

Design and Development of Cartesian Robot for Machining with Error Compensation and Chatter Reduction

N. Mithran¹ and R. Gangadevi²

*¹PG Scholar, Department of Mechanical Engineering,
SRM University, Chennai-603203.*

*²Faculty, Department of Mechatronics Engineering,
SRM University, Chennai-603203.*

E-mail: ¹mithran_n@srmuniv.edu.in, ²gangadevi.r@ktr.srmuniv.ac.in

Abstract

In industries for foundry pre-machining operation an ideal solution could be derived from Robotics based flexible automation, but with only few successive installations is found due to industrial robots generally suffer from low stiffness which deviate them from the desired path as strong process forces generated at machining time and also includes limited material removal rate, low surface quality, and chatter/vibration. This paper presents a real-time compensation algorithm based on a robot stiffness model and force control scheme is to be introduced without extending the process cycle time observing great benefit in controlling the process forces by applying the maximum allowed force, and thus removing the maximum amount of material per time unit. It also employs a stiffness model to continuously modify robot trajectory to compensate for the deviations with adaptive controller, based on a derived model of the machining process and an identified model of the robot dynamics reasoning and analyzing low surface quality in robotic machining processes and the stiffness properties of robot structure.

1. Introduction

A great contribution to factory automation have been made by Industrial robots and enable a reduction in the workforce, but very few robots have been adopted in high value-added applications such as material removal processes. The processes of

machining usually include cleaning and pre-machining, etc., machining for high tolerance surfaces, painting and assembly. flexible automation based on Robotics is considered as an ideal solution for its programmability, adaptivity, flexibility and relatively low cost, especially for the fact that industrial robot is already applied to tend foundry machines and transport parts in the process. Moreover the large sized articulated robot IRB6400's stiffness would be 0.5N/m compared to 30N/m for a standard CNC machine. In order to achieve higher dimensional accuracy, the robot deformation due to the interactive force must be compensated. From many sources of errors of machine tools, the key contributors are thermal deformation and geometric errors are traditionally known. By studying a large amount of data by Peklenik who reported that thermal errors could contribute as much as 70% of work piece errors in precision machining. As industrial robot has low stiffness, the force induced deformation of the robot structure is the single most dominant source of work piece surface error. Offline calibration strategies are often used to improve accuracy but it sacrifices operation cycle time. The surface error is measured and calculated to update the tool/work piece data of the next cut. Although offline calibration could improve robot path error as well as force induced error, the process cycle time is increased, mostly doubled. With force sensor attached on the robot wrist, force information is ready on real time. If an accurate stiffness model could be established, the force induced error could be compensated online by updating the robot targets. The solution of the inverse kinematics problem, the most critical problems in robotics, must be obtained with high precision. For instance, closed-form solutions are not guaranteed for the algebraic methods, and closed-form solutions for the first three joints of the robot must exist geometrically when the geometric method is used. Similarly, the iterative inverse kinematics solution method converges to only one solution that depends on the starting point. Additionally, these traditional solution methods may have a prohibitive computational cost because of the high complexity of the geometric structure of the robotic manipulators. For these reasons, researchers have focused on solving the inverse kinematics problem using artificial neural networks. It is natural to apply the feedback scheme for the sensor based methods to continuously adjust the robot position until the position error is within the specified limit. Although sensor based compensation methods offer higher position accuracy, they are very difficult to implement on an existing robot manipulator. Even it is possible to install the sensor, the final system cost would be expensive because of the sensor cost. This makes the sensor based methods more suitable for high accuracy discrete processes such as drilling, while the model based methods are better for continuous processes such as milling and roller hemming. The goal of this paper is to present a practical method to improve the machining accuracy through robot deformation compensation.

2. Error Sources and its Compensations

2.1 Position error sources

The position error sources can be divided into the following five groups:

- (1) Kinematic error: the position and orientation of the robot end-effector is a function of link geometric parameter such as link length and twist angle. This functional relationship can be expressed mathematically by the manipulator kinematics. Errors in the link geometric parameter due to manufacturing tolerances will propagate to cause inaccuracy in the position of the end-effector. A significant portion of research on robot positioning inaccuracy dealt with this type of error.
- (2) Robot structure error: due to the compliance of robot structures, including elastic deformation and transmission errors.
- (3) Sensor error: due to the joint angle sensor resolution and installation, there is always a finite measurement error.
- (4) Servo control error: a well-designed and tuned servo controller can achieve positioning accuracy in the range of 1-5 times the sensor resolution.
- (5) Algorithmic and computational errors: this results from truncation, round off, and other mathematical approximations occurring in the computation of a trajectory using interpolation algorithms. An incremental interpolation was reported [4] to be more sensitive to computational errors than an absolute interpolation because errors are accumulative in an increment interpolation algorithm. To reduce algorithmic and computational errors, the robot controller will need a trajectory interpolation algorithm which minimizes the propagation of errors due to truncation, round-off and approximations in the computation, et al [5].

