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# A Calibration of Kinematic Differences between the Robot Model in OLP and Actual SCARA Robot

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## Abstract

In this study, we try to coincide virtual robot system in an OLP(off-line programming) with actual robot system even though kinematic differences between them are made. The virtual robot in the OLP may be modeled according to kinematics of the actual robot system. However, it is a complicated problem to find exactly all kinematic parameters of actual robot and environment. In this paper, an automated calibration method is proposed in order to find some kinematical parameters which are necessary for the modeling of a robot and environment in the OLP. It is applicable to SCARA robot for assembly task. In this method, a well-marked worktable of environment is regarded as reference coordinate frame. The robot detects some marks on the worktable through sensors attached to the end-effector. The necessary parameters are calculated from the data of the robot joint variables when the robot detects the mark. The model in the OLP is modified by the parameters.

## 1. Introduction

The task environment of a robot is changing rapidly and task itself becomes complicated due to current industrial trends of multi-product and small lot size production. Therefore a convenient user-interfaced OLP(off-line programming) system is being developed in order to overcome the difficulty in teaching a robot task[2]. Using the OLP system, operators can easily teach a robot task off-line and safely inspect feasibility of the task through a simulation prior to the on-line execution. And, by combining the OLP system with acutal robot controller, the task program teached in the OLP can be directly applied to the actual robot[3]. By this approach, the robot can adapt itself to the change of task. Fig. 1 depicts the concept of off-line teaching.

The important factor to teach successfully a new task by off-line teaching is how similar the kinematic parameters of the model in OLP are to those of the actual robot system. If the kinematical parameters are different, the task program generated in the OLP can not work successfully at the actual robot system. That is, some task errors are inevitable because of the kinematic differences. To cope with this probem, there have been many researches for calibration, but they have usually used a very expensive 3-D measuring instrument for measuring a posture of robot and almost focused on PUMA-type robot[1].

In this paper, an easy calibration method for SCARA robot is proposed. This method regards a well-marked worktable of environment as reference coordinate frame. The posture of robot relative to the worktable is identified by sensor information which detects the mark of worktable. Thus, the kinematic model in the OLP is calibrated on the basis of this reference frame. In our previous research, the basic of this method was proposed

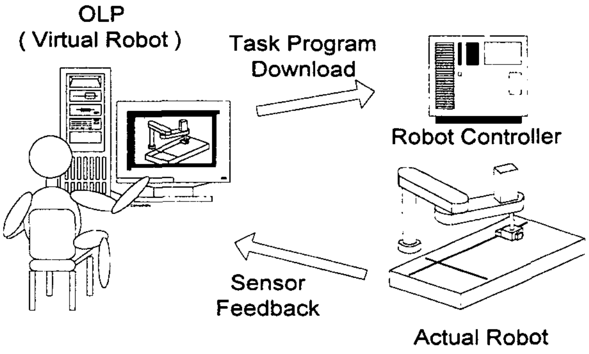


Fig. 1 Off-line teaching by OLP system.

and verified[6]. However, it was not enough to apply directly to actual task and depended on the hand-calculation by an operator. The proposed method in this paper is designed to implement an automated calibration for the case of assembly task. Some kinematical parameters are chosen for the target of the calibration because they are essential to exact modeling of a robot and environment in the OLP. The robot controller is equipped with sensor interface circuits. The sensors are composed of photosensors and a touch sensor. The robot controller is the subject which performs this calibration by a given program. This program performs a sequence of robot motion and sensing. The robot refered in this paper is FARA SCARA SM-5 made by SAMSUNG ELEC. CO.

## 2. Kinematics of SCARA robot

The configuration in Fig. 2 represents usual automatic assembly line which consists of SCARA robot and product conveyor belt. The worktable in Fig. 2 represents the conveyor belt. The SCARA robot has four degrees of freedom (DOF), called $\theta_1, \theta_2, d_3$ and $\theta_4$. The actual position of the end-effector in the base coordinate frame {B} is calculated by forward kinematics using the value of $\theta_1, \theta_2, d_3$ and $\theta_4$ obtained from encoder sensor attached to robot joint. The desired position of the end-effector in task program of OLP is converted to joint coordinates, $\theta_1, \theta_2, d_3$ and $\theta_4$ by inverse kinematics[2]. The end-effector coordinate frame {E} represents the attitude of a tool like gripper which is attached to the end-effector. The work coordinate frame {W} is set on worktable. The worktable is the space where the assembly task is done. The parts and subassembly, which are to be assembled are located on the worktable. The position of them is represented in {W}.

