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COOPERATIVE MANIPULATION OF FLEXIBLE OBJECTS: INITIAL EXPERIMENTS

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Abstract

The vast majority of the work done on multiple manipulator systems has focused on manipulating rigid objects, both in free-space motion and contact tasks. Not all objects encountered in potential robotic applications are rigid, however. Spring-loaded parts, lightweight space structure members, and heavy cabling provide just a few examples of flexible objects that robots may need to manipulate in the future.

This paper presents a testbed for the study of cooperative manipulation of flexible objects. It discusses some of the important characteristics required for this study. Using this testbed, the limitations of two control strategies used for manipulation of rigid objects are demonstrated when applied to flexible objects. The results justify the validity of the testbed as well as providing motivation for further study.

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. What happens when the manipulated object is flexible? 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 manipulators.

One of the most promising and general approaches to cooperative manipulation is object-level 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 [1, 2, 3].

The goal of this research is to extend object-level control to flexible objects. This paper presents some preliminary findings. First, an experimental testbed is described. It consists of a pair of arms and a flexible object. Next, two attempts to apply previously developed control strategies to a flexible object using this experimental testbed are discussed. The first, Object Impedance Control (OIC), developed for cooperative manipulation of rigid objects, performed poorly in attempts to regulate the free space motion of the object. In fact, this controller was unstable for higher object stiffnesses. The second control strategy, a coordinated PD control, was stable and could perform free space manipulations without undue excitation of the object's flexibility. The coordinated PD controller, however, proved insufficient for tasks involving deformation of the object. These results show that current controllers, designed for manipulation of rigid objects, perform poorly when applied to a flexible object and that the experimental testbed embodies the problem of interest.

Related Work

Some 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. It does not, however, focus on the interaction between the flexibility and the controller.

Zheng and Luh [4] used a flexible object to eliminate kinematic redundancy problems in their early work on coordinated control of multiple manipulators. These results seem to indicate that, in some cases, flexibility in the object may make the task of controlling such systems easier.

Recently, Dauchez, et al, presented experimental results for a pair of 6 dof arms deforming a spring and transporting the spring in the deformed state [5]. They used symmetric hybrid position/force control. The principal contribution of the work was the method they used to describe the task with "virtual sticks".The algorithm used, however, was so computationally complex that the controller ran at 20 Hz. Also, the hybrid control approach requires task dependent control mode switching. This can be a disadvantage when performing complex tasks.

Zheng, Pei, and Chen [6] have also done work on assembly of deformable objects. The assemblies involved sliding a long, flexible beam into a hole with a single manipulator. The principal contribution of this work was determining the proper trajectory for the arm to follow based upon the beam properties and the tightness of fit.

The goal of this research is to explore the interaction between object flexibility and the system controller.

Design Objectives

Several criteria helped shape the design of the experimental apparatus used to study cooperative manipulation of flexible objects. First, the arms should be as "ideal" as possible. An "ideal" arm would produce specified forces and accelerations at the endpoint exactly. This allows the experiments to focus on the problems introduced by flexibility in the object rather than those caused by friction at the robot joints, flexibility in the drive train, etc. The goals in designing the flexible object included (1) introducing the flexibility at a frequency of interest within the bandwidth of the control system, (2) providing the capability to change the natural frequency and stiffness of the flexible element in order to study the effect of varying these parameters, and (3) creating an object that was deformable with the available actuators in order to study assembly operations requiring deformation of the object. Finally, the testbed should not be so geometrically complex that the computational speed of the control computers severely limits the algorithms that can be applied to the system.

Experimental Apparatus

Addressing the last of the design criteria, the experimental testbed is limited to 2 dimensions, simplifying the computational complexity significantly. The flexible object has 4 degrees of freedom (DOF) and each manipulator has 2 DOF. The flexible object floats on air bearings over a granite surface plate, eliminating the effects of gravity on the system and simulating the drag-free environment of space. These simplifications enable the research to focus on the problem of interest: how flexibility affects the control of an object grasped by multiple manipulators.

Cooperating Manipulators

Figure 1 depicts one of the pair of experimental arms. Each manipulator is a direct-drive, SCARA two-link arm, with revolute "shoulder" and "elbow" joints. At the tip of each arm is a two-dimensional force sensing pneumatic gripper. These grippers fit into ports on the manipulation objects. The connection is mounted on a bearing pin joint, so the manipulator cannot apply torque at the connection. The system thus provides frictionless two-dimensional motion.

