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Experiments in Object Impedance Control for Flexible Objects

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Abstract

This paper presents a control strategy for manipulation of flexible objects by multiple robot arms. The control policy developed in this paper for flexible objects is based on a controller developed previously for rigid objects: the object impedance controller. The controller compensates for the dynamics of both the arms and the object and responds to environmental forces with a fully programmable impedance relationship. For a class of flexible objects, the required extensions to object impedance control are outlined in this paper. The paper presents experimental results for a dual arm robotic system manipulating an object with a single flexible degree of freedom in both free-space and environmental contact tasks.

1 Introduction

The advantages of using multiple manipulators include increased payload capability, improved dexterity with larger objects, and expanded functionality. Most previous research, however, focused on developing control strategies for multiple robotic arms manipulating a single, rigid body. This research ranges from early work on the coordination of multiple arm robot systems [1] to more recent studies by many on hybrid position/force control [2] [3].

Various potential robotic applications, from the assembly of spring-loaded parts in a manufacturing environment to the servicing of satellite solar arrays in orbit, will involve the manipulation of flexible objects by multiple robotic arms. Some previous work has been done on the control of flexible objects with robotic manipulators. This body of work addresses various aspects of the problem, including trajectories and task formulation. For example, Dauchez, et. al., presented experimental results for a pair of 6 dof arms deforming a spring and transporting the spring in the deformed state [4]. The principal contribution of the research was the method they used to describe the task with "virtual sticks". Zheng and Chen have performed some research on trajectory generation for deformation of flexible beams and plates by a pair of robotic manipulators [5]. This work compared trajectory generation methods for the deformation of a flexible plate by a pair of manipulators using the forces and torques measured at the endpoints as a performance measure. This project was also verified experimentally. While these projects offer some interesting insights into manipulation of flexible objects, neither looks at tasks involving interaction with the environment.

One of the most promising and general approaches to cooperative manipulation is object-based control. This technique allows the operator to issue task-level commands, such as "capture this object" or "insert this connector into that fixture". The controller takes care of the details of the operation, drawing upon a library of task primitives, freeing the user to perform other tasks. This capability has been developed and demonstrated successfully on a wide variety of experimental platforms [6] [7].

Object impedance control (OIC) was developed as an object-based control policy to control a pair of cooperative robotic arms manipulating a rigid object [8]. Object impedance control offers several significant advantages over other cooperative control policies, including full dynamic compensation for the arms and the object without calculation of the closed-chain equations of motion, good performance in both free motion and contact without control-mode switching, a parallel structure amenable to multiprocessor implementation, and simple interfaces to higher-level strategic controllers and lower-level arm dynamic controllers.

The goal of this research is to extend object-level control to flexible objects. This paper develops the flexible-object impedance controller, which extends the benefits of object impedance control to a class of flexible objects. This controller is implemented for a sys-

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tem consisting of a pair of two-link robotic manipulators working with a flexible object. Experimental results are presented for a variety of tasks, including both free-space motions and assembly operations.

2 Control Strategy

2.1 Control Goals

Impedance control, as developed by Hogan [9], enforces a relationship between the position and velocity of a controlled system and the force exerted on the system by the environment. Object impedance control extends this approach to the object level. Ideally, the object impedance controller makes each degree of freedom (dof) of the controlled object react to external forces with a programmable impedance.

The controller modifies the actual dynamics of the object to match the desired behavior specified by the impedance law. To understand some of the benefits of the impedance controller, it is easiest to separate the object into rigid body degrees of freedom and flexible degrees of freedom. For the rigid body modes, the impedance law makes the object behave as if it were attached to the environment via an orthogonal set of damped springs to a selectable point in the environment. Moving the spring endpoint results in motion of the object and placing the spring endpoint inside an obstacle in the environment will result in a controlled force exerted on the environment. Also, the point where the spring-damper system attaches to the object can be varied. For example, during an insertion, the spring attachment point could be moved from the center of mass to the connector on the object to produce a pseudo remote center of compliance (RCC). For the flexible modes of the object, the impedance law enables the operator to specify stiffness and damping for each dof.

2.2 Controller Derivation

The previous derivation of the object impedance controller assumes a rigid body [8]. For this case, the object's equations of motion were shown to be:

$$\mathbf{M}_{act}(x)\ddot{\mathbf{x}} + \mathbf{C}_{act}(\mathbf{x},\dot{\mathbf{x}}) = \mathbf{F}_{ext} + \mathbf{W}\mathbf{F}_{act} \tag{1}$$

where $\mathbf{M}_{act}$ represents the mass matrix, $\mathbf{C}_{act}$ the other terms due to the dynamics of the object, $\mathbf{F}_{ext}$ the forces from the environment, $\mathbf{W}$ the grasp matrix, and $\mathbf{F}_{act}$ the actuator forces.

