5.5 Basic System Performance

There are three areas which describe system performance.

1. Kinematics: The location of singularities and joint range of motion limits.
2. Dynamic positioning performance: Here we give a number of basic test results which describe friction, inertia, and servo stiffness of individual joints. We also give individual joint step responses. These results essentially show how well various elements of the system were built on a joint by joint basis.
3. Dynamic force reflection: This is where the system differs from most robotic systems. These results show why we designed the Silver Falcon the way we did and how it can be improved. We discuss two main criteria: How well does the system feel when the slave is not contacting anything (freespace), and how good does it feel when making contacts with the environment. We also give discrimination test results to show the lowest levels of force which we can distinguish through the master-slave system.

5.5.1 Kinematics

5.5.1.1 Singularities

We use a roll-pitch-yaw wrist. Therefore, there are two singular configurations at $q_4 = \pm\pi/2$. There is no output roll while in these configurations.

5.5.1.2 Joint Limits

The joint range of motions are:

q_0	$\pm 45^\circ$
q_1	$\pm 45^\circ$
q_2	0 m – 0.19 m
q_3	$\pm 175^\circ$
q_4	$\pm 90^\circ$
q_5	$\pm 90^\circ$
q_6	0° – 180°

5.5.1.3 Motions for Suturing

It is difficult to say whether or not the kinematics we have chosen will suffice during the course of actual surgery. However, we can consider the motions required for suturing as an example, as described in Section 4.1.2. There we saw that this motion consisted primarily of a roll motion combined with a push to pass the needle through tissue. Therefore, we need to limit the motions of the Silver Falcon wrist to those which allow an output roll in order to accomplish these motions.

As we have described, our wrist is a roll-pitch-yaw wrist with non-intersecting axes, and with two singular configurations at $q_4 = \pm 90°$. It is therefore difficult, though not impossible, to operate at a $90°$ wrist deflection. Technically we can operate when $q_5 = 90°$, and $q_4 < 90°$. However, a rotation of q_3 of less than or equal to $90°$ will always place us in a singular configuration, making this impractical.

Practically, we feel the wrist can operate at roughly a $\pm 45°$ deflection. Referring to Fig 4-3, we can therefore deviate comfortably by $\pm 45°$ from the indicated instrument shaft orientation and still maintain the proper needle orientation during the suturing motion.

5.5.2 Dynamics

We look at joint by joint dynamics of both the Silver Falcon slave, and the Phantom master. While we are primarily concerned with evaluating the Silver Falcon, the overall system response is a direct function of both the slave and the master. We will find a number of areas for improvement that will be addressed in our second design, the Black Falcon. In assessing dynamics, we will consider structural flexibility, transmission flexibility and friction. We will look at joint servo responses for both the slave and master manipulators.

Again, refer to Figure 5-2 for joint numbering and definition of cartesian axes.

5.5.2.1 Structural Stiffness

The structural stiffness was tested in the manipulator's zero position by clamping the base axes, axes 0 and 1, and deflecting the tip of the manipulator just above the wrist in the x and y directions using a digital force gage (Mark 10 Model BG2), and measuring deflection corresponding to a measured force. To test z stiffness, we applied a vertical force to the motor mounting bracket, 96 in Figure 5-9. While the actual stiffnesses are certainly not linear, these rough measurements still give a good idea of overall stiffness and represent an overall upper limit to the slave stiffness which can be achieved.

In the x direction, we measured a 12.5 mm deflection with a 6 N force giving a 480 N/m stiffness. In the y direction, a 12.5 mm deflection with $3.1 - 3.3$ N force resulted in a 250 N/m stiffness. And in the z direction, a 2.5 mm deflection with 8.4 N gave a 3400 N/m stiffness.

These numbers, particularly in the x and y directions, are quite soft and show the difficulty of making a stiff slave which must be long and slender in order to pass through a small incision in the human body. The compliance in the x and y directions is primarily due to the Thomson ball bushings/steel rod bearing structure used to support the wrist unit. Two long 1/4 in diameter parallel steel rods simply do not provide much structural stiffness in bending or in torsion. The z compliance is due to flexibility in the remote center mechanism.

5.5.2.2 Friction

The static backdrive friction was measured with our digital force gage in the x and y directions at the tip of the fingers both with the base clamped, and with it free. These values represent friction in the transmission and in the motors. Four or five trials were done in each case and averages were taken.

With the base clamped we found the friction in the wrist axes alone. The wrist friction f_{WX} in the x direction represents friction about axis 4. The wrist friction in the y direction f_{WY} with the fingers closed represents friction about axis 5. The friction about each of the fingers, f_{SF}, f_{LF}, were similar and are referred to using the notation of Section 5.2.3. These values are:

$$\begin{aligned} f_{WX} &= 0.30 \text{ N} \pm 0.1 \text{ N} \\ f_{WY} &= 0.76 \text{ N} \pm 0.1 \text{ N} \\ f_{SF} &= 0.35 \text{ N} \pm 0.1 \text{ N} \\ f_{LF} &= 0.46 \text{ N} \pm 0.1 \text{ N} \end{aligned}$$

With the base left free, the friction in the x direction was 0.19 N, and in the y direction was 0.20 N. In this case most of the motion was in the base joints and not in the wrist joints. In the Silver Falcon, the friction in the wrist joints is actually higher than in the base joints in the x and y directions when measured at the tip of the manipulator. The friction in the z direction corresponds to that in joint 2 and is 2.0 N. The system was tilted so that this joint was horizontal in order to measure its friction. The friction in this joint is considerably higher because all five motors are backdriven simultaneously. Also, these cables are directly backdriven without the benefit of additional leverage as in the case of the wrist and fingers.

The friction in the master was measured in the x, y, and z directions f_{mx}, f_{my}, f_{mz}, as shown in Figure 5-16. We also measured the friction in the actuated gripper f_{ag}. The values found were:

$$\begin{aligned} f_{mx} &= 0.18 \pm 0.05 \text{ N} \\ f_{my} &= 0.15 \pm 0.05 \text{ N} \\ f_{mz} &= 0.15 \pm 0.05 \text{ N} \\ f_{ag} &= 0.07 \pm 0.03 \text{ N} \end{aligned}$$

There are several primary causes of friction in the system:

- Brush friction in the motors. Our motors are Maxon RE025-055-035 brushed d.c. motors with a catalog value of 0.0086 Nm frictional torque. We typically measure smaller values however. On one motor we measured 0.02 ± 0.005 N at 1 in (0.0254 m)which gives 0.0005 Nm brush torque.

  Had we used precious metal brushes instead of graphite brushes, the brush friction would be roughly 25% times less. Graphite brushed motors have a higher peak torque capacity, but since we typically operate within one or two times continuous torque limits in order not to damage our motors, this capacity goes unused and precious metal brushes would be a smarter choice. The precious metal brushes are not available on the larger RE035 motors.

- Bearings add small amounts of friction. In particular the very small bearings used in the wrist have a low load capacity. We suspect that the high cable tension required to maintain frictional drive loads on the drive capstans increase friction in these bearings.

- If cable turns over very small diameter pulleys, internal friction is generated between the individual fibers of the cable. One possible mechanism is plastic deformation in the cable. The other is rubbing of the cable fibers against one another since they pass over different radii of curvature as they pass over the pulleys. We do not know the magnitude of this frictional component.

We know that changing cable tension makes a substantial difference in frictional levels, particularly in the wrist. The tradeoff is that low tension will allow one side of the cable go slack at higher torques, and slippage will occur if we rely on frictional drive capstan engagement. Increased pretension increases bearings loads, and loads on cable which wraps around capstans and pulleys and therefore friction within cable. If due to poor design, pulleys are made to rub on one another, these loads will also increase with increased cable tension.

5.5.2.3 Friction Compenstion Algorithm

Add

5.5.2.4 Inertia

The joint inertias were measured by programming known stiffnesses into each joint servo and comparing the resulting experimental output responses to simulated responses with known values. Joints are defined in 5-2. The values were taken with the slave centered in its workspace, and are:

$$\begin{aligned}
I_{s0} &= 0.09 \text{ kgm}^2 \\
I_{s1} &= 0.08 \text{ kgm}^2 \\
I_{s2} &= 1.14 \text{ kg} \\
I_{s3} &= 0.000033 \text{ kgm}^2 \\
I_{s4} &= 0.000010 \text{ kgm}^2 \\
I_{s5} &= 0.000011 \text{ kgm}^2 \\
I_{s6} &= 0.0000028 \text{ kgm}^2
\end{aligned}$$

When centered in its workspace, the slave manipulator tip is 32.5 cm (12.8 in) below the remote center of rotation. If we convert the joint 0 and 1 inertias I_{s0} and I_{s1} to cartesian inertias using this length, we find:

$$I_{sx0} = 0.85 \text{ kg}$$
$$I_{sy0} = 0.76 \text{ kg}$$

These are the inertias we feel if moving the slave manipulator by its tip.

