A Review of Robotic Force/Position Control

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Abstract: This paper reviews robotic position and force control techniques. The existing fundamental force control algorithms are compared and discussed, including explicit/implicit control, stiffness control, impedance/admittance control, and hybrid position/force control. This work is intended to give a basic guidance for understanding and utilization of the fundamental robotic control algorithm.

Key words: position control; force control; explicit control; implicit control; feedback

1 Introduction

Robotics is one of the most promising techniques in recent years despite the worries of its safety and the related economic considerations of eliminating jobs. Robots have replaced humans in numerous hazard circumstances like aerospace and deep sea, conducting operations that were previously impossible to accomplish. With the advances in microchips (Moore's Law) and micro sensor technology, more and more applications are emerging, especially in medical applications that help improving health and living conditions.

Figure 1 shows a shadow dexterous hand developed by Shadow Robot Company, as an example [1]. The hand has 24 movements and is the closest hand to a human hand, driven by 40 air muscles which are very similar to the human muscles. The air muscle uses compressed air to provide contracting force, which is usually weak. Therefore the hand is absolutely safe. This shadow dexterous hand can even mimick the movement of a real hand wearing a special glove, allowing an operator to work remotely in an inaccessible area where radiation, toxic chemicals or biological hazards may be present. Such a product is also a great help for disabled and elderly people.

Figure 1 Shadow dexterous hand with air muscles

Safety is paramount whenever a robot comes into direct contact with people. The movements have to be smooth so the right and safe pressure is required to control the motion of a robot. The key is the precise control of all moving components, determining the time history of joint inputs required to cause the end-effector to execute a commanded motion or force.

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There are many control strategies available, including position control, force control and hybrid position/force control. Advanced control methods include adaptive control, robust control and vision based control etc. In this work, we will review the basis of position control and force control by studying several papers on those topics, providing insight views on robot control.

2 Position control

The kinematic problem considers the path or trajectory of a manipulator without regarding the torque or force applied to the object. The first step of the kinematic problem is to set up the coordinate system, usually consisted of body-fixed coordinate frames attached to the joints. A transformation matrix is then established via Denavit-Hartenberg convention to relate the joint variables and the position and orientation of the end-effector. With the known joint variables, we can simply use the transformation matrix to find the location and orientation of the end-effector, this is called the forward kinematic problem.

In practice we are more interested in following a desired trajectory, called the position control, which is an inverse kinematic problem. The inverse kinematic problem usually involves a set of nonlinear equations that need to be solved simultaneously. However, solving nonlinear equations is usually not so easy, especially when a closed form solution for the joint variables is expected. Furthermore, the inverse kinematics problem may or may not have a solution, and even if a solution exists, it may or may not be unique. Numerical methods in general are the only solution to the inverse kinematic problem. In addition, a position control also needs to reject the disturbance in a reasonable range while following the trajectory. This is usually realized with a position feedback mechanism, complicating the nonlinear equation further. However, for a specific type of manipulator, one may decouple the inverse kinematic problem into two simpler parts, known, respectively, as inverse position kinematics that determines the position of the end-effector and inverse orientation kinematics that determines the orientation.

Multi manipulator systems with flexible payloads have been studied extensively for their potential applications in industries. For example, two robots each grasp a flexible metal sheet and force them together for mating in the automobile-body assembly task. This is a more complex and challenging control problem since the flexible metal sheet deforms in addition to the rigid body motion. The vibrations of the flexible body also need to be suppressed to improve the accuracy of assembling when moving the body using manipulators.

In Reference [2] the authors studied the control problem of a flexible payload with an arbitrary shape, as shown in Figure 2, where a general flexible payload is grasped by n manipulators. Two primary problems were addressed in this work.

The first one is the dynamic modeling of the payload in motion. A finite-element model was built to discretize the flexible payload, and the payload dynamics is decomposed into two parts, the rigid body motion which represents the dynamics of the undeformed rigid body, and a flexible deformation, which represents only the change in shape. This decomposition allows the rigid-body motion and the deformation to be treated separately and thus simplifies the problem.

The clamped-free model [3] is used in the modeling, where it is assumed that no deformation exists at one clamped contact and the deformation occurs at the other free contacts. As a result, the position of mass center can be determined based on the position of the fixed clamped contact, and hence the dynamics of both the rigid body and the deformations with respect to the mass center can be determined.

