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Fixtureless Robotic Manufacturing System

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Abstract

The use of dedicated fixture to hold and align workpiece in the manufacturing process is costly, time consuming and inflexible. Therefore, the demonstration of Fixtureless Robotic Manufacturing System is presented. The manufacturing cell consists of an articulated robot, an XY robot, and a position sensor (Fastrak®). The system uses Fastrak® to determine the workpiece position and orientation in real time. This information is then sent to the robotic control unit. The trajectory of the robot's end-effector is then adapted based on the real time workpiece position/orientation, and thus *a priori* knowledge of workpiece position/orientation is not required. The control units of the commercial CRS robotic system and the Roland XY plotter are modified so that joint level control technique can be implemented. Thus, all the machines in the cell system can be fully controlled. The experiment also demonstrates a fully integrated manufacturing cell that manufacturing capability is improved through this integrity.
Keywords: Robot, Control, Manufacturing.

1. Introduction

Robotic operation usually requires dedicated fixtures to precisely secure workpiece in their right position. The fixtures are part specific, and therefore must be redesigned when parts changes. The custom-made fixtures are costly and time-consuming to build and install. The flexible fixtureless assembly (FFA) [1] and the robotic fixtureless assembly (RFA) [2] uses machine vision to estimate the target pose so that the robot can servo and grasp the part without *a priori* knowledge of its position. The robot recognizes the part and is able to grasp it when it has been placed in an unstructured manner within the robot workspace.

In this project, a fixtureless robotic manufacturing system is developed. In the paper, a position sensor is used to sense the position and orientation of workpiece frame. The motion of the robot is programmed based on this movable workpiece frame. Thus, the workpiece can be at any position within the workspace of the robot and can be in motion. The aim is not only to assemble parts, but also to process it. This is a very challenging task, requiring innovation in many areas of robotics.

Since the robot motion is programmed based on the workpiece frame, a precise mathematic is used to map the robot motion into its joint space in real time. A real time controller is then used this mapped motion in joint space to simultaneously control all the robot's joints. This is a challenging task, requiring a much more difficult control technique compared to the conventional PID controller.

In this project, we developed a fully integrated robotic manufacturing cell. The controller of the CRS articulated robot is modified such that joint level control technique can be implemented. The Roland XY plotter is also modified such that its motion can be programmed. The TCP network is used to communicate between machines in the cell.

The preliminary results demonstrate that the robot can perform its task in floating workpiece frame. Furthermore, workpiece needs not to be fixed in operation. The manufacturing workcell is more flexible.

2. The CRS Robotic System

The CRS robotic system, shown in Fig. 1, is a 5 Degrees of freedom articulated robot. Each joint is driven by DC servo motor through harmonic drive and its position is sensed by incremental encoder. The DH parameters of the robot are as followings:

Table 1 DH parameter of the CRS robotic system

i	α_i	a_{i-1}	d_i	θ_i
1	0	0	10”	θ_1
2	-90°	0	0	θ_2
3	0	L_1=10”	0	θ_3
4	0	L_2=10”	0	θ_4
5	-90°	0	2”	θ_5

The forward kinematics can be expressed as [3]

$$ {}^{0}_{E}T = \begin{bmatrix} c_1 & s_1 & 0 & c_1(L_1c_2 + L_2c_{23}) \\ s_1 & -c_1 & 0 & s_1(L_1c_2 + L_2c_{23}) \\ 0 & 0 & -1 & L_1s_2 + L_2s_{23} + 10 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

The inverse kinematics of the CRS robotics system is found to be [3]

$$ \theta_1 = a\tan 2(Y, X) \; or \; a\tan 2(Y, X) + \pi \quad (2) $$

$$ \theta_3 = a\tan 2(s_3, c_3) \quad (3) $$

where $c_3 = \dfrac{X^2 + Y^2 + Z^2 - L_1^2 - L_2^2}{2L_1L_2}$

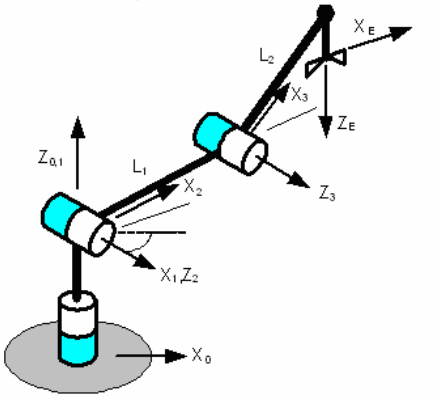
$s_3 = \pm\sqrt{1 - c_3^2}$

and $\theta_2 = a\tan 2(s_2, c_2) \quad (4)$

where $s_2 = \dfrac{(L_1 + L_2c_3)X - (L_2s_3\sqrt{X^2 + Y^2})}{X^2 + Y^2 + Z^2}$

