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An Add-On Pose Measurement Device for Rapid Robot Teaching

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Recent advancement of collaborative robotics has broadened the applications of robots in manufacturing and service sectors. Apart from the fact that collaborative robots allow the operator to share their workspace without fences, the ease of robot teaching using walk-through method is a big draw. However, the walk-through method has several weaknesses. The major one is that the power-assistive motion control limits the speed of the robot during teaching. As a result, such teaching method is too slow for the robots to be used in high-mix and low-volume production. This paper presents a novel robot path teaching method that can acquire the robot tool paths quickly. Using a device called Robot Teach Handle (RTH) attached at the robot wrist, operator holds the device and moves its end-effector along a desired path without moving the robot itself. The device is a serial linkage system with 7 passive rotary joints that connect a probe and a base with lightweight links. The base can be rigidly attached to the link of a typical industrial robot. The pose of the probe is obtained from the joint angles of the RTH using forward kinematics. It is then transformed to the robot base coordinate system providing the desired robot end-effector pose for precision process automation. The major advantage of the robot teaching method is that the robot path teaching time is much shorter than the comparable method of walk-through teaching. In realizing new teaching method, we have developed several key capabilities. They include the error compensation for 7- joints serial-linked mechanism, calibration algorithm for localization of the RTH mounted on the host robot and high-precision serial mechanism in particular the rotary joints. In this paper we will present the methods for achieving high accuracy pose measurements of the RTH probe, in terms of the applications of precision machine design principles and the methods for reducing the systematic errors in the joints and overall linkage system.

1. Introduction

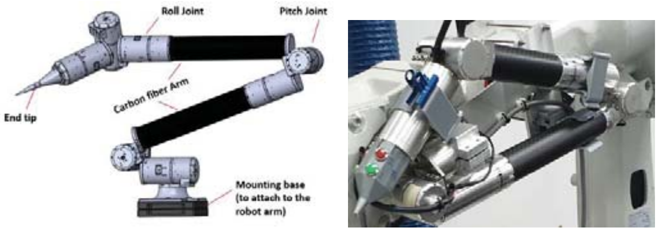
Industrial robots are widely used in factories manufacturing high-volume products. Automotive assembly line for examples mainly involves robots for handling, welding, dispensing and painting. Such processes are also common in companies dealing with small batch sizes and low volume products. However, mainly human rather than robot is to carry out the processes in those companies. A key reason is that today industrial robots lack effective intuitive teaching methods [1]. Intuitive robot teaching methods includes walk-through teaching [2] and teach pen method [3]. In the walk-through teaching method, operator holds the robot end-effector to capture the desired pose and path. A drawback of the walk-through is slow movement of the robot during the teaching process to comply to the safety standards. Another shortcoming is that such method only available for collaborative robots or robots specially instrumented. As for the teach pen method, operator trace the desired pose and path while a stationary sensor captures the pose of the tech pen. If the teach pen is moved out of sight of the sensor, the method fails. To address the shortcomings of both methods, we have developed a new method for acquiring the robot end-effector tool path easily and quickly without the drawbacks of the intuitive robot teaching methods describes above. Section 2 below describes the design of the teaching device called Robot Teach Handle (RTH) and Section 3 discusses the calibration and localization for realizing the unique functions of the RTH.

2. Design of the Robot Teaching Device

The new robot teaching method allows operator to programme the robot inside the robot workspace without moving the robot. The main device is called RTH. It consists of a pointer which is serially connected by rigid links and up to 7 revolute joints embedded with encoders for providing the position and orientation of the pointer. Several buttons are located at the pointer for data capturing. To achieve the process precision, the accuracy of the RTH needs to be better than +/- 1 mm and +/- 1 degree in the 6-DoF within the RTH workspace. The accuracy of the RTH is achieved by applying the precision machine design principles in the RTH joints as well as calibrations for reducing the systematic errors of the RTH arm.