For a rigid body system, $\mathbf{x}$ is a 6 by 1 vector that contains the center of mass coordinates of the body and $\mathbf{F}_{act}$ is a 6n by 1 vector containing the forces and torques applied by the n actuators. Thus, each arm grasping the object has sufficient degrees of actuation (doa) to fully control the object. The controller does not break down, however, when each arm has fewer doa than the object has dof, provided the sum of the actuation degrees for all of the arms grasping the object equals or exceeds the object's dof. This constraint does not present a significant problem for rigid objects, since, in most cases where multiple arms grasp the object, the number of doa will exceed the number of dof of the object, creating a redundant system.

Equation 1 can describe the equations of motion for more complex objects, including objects with lumped flexibility. In this case, however, the number of dof in the object could exceed the number of doa in the manipulators. Also, internal dynamics could separate the actuator inputs from the desired control coordinates, depending upon how the object is grasped. If these conditions do not exist, however, for a particular system, it is possible to fit it into the object impedance control framework.

Given the equations of motion for a system with lumped flexibility in the form of Equation 1, a simple test for the applicability of object impedance control involves calculating $rank(\mathbf{W})$. If $rank(\mathbf{W}) \geq n$ where n represents the number of degrees of freedom of the object, then object impedance control can be successfully applied to the system with only minor modifications.

As in the system with a rigid object, the desired object behavior can be specified in matrix form:

$$\mathbf{M}_{des}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{C}_{des}(\mathbf{x},\dot{\mathbf{x}}) = \mathbf{F}_{ext} + \mathbf{F}_{imp} \tag{2}$$

where $\mathbf{M}_{des}$ represents the desired mass matrix, probably diagonal, $\mathbf{C}_{des}$ the desired nonlinear terms, and $\mathbf{F}_{imp}$ the impedance force. For flexible objects, however, the vector $\mathbf{x}$ is augmented to include coordinates that describe the flexible degrees of freedom as well as those describing the rigid body motions. The only limitation placed on these coordinates is that they fully describe the position of the object.

Solving Equation 2 for $\ddot{\mathbf{x}}$ and using the result to set the commanded acceleration of the object, $\ddot{\mathbf{x}}_{cmd}$, produces the equation:

$$\ddot{\mathbf{x}}_{cmd} = \mathbf{M}_{des}^{-1}(\mathbf{F}_{ext} + \mathbf{F}_{imp} - \mathbf{C}_{des}) \tag{3}$$

Similarly, substituting this result into Equation 1 and solving for $\mathbf{F}_{act}$ produces the commanded actuator forces, $\mathbf{F}_{cmd}$, for each of the manipulators:

$$\begin{aligned}\mathbf{F}_{cmd} \quad = \quad & \mathbf{W}^{\dagger}\{\mathbf{M}_{act}[\mathbf{M}_{des}^{-1}(\mathbf{F}_{ext} + \mathbf{F}_{imp} - \\ & \mathbf{C}_{des})] + \mathbf{C}_{act} - \mathbf{F}_{ext}\}\end{aligned} \tag{4}$$

where $\mathbf{W}^{\dagger}$ represents the weighted pseudo-inverse of $\mathbf{W}$.

To compensate for the dynamics of each arm, the object-level controller also generates the desired accelerations for each grip point based on the object kinematics. The desired accelerations and forces for each arm are then passed to the arm controllers, which use the arm equations of motion to calculate the appropriate joint torques.

2.3 External Force Estimation

Since impedance control attempts to respond to external forces with a programmable impedance, the controller requires some estimate of these external forces. Equation 1 can provide this estimate, assuming $\ddot{\mathbf{x}}$ and $\mathbf{F}_{act}$ are measured/estimated. For the experiments presented here, a pseudo-differentiator cascaded with a 2nd order low-pass filter on the velocities was used to produce estimates of the actual accelerations, $\ddot{\mathbf{x}}$. Actuator limitations often meant that the actual forces applied by the arms did not equal the commanded forces, so the readings from the force sensors located at the arm endpoints were used for $\mathbf{F}_{act}$.