2.2 Compliance with joint stiffness

A robot manipulator deforms under external forces because of its compliance. For many industrial manipulators it is reasonable to assume that: 1) the compliance in the joints (gearbox and motor) is the dominant source of the robot deformation, 2) the links are infinitely stiff, 3) a joint PID control loop is used and the active joint stiffness provided by the control loop has small variation over time at the steady state. It is worthwhile to point out that, robot manufacturers are moving toward the new generation slim manipulators and these 3 assumptions might be invalid.[7]

A. Joint Stiffness

With the above three assumptions, the stiffness of a 6-axis serial robot manipulator shown in Fig. 1 can be represented by its link side joint stiffness: a constant 6*6 diagonal matrix with each diagonal term defining the stiffness of a joint.[7]

$$K_{\theta} = \text{Diag}([k_{\theta 1} \ k_{\theta 2} \ k_{\theta 3} \ k_{\theta 4} \ k_{\theta 5} \ k_{\theta 6}]^T) \quad (1)[7]$$

B. Cartesian Stiffness

As the deformation is often observed and compensated at the tool tip, the Cartesian stiffness at the tooltip K is important. It can be computed as

$$K_t = J_t^{-T} K_0 J_t^{-1} \quad (2)[7]$$

Where J_t is the Jacobean matrix that transforms a small joint angle displacement $\Delta\theta$ to the translational and rotational displacements Δx_t of a Cartesian frame attached to the tool tip

$$\Delta x_t = J_t \Delta\theta \quad (3)[7]$$

The deflection caused by the external force vector can be calculated through the Cartesian stiffness as:

$$F_t = K_t \Delta x_t = J_t^{-T} K_0 J_t^{-T} \Delta x_t \quad (4)[7]$$

The joint stiffness matrix K_0 reflects the natural entity of a manipulator structure. It is diagonal, positive definite and constant irrespective of the external force or the robot configuration. In contrast, the Cartesian stiffness matrix K_t is configuration dependent. Here we did not use the enhanced stiffness modelling, where an external force and robot configuration dependent stiffness term is included in the Cartesian stiffness formulation. This is because under the rated robot payload range, the contribution of this extra stiffness term to the total robot deformation is very small. In addition, the conventional formulation (2) has the computational advantage. [7]

3. Elman neural network

A recurrent network is distinct from a feed-forward neural network because it has at least one feedback loop. The presence of these feedback loops has a profound impact on the learning capability of the network and on the network performance. Moreover, these feedback loops involve the use of particular branches composed of unit-delay elements, denoted as Z_{-1} , which results in nonlinear dynamic behavior by virtue of the nonlinear nature of the neurons. The nonlinear dynamics play a key role in a recurrent network's storage function. An Elman network is a recurrent neural-network model that is able to provide a standard state-space representation for dynamic systems. Therefore, this network architecture can be used as a recurrent neural equalizer. Such a network constitutes a fully connected recurrent network cascaded with a feed-forward network. The topology of the feedback Elman network used in the neural network block of this study is illustrated and consists of three layers: input, hidden, and output. A sigmoidal activation function has been used in the hidden and output layers. [1]

4. Deformation Compensation

4.1. Position error compensation approach

4.1.1. Cutting force disturbance error. Due to cutting force, there is torque disturbance at the robot joint. This is the largest source of error. This error can be compensated by using the wrist-force sensor measurement and compensate the

reflected torques at the joints. The movement of robot hand with tool is a position only control problem when there is no cutting. When there is cutting, then the cutting force will react to the robot arm joints as a known disturbance torque input (calculated from the measurements of wrist force sensor) and can be compensated[5]

4.1.2. Motion error. Motion error is the difference between the forward kinematic function and the actual position. The actual position may have some error due to the forward kinematics where θ_n are sensor measured joint angles. The other position error source is the compliance of the robotic manipulator under cutting force[5].

The constant and diagonal joint stiffness model lends itself to the real time implementation due to the low computation cost. After filtering the force sensor noise and compensating the gravity of the force sensor payload, the force signal was translated into the robot tool frame. Based on the stiffness model identified before, the deformation due to the external contact force is calculated in real time and the joint reference for the robot controller is updated which has been implemented in the ABB's IRC5 robot controller using the existing force control platform. The deformation is calculated every 4ms[5].

5. Conclusions

This paper describes in detail the modeling, identification and compensation of robot deformation caused by the external process forces from the machining applications. Lab measurement and application tests have shown that, with a simple joint stiffness model based feed forward approach the deformation compensation can reduce the contact force induced position error by more than 60%. While robot deformation compensation is technically feasible, more efforts are needed to make it available as a product to be used in the field. Although regenerative chatter is the most widely accepted reason for high frequency vibration in machining process, it has little relationship with low frequency structure vibration during robotic machining process. An analysis of mode coupling chatter shows that if the structure stiffness is not significantly higher than process stiffness, mode coupling chatter may happen. Since the stiffness of the CNC machine is usually hundreds of times larger than process stiffness, mode coupling chatter rarely happen. For robot, the difference is only 5 to 10 times. This mode coupling effect is the dominant reason for structure vibration in robotic machining process. The coupling of the robot structure makes the problem even more complicated. Since the deformation is configuration dependent and coupled, it is very hard to predict its magnitude and direction without a proper robot stiffness model. The pattern of the robot structure deformation is related to all of the following parameters: robot configuration, the location in the work space, and the direction as well as the magnitude of the process force. Thus, it is difficult or even impossible to reduce the force induced deformation by traditional offline calibration. The simulation results show that the torque compensation is very important for a tracking

performance. Position error compensation is analysed in the cutting process through reference points by using wrist-force sensor. Wrist-force sensor measurement is utilized not only in the force compensation but also as a way to measure the exact tip position independent of the internal joint sensor measurement errors. Implementation of the proposed control system on the actual hardware will address the practical issues such as sampling (and the associated aliasing, and sensor noise filtering), quantization errors, actuator saturation and friction.[1,3,4,7]

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