In the automated assembly line, the most of task is a pick and place motion[5]. A gripper picks a part and place it on a subassembly. In this case, the kinematic relation between the gripper and the parts should be exactly known to the OLP so that the task program teached in OLP can accurately work in actual environment.

The primary cause which induces teaching error of task program is the differences in joint variables, $\theta_1, \theta_2, d_3$ and $\theta_4$ between the OLP and the actual robot. These differences are induced from zero-return of the actual robot. The zero-return is the process that a robot returns to its origin(or zero) position for each joint. The robot which used in this paper is equipped with incremental encoders. If joint sensors are incremental encoders, the robot can not acquire its absolute position. Thus, the robot should find its zero position. The position is identified by limit sensor attached to the joint. However, because the position of the limit sensor which detects the zero position does not known exactly, the zero position of actual robot are somewhat different from the nominal zero position in OLP. Fig. 3 shows the zero position of link 1 and link 2. The rotational errors of link 1 and 2 are named as $\theta_{a0}$ and $\theta_{b0}$. $\theta_{a0}$ represents the offset angle of link 1. The nominal zero position of link 1 is defined in the proposed calibration method to be parallel with x-direction of {W}. This definition enables {B} to be set up parallel with {W}. $\theta_{b0}$ is the offset angle which must be calibrated in order to align the link 2 with link 1. And the dimensional errors of link length $L_1$ and $L_2$ should be calibrated also in order to assure precise positioning in XY plane. Though not shown in Fig. 3, the zero position of $d_3$ and $\theta_4$ should be calibrated in order to precisely describe any tool like gripper with which the end-effector is equipped.

The other factor that make a teaching in OLP

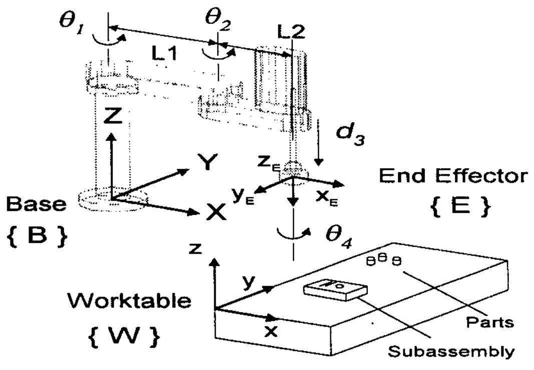


Fig. 2 Coordinates of a assembly line.

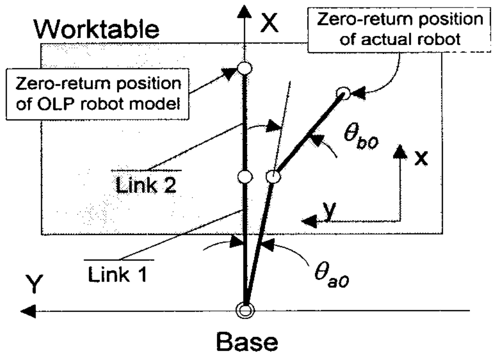


Fig. 3 Kinematic differences of zero position.