$c_2 = \dfrac{(L_1 + L_2c_3)\sqrt{X^2 + Y^2} - L_2s_3Z}{X^2 + Y^2 + Z^2}$

a) The CRS robot



b) Kinematics diagram

Figure 1 The CRS Robotic System

3. The Mapping

In general, position vector described with respect to (wrt) some frame, {W}, as shown in Fig. 2 can be mapped or described wrt another frame, {B}. In order to transform its description, the position (origin) and orientation of frame {W} wrt frame {B} is required. The origin of frame {W} wrt frame {B} is usually called $^{B}P_{PORG}$ and the orientation of frame {W} wrt frame {B} can be described by rotation matrix $^{B}_{W}R$. The general mapping can be expressed as follows [4];

$$^{B}P = {}^{B}_{W}R\,{}^{W}P + {}^{B}P_{WORG} \tag{5}$$

where ^{B}P is the position vector described in {B}
^{W}P is the position vector described in {W}
$^{B}_{P}R$ is the rotation of {W} wrt {B}
$^{B}P_{PORG}$ is the origin of {W} wrt {B}

This mapping expression can be written in a compact form as follows [4];

$$\begin{bmatrix} ^{B}P \\ 1 \end{bmatrix} = \begin{bmatrix} & ^{B}_{W}R & & ^{B}P_{WORG} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ^{W}P \\ 1 \end{bmatrix} \tag{6}$$

or

$$^{B}P = {}^{B}_{W}T\,{}^{W}P \tag{7}$$

The 4x4 matrix operator, $^{B}_{W}T$, in this equation is called homogeneous transform.

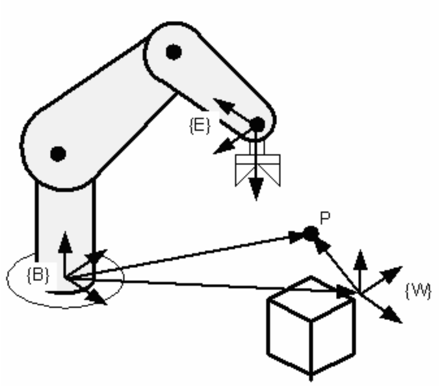


Figure 2 Transformation

In the project, the position and orientation of workpiece frame {P} wrt robot's base frame {B} is sensed by Fastrak® position sensor in real time. Thus, the homogeneous transform at each servo time can be determined and the trajectory described in frame {P} can be transformed into its description in frame {B}. The robot's inverse kinematics is then used to map the trajectory described in robot frame {B} into robot's joint space.

4. Manufacturing Cell Architecture

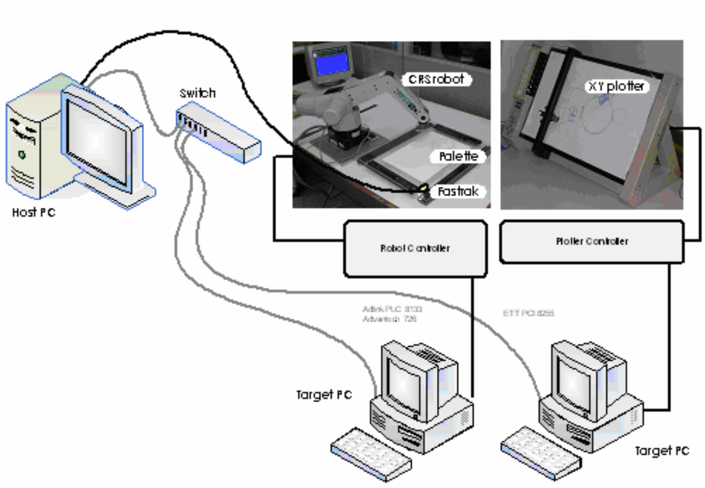


Figure 3 System Architecture

The Fixtureless Manufacturing Cell, shown in Fig 3., consists of the CRS robotics system, Roland plotter, Fastrak® position sensor, the movable palette and three computers. The CRS robotics and the Roland plotter controllers are modified such that the joint level control technique can be implemented. The Matlab-xPC is used for real time control of both systems. Using the xPC, the robot control is written in Matlab-simulink in host computer and is then uploaded to the target xPC where control cards are installed and is being used for real time control. All the robot joints are simultaneously controlled at 0.1 msec speed.

