AN EXPERIMENTAL COMPARISON OF TRADEOFFS IN USING COMPLIANT MANIPULATORS FOR ROBOTIC GRASPING TASKS

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Technical Report No. 96-015
Control and Dynamical Systems
(Submitted on September 15th, 1996.)

ABSTRACT. Controllers developed for control of flexible-link robots in hybrid force-position control tasks by a new singular perturbation analysis of flexible manipulators are implemented on an experimental two-robot grasping setup. Performance criteria are defined for the grasping task. We present preliminary experimental data to show the tradeoffs between controller complexity and performance enhancement as we deal with greater flexibility. Various performance criteria are set up and experimental results are discussed within that setting. We conclude that large flexibility can be controlled and can lead to reasonable performances.

1. INTRODUCTION

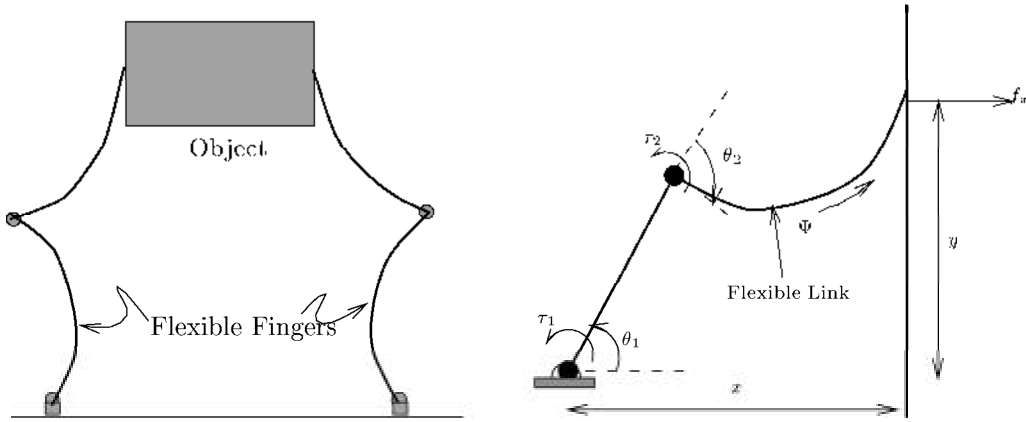
In this paper we present experimental results on grasping with flexible link robots. The theoretical basis of this work is [11] [10] where we developed the controllers we use for this experimental study and formally proved their stability.

This work is motivated by the need to decrease the size and weight of robot manipulators while at the same time increasing performance. Examples of some of the applications to which this work applies include space manipulation tasks, where the weight limitations of the manipulator introduce significant flexibilities, and non-invasive surgical techniques, where the size of the manipulator (2–6 mm fingers) and the environment in which it operates make the use of small flexible links a potentially attractive alternative to existing methods. In addition, many micro- and nano-robotic devices make use of flexible elements as an integral part of their structure [8].

In addition to understanding the effects of flexible links on manipulation tasks, our research is directed at exploring the *benefits* of using flexible links in robotic manipulation tasks. It is well known that compliance increases the robustness properties of a robot manipulator performing a task. Rather than try to design away flexibilities because they increase the complexity of the system, it is important to try to gain an understanding of how to use flexibilities to increase the performance of a system. In a grasping situation, flexibilities in robot structures can be used for application of internal forces by pre-tensing the robot itself. Thus, small errors in control of position will be accommodated by the flexibility of the structure.

Control of robots with flexible links has so far concentrated primarily on positioning of the end-point of a flexible robot. Control of a single link flexible robot has been investigated at the theoretical as well as experimental level as early as 1984 [1]. The control of multiple-link, flexible robots is considerably more difficult and is an area of active research (see [2] for a recent survey). Experimental work in this area is particularly difficult to find, in part due to some of the theoretical difficulties inherent in the problem.

Considerably less work is available on the dynamics and control of flexible link robots in contact with the environment. Some initial work has been performed by Latornell and Cherchas, who have studied force and motion control of a single flexible manipulator link [4]. In addition, Kozel, Koivo and Mahil have studied



(a) Full grasping problem. (b) Simplified: finger against wall.