The second problem is a control design to damp out the flexible vibration in the motion. In this work, the dynamic equations of motion of the payload are obtained via the Lagrange energy method and the gravity effect is considered. The authors proposed to use the PD-position feedback plus gravity compensation with proper design of the control gains. By carefully selecting the control gains, the flexible vibration at each contact can be damped out. The authors showed that the suppression of the vibration at each contact is helpful to suppress all vibrations of the payload. One should note that an assumption of small static and dynamic deformation is made in the control design.

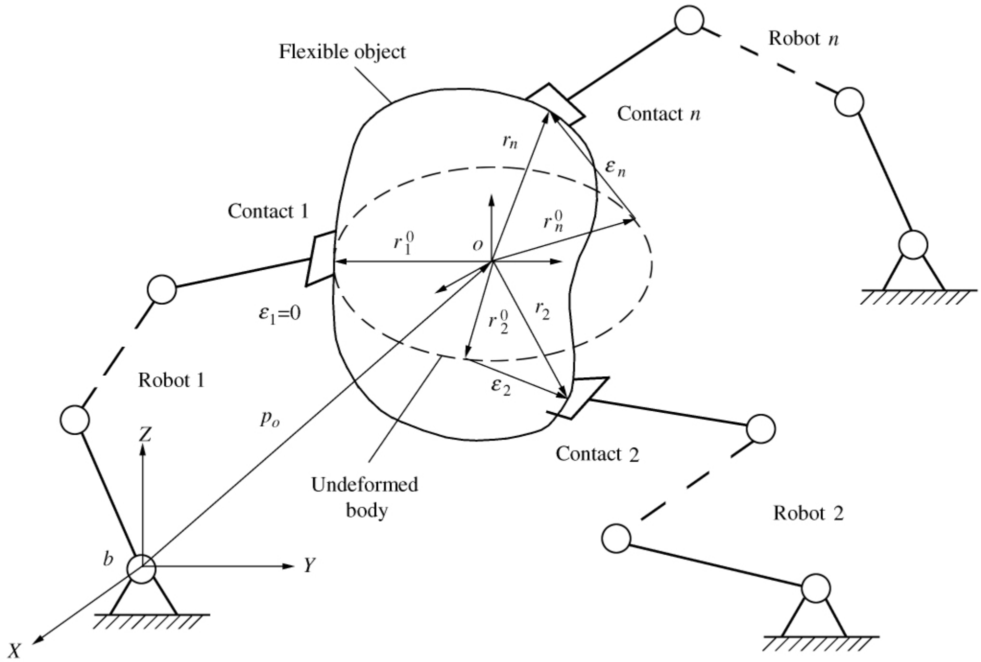


Figure 2 A general flexible object manipulated by multiple robots

The authors then evaluated the method by manipulating a flexible sheet from an initial position/orientation to a desired one with two CRS A460 robots. Since the sheet is very thin, vibrations will appear during the motion and the vibrations need to be suppressed for achieving the desired motion trajectory. It was observed in the experiment that all vibrations of the sheet were damped out quickly by carefully controlling the gain and also due to the material damping of the flexible motion. Eventually, no obvious static deformation exists. The experiment proves that the suppression of the vibration at each contact is helpful to suppress all vibrations of the payload. Through proper design of the control gains, the influence of the gravitational component on the rigid motion can also be reduced as far as possible.

3 Force control

Position control by tracking motion trajectories is adequate for tasks such as delivering materials from one position to another. However, in many applications where the manipulator closely interacts with the objects, such as the window washer example in the book, it is also necessary to control the forces of interaction rather than simply controlling the position of the end-effector, since a slight position error could lead to extremely large forces of interaction (especially when the object is rigid), which may damage the end-effector or the object. Robot force control involves integration of task goals like position, velocity and force feedback, and the adjustment of the applied torque to the robot joints. Depending on the type of feedback signal (position, force, velocity) and the choice of command input signals, force control can be further categorized as fundamental robot force control algorithms and advanced robot force control strategies [5]. Here we only review several fundamental force control algorithms, so as to understand the ideas behind force control. Advanced robot force control methods are usually based on these fundamental control algorithms.