Fastrak® is used to sense the position of the movable palette and then sending the position and orientation of the palette to the target xPC via the host PC. This host PC feeds the position information to the target xPC through 10 Mbps TCP/UDP protocol. The xPC then, maps the reference trajectory, which is defined in movable workpiece frame into the fixed reference frame, then performs the inversed kinematics calculation. The trajectory is now mapped into robot's joint space. The xPC, again, simultaneously controls all joints to follow the joint trajectory. The roughly designed PD controller is used to control these joints. In the experiment, the axes of the robot fixed reference frame and the transmitter of Fastrak® are aligned but the relative position is unknown.

The target xPC sends the results including joint position, the joint position command, and the reference position of the workpiece, back to the host PC through TCP/UDP protocal. The host PC then displays the graphic interpretation of the results without degrade the speed of the real time control.

5. Experimental Results

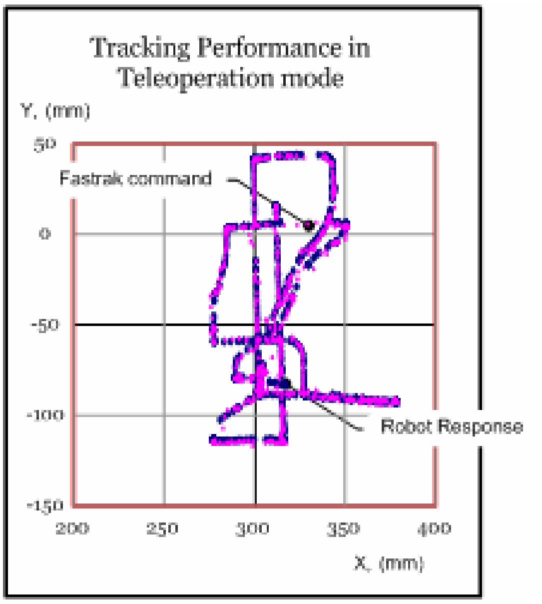


Figure 4 The performance in master-slave mode

In the first experiment, the system is tested in master-slave mode where the robot is to follow the trajectory of Fastrak® which is fixed on the palette and is manually translated in XY plane. It is noted that the origin of Fastrak® wrt to the origin of the robot frame is unknown. Thus, the trajectory of the robot is shifted to the trajectory of Fastrak® so that we are able to see the following error. The result is shown in Fig. 4.

The PD control, which the PD gains are roughly tuned, is used for position based joint control. The result demonstrates that the robot motion follows the motion of Fastrak® quite well (shown in Fig. 4). However, the robot motion is not very smooth since the point to point control (PTP) technique is used to control the robot motion.

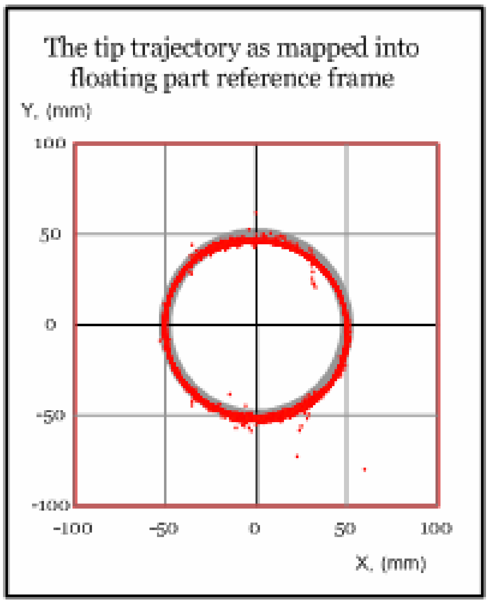


Figure 5 The tip trajectory in part frame

In the second experiment, the robot is programmed to draw a circle of radius 50 mm on a movable palette. The palette is able to translate in XY horizontal plane. The performance of the PD controller is shown in Fig 5. The relative position between Fastrak®'s transmitter and the robot fixed frame is unknown.