FIGURE 1. Full grasping problem and related simplified problem.

the force relationships between flexible manipulators in contact with their environment [3], Mills has studied the stability of a flexible link manipulator during constrained motion tasks using a singular perturbation approach [6], and Matsuno, Sakawa, and Asano have studied hybrid position/force control under quasi-static assumptions [5].

In what follows we present data from an experimental planar, two-finger setup with both flexible and rigid link robots. We performed grasping experiments with flexible and rigid link robots, using control laws presented in other publications. Multiple data runs are performed to determine the repeatability of the experiments and then analysed to extract meaningful information.

2. Controllers for force-position control of flexible manipulators

In this section we briefly describe the controllers we use to control our experimental setup. These controllers are discussed in detail in [10] and [11]. We shall therefore only mention relevant points in this paper.

In the references mentioned above we analysed a single flexible manipulator pushing against a wall as a simplified version of the full grasping problem (Figure 1). The extension of the results to the grasping case are fairly straightforward because the dynamic equations of both are similar. Each finger in the grasping setup can be viewed as a holonomically constrained manipulator (except in the case of finger rolling) which is identical to the case of a single manipulator pushing against a wall.

2.1. **Finite Link Model.** We wish to consider deflections in excess of those to which the linear model applies, but the full nonlinear beam model is not very tractable. Therefore, for our analysis and simulation, we choose to use a finite link model for the flexible link. This model replaces a flexible link with a series of rigid sub-links connected through linear torsional springs, such that the lengths of the sub-links add up to that of the original link. With appropriate values for the spring constants this model can estimate the actual modes of a flexible beam [12]. Larger numbers of sub-links improve the approximation. For example, it is shown in Zaki and El Maraghi [13] that three sub-links give a good approximation for the first mode of a free cantilever. The number of sub-links required to get good estimates for higher modes would of course be larger.

Figure 2 shows a two link planar robot finger pushing against a wall. Only the last link is flexible, and it is modeled by breaking the link into three sub-links of equal length. The various quantities shown in the figure are described in the next section.

2.2. **The Dynamic Model.** We use $q \in \mathbb{R}^n$ to denote the vector of all joint angles, Θ is the vector of actuated joint angles, Ψ the vector of unactuated joint angles and X the workspace variables (refer to

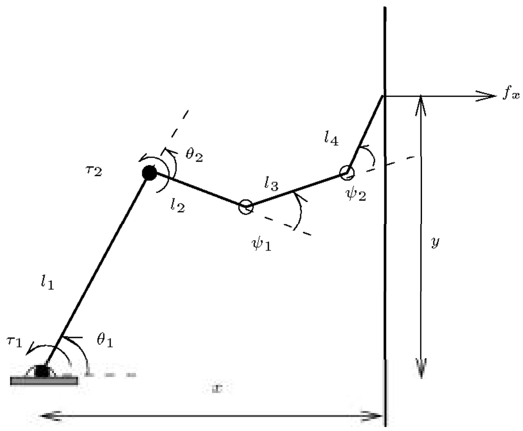


FIGURE 2. Finite link approximation.

Figure 2), i.e.,

$$q = \begin{bmatrix} \Theta \\ \Psi \end{bmatrix} \qquad \Theta = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} \qquad \Psi = \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix} \qquad X = \begin{bmatrix} x \\ y \end{bmatrix}.$$

The dynamic equation is then given by

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + K_s q + K_f \dot{q} + A\lambda = \begin{bmatrix} \tau \\ 0 \end{bmatrix},$$
$$h(q) = 0, \tag{1}$$

with,

M	the inertia matrix,
C	the coriolis matrix,
τ	the applied actuated joint torques,
K_s	diagonal matrix of spring constants (0s for joints without springs),
K_f	diagonal matrix of joint damping coefficients,
λ	the Lagrange multiplier from the constraint, and,
h	the constraint equation.

The bottom zeroes in the torque vector are due to the unactuated joints. Also note that λ is in this case the actual force of constraint against the wall.

