Robotics and Computer-Integrated Manufacturing 29 (2013) 293–300

Contents lists available at SciVerse ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

# Robotic assembly automation using robust compliant control

Heping Chen [a], Yong Liu [b,*]

[a] Ingram School of Engineering, Texas State University, San Marcos, TX 78666, United States
[b] Department of Computer Science and Technology, Nanjing University of Science and Technology, Nanjing, China

ARTICLE INFO

*Article history:*
Received 8 May 2012
Received in revised form
9 August 2012
Accepted 1 September 2012
Available online 28 September 2012

*Keywords:*
Industrial robot
Robust impedance control
Assembly automation
Variable structure

ABSTRACT

Industrial robots used to perform assembly applications are still a small portion of total robot sales each year. One of the main reasons is that it is difficult for conventional industrial robots to adapt to any sort of change. This paper proposes a robust control strategy to perform an assembly task of inserting a printed circuit board (PCB) into an edge connector socket using a SCARA robot. The task is very challenging because it involves compliant manipulation in which a substantial force is needed to accomplish the insertion operation and there are some dynamic constraints from the environment. Therefore, a robust control algorithm is developed and used to perform the assembly process. The dynamic model of the robotic system is developed and the dynamic parameters are identified. Experiments were performed to validate the proposed method. Experimental results show that the robust control algorithm can deal with parameter uncertainties in the dynamic model, thus achieve better performance than the model based control method. An abnormal case is also investigated to demonstrate that the robust compliant control method can deal with the abnormal situation without damaging the system and assembly parts, while pure position control method may cause damages. This strategy can also be used in other similar assembly processes with compliant applications.



## 1. Introduction

Assembly tasks using industrial robots have increased in both number and complexity over the years because of the increasing requirements of product quality and quantity in manufacturing processes. However, assembly robots are still a small portion of total robot sales each year. One of the main reasons is that it is difficult for the conventional industrial robots to adjust to any sort of changes in the assembly processes. Therefore, robust industrial robotic systems are rapidly expanding the realms of possibility in robotic assembly applications because they can perform assembly tasks with high autonomy and adaptability to the environments.

In assembly applications that require the robot to impose compliant manipulation on its environment, the interaction force must be accommodated rather than resisted. Hybrid methods that the end-effector's motion is divided into the free motion subspace and environment constraint subspace can be used to deal with the problem, for example, an adaptive implicit hybrid force/pose control method was developed for compliant motion in [1]. However, the position control and force control are implemented in two subspaces, which is not suitable for the problem that the end-effector follows a desired motion in the task space while controlling the interaction force with the environment in the same direction of motion to achieve precise and safe task execution. Hence the end-effector's position response as well as the interaction force in the same direction of motion should be commanded and controlled simultaneously. Since they are physically constrained by the environmental dynamics, the motion and the interaction force should be compromised with a desired dynamic behavior to achieve a proper response. The philosophy of impedance control is suitable for such compliant applications. In the impedance control [2], the dynamic behavior of the robot is specified in terms of the mechanical impedance as seen from the environment. The end-effector is allowed to respond to a sensed environmental force according to a relation with the position error [3,4]. Although both position and force in the impedance control cannot be controlled simultaneously, the manipulator will be able to maneuver in a constraint environment while maintaining appropriate contact force by controlling the manipulator and modulating the impedance of the system. With this method, no switching in the control system is needed as the robot travels from free space to the constraint space. The force feedback loop closes naturally when the robot interacts with the environment and thus provides safety against breakage caused by excessive contact force. The specification of the impedance control consists of a desired motion trajectory plus a dynamic relationship between the motion errors and the interaction force. In this form, it is essentially a proportional plus derivative (PD) position controller,

* Corresponding author.
*E-mail addresses:* hc15@txstate.edu (H. Chen), liuy1602@njust.edu.cn (Y. Liu).