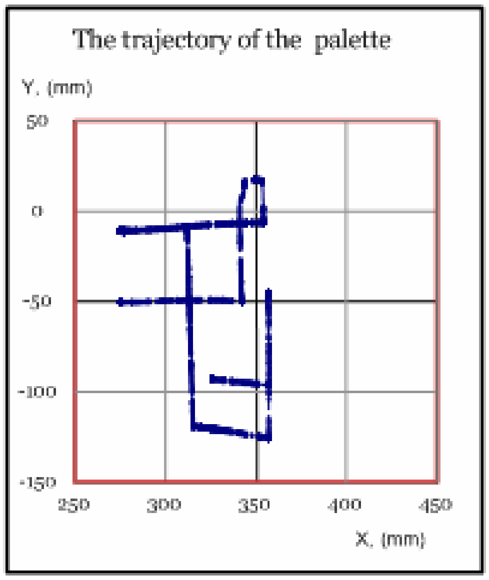
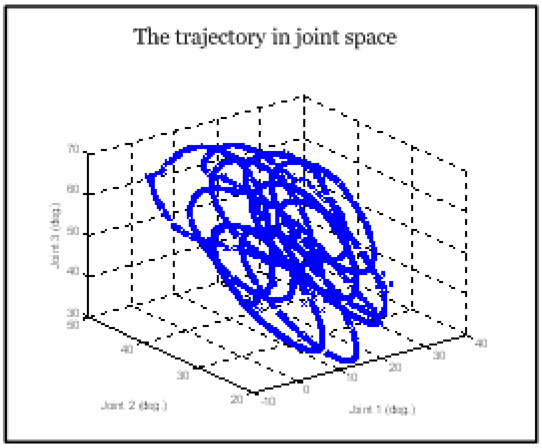
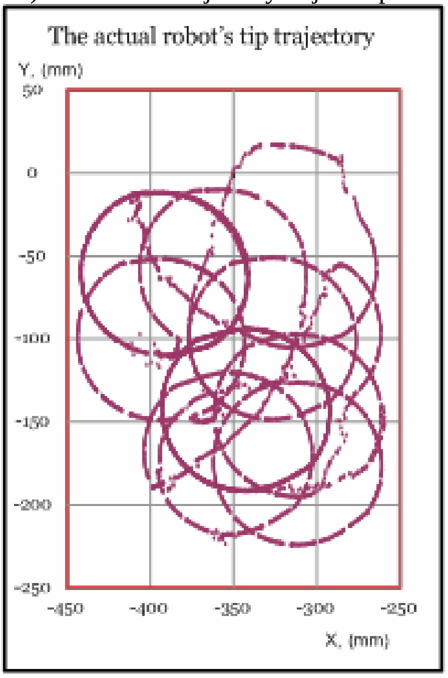


Figure 6 The position of the movable palette

After the robot drew a circle for a couple times, we translate the palette in both X and Y directions as shown in Fig 6. The robot is able to adapt its tip trajectory to follow the circle as shown in Fig 5. The robot trajectory, measured by joint's encoders are shown in Fig 7., both in joint space (Fig 7a) and in Catesian space (Fig. 7b). The joint trajectory can be mapped into robot's Cartesian space using robot forward kinematics. It is obviously seen that the tip trajectory, either in joint space or in Cartesian space, has a response to Fastrak® receiver's position.



a) The robot's trajectory in joint space



a) The robot's trajectory in catesian space

Figure 7 The trajectory of the robot

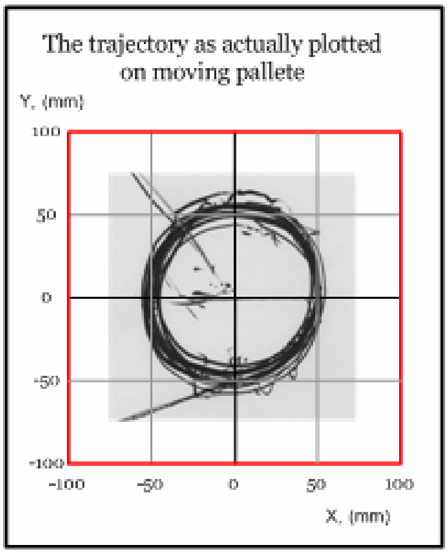


Figure 8 The tip's trace on the movable palette

The Fastrak®'s receiver position, which is the position of workpiece reference frame, is used to compensate the tip trajectory in real time. The result is shown in Fig 5. It is demonstrated that the robot is able to draw a circle on the movable palette as desired. The actual tip's trajectory on the palette is shown in Fig 8. We are now able to demonstrate that the robot can perform its task on a movable palette. The simulated plot, shown in Fig 5., differs from the real plot, shown in Fig 8., because the axes of Fastrak® transmitter, the movable palette, and the robot are not perfectly aligned.

In fact, we need to know the position of Fastrak®'s transmitter relative to the robot fixed frame in order to demonstrate the performance of our technique when rotation of the palette is involved. The result is not shown in the paper.

6. Conclusion

In this project, the robot is able to perform its task on movable workpiece. The proposed technique used positioning sensor to sense workpiece position in real time and also perform mapping and inverse kinematics calculation in real time to map the motion defined in workpiece frame to the robot joint space. The manufacturing cell is then more flexible and can handle more comprehensive manufacturing tasks.

7. Future Works

We are now developing a Laser Positioning System (LPS) [5] to sense the robot's end effector and workpiece directly in real time. This device is designed to sense the position faster and more accurate and thus enhance the overall performance. The adaptive control is to be developing for control the robot's joints along with control library to support a complicated control technique. We aim to develop a new control strategy to directly control the motion of the robot's end effector relative to the workpiece by using our developed LPS to sense both the tip and the workpiece.

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