The Phantom inertias were measured directly in cartesian space and are given below. The inertia of the actuated gripper is given in joint space:

$$\begin{aligned}
I_{mx} &= 0.23 \text{ kg} \\
I_{my} &= 0.16 \text{ kg} \\
I_{mz} &= 0.18 \text{ kg}
\end{aligned}$$

$$I_{ag} = 0.000115 \text{ kgm}^2$$

5.5.2.5 Individual Joint Responses

To give an idea of servo performance, we give representative step responses for each joint of the Silver Falcon. The joint gains were tuned experimentally to be reasonably good and are given below. The magnitude of the responses corresponds to essentially the largest magnitude we could perform without torque limiting the motors.

$$\begin{array}{ll}
K_{qs0} = 24 \text{ Nm/rad} & B_{q0} = 1.2 \text{ Nms/rad} \\
K_{qs1} = 24 \text{ Nm/rad} & B_{q1} = 1.2 \text{ Nms/rad} \\
K_{qs2} = 6000 \text{ N/m} & B_{q2} = 60 \text{ Ns/m} \\
K_{qs3} = 2.4 \text{ Nm/rad} & B_{q3} = 0.0084 \text{ Nms/rad} \\
K_{qs4} = 0.24 \text{ Nm/rad} & B_{q4} = 0.0024 \text{ Nms/rad} \\
K_{qs5} = 0.48 \text{ Nm/rad} & B_{q5} = 0.0048 \text{ Nms/rad} \\
K_{qs6} = 0.12 \text{ Nm/rad} & B_{q6} = 0.0012 \text{ Nms/rad}
\end{array}$$

The master servo stiffness are

$$\begin{aligned}
K_{xm0} &= 480 \text{ N/m} \\
K_{xm1} &= 480 \text{ N/m} \\
K_{xm2} &= 480 \text{ N/m} \\
K_{qm6} &= 3.0 \text{ Nm/rad}
\end{aligned}$$

The length of the gripper handles is 0.079 m, so the cartesian space gripper servo stiffness at the tip of the handles is 480 N m.

Figures 5-19 and 5-20 show step responses for the base joints, axes 0 and 1. These responses are slightly underdamped and not particularly fast. The damping gains are limited primarily by the limited encoder resolution on these axes. This in turn limits the stiffness gains and thus the overall speed of response. Use of higher resolution encoders would improve these responses.

A more involved change would be to increase the magnitude of the cable reductions on these axes from their current values of 19:1 for joint 0 and 19.3:1 for joint 1 in order to inertia match the motor rotors with the inertia of the pitch and yaw axes. Inertia matching the rotor inertia to the output link inertia maximizes the output link acceleration for a given input torque. The base motor rotor inertia (Maxon RE-035-034) is 6.96×10^{-6} kgm^2. For joint 0, the measured link inertia is almost entirely

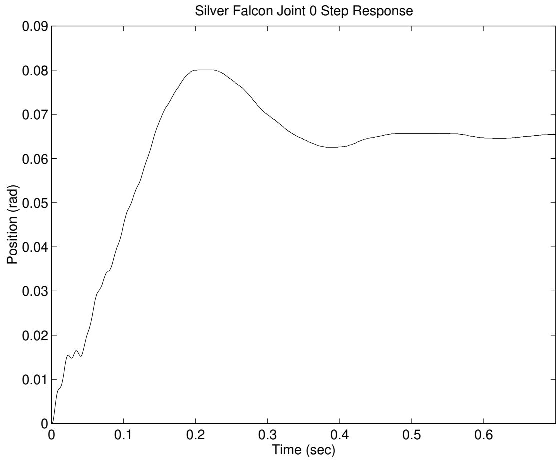

Figure 5-19: Silver Falcon Joint 0 response to a 0.07 rad step input.

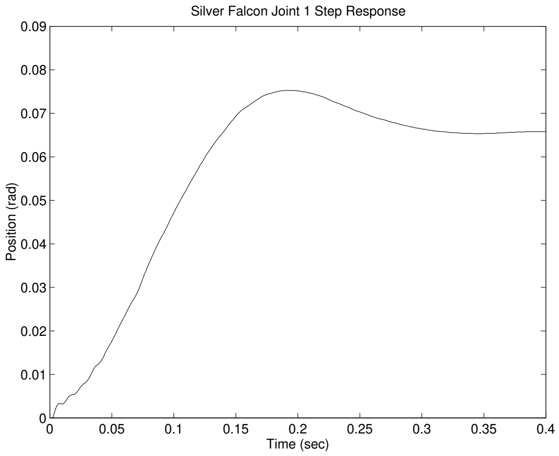

Figure 5-20: Silver Falcon Joint 1 response to a 0.07 rad step input.

due to the output link inertia. That is:

$$\begin{aligned} I_{output} &= I_0 - I_{rotor} R^2 \\ &= 0.09 - 6.96 \times 10^{-6} 19^2 = .087 \text{ kgm}^2 \end{aligned}$$

To inertia match the rotor inertia to that of the output link would require a reduction of:

$$\sqrt{\frac{0.087}{6.96 \times 10^{-6}}} = 112$$

which is not possible with single stage cable reduction in a reasonable size.

Finally, we can see that the overall dynamics are fairly clean, with the exception of some high frequency very low amplitude (roughly 80 Hz) oscillations at the beginning of the responses. This is due to flexibility of the steel drive cables.

Figure 5-21 is a 3.5 mm step response for joint 2. This is a very rapid response, but with a number of slower oscillations which prevent settling of the system. These oscillations are caused by flexibility of the base positioner structure and are actually visible. We can show this by repeating the step response while supporting the motor block by holding it against a 1/4 in diameter steel rod braced agains the table on which the system is mounted, Figure 5-22. The structural oscillations are essentially gone.

Figure 5-23 gives the 0.05 radian step response for joint 3. This is a fairly straight-

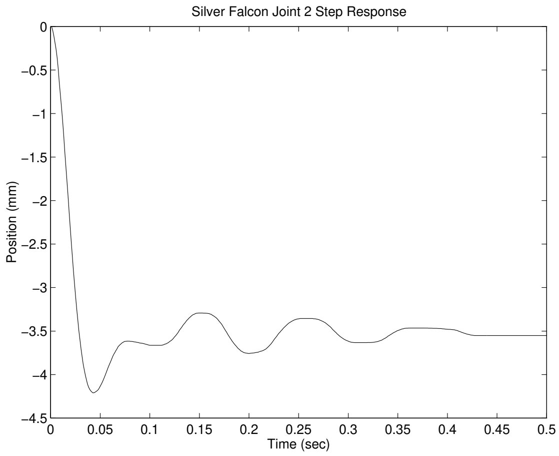

Figure 5-21: Silver Falcon Joint 2 response to a 3.5 mm step input.

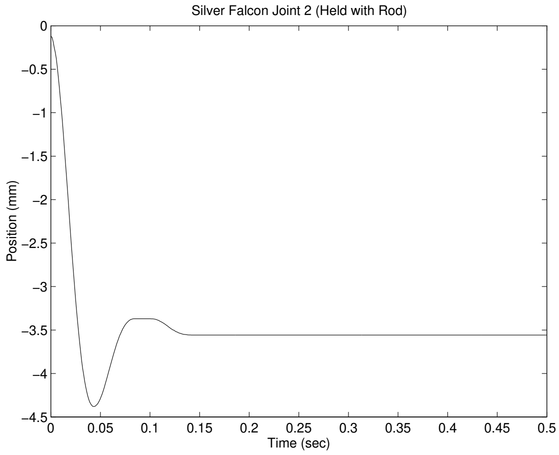

Figure 5-22: Silver Falcon Joint 2 response to a 3.5 mm step input with motor block braced against table with 1/4 inch steel rod.

forward 2nd order type response. Figures 5-24 gives a 0.3 rad step responses for joint 4. Note that the joint never quite reaches .3 rad due to stiction in the wrist mechanism.

Figures 5-25 gives a 0.1 rad step response for joint 5, motion of a point midway between the two fingers. This response is for both fingers moving together with the distance between them commanded to remain constant. This joint also does not reach its commanded value due to stiction in the wrist. Also, there is a slight oscillation superimposed on the response due to cable flexibility between the motor and the wrist stiction.

Figure 5-26 gives a 0.3 rad step response for joint 6, gripping. This plot is very similar though the joint comes to rest slightly beyond its setpoint due to wrist stiction. A similar oscillation due to cable flexibility can be observed here also.