2.1 RTH Arm

The RTH arm (Fig 1(a)) comprises of a shoulder assembly (two pitch joints), elbow assembly (1 roll joint, and 1 pitch joint) and a wrist assembly (2 roll joint and 1 pitch joint). The links that joins the two assemblies are made of carbon fibre composite. The material provides the necessary rigidly with low mass. The design considerations for the RTH arm are as follows: 1) Low-cost components without sacrificing specification requirements; 2) Achieve high stiffness in joints; 3) Lightweight of entire arm; 4) Design for manufacturing and assembly; 5) High dexterity kinematical spherical joint at both base and wrist of the arm.



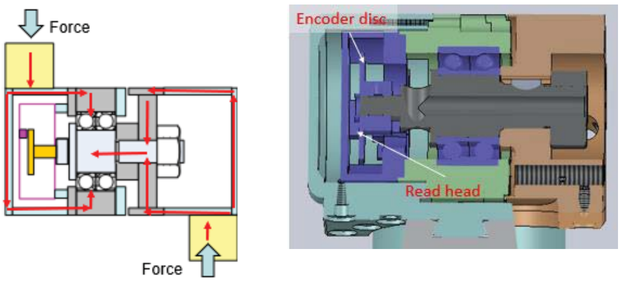
(a) Two types of revolute joints in the arm: Roll joints (3 units) and Pitch joints (4 units).

(b) RTH in the folded position on robot arm after programming

Figure 1 – RTH (a) mounted on the link 4 of an ABB robot, (b) RTH Arm

2.2 RTH Joints

The joints in the RTH provides high dexterity and the values of the joint angle for determining the pose of the RTH tip. The joints also contribute the most to the RTH tip pose errors since the joint has the most sources errors from the bearings, encoder and supporting structures (See Fig 2). To achieve the high-stiffness in the joint, a close-loop structural concept is applied. As shown in Fig 2 (a), the force loop marked in red is passing thought a parallel configuration. the schematic drawing of the internal joint configuration.



(a) Force loops pass through parallel configuration

(b) 3D model of the internal of the joints

Figure 2 (a) Schematic drawings of the internal configuration, (b) 3D model of the internal configurable of the joint

2.3 RTH Arm Localization and Calibration

2.3.1 Localisation of RTH

The RTH can be mounted on any point on the robot arm for high adaptability and ease of handling. In general, the RTH is mounted at the wrist of the robot where it would allow high accuracy for the robot teaching point and also most convenience for operation. When the RTH is first used on a particular robot or when there is a need to change the mounting position of the RTH, the localization procedure has to be performed. The objective of the localization is to obtain the RTH pose (position and orientation) in the robot coordinate frame.

Localisation of the RTH frame with respect to the robot frame can be expressed as ${}^{R}T_{H}$, where T is the 4x4 homogenous transformation matrix, R is the robot frame and H is the RTH frame. Let's say H is fixed. Using RTH, the pose ${}^{H}T_{p}$ of waypoint p^{th} can be obtained in the RTH frame. Then, representation of waypoint p^{th} in the robot frame ${}^{R}T_{p}$ can be obtained as follows

$$ {}^{R}T_{p} = {}^{R}T_{H}\,{}^{H}T_{p} $$

Assuming the RTH is mounted at the wrist joint (on the link that joins 4th and 5th joints), transformation matrix from RTH to robot frames can be obtained as

$$ {}^{R}T_{H} = {}^{R}T_{TCP}\left({}^{H}T_{TCP}\right)^{-1} $$

where ${}^{R}T_{TCP}$, is the tip pose can be obtained from robot controller; ${}^{H}T_{TCP}$ is the transformation matrix from robot tool centre point TCP to RTH frame which can be obtained accurately using the below calibration technique.