2.4 Controller Block Diagram

Figure 1 depicts a block diagram of the resulting controller, the flexible-object impedance controller. The shaded object-level controller box incorporates all changes from the rigid OIC to enable control of flexible objects. In the flexible object impedance controller, measured and desired positions and velocities of the object are used to calculate an appropriate impedance force, and measured forces at the manipulator endpoints are used to estimate the external force on the object. The desired behavior equations use these two signals to generate a new commanded acceleration. Object kinematics translate the desired object acceleration into desired endpoint accelerations while the object dynamics generate consistent commanded endpoint forces. The arm controllers use these two commands to generate appropriate torques. Measurements of the object position and velocity along with the forces applied by the arms to the object close the loop.

3 Experimental Apparatus

The experimental hardware consists of a pair of robotic manipulators, the flexible object, the real-time control computer system, an overhead vision system, and a Sun workstation. More detailed descriptions of the manipulators, real-time vision system, and computers are contained in [10] while [11] describes the flexible object in greater detail.

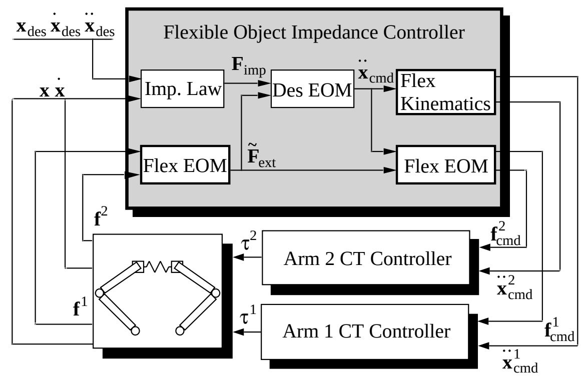

Figure 1: **Block Diagram**

Block diagram for the flexible-object impedance controller. Interfaces to the higher-level strategic controller and lower-level arm controllers remain unchanged.

3.1 Cooperating Manipulators

The robotic manipulators are direct-drive, two-link arms in the SCARA configuration. The arms move in a plane and interact with objects floating on air-bearings over a granite surface plate, providing a two-dimensional simulation of the drag-free, zero-gravity environment of space. Each arm is equipped with a pneumatic gripper instrumented with strain gauges that fits into ports on the floating objects.

The manipulators have a reach of 0.65 meters. Joint angles are measured by a rotary variable differential transformer (RVDT) mounted on each motor shaft. A camera mounted on the ceiling and a 2-d vision system provide manipulator endpoint position as well as position information for various objects within the workspace at an update rate of 60 Hz using passive vision targets mounted on both the arm endpoints and the objects.

3.2 Flexible Object

The flexible object consists of two pads that float on an air cushion over the granite surface plate. These pads are joined by a six bar linkage. The linkage is designed to add a single flexible degree of freedom to the object. Figure 2 shows the object in both the nominal configuration (solid lines) and the deformed configuration (dashed lines). The circles represent pin joints in the mechanism while the thicker lines show the two sections of steel wire that give the object its flexibility. Each pad also has two gripper ports and a target for

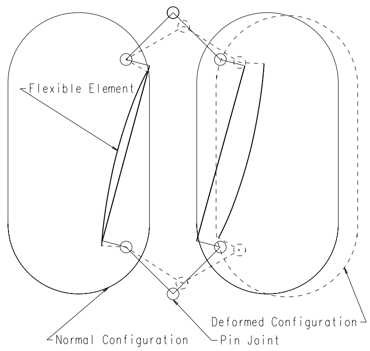

Figure 2: **Flexible Object**

This flexible object, which floats on a granite surface plate, uses a six bar mechanism with 2 flexible elements to provide a single flexible degree of freedom.

tracking by the overhead vision system (not shown in the drawing).

4 Implementation

In discussing the implementation of flexible-object impedance control for the experimental system, several details become important. First, as Figure 3 shows, each half of the flexible object has a pair of gripper ports, represented by circles in the drawing. With a pair of robot arms, several possible grasp configurations are possible. For these experiments, each arm grasped a different half of the object. Second, the coordinates used to derive the kinematic and dynamic equations describing the flexible object are depicted in Figure 3. So, $\mathbf{x} = [x1\ y1\ \theta\ s]^T$ for the impedance law used for the experiment.

5 Experimental Results

5.1 Trajectory Tracking

The first experiment compares the performance of the flexible-object impedance controller (FOIC) to the object impedance controller (OIC) for a free space slew of the flexible object. The OIC only has a rigid model of the flexible object, including accurate inertia parameters but neglecting any flexibility. The rigid object impedance controller, described in [8], attempts to control the x, y, and θ coordinates of the center of mass of the object. The slew performed, depicted in Figure 4, moves the object 0.6 meters in X, 0.4 meters in Y, and 2 radians in θ in 2.5 seconds. The actual command reference is a fifth-order trajectory in x, y, and θ, while the spring compression should remain constant at 0.