1) Explicit force control

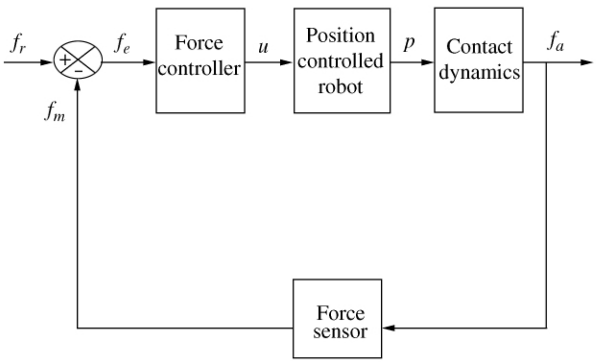


Figure 3 Explicit force control [6]

Figure 3 shows the scheme of conventional explicit force control. Here f_r is the reference force and f_m is the measured force from the end-effector. The measured force is directly used for feedback and the force error vector f_e is formed by comparing the measured force with the reference force. A control signal u is generated by the force controller, which is used as the reference position to be tracked by the robot. The end effector at position p generates the forces and torques through interaction with the current contact dynamics, and f_a is the actual applied force to the object [6].

On the contrary, implicit force control has no force feedback. Instead, the position is controlled based on the predefined position for a desired force. Hence, a position feedback gain is needed such that the robot arm can obtain a particular stiffness.

2) Stiffness control

Stiffness control includes active and passive stiffness control, which are similar to the explicit and implicit force control to some extent. Passive stiffness control is the simplest stiffness control where the end-effector can be thought of as being equipped with a mechanical device composed of springs with constant stiffness. By contrast, active stiffness control can be regarded as a programmable spring. The stiffness of the closed-loop system is altered via the force feedback. Figure 4 shows the basic principle of an active stiffness control. Where X_D is the desired position vector; X is the output position and K_F is the compliance matrix for modifying position command based on the output force F; ΔX is the position error vector; K_x represents the stiffness matrix; J is the robot's Jacobian matrix; τ_p is the vector of command input to joints and we can see that $\tau_p = J^T K_x \Delta X$. In box 2 is the basic robot system which includes a robot and its environment, velocity feedback and nonlinear compensation for the gravity effect, etc.

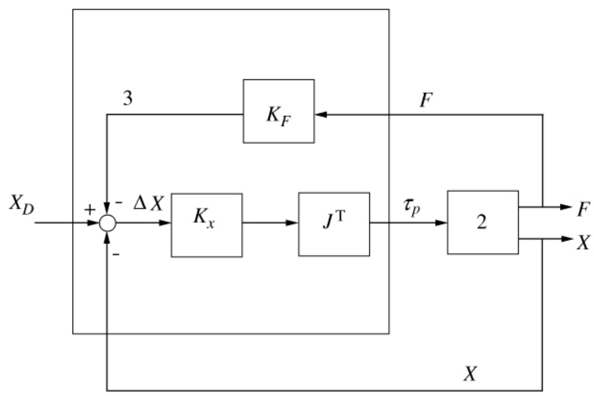


Figure 4 Active stiffness control [5]

3) Impedance control and admittance control

The fundamental idea of impedance and admittance control is that the manipulator control system is designed not only to track a motion trajectory, but also to regulate the mechanical impedance/admittance, which are defined as follows for a linear case.

