

The accuracy of the trajectory measurement of a workpiece is limited by the correlation between the camera trajectory and the trajectory of the assembly point on the moving workpiece. The automated assembly in motion based on a sensor fusion concept, e.g. using a compliant force-torque sensor for precise guidance of the assembly robot within contacting phase of both assembly parts, is currently under development.

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