We now introduce the controllers. The aim for all the controllers is to regulate the end-position of the manipulator to the desired point (X_0) and to apply a desired force(λ_0) against the constraint at the desired point.

2.3. **Joint-PD based control** [10]. This strategy requires precomputed values of the actuated joint angles and torques at the final equilibrium position desired. It should be pointed out that the computation of the equilibrium torques and angles is relatively simple (though recursive) as it is the solution to a problem of static equilibrium.

The controller action is a PD control on the joint angles with additional feedforward torques equal to the precomputed equilibrium values. In joint space the control torque is given by

$$\begin{bmatrix} \tau \\ 0 \end{bmatrix} = -K_p(q - q_0) - K_d\dot{q} + \begin{bmatrix} \tau_0 \\ 0 \end{bmatrix}, \tag{2}$$

where K_p and K_d are diagonal with the bottom two rows of each consisting entirely of zeroes and q_0 is the equilibrium position in joint space. Note that torques cannot be applied to the passive joints. The equilibrium torque, τ_0, is required to hold the manipulator at its equilibrium position.

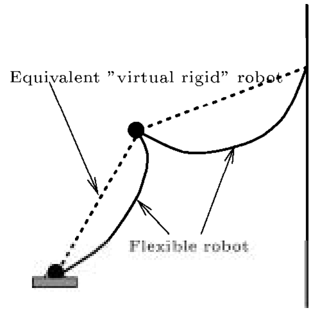


FIGURE 3. Motivation for a instantaneous Jacobian based controller.

2.4. **The $\mathbf{J}_*$ controller** [11]. A singular perturbation analysis of the flexible manipulator system shows the existence of two time-scales. The fast system stabilises to the reduced manifold and then the system evolves on the slow manifold. The important fact about the slow system is that it is completely determined by the actuated and sensed Θ variables. In what follows we use $J_{\alpha\beta} = \frac{\partial \alpha}{\partial \beta}$. The Jacobian between the configuration space and the workspace can be derived as follows for the reduced order system

$$X = g(\Theta, \Psi(\Theta))$$

therefore,

$$\dot{X} = J_{X\Theta}\dot{\Theta} + J_{X\Psi}\dot{\Psi} = (J_{X\Theta} + J_{X\Psi}J_{\Psi\Theta})\dot{\Theta} = J_*\dot{\Theta} \tag{3}$$

Note that J_* is a square matrix for a manipulator with number of actuated joints equal to the the number of workspace coordinates (which is the case we are dealing with) and we assume it is invertible in what follows (this is a reasonable assumption). In a real system we can compute J_* online from the knowledge of Θ and λ using the flexible-sublink model. Denoting the constraint $h = 0$ in the workspace as $s(X) = 0$, note further that J_{sX} is known and $J_{X\Theta}$ can be computed from the knowledge of the manipulator tip and the positions of its actuated joints.

The J^* control law is

$$\tau = J_*^T(K_p(X_0 - X) - K_d\dot{X}) + (J_{sX}J_{X\Theta})^T\lambda_0. \tag{4}$$

This is a workspace PD control law with the transpose of the Jacobian J_* being used to map the workspace position correction forces to the joint space. Note that since we derive J_* from the constraint equations its effect is restricted to the unconstrained directions. Therefore, its transpose cannot be used to transform static forces against the constraint, between the workspace and the joint space (like Jacobians for fully actuated non-redundant manipulators can).

2.5. **The Instantaneous Jacobian controller** [10][11]. We call $J_{X\Theta}$ the Instantaneous Jacobian of the flexible manipulator because it is the Jacobian of a rigid link robot with the same number of links as the original, with joints at the current actuated joint positions of the flexible robot, and endpoint coinciding with the endpoint of the flexible robot. $J_{X\Theta}$ is a Jacobian computable once the endpoint and the joint positions of the manipulator are known. Not only is the shape of the flexible beam not required, neither is a model of the flexibility required.