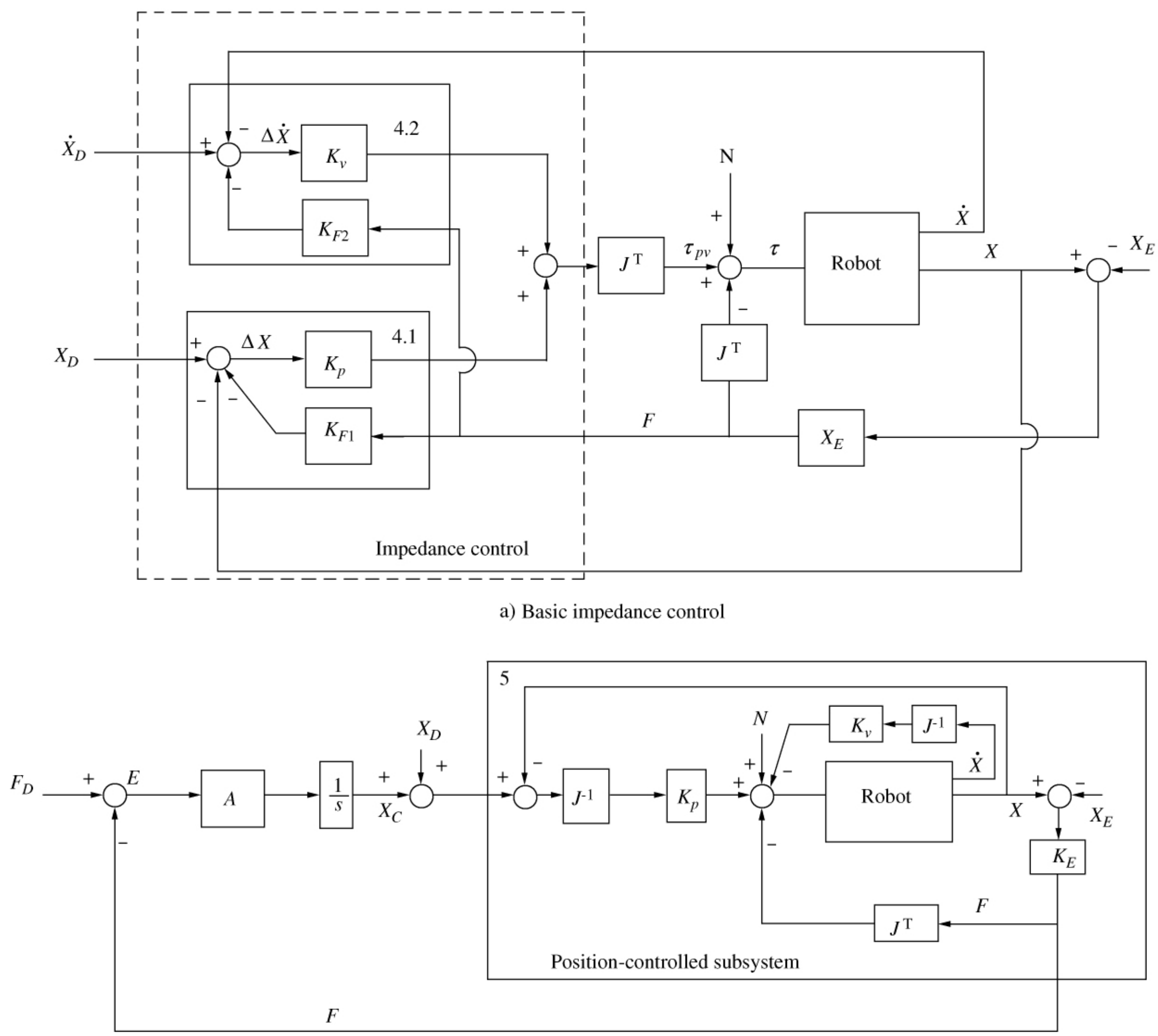
$$sZ_m(s) = \frac{F(s)}{X(s)} = Ms^2 + Ds + K$$

$$A(s) = \frac{\dot{X}(s)}{F(s)}$$

Where Z_m is the mechanical impedance and A is the mechanical admittance; M, D and K represent the desired inertia, damping and stiffness matrices, respectively.

Impedance control is to guarantee the behavior of the controlled system acting as dictated by an equation.

Figure 5a) shows the structure of a basic impedance control loop, which determines an appropriate value for Z_m. From the figure we can see that the impedance control is actually similar to the stiffness control except that there is an additional feedback loop for the velocity and the effect of the contact force on the velocity, described by the stiffness matrix K_{F2}. In this sense, impedance control is a proportional and derivative controller in which the measured forces are used to modify the position and velocity. The position modification results from multiplying the sensed forces by matrix K_{F1} that has the same role as in the stiffness control. The velocity modification results from multiplying the sensed forces by matrix K_{F2}. Both of the modifications add up to generate the control torque for the robot. K_E is a stiffness related to the environment. One should also note that from the definition of the impedance, the velocity is related to the damping of the system, therefore the impedance control is capable of modifying the damping, and thus normally employed when a robot needs to adapt to the damping characteristics of its environment.