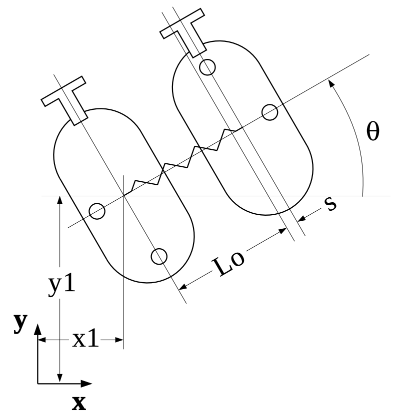

Figure 3: **Coordinate Definitions**

The coordinates used to derive the equations of motion for the experimental flexible object.

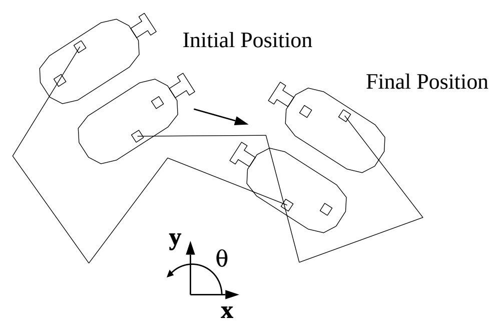

Figure 4: **Example Slew**

Slew used to compare object impedance control to flexible-object impedance control.

As Figure 5 shows, both controllers move the center of mass of the object along the desired trajectory with very little error. During the slew, however, the flexible dof does get excited. The OIC, with no model of the flexibility, does not attempt to control the excited dof. The vibrations of the flexible dof do not affect the coordinates being controlled: the positions and velocities of the center of mass of the object. The FOIC, on the other hand, includes a model of the object's flexibility and explicitly controls the flexible dof. Thus, any deformation of the flexible dof is quickly regulated based on the desired impedance law.

5.2 Force Control

One of the benefits of impedance control is the ability to control both position and force using the same controller. To test this ability, an obstacle was placed in the path of the flexible object during a 4 second slew in the **x** direction. The top plot in Figure 6 con-

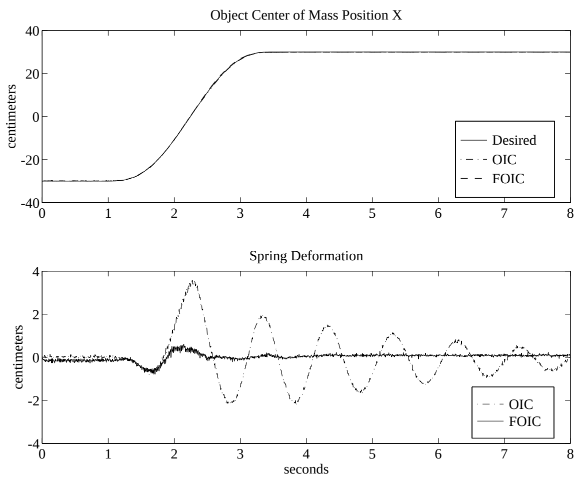

Figure 5: **Slew Performance Comparison**

The object impedance controller without a model of the flexibility does not damp the flexible mode once it gets excited in the slew. The flexible-object impedance controller, however, explicitly controls the flexible dof.

tains two traces: the estimated external force from the controller, and the force that would exist between the object and the environment if the object exhibited the desired impedance. The test consists of 2 steps. First, the flexible object collides with a granite block placed in it's path. This occurs toward the end of the slew (the slew ends at the 2 second mark on the plot). Second, just after 4 seconds, a step command in desired position of the object was given to increase the force exerted on the granite block. The rise time between the ideal and actual forces is a characteristic of the filtering of the estimated external force.

The bottom plot in Figure 6 shows that the flexible dof remains undeformed, besides a few brief transients, during this operation. This occurs despite the fact that the object exerts a 2 Newton force on the environment in the **x** direction.

This experiment demonstrates that the flexible object impedance controller can stably contact a stiff environment without switching control modes and that it can regulate the interaction forces between the object and the environment.

5.3 Insertion Task

The last experiment presented in this paper demonstrates the ability of the flexible-object impedance controller to perform a typical task. The selected task involves inserting a male connector located on the object, depicted in Figure 3 as the T-shaped objects at the top of each half of the flexible object, into a female connector in the environment. The target assembly operation requires controlled deformation of the flexible object to succeed.