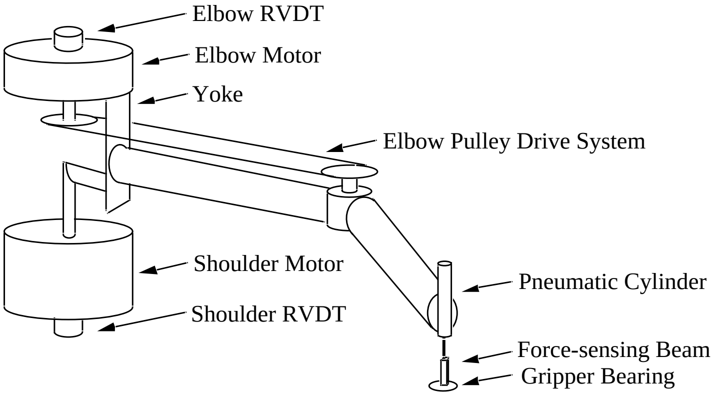

Figure 1: **Arm Schematic**

A schematic view of one of the two link, SCARA, arms used in the experimental testbed.

The manipulators have a reach of 0.65 meters and are separated by 0.60 meters at the shoulder hub. The motors on the manipulator are DC limited-angle torquers. A motor located at the shoulder transmits torque to the elbow joint through a steel cable. Joint angles are measured by a rotary variable differential transformer (RVDT) mounted on each motor shaft. Each arm also has a vision target located over the gripper for use with an overhead vision system. See [7] for a detailed description of the manipulators.

Many factors, including the direct drive nature of the arms, the vision and force sensors at the endpoint, the two dimensional nature of the experimental system that eliminates the need for gravity compensation, and accurate calibration of the motors bring these manipulators close to the "ideal".

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. These segments can easily be switched out to change the stiffness of the flexibility in the object. Each pad also has two gripper ports and a target for tracking by the overhead vision system (not shown in the drawing).

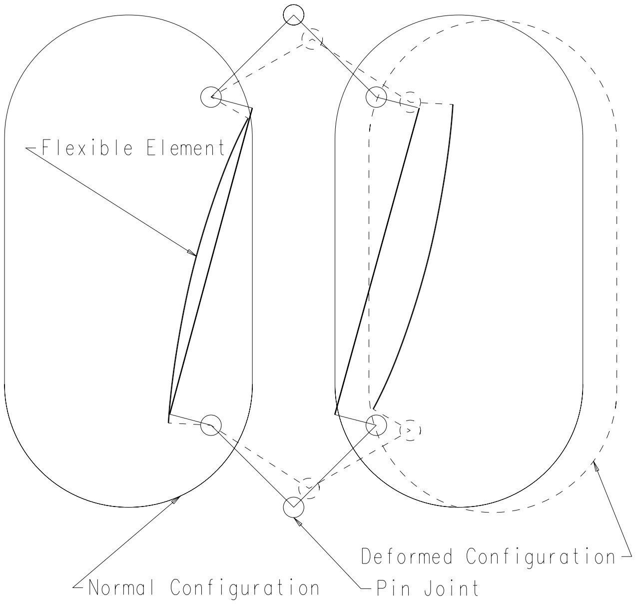

Figure 2: **Flexible Object**

This flexible object, which floats on a granite surface plate, uses a six bar mechanism with 2 flexible elements. The object thus has three rigid degrees of freedom and one flexible degree of freedom.

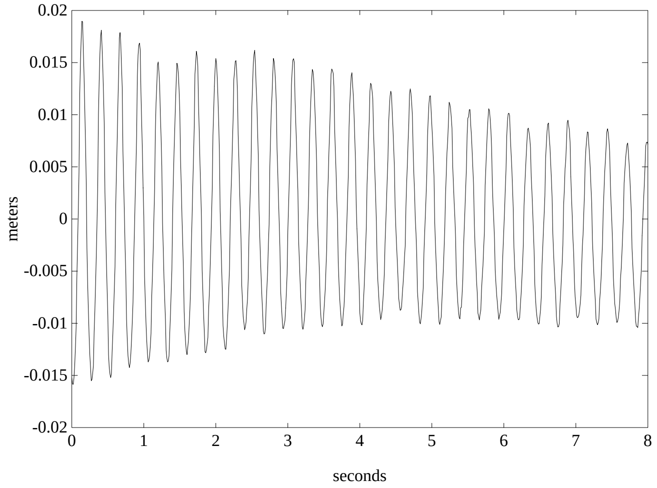

Figure 3: **Free Vibration of Flexible Object**

This plot shows the deflection from the nominal separation of the two pads of the flexible object for a nonzero initial condition. Note the lightly damped response.