The Phantom joint step responses are given in Figures 5-27, 5-28, and 5-29. These responses show some slight non second order response characteristics. There are visible high frequency cable dynamics visible as small oscillations at the beginning of the joint 1 and joint 2 responses. Also, the settling of the joint 0 response appears slightly nonlinear. The Phantom is most flexible in this direction structurally, which may account for this.

The actuated gripper step response is shown in Figure 5-30.

Overall, there are several points to note about the Phantom performance. First,

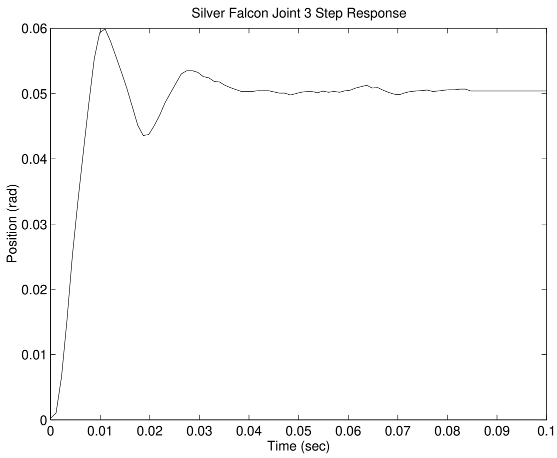

Figure 5-23: Silver Falcon Joint 3 response to a 0.05 step input.

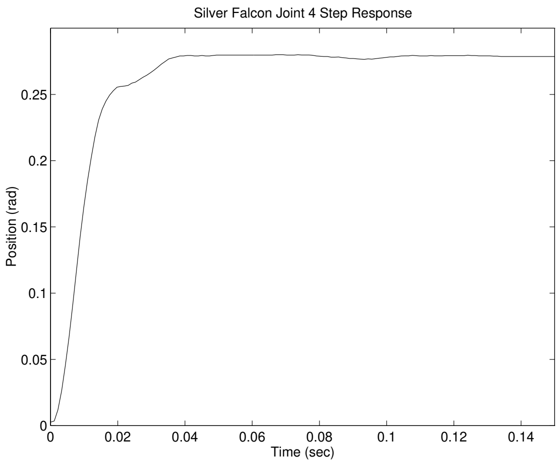

Figure 5-24: Silver Falcon Joint 4 response to a 0.3 rad step input.

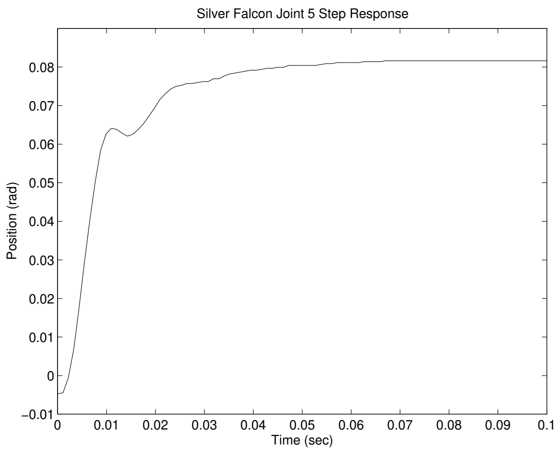

Figure 5-25: Silver Falcon Joint 5 response to a 0.1 rad step input.

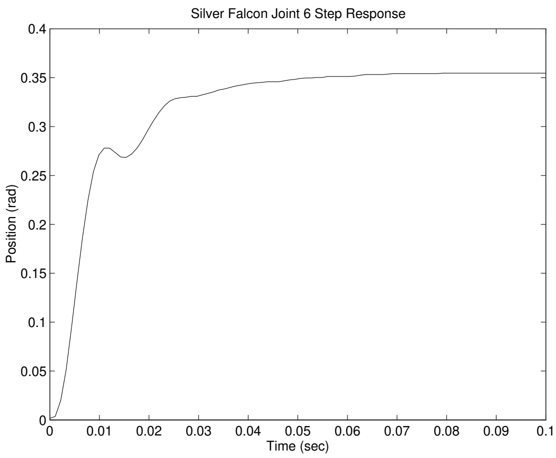

Figure 5-26: Silver Falcon Joint 6 response to a 0.4 rad step input.

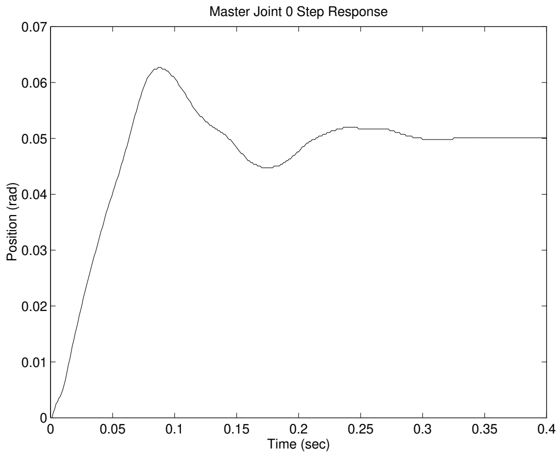

Figure 5-27: Phantom Joint 0 response to a 0.05 rad step input.

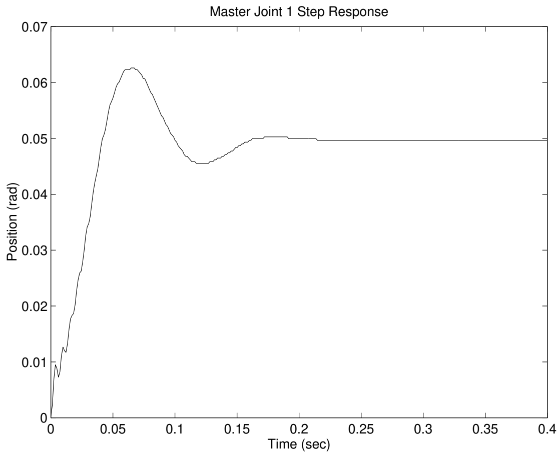

Figure 5-28: Phantom Joint 1 response to a 0.05 rad step input.

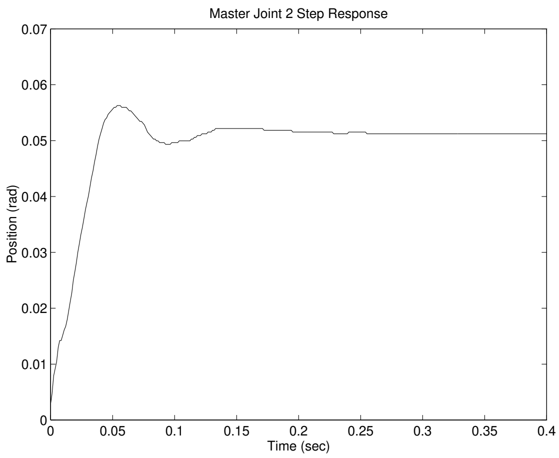

Figure 5-29: Phantom Joint 2 response to a 0.05 rad step input.

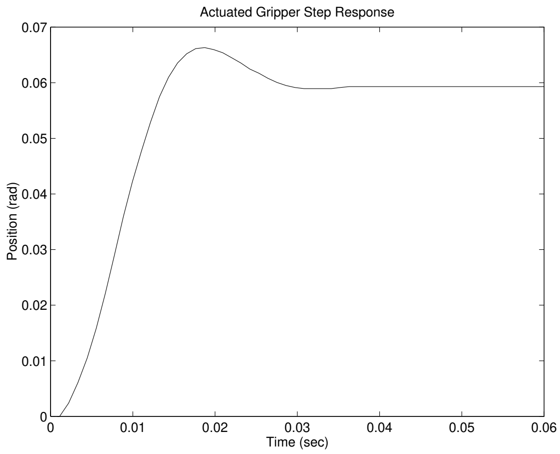

Figure 5-30: Actuated Gripper response to a 0.06 rad step input.

the maximum stiffness which we can achieve when servoing joints to fixed positions is roughly 480 N/m. This is fairly soft. (Tan et al., 1994) demonstrated that humans feel stiffnesses of above roughly $25,000$ N/m as infinitely rigid in static pushing tests. We have found that using our Phantom haptic interface to feel virtual walls is easier than servoing to a fixed position, and we can achieve a "wall" stiffness of roughly 2000 N/m. This provides a satisfactory feeling of pushing on a "wall", though the wall does not feel infinitely rigid. A stiffness of 480 N/m is four times softer and correponsds to a fairly mushy wall. If this is the best our master can achieve, then we are fundamentally limited in achieving a rigid master/slave connection.