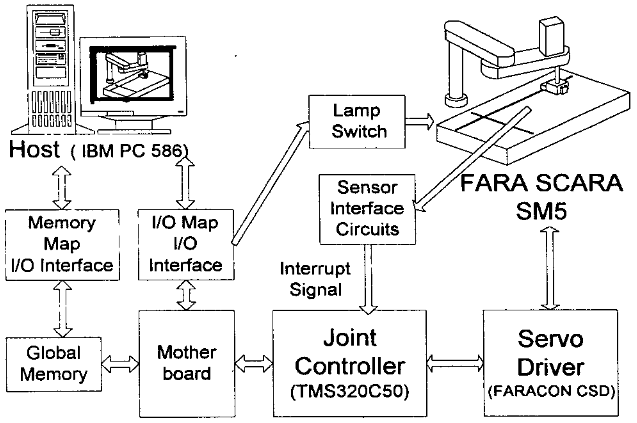


Fig. 4 System configuration.

difficult is that the position of objects like parts and subassembly in environment are not exactly known in OLP. Informing the exact position of parts and subassembly in the OLP is an other complex problem in the assembly line where exists frequent changeover of product. One of the solution for this problem is the use of well-defined worktable. The position of parts and subassembly on the worktable can be obtained easily even if there are changeover of product. Thus the remained problem is to find the transformation matrix between {B} and {W}. If X, Y and Z axis of {B} are parallel with x, y and z axis of {W}, there is only translation.

The kinematic parameters to be calibrated are summarized as the following.

- The zero position of $\theta_1, \theta_2, d_3$ and $\theta_4$
- The position of worktable in {B}
- The length of link 1 and 2

These are chosen for the reason that they mainly affect the precision in operating a robot.

## 3. System configuration

To implement the automated calibration, photo sensors and a touch sensor are attached to a robot system and an worktable which is marked by light is provided as reference frame. Fig. 4 shows the configuration of the whole system.

### 3.1 The robot system

The robot system used in this research is an integrated robot control system which consists of an open architecture robot controller that is using high speed DSP(TMS 320C50) for real-time control and an OLP based on personal computer(PC)[3]. The robot controller is mainly composed of 4 units of joint controllers which control 4 joint motors of robot and 4 units of servo drives respectively. The OLP has functions of task-teaching for virtual robot, dynamic simulator with various control algorithms, three dimensional animation to visualize a virtual operation of a robot, and trajectory planning.

To implement communincation between the OLP and the actual robot controller, interfacing circuits are installed between host computer and joint controllers. This circuits are composed of two kinds of parallel interface method for PC. Interfacing on memory map of PC is used to enable host computer to access to global memory. Through this global memory, host computer can communicate data with joint controller when robot is in operation. Interfacing on I/O map of PC is used in order to enable host computer to directly access to digital input & reset port of DSP in joint controller. The integrated robot control system is designed for the purpose of implementation of a system which can operate directly on-line robot by off-line teaching and inform the OLP about the state of the robot through an parallel interface between the host PC(personal computer) and the robot controller[3]. Fig. 4 shows the configuration of the integrated robot control system.

### 3.2 Worktable for reference frame

Fig. 5 shows the shape of the worktable. The surface of worktable is covered by a plotting paper for the purpose of positioning easily parts and subassembly. It is used as a reference frame. The coordinate frame is marked by reference lines. The lines are narrow slits which are lighted by lamps under the surface plate. By the photosensor, they can be detected. The reference lines are parallel with x or y axis of {W}. The worktable should have at least two lines for each direction to apply the proposed calibration scheme. To simplify calculation, One of lines had better coincide with axes of {w} for x and y direction, respectively. In process of calibration, each reference line is turned on when needed, otherwise is turned off by digital output of host computer.

### 3.3 Sensor configuration

Fig. 6 shows the configuration of sensors attached to the end-effector. A gripper is attached to the end-effector also. Because the sensors and the gripper are close to each other, the positional relation between the sensors and the fingers of the gripper can be easily measured. The photosensor used in experiment is photodiode. The photosensor 1 is located at the center of link 4. The photosensor 2 is located some distance away form the center. The touch sensor is attached to side of

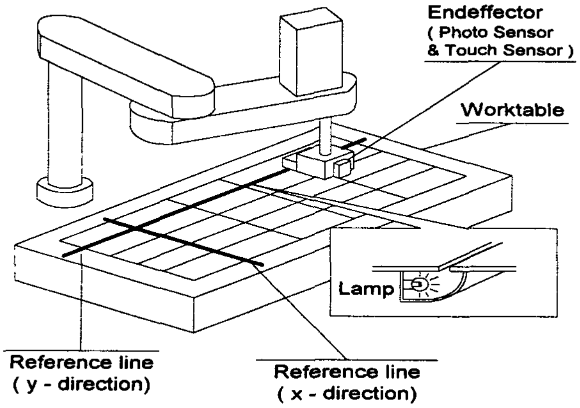


Fig. 5 Configuration of the worktable.