As Figure 3 shows, the free vibration of the flexible object, with the particular stiffness used in these initial experiments, has a natural frequency of 3.06 Hertz. This plot also shows the very lightly damped characteristic of the linkage. The linkage gives the object a range for the distance between the pads of between .025 meters and .09 meters, with a nominal separation of .064 meters.

Current Control Strategies

This section briefly outlines the two control strategies applied to the experimental system. The motivation for these experiments was to demonstrate that deficiencies exist with current control strategies when applied to flexible objects and to test the validity of the experimental testbed.

Object Impedance Control

The Object Impedance Control (OIC) strategy enforces a controlled impedance of the manipulated object [8]. Equation 1 contains the particular impedance relationship chosen for this controller.

$$m_d(\ddot{x} - \ddot{x}_{des}) + k_v(\dot{x} - \dot{x}_{des}) + k_p(x - x_{des}) = f_{ext} \quad (1)$$

Here, x is the coordinate of any one DOF of an arbitrary frame fixed relative to the object's frame. The constants m_d, k_p, and k_v can be specified independently for each degree of freedom. x_{des} represents the desired position of the chosen frame and $\ddot{x}_{des}$ is acceleration feedforward. The derivation of the control equations based on the desired object behavior specified in Equation 1 is fully contained in Schneider [8]. Basically, the controller attempts to cancel the actual object dynamics and make the object behave according to Equation 1. This produces a desired acceleration, $\ddot{x}_{des}$, and force, f_{des}, at each arm endpoint. Then, if M and J represent the mass matrix and Jacobian for a given arm and q is the vector of joint angles, the arm kinematics yield:

$$\ddot{q}_{des} = J^{-1}(\ddot{x}_{des} - \dot{J}\dot{q}) \quad (2)$$

Combining this with the arm equations of motion, where C contains the nonlinear coriolis and centrifugal terms,

$$\tau = M\ddot{q}_{des} + C(q, \dot{q}) + J^T f_{des} \quad (3)$$

produces the desired torques for each arm, τ. These equations are for the simplified planar case.

This technique requires an accurate model of the dynamic behavior of the object. It also uses the location of the object in the feedback loop. Endpoint feedback techniques are generally not very robust to the introduction of unmodelled modes of vibration. Consequently, the unmodified Object Impedance Controller applied to a flexible object was expected to perform poorly.

Object PD Control

The second control strategy tested was a very simple coordinated PD control. Coordinated control refers to an approach that uses the desired motion of the center of mass of the object to calculate the desired motion of the the grip points. This control makes no attempt to compensate for dynamic forces, relying on the strictly kinematic relationship between the grip points and the object center of mass. This approach treats the arms as a simple force source, calculating the force that each arm should apply using a PD control law on the gripper port. This yields

$$f_{arm} = k_p(p_{des} - p) + k_v(\dot{p}_{des} - \dot{p}) \qquad (4)$$

where f_{arm} is the desired arm endpoint force, k_p and k_v are specifiable position and velocity gains, p represents the endpoint position of the arm, and p_{des} is the desired arm endpoint location. The desired arm endpoint location, p_{des}, comes from the kinematic relationship between the desired object center of mass and the grip point on the object. The controller simply runs the desired endpoint force, f_{arm}, through the Jacobian, J, to produce the torques at the joints, τ.

$$\tau = J^T f_{arm} \qquad (5)$$

This control should be stable regardless of the object's dynamics, since it essentially treats the motion of the object, including the flexibility, as a disturbance to the arm endpoint.

Experimental Results

Object Impedance Control

Experimentally, the Object Impedance Control strategy proved unstable for motions that provided sufficient excitation to the flexible object. Figure 4 shows a time history of the spring mechanism compression for a slew of 0.15 meters in 1.0 seconds in the upper plot. The lower plot shows the desired and actual center of mass X position. The slew begins at about 1.5 seconds. Clearly, the interaction between the object's flexibility and the controller is leading to instability. Also note that, despite the excitation of the flexibility, the object's X position does not deviate significantly from the desired.

Object PD Control

As Figure 5 shows, the gripper point PD controller was stable for the same slew that caused the object impedance controller to go unstable.

So, the simple PD controller works well for free space motions. While the flexibility was excited somewhat, the PD controller quickly damped it out once it began regulation.