The master stiffness could be substantially improved by increasing rotor inertia by using either larger motors (Maxon RE035 instead of RE025), or by equivalently increasing the reduction used. Damping gains and hence corresponding stiffness gains could be increased by using higher resolution encoders such as Canon TR36 laser encoders with 14,400 counts per revolution. SensAble Technologies Inc. which currently manufactures and sells the Phantom uses a higher resolution Hewlett-Packard encoder than on the version which I am using as a master. My version uses 500 count (2000 after quadrature) encoders while the newer version uses 1000 count (4000 after quadrature) encoders.[5]

The second point to note is that the Phantom endpoint inertia is significant. As we discussed in Chapter 2, inertia is necessary to achieve stiffness in a servo system. However, the tradeoff is that with a system such as this, it will never feel as if we are touching objects directly with our fingers. There will always be a mass of at least, in our case, roughly 0.2 kg between our fingers and the environment which we sense through the teleoperator slave.

5.6 Force Reflection

When implementing a master/slave teleoperator with force reflection, we have found there are several qualities which describe the quality of force reflection, but which are difficult to achieve well and difficult to achieve at the same time:

- Freespace motions of the system should feel free. The user who is operating the master should feel the master and little else. They should not feel as if they are "dragging" or "carrying" the slave along with them. Obviously, if no

[5]For historical reference, the Phantom which I am using is the original one which Thomas Massie made in the A.I. Lab machine shop in the Spring of 1993.

forces from the slave are sent to the master (force reflection is turned off and the master is used only as a positioning input), then this will be the case.

- Contact should feel like contact. Forces between the slave manipulator and the environment should be reproduced at the master. For example, if we make a hard contact with the slave we can observe bandwidth limitations in the master/slave connection by observing the sharpness of the resulting force response at the master.
- The system should be sensitive. The lowest level of force which can be felt should be as low as possible. The ability to discriminate when contact occurs and how delicately contact occurs depends on this value.
- Because the system is multi-dimensional, these properties should be equally good in all directions. There should not be preferential directions which will mislead the surgeon while they operate.

Below we compare two different controllers which were implemented on the Silver Falcon and Phantom, the Jacobian Transpose controller and the Inverse Jacobian controller. These were both described in Chapter 3. The Inverse Jacobian control gave us the best overall performance which we were able to achieve with our system. This comparison will show that:

- the Inverse Jacobian controller hides the inertia of the slave base positioner roughly twice as well as does the Jacobian Transpose controller and is therefore the better of the two.
- The Silver Falcon base positioner has a limited servo response which limits the Inverse Jacobian controller from better hiding the base positioner inertia from the user.
- Using the Inverse Jacobian control, forces are not felt in a direction pointing into the fingers of the wrist unit since there are no redundant degrees of freedom in this direction.

We then give discrimination test results showing the lowest forces which can be felt by a user through the system using the Inverse Jacobian controller.

In the plots given below, we are concerned with the forces output by the master and the slave manipulators. However, neither manipulator uses explicit force sensing at their output, so we cannot actually measure the force outputs. As a result we must estimate output forces using commanded joint torques. Fortunately, both systems were designed so that joint torques would provide good estimates of output forces.

The error between joint torques and output forces are caused by friction in the joints and motor brushes and by inertia in the systems links. Friction levels are given above in Section 5.5.2.2, and inertias are given in 5.5.2.4. For the slave, we use only wrist torque measurements to determine the slave endpoint force in order to avoid errors which would be caused by the inertia of the base positioner which is much larger. This is in effect the whole idea of macro-micro control. The exception is for forces in the direction of the fingers of the Silver Falcon. Redundant positioning degrees of freedom do not exist in this direction, so that the entire slave must move for these motions. In the plots shown here, the fingers are always pointing downwards, in the $-z$ direction, so we expect more error in this direction between the forces shown in the plots and the actual forces at the tip of the manipulator.

5.6.1 Freespace Responses

The freespace response plots show how much of the slave inertia is felt by the user operating the master. One way to do this is to move the master in a sinusoidal motion by hand in the x, y, and z directions and recording endpopint forces and positions for the master and slave manipulators. However, it is not really possible to move in a perfect sinusoid. Instead we commanded a sinusoidal position command to the slave (i.e. a virtual master following a sinusoid) and recorded the forces which were calculated by the controller and sent back to the master. If the master were to track a perfect sinusoid, these represent the forces which the user would have to apply in order to overcome inertia and friction reflected back from the slave.

5.6.1.1 Jacobian Transpose Controller

Figures 5-31, 5-32, and 5-33 show freespace responses in the x, y, and z directions using the Jacobian Transpose controller with a force scaling factor of 2:1. Recall that the Jacobian Transpose controller forces the user to feel the inertia of the slave in addition to that of the master, multiplied by the force scale factor used.

Consider Figure 5-31, the x direction freespace response. We can see that:

- The slave lags the master as it tries to track its motions.
- There are roughly +2.5 N and -3.5 N peak forces at the master despite the fact that the slave is not touching anything.

The forces we feel in the slave are inertial forces, frictional forces, and forces required to bend electrical cabling. Gravity forces are cancelled (fedforward) in the controller,

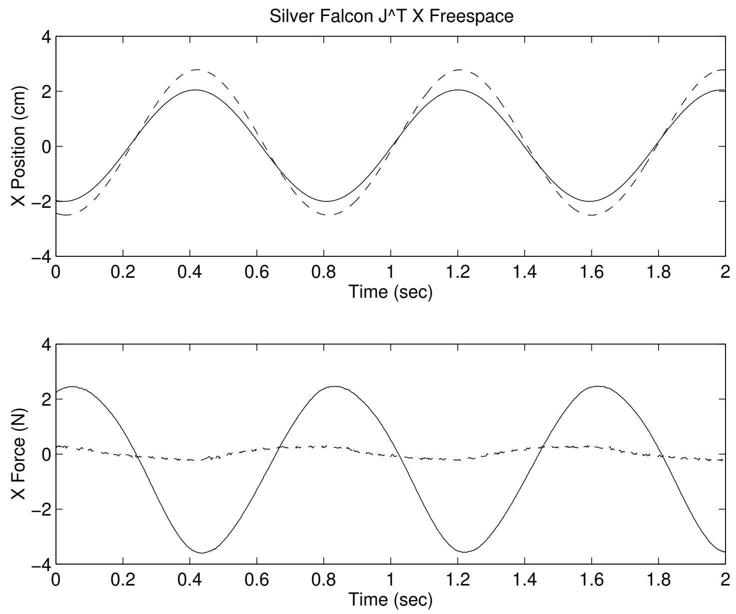

Figure 5-31: Freespace response for the Silver Falcon slave and Phantom master in the x direction using the Jacobian Transpose controller. The solid line represents the master, and the dashed line represents the slave.

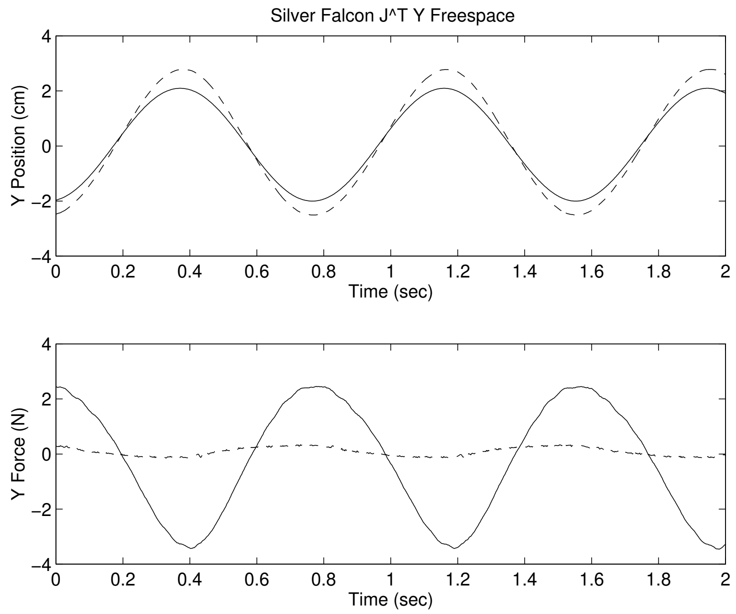

Figure 5-32: Freespace response for the Silver Falcon slave and Phantom master in the y direction using the Jacobian Transpose controller. The solid line represents the master, and the dashed line represents the slave.