a) Basic impedance control

b) Admittance control

Figure 5 Basic impedance control and admittance control

Admittance is actually the inverse of the impedance noticing that $\dot{X}(s) = sX(s)$. Figure 5b) shows the structure of a common admittance control. The output force is used as the feedback and the admittance matrix A relates the force error vector between the output force and desired force to the velocity of the end-effector, which is later transformed to the end-effector displacement by integration. This correction together with the desired displacement is used as the input to a basic position control system. Comparing with the impedance control, admittance control focuses more on desired force tracking control.

4 Hybrid force/position control

Hybrid position/force control combines force and torque information with positional data (based on a position control system). In hybrid position/force the position control and force control are considered seperately. Figure 6 shows the hybrid position/force control scheme; the output force and displacement are used as the feedback for the force and displacement control, respectively. Here S is called the compliance selection matrix, which is a diagonal matrix that has either 1 or 0 on its diagonal. The matrix S hence determines the degree of freedom for which force or position are to be controlled, which guarantees the uncoupling between position control and force control, and allows us to design their control law separately. With this setup, different control performance requirements for the desired position and force trajectories tracking can be simultaneously realized. The command torque is the combination of the torques from the position. τ_p is force control τ_f. Normally, the position control law consists of a PD action, and the force control law consists of a PI action. This is because for the position control a faster response is more desirable, and for the force control a smaller error is more preferable. The command torque is then used as the input of a general robot system which may contain gravity and environmental compensations.

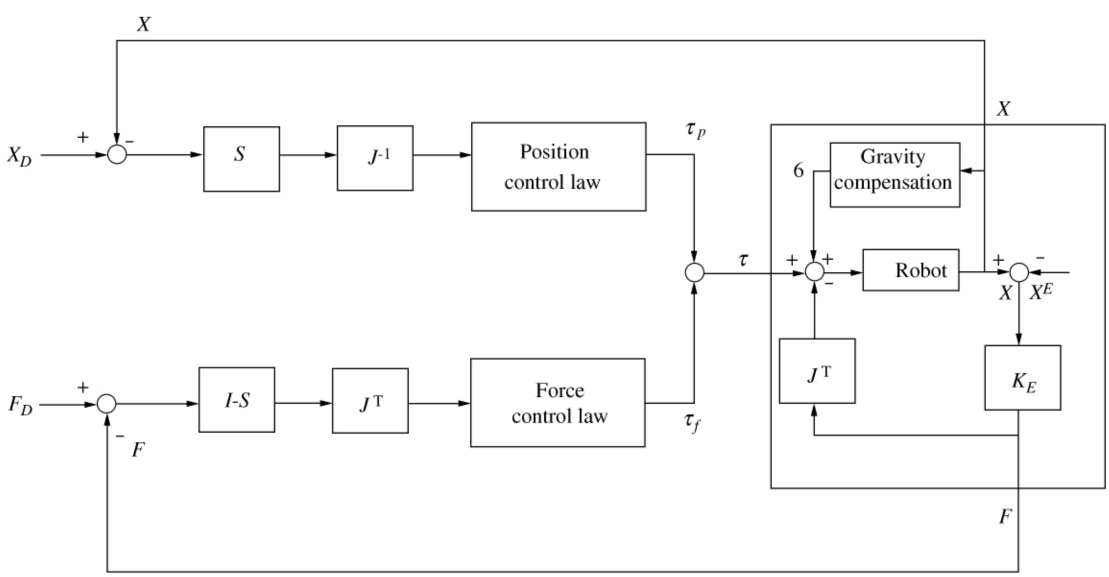


Figure 6 Hybrid force/position control

5 Conclusions

In this paper, an overview of robotic position and force control techniques has been made. The existing fundamental force control algorithms are discussed, including explicit/implicit control, stiffness control, impedance/admittance control, and hybrid position/force control. Though there are still many other advance robot control methods available, including adaptive control, robust control and learning control etc., they are not included. This work is intended to give a basic guidance for understanding and utilization of the fundamental robotic control algorithm.

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Brief Biographies

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