Obviously, the following statement holds

$$ {}^{H}T_{TCP} = {}^{H}T_{5}\;T_{J5}\,{}^{5}T_{6}\,T_{J6}\,{}^{6}T_{TCP} $$

where, ${}^{H}T_{5}$, ${}^{5}T_{6}$, and ${}^{6}T_{TCP}$ are constant transformation matrix (to be calibrated) from RTH to 5th joint, from 5th joint to 6th joint, and from 6th joint to TCP, respectively; T_{J5} and T_{J6} are transformation matrix corresponding to the rotational joints 5th and 6th, respectively. It is assumed that robot joints are with negligible errors.

2.3.2 Calibration Model

To accurately determine ${}^{H}T_{5}$, ${}^{5}T_{6}$ and ${}^{6}T_{TCP}$, we introduce 2 stages calibration method for RTH. First, we introduce joint compensation modules to deal with misalignment issue between encoder disk and the joint axis. An illustration of this misalignment is shown in Fig 3.

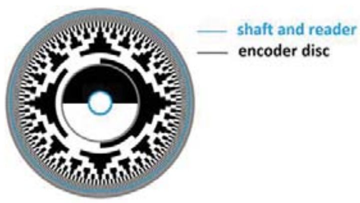


Figure 3 Misalignment Error between Shaft/reader and encoder disc

Due to assembly errors, misalignment is non-negligible. Consequently, the joint angle value is not in a linear correlation with pulses counted. To identify the non-linear correlation, we use a CMM arm to measure absolute angle while performing rotation of each joint. Then we build a non-linear compensation for each joint (from 1 to 6) based on the measured data. Next, to identify transformation matrix between joints of the RTH a linear calibration model using the POE formula to represent the frames is applied.

$$ y = Jx $$

Here, y is the vector representation of $\log\left[{}^{H}T_{TCP}^{a}\,{}^{H}T_{TCP}^{-1}\right] \in se(3)$. It represents the kinematic error of the TCP in the RTH frame. ${}^{H}T_{TCP}^{a}$ is obtained by taking measurements using the RTH, ${}^{H}T_{TCP}^{-1}$ is the inverse matrix of calculated transformation matrix. X represents the 3 sets of six dimensional kinematic errors (i.e., ${}^{i}t_{j}$) that arise from the 3 fixed forward kinematic transformations frames ${}^{H}T_{5}$, ${}^{5}T_{6}$ and ${}^{6}T_{TCP}$. For each ${}^{i}t_{j}$, the first three parameters represent the position errors (δ_x , δ_y , δ_z), while the remaining three terms represent the orientation errors ($\delta_{\theta x}$, $\delta_{\theta y}$, $\delta_{\theta z}$). J is the calibration Jacobian matrix that reflects the 18 kinematics error parameters, $Ad_{{}^{i}T_{j}}$ is the adjoint representation of ${}^{i}T_{j} \cdot {}^{H}T_{TCP}^{-1}$ and J are determined from the nominal kinematic model. All the terms are calculated using Lie algebra.

To carry out calibration, let the training data set be n,

$$\tilde{y} = \tilde{J}x$$

where,

$\tilde{y} = \left[\tilde{y}_1^T \quad \ldots \quad \tilde{y}_n^T\right]^T \in \Re^{6n\times 1}, \tilde{J} = \left[\tilde{J}_1^T \quad \ldots \quad \tilde{J}_n^T\right]^T \in \Re^{6n\times 18}$.

Consequently, x can be obtained via an iterative least square algorithm and pseudo inverse of the Jacobian.

$$x = \left(\tilde{J}^T \tilde{J}\right)^{-1} \tilde{J}^T \tilde{y}$$

After each iteration, the transformation matrices ${}^{H}T_5$, ${}^{5}T_6$ and ${}^{6}T_{TCP}$ are updated as ${}^{H}T_{5\,(k+1)} = e^{\delta\,{}^{H}T_5}\left({}^{H}T_{5\,(k)}\right)$,

$${}^{5}T_{6\,(k+1)} = e^{\delta\,{}^{5}T_6}\left({}^{5}T_{6\,(k)}\right), \text{ and } {}^{6}T_{TCP\,(k+1)} = e^{\delta\,{}^{6}T_{TCP}}\left({}^{6}T_{TCP\,(k)}\right)$$

where, $\delta\,{}^{H}T_5$, $\delta\,{}^{5}T_6$, and $\delta\,{}^{6}T_{TCP}$ are matrices representations of $\delta\,{}^{H}t_5$, $\delta\,{}^{5}t_6$, and $\delta\,{}^{6}t_{TCP}$, which can be calculated using rotation matrix decomposition.