the end-effector and its head projected down so that it can touch the surface of worktable first than any other part of the end-effector. Some sensor interface circuits are designed for robot controller. The signal from sensor is sent to robot controller through interrupt port of DSP so that the processor can read the joint angle at the moment of sensing the mark.

## 4. Calibration scheme

A sequence of the process of calibration which consists of series of robot motion is established to efficiently calibrate the required kinematic parameters. This operation is implemented by robot controller. The sequence is programmed in operating system for robot controller. It is performed after zero return of the robot. It is composed of 7 steps. Each step is explained in detail as follows:

### Step 1:

$d_3$ of link 3 is to be calibrated. The end-effector downs until the touch sensor detects the top plate of the worktable. The OLP acquires the encoder data of link 3 at this moment as the position of the worktable in z-direction. And throughout next steps, the link 3 is fixed to a position where the end-effector is close to the top plate of worktable so that the photosensor can detect light of the reference line.

### Step 2:

$\theta_2$ of the link 2 is to be calibrated. Fig. 7 depicts the calibration process. In this step, the reference line of y-direction is only lighted. The link 1 is fixed to original position while the link 2 rotates only. The link 2 rotates right at slow speed until the photosensor 1 detects the reference line.

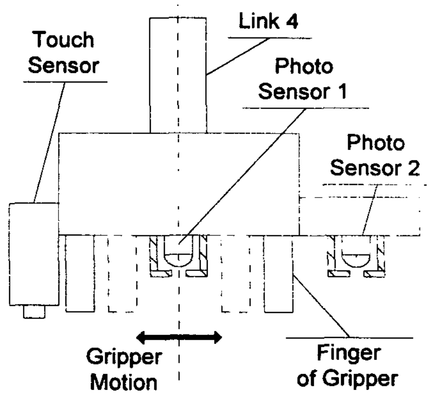


Fig. 6 Sensor configuration in the end-effector.

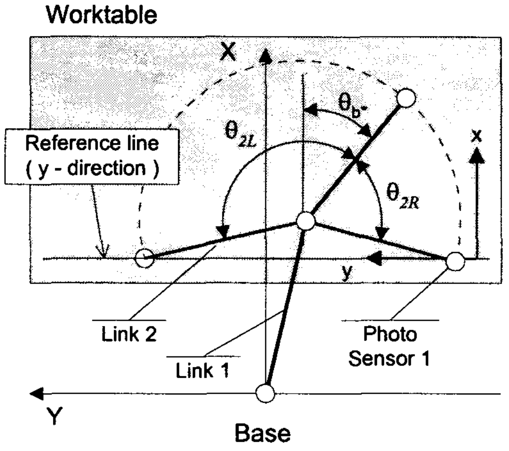


Fig. 7 The calibration of $\theta_2$ of link 2.

The angle $\theta_{2R}$ between the zero position and the reference line can be acquired from encoder data at that moment. Then, the link 2 rotates left until photosensor 1 detects the reference line again. The angle $\theta_{2L}$ can be acquired, too. And then $\theta_b^*$ is calculated by Eq.(1).

$$\theta_{b*} = \frac{|\theta_{2L}| + |\theta_{2R}|}{2} - |\theta_{2R}| \qquad (1)$$

When the link 2 rotates $\theta_b^*$ from zero position, it becomes vertical to reference line geometrically. This means that the link 2 is parallel with x axis of {W}.