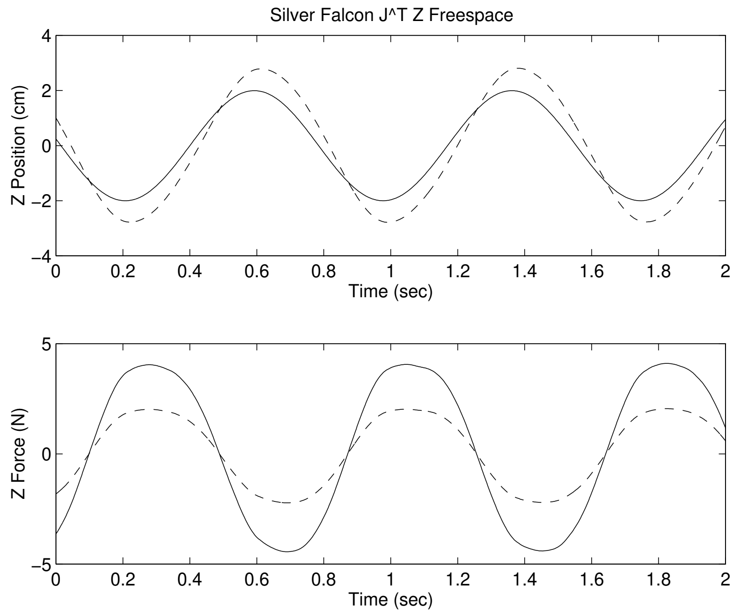

Figure 5-33: Freespace response for the Silver Falcon slave and Phantom master in the z direction using the Jacobian Transpose controller. The solid line represents the master, and the dashed line represents the slave.

and not shown in the graphs. The spring counterbalance is not used in these tests.

We may do a rough calculation to estimate the inertia in the slave. The master trajectory in Figure 5-31 is sinusoidal with a frequency and amplitude of:

$$\omega = 8.0 \text{ rad/s}, \; A = 0.02 \text{ m}$$

The maximum acceleration is then:

$$\ddot{x} = \omega^2 A = 1.28 \text{ m/s}^2$$

The inertia of the slave tip in the center of its workspace in cartesian space was previously measured as 0.85 kg, and the force scale is 2. The resulting force which the master needs to apply is:

$$0.85 \text{ kg} \times 1.28 \text{ m/s}^2 \times 2 = 2.2 \text{ N}$$

which is approximately what we read in the lower graph in Figure 5-31. We are unsure as to why the plot does not show completely symmetric positive and negative force values, but suspect that this is due to forces required to bend the electrical cables.

Note that the user also feels the inertia of the master itself which is not shown in the plots. We know this is 0.23 kg in the x direction, so that the total inertia which the user feels in the x direction is 0.85 kg $\times$ 2 + 0.23 kg = 1.93 kg. This is a substantial inertia for the user to carry!

The y direction response is similar as shown in Figure 5-32, but the z response appears different in that torques applied to the master are larger, roughly ± 4 N, and not as smoothly sinusoidal. The slave force in the lower graph is half (in fact exactly half) that of the master force. The master forces correspond directly to the tracking error in the slave. Because there is substantially more inertia and friction along the joint 2 (linear in-out) axis than in the x and y directions, the tracking performance is poorer. This translates directly into an increased force applied to the master. Since there are no wrist axes which move in the z direction, the slave force shown in the graph represents the force required to move this entire joint. Because of the force scale factor of 2, the master forces are exactly twice those required to move the slave joint. These force are so large that it is difficult to move the slave without reaching the torque limits of the Phantom master. These limits were set to twice the continuous motor torque, which when in the zero postion are:

$$
\begin{aligned}
f_{MX} &= 4.1 \text{ N} \\
f_{MY} &= 4.1 \text{ N} \\
f_{MZ} &= 3.3 \text{ N}
\end{aligned}
$$

5.6.1.2 Inverse Jacobian Controller

Now we consider freespace motions for the Inverse Jacobian controller. Consider the x direction response shown in Figure 5-34. Again we notice that there is a lag between the response of the slave and the motion of the master. However the lag is somewhat less than in the previous Jacobion Transpose case.

As we would expect, the slave force is nearly zero, since the manipulator is not touching anything and we are using sensitive wrist axes to measure this force.

The master force is +1.0 -1.6 N for same amplitude and frequency input sinusoid. This means that we feel approximately 1.0/2.1 $\times$ 2 times 0.85 kg= 0.81 kg inertia from the slave, or a total inertia of 1.0 kg, instead of 1.93 kg as in the case of the Jacobian Transpose controller.

A reasonable question would be why don't we feel less? After all, one of the main benefits of the Inverse Jacobian control is to hide inertia. The reason is that the slave base actuators are not strong enough to properly track the master. The forces sent to the master are due to errors in the base joints, not in the wrist joints. Using

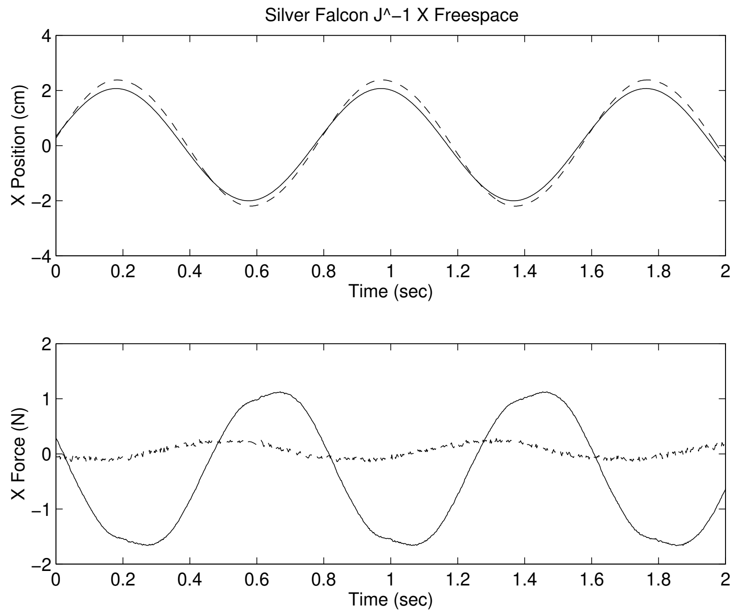

Figure 5-34: Freespace response for the Silver Falcon slave and Phantom master in the x direction using the Jacobian Inverse controller. The solid line represents the master, and the dashed line represents the slave.

the Inverse Jacobian controller, any tracking errors in the x direction should be due to wrist deflection. Since the wrist inertia is low, this deflection should be due to an outside force, and *should* be fed to the master as a force. However, if the base positioner does not properly track the master position, then this tracking error will be misinterpreted as a force despite the lack of contact between the slave and the environment. In this way, the base position tracking ability is important for the slave to accurately measure forces. Figure 5-35 shows a similar response for the y direction.

In the z direction, the graphs look different, see Figure 5-36. There is virtually no tracking error. This is because in this direction, which is along joint 2, we have five actuators/encoders contributing to this axis resulting in a stiff, high performance axis as we showed in Figures 5-21 and 5-22. (The slower motions made here do not appear to excite any structural dynamics.)

As in the case of the Jacobian Transpose controller, the slave forces appear non-zero even when the slave is moving in freespace. This is because we do not have a redundant micro freedom in this direction. Hence the slave torques represent the force required to move the base positioner instead of a light wrist joint.

The master shows very small forces however. Because the base positioner is so

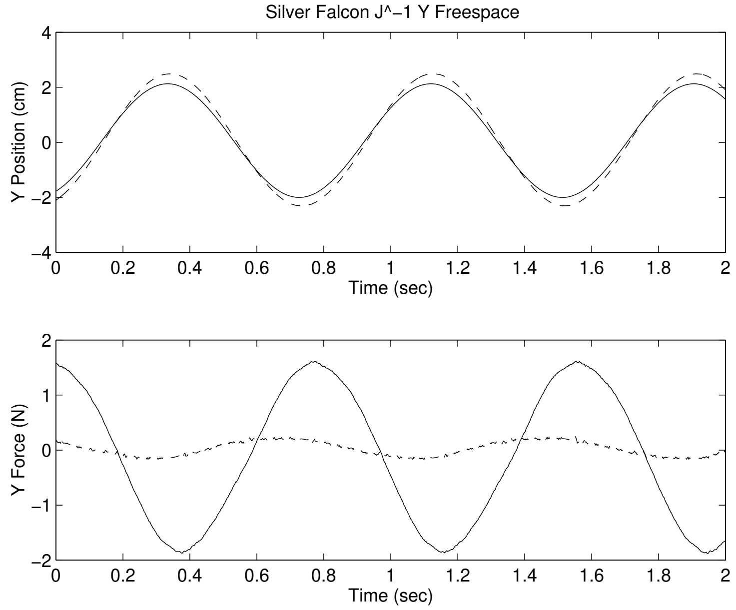

Figure 5-35: Freespace response for the Silver Falcon slave and Phantom master in the y direction using the Jacobian Inverse controller. The solid line represents the master, and the dashed line represents the slave.