Consider a control scheme where the instantaneous Jacobian is constructed at each configuration of the finger based on feedback of the endpoint of the finger. It is then used to calculate the joint torques required to apply the desired force against the wall and to move the tip towards the goal point. The control law is given by

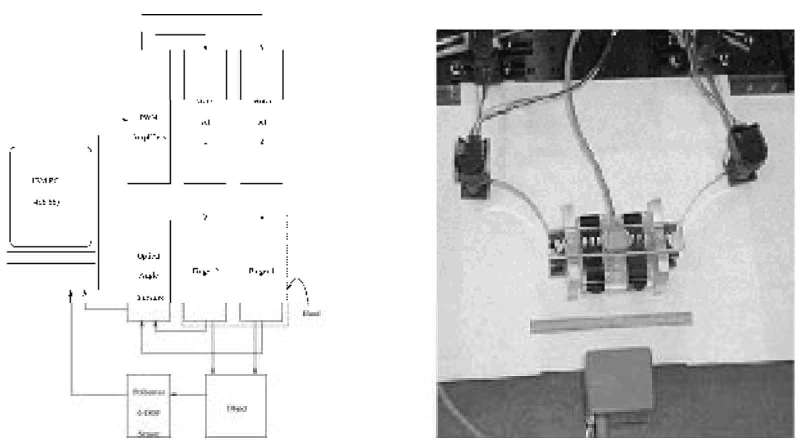
$$\tau = J_{X\Theta}^T(K_p(X_0 - X) - K_d\dot{X} + J_{sX}\lambda_0). \tag{5}$$

Figure 3 shows the motivation for the control law. At each instant the actual robot is replaced by a "virtual rigid robot" (shown by the dotted line in the figure) and the torques are calculated based on that. Note that in any robot the application of joint torques based on the Jacobian calculation does not require the shape of the links to be known. Knowledge of the positions of the joints suffices. Therefore, there is some intuitive sense in this control law.

3. Experimentation

In this section we describe work undertaken with an experimental system to test out our controllers.

3.1. Hardware Setup. We briefly describe the experimental setup here. For a detailed description see [9]. The schematic for the harware setup is as shown in Figure 4a. Figure 4b is a picture of the grasping setup



(a) Hardware setup (b) Grasping setup

Figure 4. Experimental setup

with a six inch long ruler for comparison of sizes. The x-direction is parallel to the line joining the base of the right-hand finger to the left-hand finger and the y-direction points outwards (to make the usual right-handed coordinate system). The last link of each finger is flexible. The robotic fingers are 2-DOF, tendon-driven, planar fingers with interchangeable links. The links used for the fingers can be easily changed for links of different lengths, materials or flexibilities. We are able to sense the configuration of the fingers using optical angle encoders and the configuration of the object using a Polhemus six-degree-of-freedom sensor. The joints are driven by DC motors mounted behind the fingers using tendons made of fishing line. Each joint is driven by one motor (N-configuration). The whole setup is interfaced to a Intel 80486 based PC with a 66 Mhz. processor. At the time of writing we could not measure the forces being applied by the fingers due to failure of the force-sensitive resistor based force sensors. As we are yet to receive replacements for these, the experimental data presented here is preliminary and incomplete. We hope to complete the experimental study in time for the final version of this paper.

For the experiments described in this paper the base-link of each robot was rigid (0.0625 inch thick steel stock) and the end-link was varied in thickness. The thicknesses tried out were (in inches) 0.0625, 0.020, 0.010 and 0.008 of steel stock half an inch in width.

3.2. Software. The software written for this experiment used the Sparrow real-time control kernel [7]. This package controls servo loop execution, provides a simplified interface to sensor and actuator hardware, and allows data logging. The sample rate for the feedback control laws was 150 hertz and the controller was run at 25 hertz.

3.3. Experimental Procedure. The intention of the experimentation was to exhibit that flexibility can be handled by relatively simple controllers with minimal additional hardware requirements. We also intend to show that the compliance due to flexibility is useful and can lead to performance enhancements in robotic manipulation tasks.

We intend to carry out the following series of experiments to test our thesis.