### Step 3:

$\theta_1$ of the link 1 is to be calibrated. Fig. 8 depicts the calibration process. The reference line of y-direction is only lighted. The link 2 maintains its orientation vertical to reference line and the link 1 rotates at slow speed. The link 1 rotates right

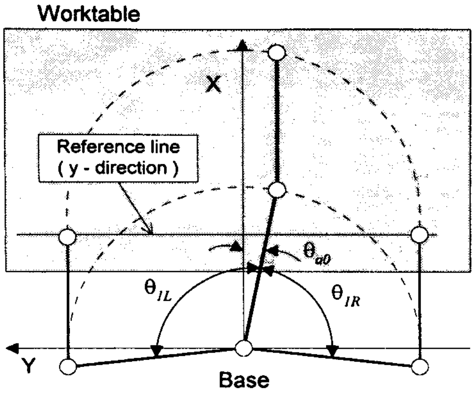


Fig. 8 The calibration of $\theta_1$ of link 1.

until the photosensor 1 detects the reference line. The angle $\theta_{1R}$ can be acquired from encoder data at that moment. Then, the link 1 rotates left until the photosensor 1 detects the reference line again. The angle $\theta_{1L}$ can be acquired, too. And then $\theta_{a0}$ is calculated by Eq.(2).

$$\theta_{a0} = \frac{|\theta_{1L}| + |\theta_{1R}|}{2} - |\theta_{1R}| \tag{2}$$

When the link 1 rotates $\theta_{a0}$ from zero position, it becomes vertical to reference line geometrically. The result of this step and step 2 make the link 1 and link 2 of actual robot align and parallel with x axis of {W}. Therefore OLP can coincide its model with the actual robot owing to these results.

**Step 4:**

$\theta_4$ of the link 4 is to be calibrated. The reference line of y-direction is only lighted. The link 1 is fixed to previous position and the link 2 rotates. The link 2 rotates right until the photo sensor 1 detects the reference line. Then the link 2 is fixed to that position. And then, the link 4 rotates right until the photosensor 2 detects the reference line. The rest of this process is similar to that of step 2. As the result of this step, the orientation of the actual end-effector becomes parallel with x-direction of {W}.

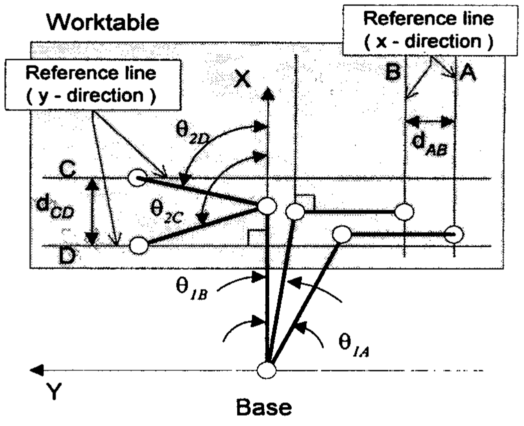


Fig. 9 The calibration of $L_1$ and $L_2$.

**Step 5:**

$L_1$, the length of the link 1 is to be calibrated. Fig. 9 depicts this calibration process. In this step, two x-direction reference lines which are named A and B are lighted. The distance between A and B is $d_{AB}$. The link 2 maintains its orientation vertical to reference line and the link 1 rotates right. When the photosensor 1 meets the reference line A and B, the angles of link 1 are stored in OLP as $\theta_{1A}$ and $\theta_{1B}$, respectively. Then the length of link 1 is calculated as follows.

$$d_{AB} = L_1 \sin\theta_{1A} - L_1 \sin\theta_{1B} \tag{3}$$

$$L_1 = \frac{d_{AB}}{\sin\theta_{1A} - \sin\theta_{1B}} \tag{4}$$

**Step 6:**

$L_2$, the length of the link 2 is to be calibrated. Fig. 9 depicts this calibration process. In this step, two y-direction reference lines which are named C and D are lighted. The distance between C and D is $d_{CD}$. The link 1 is fixed to its position vertical to the reference line and the link 2 rotates left. When the photosensor 1 detects the reference line C and D, the angles of link 2 are stored in OLP as $\theta_{2C}$ and $\theta_{2D}$, respectively. Then the length of link 2 is calculated as follows.