0736-5845/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rcim.2012.09.001

with position and velocity feedback gains adjusted to obtain different apparent impedances and no attempt is made to follow a commanded force trajectory exactly. Although there are some research papers about studying the robust impedance method [5,6], only were simulations performed without experimental implementation.

In this paper, the impedance control method is implemented using an PCB assembly process by an industrial robot. A model based control approach is adopted to perform the compliant assembly process. Due to parametric uncertainties, the exact values of the system dynamic parameters cannot be identified exactly. Therefore, there are some parameter uncertainties in implementing the model based control algorithm. However, the generalized impedance (6) is the desired performance model for the robot to achieve. To deal with the dynamic model parameter uncertainties, a robust impedance control methodology is implemented. By introducing a dynamic compensator in forming the sliding surface, the resultant sliding mode can be identified with the desired performance model. The main contribution of this paper is to implement the robust control algorithm using the robotic compliant assembly process. The dynamic model of the robotic system is developed first. A robust impedance control method is then developed based on the dynamic model. The model parameters are identified when implementing the control method. Experiments are then performed and experimental results is analyzed. An abnormal case is also demonstrated and the results show the robustness of the robust impedance control method.

## 2. Robust impedance control algorithm

### 2.1. Dynamic equation of motion

Consider a rigid manipulator of $n$ links which makes contact with the environment by its end-effector, the dynamic equation of motion in the joint space is [7]

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{b}(\boldsymbol{q},\dot{\boldsymbol{q}})+\boldsymbol{g}(\boldsymbol{q})+\tau_e=\boldsymbol{\tau} \quad (1)$$

where $\boldsymbol{q},\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ are the vectors of the manipulator joint angles, joint velocities and joint accelerations, respectively; $\boldsymbol{M}(\boldsymbol{q})\in\Re^{n\times n}$ is a symmetric positive definite (SPD) manipulator inertia matrix; $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}\in\Re^{n}$ is a vector of Coriolis and centrifugal torques; $\boldsymbol{b}(\boldsymbol{q},\dot{\boldsymbol{q}})\in\Re^{n}$ is a vector of torques due to friction acting on the manipulator joints; $\boldsymbol{g}(\boldsymbol{q})\in\Re^{n}$ is a vector of gravitational torques; $\tau_e\in\Re^{n}$ is a vector of forces/torques exerted on the environment by the manipulator end-effector expressed in the joint space; $\boldsymbol{\tau}\in\Re^{n}$ is a vector of applied joint torques.

Many of the robot assembly tasks involve interactions with the environment. Depending on the manipulator task specifications, different task frame will be defined. A vector $\boldsymbol{r}\in\Re^{n}$ with respect to a general task frame is defined as

$$\boldsymbol{r}=\boldsymbol{r}(\boldsymbol{q}) \quad (2)$$

By differentiating (2) with respect to time $t$, the following equations are obtained

$$\dot{\boldsymbol{r}}=\boldsymbol{J_q}\dot{\boldsymbol{q}},\quad \text{where } \boldsymbol{J_q}=\frac{\partial\boldsymbol{r}(\boldsymbol{q})}{\partial\boldsymbol{q}}$$
$$\ddot{\boldsymbol{r}}=\boldsymbol{J_q}\ddot{\boldsymbol{q}}+\dot{\boldsymbol{J}}_q\dot{\boldsymbol{q}} \quad (3)$$

$\boldsymbol{J_q}\in\Re^{n\times n}$ is the Jacobian matrix and assumed to be nonsingular in the finite work space $\boldsymbol{q}\in\Omega_q$. Multiplying both sides of (1) with $J_q^{-T}$ and using relations in (3), the dynamic equation (1) can be expressed in terms of the task space variable $\boldsymbol{r}$ as

$$\boldsymbol{M_r}(\boldsymbol{r})\ddot{\boldsymbol{r}}+\boldsymbol{C_r}(\boldsymbol{r},\dot{\boldsymbol{r}})\dot{\boldsymbol{r}}+\boldsymbol{b_r}(\boldsymbol{r},\dot{\boldsymbol{r}})+\boldsymbol{g_r}(\boldsymbol{r})+\boldsymbol{\Gamma}_e=\boldsymbol{\Gamma} \quad (4)$$