Step response with varying flexibility: Step response data with varying flexibility of the manipulator would indicate the robustness of the grasp. Rigid manipulators tend to drop objects due to very small errors in their position. Flexible manipulators can conceivably use the flexure of their structure to make the grasp robust.

Step response with varying internal force: Maintaining the internal force commanded during manipulation is usually a hard problem. We envisage that flexible manipulators would have an advantage over rigid manipulators due to their compliance. Our simulations indicate that the application of the correct constraint force is achieved by the fast subsystem of the flexible manipulator and thereafter remains fairly constant even with change in the manipulator's configuration.

Trajectory tracking: We expect trajectory tracking performance of flexible manipulators to be worse than that of rigid manipulators. This would be due to flexibility related internal motions of the manipulator structure during overall motion of the grasped object. Our aim is to relate this degradation to the flexibility and to determine trade offs between this and the advantages presented by using flexible manipulators.

Controller characteristics: One of the basic aims of this work is to implement and characterize the controllers developed by the authors. This allows issues of practical importance, like the additional processing power and time required to implement these controllers on real systems to be addressed.

3.4. **Experimental Work and Results.** At the time of writing we are still engaged in carrying out our proposed experimental work. We present some preliminary data from experiments carried out so far.

We carried out step response experiments with a rigid workspace controller and an instantaneous Jacobian based flexible controller. Figure 4b shows the most flexible of these links being used. Note that the beam distorts well beyond the realm of linear beam theory. The following table describes the notation used in the figures.

Controller	Rigid 0.0625"	Flexible 1 0.020"	Flexible 2 0.010"	Flexible 3 0.008"
Rigid	rr	rf1	Not used	Not used
$J_{X\Theta}$ based	fr	ff1	ff2	ff3

We able to run two of the controllers by the time of writing of this report. The others will be implemented as soon as we have the additional sensing required to implement them. We found the additional time required by the instantaneous Jacobian based controller to run was marginally higher than the usual workspace PD rigid controller. The times on our setup were 1.320 ms for the rigid controller and 1.392 ms for the instantaneous Jacobian based controller.

Figure 5 shows the typical step responses for the different controller-flexibilities tried out. The task was to perform a step in the y-direction (pointing out from the base to Note that the workspace PD rigid controller (which uses the usual manipulator Jacobian) is unable to control even the "stiffest" of the flexible link manipulators. Thus the flexibilities considered in the experimental work are non-trivial and cannot be ignored. Due to the poor performance of the rigid controller on the first flexible manipulator, we did not try using it on the other (more flexible) manipulators.

The step response data collected was processed further to extract information more useful for our purposes. We selected the five best performances for each controller-flexibility and analysed that data. We did not process the data from the "rf1" combination further as it did not stabilize.

Figure 6 shows the settling time for each combination. Note that the "rr" combination did not have the fastest settling time. The reason for the poor performance of the "fr" combination was due to the intermittent loss of contact between the tip of the rigid fingers and the object. As the controller assumes that the tip of the finger is touching the object at a specific point and uses that to calculate $J_{X\Theta}$ any loss of contact causes joint torques to be calculated erroneously. The flexible manipulators did not have this problem becuse the compliance in their structure ensured that they remained in contact with the object.

Figure 7 is the error in the final y-position of the object. The "ff" combinations seem to perform as well as the "rr" combination. However, the error bars are too large to allow drawing of any further or more discriminationg conclusions.

Figure 8 is the two-norm of the error in the y-position for 1.66 seconds (250 time steps) after the step is commanded. The "rr" combination performs better than the "ff" combinations in this test.