$$d_{CD} = L_2 \cos\theta_{2C} - L_2 \cos\theta_{2D} \tag{5}$$

$$L_2 = \frac{d_{CD}}{\cos\theta_{2C} - \cos\theta_{2D}} \tag{6}$$

**Step 7:**

$d_X$ and $d_Y$, the position offset of X and Y direction between {B} and {W} are to be calibrated. Fig. 10 depicts this calibration process. It is similar to that of step 5 and 6. The x-direction reference line becomes the x axis of {W} and the y-direction reference line becomes the y axis of {W}. $d_X$ is calculated by Eq.(7).

$$d_X = L_1 \sin\theta_{1X} + L_2 \tag{7}$$

Where $L_1$ and $L_2$ are given by step 5 and 6.

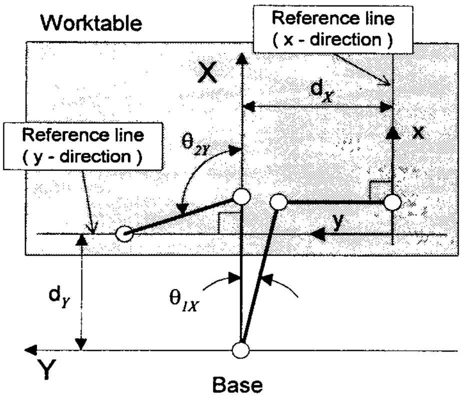


Fig. 10 The position of the work table.

$d_Y$ is calculated by Eq.(8).

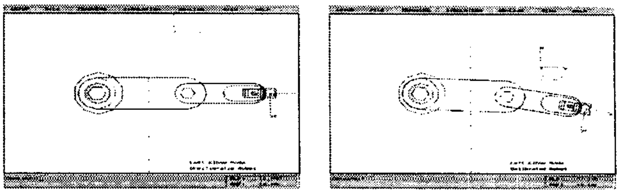
$$d_Y = L_2 \cos\theta_{2Y} + L_1 \tag{8}$$

After this step, the OLP can obtain the actual positions of parts and subassembly if the coordinates of them on {W} are given.

Fig. 11(a) shows the zero position in the OLP before calibration, and Fig. 11(b) shows the result after calibration. Fig. 12 shows a pick and place motion of robot in OLP. Fig. 13 shows the pick and place motion of the actual robot, after the calibration. The robot is operated by the task program teached in the OLP.

## 5. Conclusion

An automated calibration method is proposed for SCARA robot in an assembly line. In this method, the worktable is chosen as reference frame for calibration. Sensors on the end-effector of robot detects marks on the worktable. Through sequence of sensing motion, the robot detects the position of the worktable and aligns easily its attitude with the worktable automatically. The OLP can gather the data from actual robot in the integrated robot control system. Thus, the OLP accept the actual posture of the robot and the worktable. And, the robot can adjust itself to a changed task by the teaching of OLP.



(a) (b)

Fig. 11 The zero position of robot in OLP.

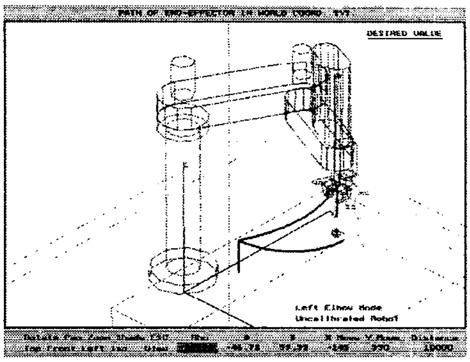


Fig. 12 Pick and place motion in OLP.

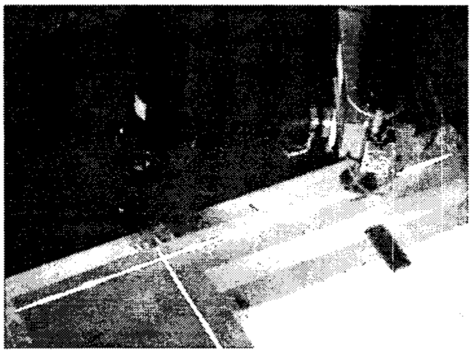


Fig. 13 Pick and place motion of actual robot.

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