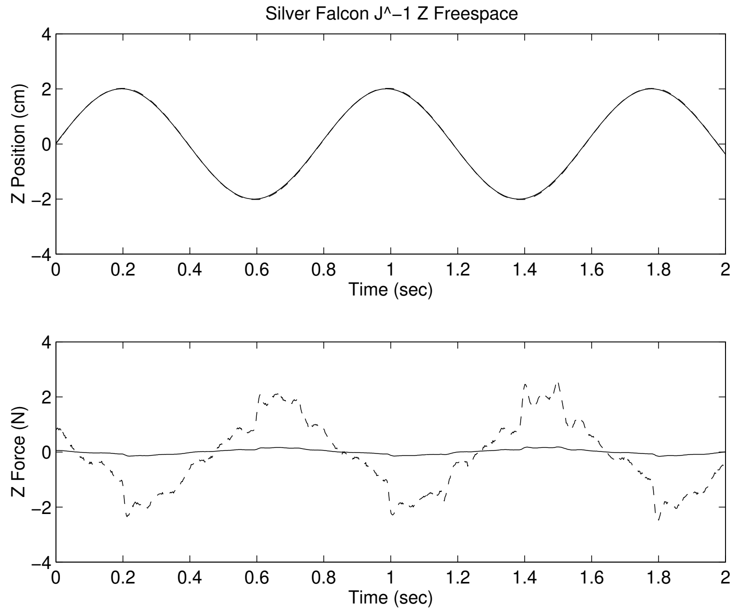

Figure 5-36: Freespace response for the Silver Falcon slave and Phantom master in the z direction using the Jacobian Inverse controller. The solid line represents the master, and the dashed line represents the slave.

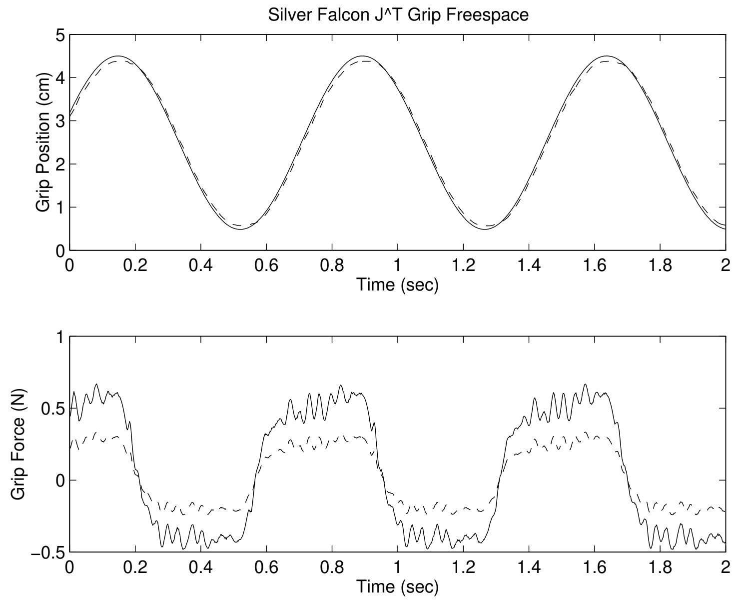

Figure 5-37: Freespace response for the Silver Falcon slave and Phantom master for the gripper using the Jacobian Inverse controller. The solid line represents the master, and the dashed line represents the slave.

good in this direction, along joint 2, there is little tracking error. Because we rely on the wrist to provide force information, and because we do not have a micro freedom available in this direction, the only forces sensed are due to errors in the base positioner, which are small. Therefore, the controller sees very little force applied to the slave and applies very little force to the master. In the z direction, freespace motions feel very good. A lesson to learn from this is that if the positioning ability of the base positioner is very good, the freespace motions will also feel considerably better.

5.6.1.3 Gripper Freespace Response

Gripping motions are no different with either the Jacobian Transpose controller or with the Inverse Jacobian controller. In each case, because we have one degree of freedom input and one degree of freedom output, each form of control reduces to the basic force reflecting teleoperator described in Chapter 2. Freespace response for the gripping motion is shown in Figure 5-37. While the tracking response appears quite good in terms of magnitude, the error is closer to a square wave than a sinusoid and there is a substantial vibration present. Of course grip forces will only be applied to the user if the actuated gripper is used. The reason is that the gripper dynamics are largely friction dominated because the wrist elements are so light, instead of inertia dominated as are the other axes. The square wave indicates that coulomb friction forces dominate which change direction as the velocity changes direction, and the vibration is caused by a repeated breaking of stiction forces.

Note that the friction force shown is between roughly 0.2 N and 0.3 N. However, we measured 0.35 N and 0.46 N in the fingers. So we would expect roughly 0.4 N of friction in the grip responses. Recall however that we are using a friction compensation algorithm which adds 0.00072 Nm of torque in motor space, which corresponds to 0.12 N at the fingertips when multiplied through the appropriate ratios. Given this, we would expect roughly 0.28 N of friction which correlates with the values we see.

5.6.2 Contact Responses

The contact response plots were made by moving the master by hand such that the slave moved into contact with a rigid aluminum block. As always, we use a 2:1 force scaling. Because the master is moved by hand, these plots are not precisely repeatable. Contact velocities and trajectories differ slightly between all the plots. Nevertheless, the qualitative results do not change. Repeatedly performing these contact plots results in qualitatively similar data. Each contact plot consists of freespace motion, contact, and relatively steady state application of force.

To summarize, in comparing the Jacobian Transpose and Inverse Jacobian controllers in the x and y directions, we find that they differ in their freespace behavior. We just looked at this in detail in the previous section and is expected. We also find they differ somewhat though not strikingly during contact and not significantly during steady state contact.

In z direction where no micro wrist freedom exists in this wrist orientation, we expect a big difference. The Jacobian Transpose controller is particularly bad in freespace, but is force reflecting in the z direction. The Inverse Jacobian controller is good in freespace, but is not at all force reflecting in the z direction.

5.6.2.1 Jacobian Transpose Controller

Figure 5-38 shows the contact respsonse in the x direction.

During freespace motion prior to contact, the force applied to the master deviates from the slave force because the user must move the slave inertia. Upon contact, the wrist tip stops against the aluminum block, but the slave inertia causes the base to continue moving. This causes a relatively large deflection in wrist, causing the slave

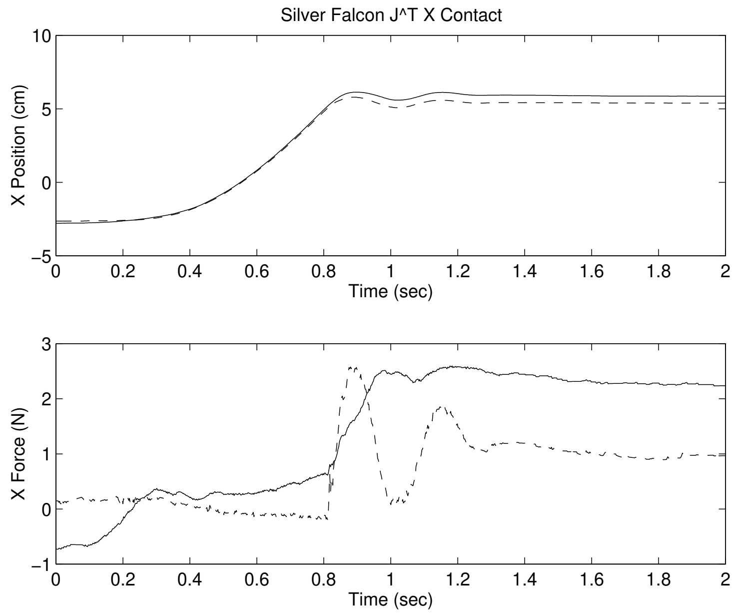

Figure 5-38: Contact response for the Silver Falcon slave and Phantom master in the x direction using the Jacobian Transpose controller. The solid line represents the master, and the dashed line represents the slave.

force to reach 2.5 N. The inertia of slave bounces against the wrist servo stiffness and settles to a slave contact force of about 1 N and master force of about 2 N.

Note that in the position response, the slave does not appear to come directly to a rest during the contact, but rather has a rounded decelleration. This is in fact not the case. The slave tip comes to an abrupt stop when it hits the aluminum block as we can see when watching the tests. However, the position is measured from encoder measurements. Therefore, the stiffness of the environment is modified by any structural flexibility in the system between the motors and the slave tip. This directly limits the crispness of the contact, and is evident in all the position repsonse plots shown here with the exception of the gripper contact response plot in Figure 5-44.