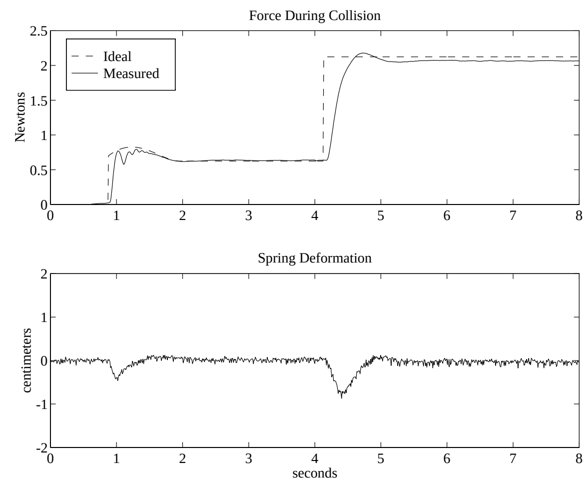

Figure 6: **Contact Force Control**

The extended object impedance controller can bring the controlled object into stable contact, even with a very stiff environment.

Figure 7 depicts the sequence of motions to perform the insertion. Note that flexible dof must be deformed for the assembly to work and this deformation must be controlled to within a few millimeters when rotating the object into place between snapshots 4 and 5.

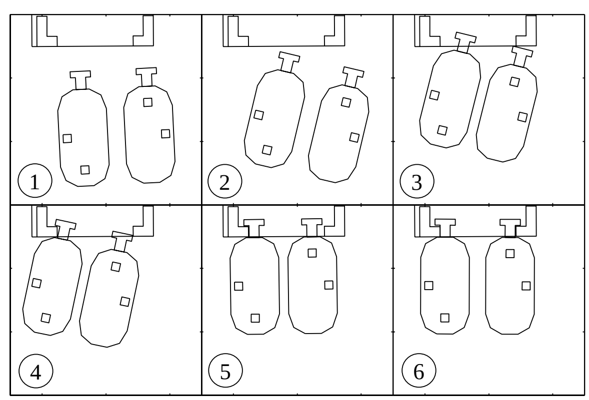

Figure 7: **Assembly Sequence**

The strategic controller uses this sequence of motions to perform the assembly task.

Figure 8 shows the forces between the flexible object and the fixture during the assembly task. The upper plot shows the estimated external forces acting in the

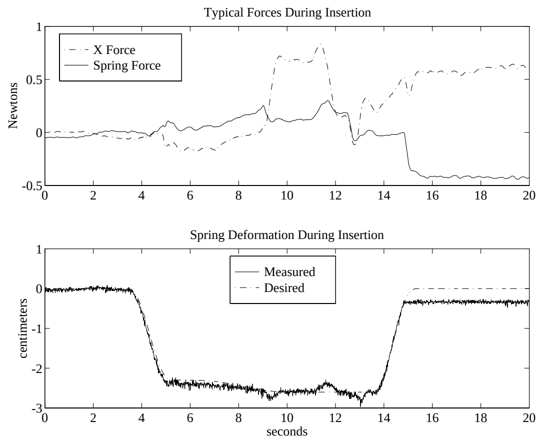

Figure 8: **Insertion Forces**

Typical forces and spring deformation during the assembly task.

x direction and to deform the spring. The bottom plot shows the desired and actual values for the spring deformation during the assembly task. During the operation, the strategic-level controller modifies the desired stiffnesses in the various controlled dof. While the x1 and y1 dof become more compliant, the stiffness for the spring deformation increases due to the tight tolerances on the assembly task. At the conclusion of the assembly operation, the deformation of the spring is held at a non-zero value by the fixture.

6 Conclusions

This paper presents an extension of object impedance control to a class of flexible objects. To apply flexible-object impedance control as outlined in this paper, the rank of the grasp matrix must be greater than or equal to the number of degrees of freedom of the object. If this condition is met, applying flexible object impedance control requires developing a lumped parameter model of the object and adding coordinates that describe this lumped parameter model to the impedance control law.

If applicable, flexible object impedance control offers all of the advantages of object impedance control: full dynamic compensation, simple interfaces to higher and lower level controllers, and good performance in both free-space and contact tasks with no control mode switching.

The flexible-object impedance controller was experimentally demonstrated effective in performing typical tasks that might be required of a cooperative robot system manipulating a flexible object: accurate trajectory tracking, stable contact and force control, and assembly operations requiring controlled deformation of the flexible object.

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