To evaluation the calibration result, two deviation metrics between measured and calibrated frames are mathematically defined as δp and δR. Using a calculation loop with measured data, the vectors of TCP are obtained, which can be expressed in term of

$${}^{H}T_{TCP}^{a} = \begin{bmatrix} {}^{H}R_{TCP}^{a} & {}^{H}p_o + \left({}^{H}R_{TCP}^{a}\right)^{-1}\left[0 \quad 0 \quad CTWD\right]^T \\ 0 & 1 \end{bmatrix}$$

3. Experimental Results

The accuracy of the RTH system is defined as the play back pose errors of the robot end-effector set by the RTH arm. It is a function of the following errors:

(1) Localisation errors – The localisation errors depend on the transformation matrix ${}^{R}T_{H}$, which relates the RTH and robot frames. Applying the method discussed in Section 2.3.1, and based on the assumption of the robot accuracy of 0.025 mm, the localisation errors is estimated to be in the range of +/- 1 mm.

(2) RTH arm errors – The coordinate measurement error of the RTH arm. It is due to the kinematic and dynamic deviations resulted from the stiffness of the joints and links, and accuracy of the encoders in the joints. Applying the method described in Section 2.3.2. The joint transformation matrices were obtained. Using the FARO CMM arm, the errors of the RTH arm is measured in the range of +/- 2 mm.

By implementing the calibration methods to the RTH, the new robot teaching method is demonstrated (Fig 4). The steps of teaching the end-effector path are as follows: (1) Initiate the RTH on robot controller, (2) Detach the RTH from the robot arm, (3) Record the waypoints of the end-effector path, (4) Put back the RTH onto the robot arm, and (5) start the robotic process such as arc welding.

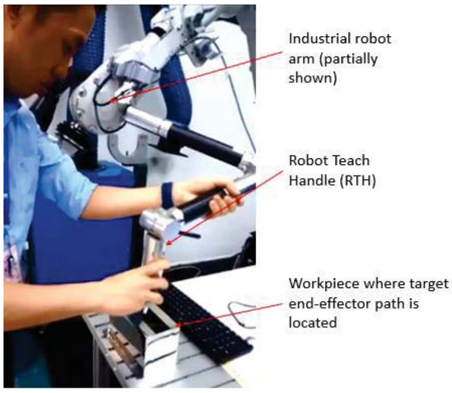


Figure 4 – Robot teaching using RTH

Table 1 shows a comparison of the walk-through and RTH teaching methods for the teaching a typical 3D end-effector path. It shows that RTH method tales much shorter time than the walk-through teaching methods.

	Walk-through Teaching Method	**Robot Teach Handle**
Setup	10 sec.	5 sec.
Moving from point to point	7 sec./mm, 5 sec./mm	4 sec./mm
Align the selected point	68 sec	5 sec.
Total movement time	484 sec. (8.06 mins)	46 sec.
Teaching rate	0.22	0.02

Table 1 Comparison of the two intuitive robot teaching methods

4. Conclusion

This paper presents a novel robot path teaching method that can acquire the robot tool paths quickly. Using a device called Robot Teach Handle (RTH) attached at the robot wrist, operator holds the device and moves its end-effector along a desired path without moving the robot itself. It is demonstrated that the accuracy of the path teaching can be realised with proper design of the pose capturing device and implementation of the calibration algorithms.

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