The y direction contact response looks qualitatively similar though with less wrist deflection, possibly because of the greater friction in this axis, and because the contact speed was slower. 5-39

The z contact response looks considerably different. The freespace motion clearly requires greater forces in order to move the heavier joint 2 axis. The contact is fairly sharp, but does not feel very distinct because the increase in force due to contact is only 1 N whereas 2 N of force were required just to move the slave inertia.

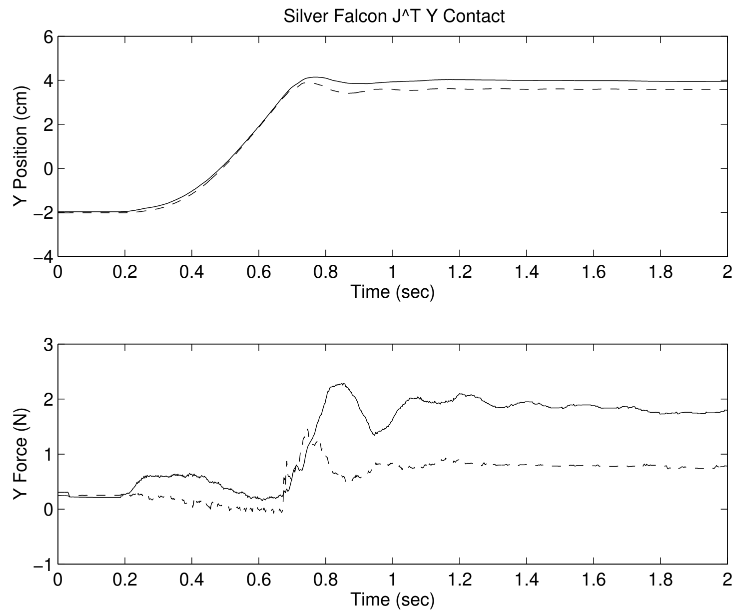

Figure 5-39: Contact response for the Silver Falcon slave and Phantom master in the y direction using the Jacobian Transpose controller. The solid line represents the master, and the dashed line represents the slave.

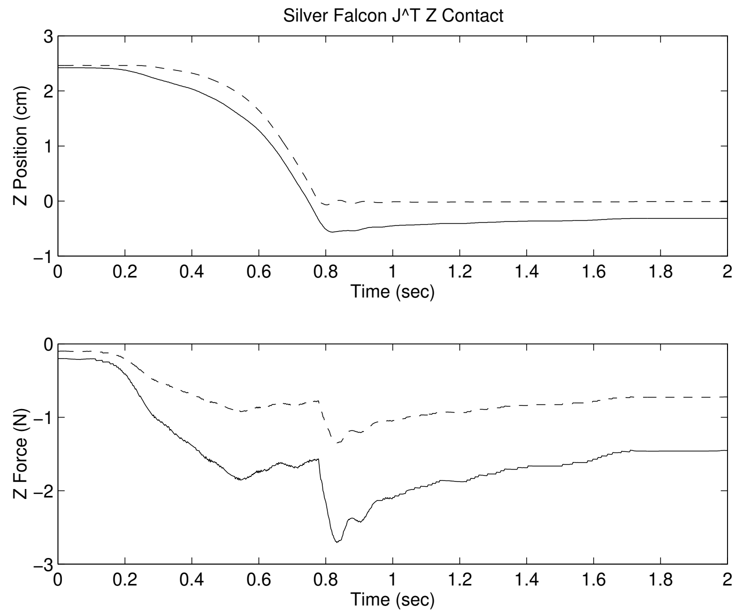

Figure 5-40: Contact response for the Silver Falcon slave and Phantom master in the z direction using the Jacobian Transpose controller. The solid line represents the master, and the dashed line represents the slave.

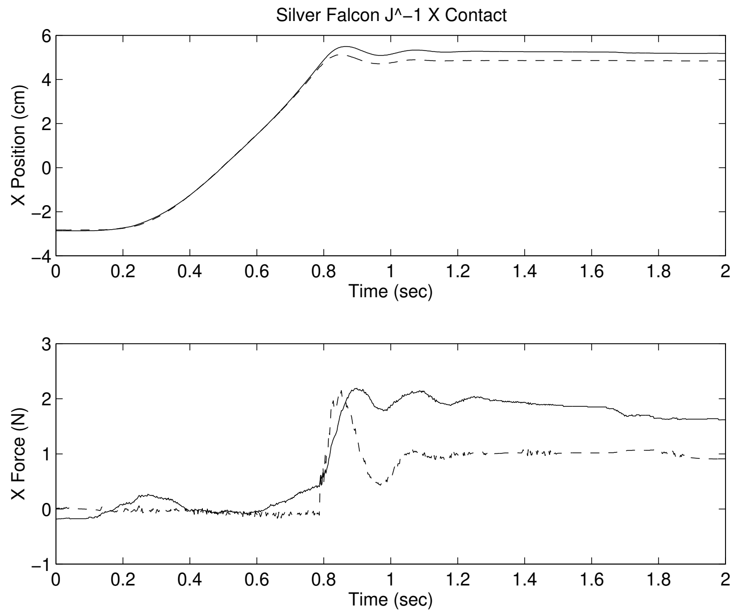

Figure 5-41: Contact response for the Silver Falcon slave and Phantom master in the x direction using the Jacobian Inverse controller. The solid line represents the master, and the dashed line represents the slave.

Note that since inertial forces required to stop the slave manipulator are not shown in these plots, and because there is no low inertia wrist elements flexing during this contact, the actual contact force is likely to be substantialy higher than shown in the plots. 5-40

5.6.2.2 Inverse Jacobian Controller

The x and y direction contact plots are shown in Figures 5-41 and 5-42 respectively. These are similar to those using the Jacobian Transpose controller. There are two subtle differences. The magnitude of forces during freespace motions are slightly less, particularly in the x response, and the level of oscillation in the base position after contact is made is slightly less. These can both be explained by a reduced base inertia as felt by the master.

The z direction plots are different however, as shown in Figure 5-43. There is essentially no force reflection in the z direction. This is because there are no micro freedoms in the z direction with the wrist oriented in the zero postion (with the fingers pointing straight down). Note that if the wrist were bent at 90° , say by moving q_4 to 90° , then the plot would look similar to Figure 5-41, though perhaps slightly better

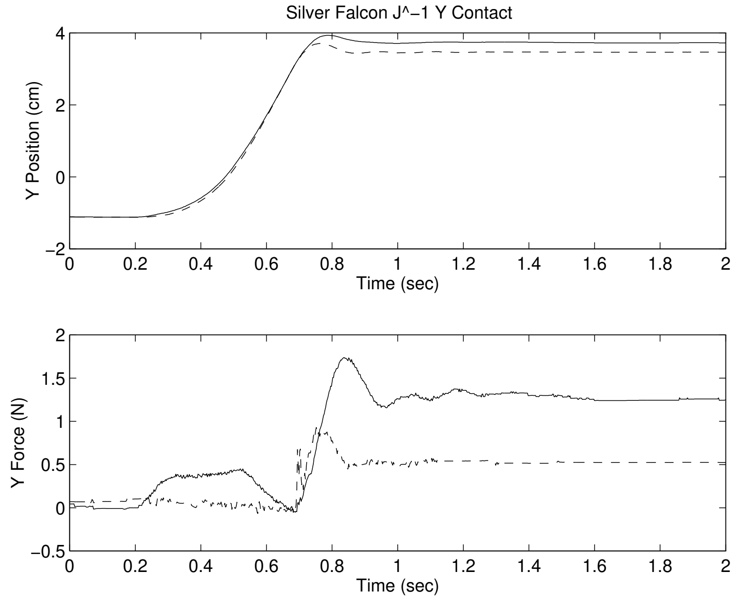

Figure 5-42: Contact response for the Silver Falcon slave and Phantom master in the y direction using the Jacobian Inverse controller. The solid line represents the master, and the dashed line represents the slave.