We also performed experiments by varying the internal force keeping other parameters (including controller gains) constant. The analysed data is presented in Figure 9. In the "rr" case the settling time increases as a function of the internal force. This is because there is a tradeoff involved in how the controller sets the "position-control force" and the internal force. As the motors saturate application of higher internal forces

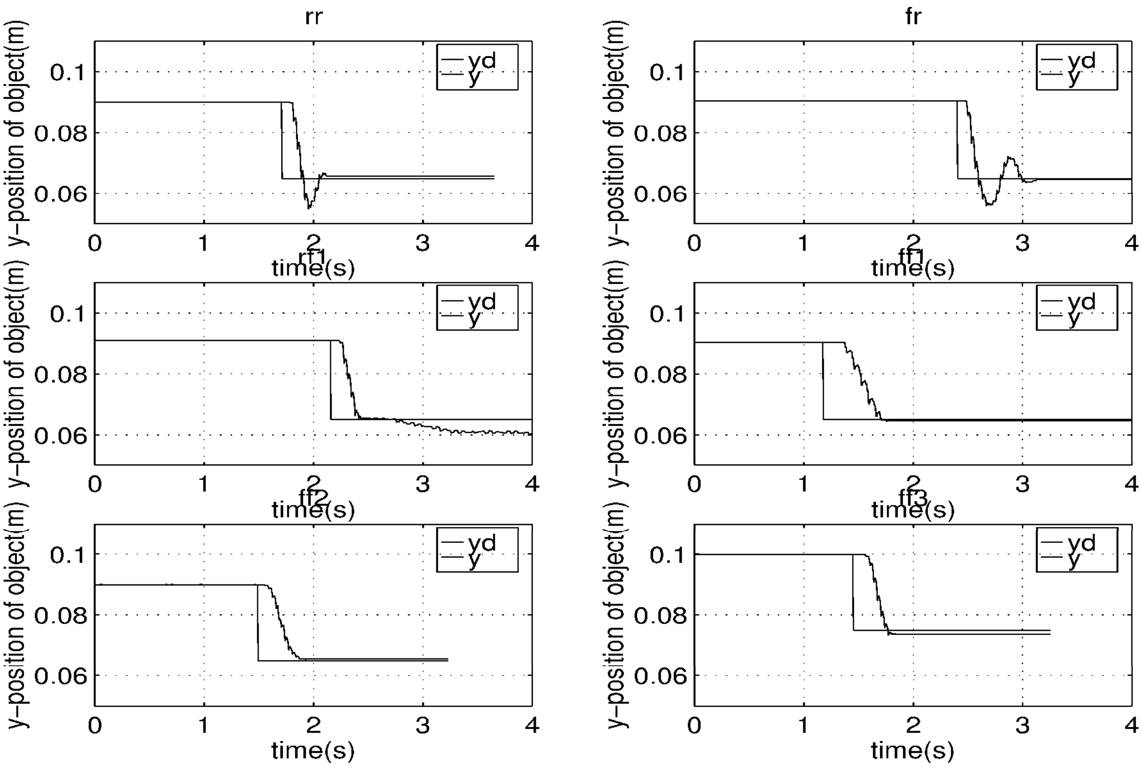


FIGURE 5. Typical step responses

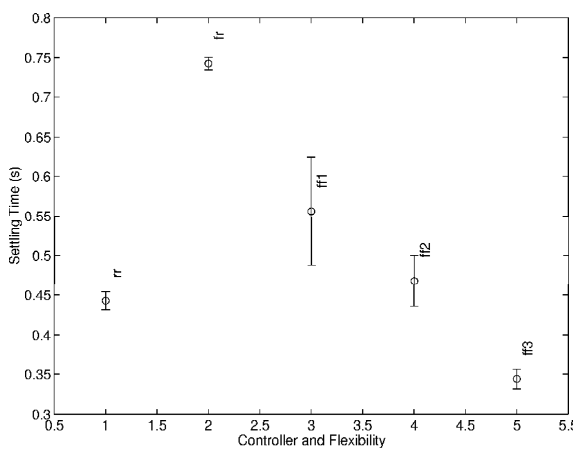


FIGURE 6. Settling time

is at the cost of the position-control force. In the flexible case the relationship is more complicated. Though the same tradeoff exists, application of additional internal force changes the geometry of the robot itself. Therefore the joint torques required would be different. We note that the settling time is much shorter for the rigid robot. Further, it is evident that for the flexible case the performance in terms of the settling time does not suffer as a result of the increased internal force (which would cause greater distortion of the flexible link).