where

$$\boldsymbol{M_r}(\boldsymbol{r})=\boldsymbol{J_q}^{-T}\boldsymbol{M}(\boldsymbol{q})\boldsymbol{J_q}^{-1}$$
$$\boldsymbol{C_r}(\boldsymbol{r},\dot{\boldsymbol{r}})=\boldsymbol{J_q}^{-T}\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\boldsymbol{J_q}^{-1}-\boldsymbol{J_q}^{-T}\boldsymbol{M}(\boldsymbol{q})\boldsymbol{J_q}^{-1}\dot{\boldsymbol{J}}_q\boldsymbol{J_q}^{-1}$$
$$\boldsymbol{b_r}(\boldsymbol{r},\dot{\boldsymbol{r}})=\boldsymbol{J_q}^{-T}\boldsymbol{b}(\boldsymbol{q},\dot{\boldsymbol{q}})$$
$$\boldsymbol{g_r}(\boldsymbol{r})=\boldsymbol{J_q}^{-T}\boldsymbol{g}(\boldsymbol{q})$$
$$\boldsymbol{\Gamma}_e=\boldsymbol{J_q}^{-T}\tau_e$$
$$\boldsymbol{\Gamma}=\boldsymbol{J_q}^{-T}\boldsymbol{\tau} \quad (5)$$

### 2.2. Robust control algorithm

The generalized impedance in the task space is chosen as a second-order function relating the motion errors to the interaction force errors [8]

$$\boldsymbol{M_d}\ddot{\boldsymbol{e}}_{\boldsymbol{p}}+\boldsymbol{B_d}\dot{\boldsymbol{e}}_{\boldsymbol{p}}+\boldsymbol{K_d}\boldsymbol{e_p}=-\boldsymbol{K_f}\boldsymbol{e_f} \quad (6)$$

where $\boldsymbol{e_p}$ and $\boldsymbol{e_f}$ are the tracking errors of the motion and the interaction force, respectively; $\boldsymbol{M_d}$, $\boldsymbol{B_d}$ and $\boldsymbol{K_d}\in\Re^{n\times n}$ are the desired constant inertia, damping and position stiffness matrices, respectively; $\boldsymbol{K_f}\in\Re^{n\times n}$ is the force stiffness matrix. The generalized impedance parameters $\boldsymbol{M_d}$, $\boldsymbol{B_d}$, $\boldsymbol{K_d}$ and $\boldsymbol{K_f}$ are specified as positive definite diagonal matrices in which $\boldsymbol{M_d}$ is assumed to be nonsingular. $\boldsymbol{K_f}$ provides an additional freedom in the selection of impedance parameters as the desired performance for the robot. The desired interaction force trajectory $\boldsymbol{\Gamma_d}$ is introduced such that the interaction force can be controlled during compliant manipulation.

For the robot manipulator described by (4), the robotic system achieves the target generalized impedance (6) if the following model-based generalized impedance control (GIC) law is implemented

$$\boldsymbol{\Gamma}=\boldsymbol{M_r}(\boldsymbol{r})\ddot{\boldsymbol{r}}_{\boldsymbol{d}}^{*}+\boldsymbol{C_r}(\boldsymbol{r},\dot{\boldsymbol{r}})\dot{\boldsymbol{r}}+\boldsymbol{b_r}(\boldsymbol{r},\dot{\boldsymbol{r}})+\boldsymbol{g_r}(\boldsymbol{r})+\boldsymbol{\Gamma_e} \quad (7)$$

where

$$\ddot{\boldsymbol{r}}_{\boldsymbol{d}}^{*}=\ddot{\boldsymbol{r}}_{\boldsymbol{d}}-\boldsymbol{M_d}^{-1}(\boldsymbol{B_d}\dot{\boldsymbol{e}}_{\boldsymbol{p}}+\boldsymbol{K_d}\boldsymbol{e_p}+\boldsymbol{K_f}\boldsymbol{e_f}) \quad (8)$$