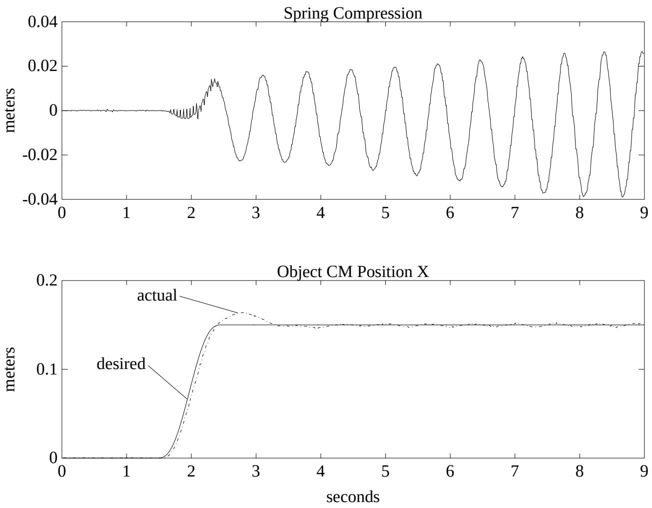

Figure 4: **Object Impedance Slew**

As this plot of the spring compression during a slew shows, the Object Impedance Controller can excite the flexible mode in the object.

The next test involved directly manipulating the flexibility in the object. Figure 6 shows the distance between the ports for a desired compression of -0.12 meters beginning at about 2.5 seconds. The actual compression achieved, -0.0275 meters in this case, depends upon the proportional gains used in the controller. Also note that the object rotates as it compresses. So, while this simple coordinated PD controller can damp out the object vibrations when the spring is unstretched, it does not control the object adequately for manipulations involving deformation.

Conclusions

This paper describes a hardware testbed developed to study the problem of manipulation of flexible objects. It discusses the criteria used to design a testbed to study the problem of interaction between the system controller and the flexibility in the object. A flexible object composed of two rigid bodies coupled by a mechanism designed to be flexible in one dimension is the principal difference between this system and systems studied in previous work. To validate the testbed and demonstrate that a problem does exist, two controllers were applied to the experimental system. For the first strategy, Object Impedance Control, the results demonstrated a sensitivity to modelling error. The controller performed marginally, at best, and sometimes proved unstable, depending upon the stiffness of the object. The second approach, a coordinated PD controller was stable and did exhibit reasonable performance in free motion. However, it did a poor job of con-

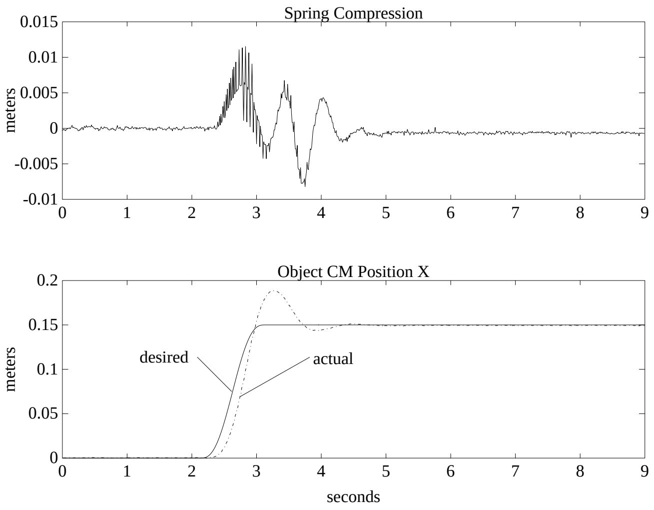

Figure 5: **PD Slew**

While the PD controller applied to the flexible object exhibits significant overshoot, it does damp out any excitation of the flexibility.

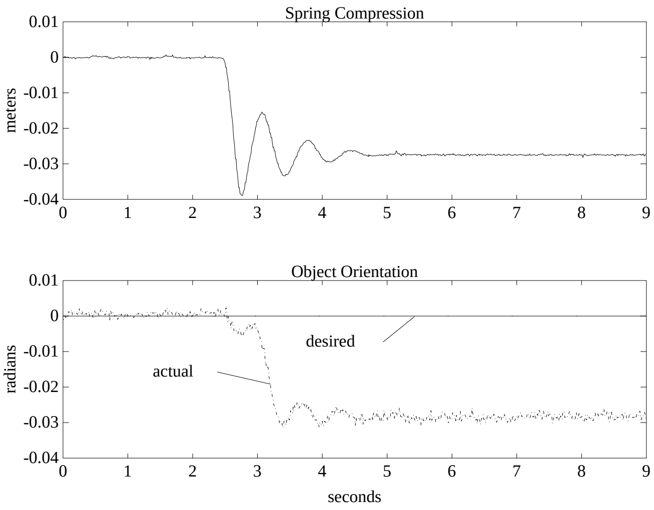

Figure 6: **PD Spring Compression**

When commanded to deform the flexible object, the PD controller rotated the object as well as compressing it.

trolling the object for tasks that involved deformation.

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