4. CONCLUSION

Though we have not been able to complete our experiments, preliminary data does indicate that the simple control laws proposed are able to control flexible robot manipulators in a grasping situation and extract performance from them comparable to that of rigid robots.

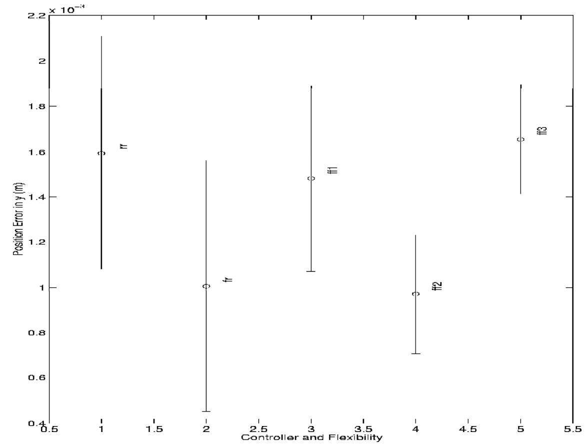


FIGURE 7. Final position error

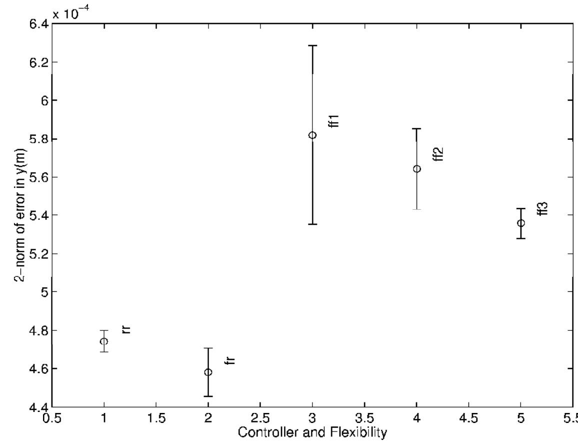
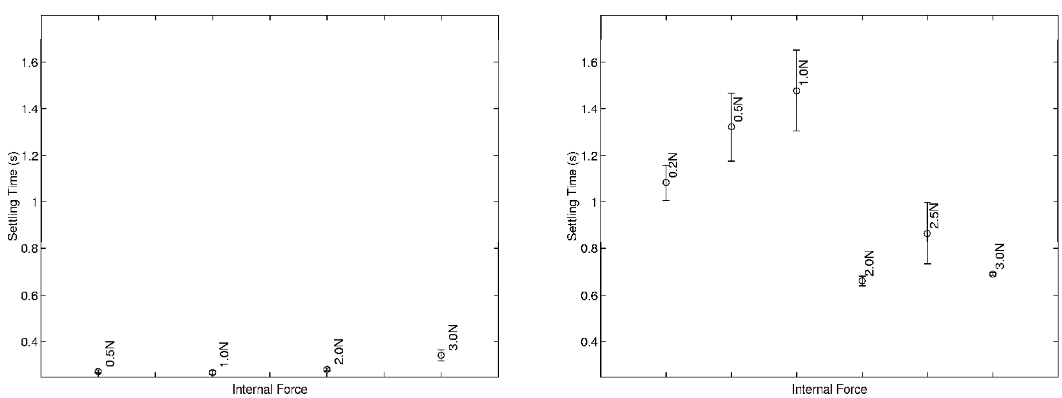


FIGURE 8. Final position error



(a) Configuration "rr" (b) Configuration "ff2"

FIGURE 9. Settling time with varying internal force

In general it was found that flexiblity did not degrade the performance of the system very much. Where it did there were indications that performance could be improved by changing parameters like the internal force. We were able to handle large amounts of internal force and deflections of the tip of the flexible links (exceeding 60 % of the length of the link).

There were certain issues during experimentation which pointed qualitatively at the advantages of having flexible links in manipulation tasks. Chief among these was maintaining contact with the object during manipulation which was problematic sometimes with the fully rigid robot. Quantitavie data on this would be possible once we have force sensors at the tips of the manipulator.

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