Due to parametric uncertainties, the exact values of $\boldsymbol{M_r}(\boldsymbol{r})$, $\boldsymbol{C_r}(\boldsymbol{r},\dot{\boldsymbol{r}})$, $\boldsymbol{b_r}(\boldsymbol{r},\dot{\boldsymbol{r}})$ and $\boldsymbol{g_r}(\boldsymbol{r})$ in (4) may not be known, but the estimated values $\hat{\boldsymbol{M}}_{\boldsymbol{r}}(\boldsymbol{r})$, $\hat{\boldsymbol{C}}_{\boldsymbol{r}}(\boldsymbol{r},\dot{\boldsymbol{r}})$, $\hat{\boldsymbol{b}}_{\boldsymbol{r}}(\boldsymbol{r},\dot{\boldsymbol{r}})$, $\hat{\boldsymbol{g}}_{\boldsymbol{r}}(\boldsymbol{r})$ can be identified. The modeling errors are defined as

$$\Delta\boldsymbol{M_r}(\boldsymbol{r})=\boldsymbol{M_r}(\boldsymbol{r})-\hat{\boldsymbol{M}}_{\boldsymbol{r}}(\boldsymbol{r})$$
$$\Delta\boldsymbol{C_r}(\boldsymbol{r},\dot{\boldsymbol{r}})=\boldsymbol{C_r}(\boldsymbol{r},\dot{\boldsymbol{r}})-\hat{\boldsymbol{C}}_{\boldsymbol{r}}(\boldsymbol{r},\dot{\boldsymbol{r}})$$
$$\Delta\boldsymbol{b_r}(\boldsymbol{r},\dot{\boldsymbol{r}})=\boldsymbol{b_r}(\boldsymbol{r},\dot{\boldsymbol{r}})-\hat{\boldsymbol{b}}_{\boldsymbol{r}}(\boldsymbol{r},\dot{\boldsymbol{r}})$$
$$\Delta\boldsymbol{g_r}(\boldsymbol{r})=\boldsymbol{g_r}(\boldsymbol{r})-\hat{\boldsymbol{g}}_{\boldsymbol{r}}(\boldsymbol{r}) \quad (9)$$

where $\Delta\bullet$ represents the modeling errors of $\bullet$ (matrix or vector) and $\hat{\bullet}$ represents the estimated values of $\bullet$ which are available. The modeling errors (9) are assumed to be bounded by

$$\|\Delta\boldsymbol{M_r}(\boldsymbol{r})\|\le\delta M_r$$
$$\|\Delta\boldsymbol{C_r}(\boldsymbol{r},\dot{\boldsymbol{r}})\|\le\delta C_r$$
$$\|\Delta\boldsymbol{b_r}(\boldsymbol{r},\dot{\boldsymbol{r}})\|\le\delta b_r$$
$$\|\Delta\boldsymbol{g_r}(\boldsymbol{r})\|\le\delta g_r \quad (10)$$

where the symbol $\|\bullet\|\equiv\|\bullet\|_2$ denotes an Euclidean vector norm or an induced matrix norm [9], i.e., a norm of matrix $N$, $\|\boldsymbol{N}\|=\|\boldsymbol{N}\|_2=[\lambda_{\max}(\boldsymbol{N}^T\boldsymbol{N})]^{1/2}$, where $\lambda_{\max}(\boldsymbol{N}^T\boldsymbol{N})$ is the maximum eigenvalue of matrix $\boldsymbol{N}^T\boldsymbol{N}$. The positive scalars $\delta M_r$, $\delta C_r$, $\delta b_r$ and $\delta g_r$ denote the bounds which are known.

The generalized impedance (6) is the desired performance model for the robot to achieve. Hence it cannot deal with parameter uncertainties. Thus a robust control method should be introduced. With variable structure model reaching control (VSMRC), the