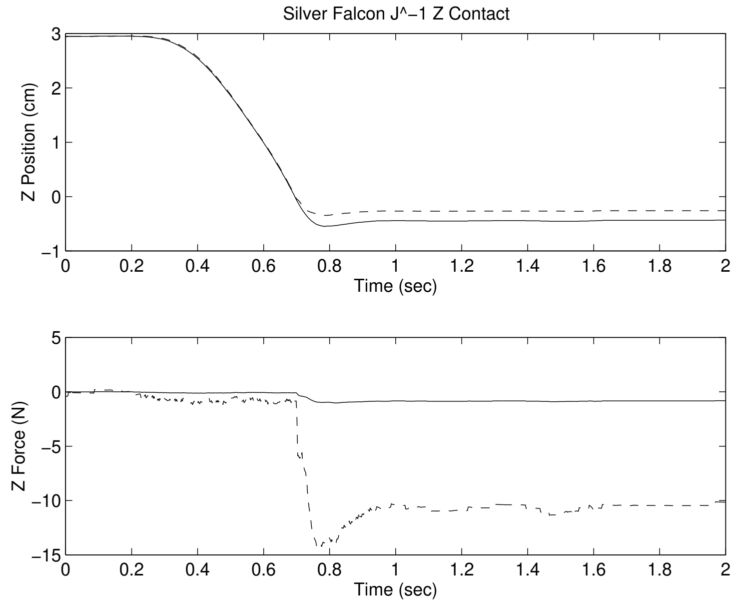

Figure 5-43: Contact response for the Silver Falcon slave and Phantom master in the z direction using the Jacobian Inverse controller. The solid line represents the master, and the dashed line represents the slave.

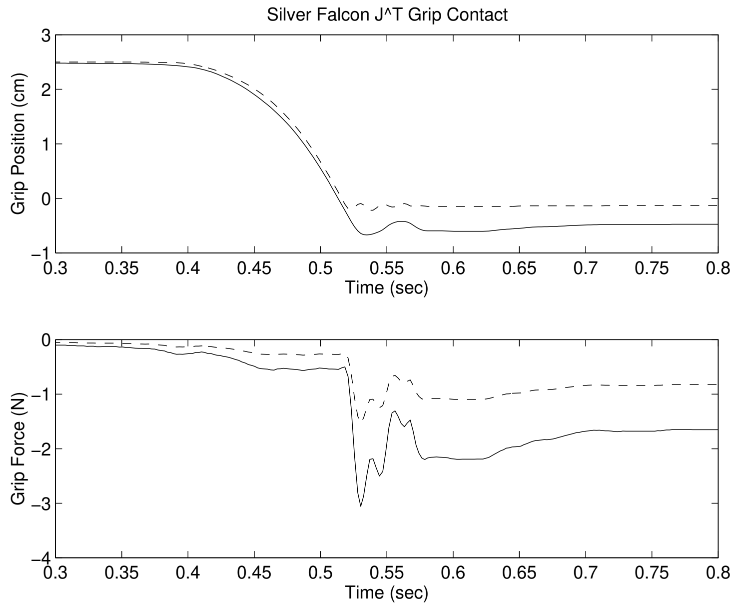

Figure 5-44: Contact response for the Silver Falcon slave and Phantom master for the gripper using the Jacobian Inverse controller. The solid line represents the master, and the dashed line represents the slave.

because the tracking performance of joint 2 is better than that of the joints 0 and 1 of the base positioner.

5.6.2.3 Gripper Contact Response

These plots show the slave gripper (joint 6) operated using the actuated gripper as a master. As we mentioned before, this is effectively the basic force reflecting teleoperator described in Chapter 2. Figure 5-44 shows the contact response. This figure shows a very quick motion. Note that the graph represents 0.5 seconds instead of 2.0 seconds as in the other graphs. When performing the test, we can see that the fingers clamp together without oscillation. The plot shows a slight oscillation in the slave position response which most likely represents an oscillation between the inertia of the motor rotors and that of the servo. The actuated gripper position slightly overshoots and then settles to about -1.8 N, while the slave contact force (grip force) is maintained at half this value.

This response is probably the best feeling contact response of any shown in the thesis. We feel a very crisp contact, as indicated by the very low forces prior to contact followed by a very sharp rise to -3 N force in roughly 10 ms.

We submit that the reason why this response feels good is that our measurement of the endpoint position of the slave is more accurate for the gripper than any other axes due to the relative lack of structural flexibility between the motors and gripper. Of course the actuated gripper is a very good master, given that it has less inertia and lower friction than the Phantom.[6] To test whether the quality of the master, or the quality of our slave endpoint measurement improved the quality of the contact, we performed a qualitative experiment. The Phantom x axis and the actuated gripper were swapped so that the Phantom controlled gripping, y, and z slave motions, and the actuated master controlled the x motion of the slave. Both were programmed with the same stiffness gains (480 N/m). Now x contact was felt with the actuated gripper, and gripping contact was felt with the master. The grip contact, felt through the Phantom, still felt good, whereas the x contact, felt through the actuated gripper, felt much as it did before. It appears as though the inertia and structural flexibility of the slave are more to blame rather than the quality of the master.

5.6.2.4 Discrimination Tests

With the wrist in its zero position (the fingers pointing straight down), we measured the ability to distinguish small forces. These tests were done using the Inverse Jacobian controller, which we felt to be our best controller. We attached a string to our digital force gage and gripped a loop tied in the other end of the string with the gripper jaws. I then moved the master so that the slave moved in the x, y and z directions until I just began to feel a force indicating that the string had become taught. My eyes were closed. The force levels were then recorded. This represents the smallest force which I could distinguish above the freespace forces. Six measurements were made in each direction and the values averaged. The values were:

$$\begin{aligned} f_{dx} &= 0.23 \text{ N} \\ f_{dy} &= 0.26 \text{ N} \\ f_{dz} &= N.A. \end{aligned}$$

In the z direction, the string slipped out of the fingers above 3 N without ever feeling any force at the master. This is expected since we have previously shown there is essentially no force reflection in a direction pointing directly into the fingers, and with the fingers pointing downwards, this corresponds to the z direction.

[6] Things become easier when you're working with only one degree of freedom.

5.7 Summary

The Silver Falcon provided us with a testbed to study a number of issues in teleoperation for MIS surgery:

- We tested and confirmed the feasibility of using a cable actuated wrist as an end effector suitable for MIS surgery.
- We found that the double parallelagram remote center kinematics works well to provide a remote center of rotation without using additional redundant joints.
- It is possible to use a kinematically dissimilar master and slave in conjunction with a cartesian controller.
- We found that macro-micro control works but requires a wrist with more degrees of freedom if we are to feel forces in all three directions. Using our roll-pitch-yaw wrist, motions in the direction of the fingertips do not have a micro freedom available.
- The standard Jacobian Transpose method of cartesian control simply transmits too much inertia to the user via the master to be useful.
- The Inverse Jacobian controller reduces the slave inertia transmitted to the surgeon via the master, but relies on the micro freedoms to provide force feedback.
- Force scaling is possible, but the force scale factor is limited largely by friction in the slave wrist. We used a force scale factor of 2:1 in all the results given in this chapter.
- Building the Silver Falcon gave us experience with a number of practical design issues including motor sizing, cable friction, bearing friction, motor brush friction, encoder resolution, and stuctural design.

There are a number a number of areas which call for improvement:

- We need to add a degree of freedom to the wrist if we intend to achieve 3 directions of macro-micro force feedback.
- The grip force was insufficient to securely hold needles. This is a fundamental practical issue, and must be addressed in a new system.
- A system used in the operating room will need interchangeable tools and instruments. This is a severe contstaint and we need to study how this will affect the overall design.

- The structural rigidity must be improved, both of the main base unit and of the wrist unit.
- The base unit axes (0 and 1) should be designed for improved tracking performance.
- For safety, the system should be counterbalanced. In the event of a complete system shutdown with no power, the system should not move on its own. Because the slave may be tilted above a patient, it is difficult to design a spring counterbalance that will compensate for this reorientation. The most straightforward solution is gravitaitonal counterbalancing.

Chapter 6

Black Falcon Teleoperator Slave

This chapter presents our second teleoperator slave design, the Black Falcon. We begin by summarizing the changes which have been made and the goals achieved. We describe the design and conclude with a performance evaluation of the system. The Black Falcon was tested using two different master manipulators. For our force reflection tests, we used the Phantom Haptic interface which was described in Chapter 5. In order to perform motion scaling, we found we needed a larger master workspace. Therefore, to demonstrate tasks such as suturing with motion scaling we used a larger version of the Phantom, know as the Tool Handle (**?**). The tool handle is essentially a scaled up Phantom with 16 in link lengths instead of 5.5 in link lengths.

6.1 Goals Achieved

The Black Falcon incorporates lessons learned from designing and testing the Silver Falcon to develop a more complete testbed for future research in telesurgy and telemanipulation. The primary issues we addressed were allowing interchangable tools, gravitationally counterbalancing the system, designing a wrist which would allow full three degree of freedom macro-micro control, and increasing the overall size, rigidity and strength of the system. Below is a brief description of these features. A photo of the Black Falcon is shown in Figure 6-1.

- A similar remote center linkage was used on the Black Falcon as was used in the Silver Falcon.
- In order to counterbalance the system, we relocated all of the system motors to locations below the center of the main gimbal. The mass of the entire structure

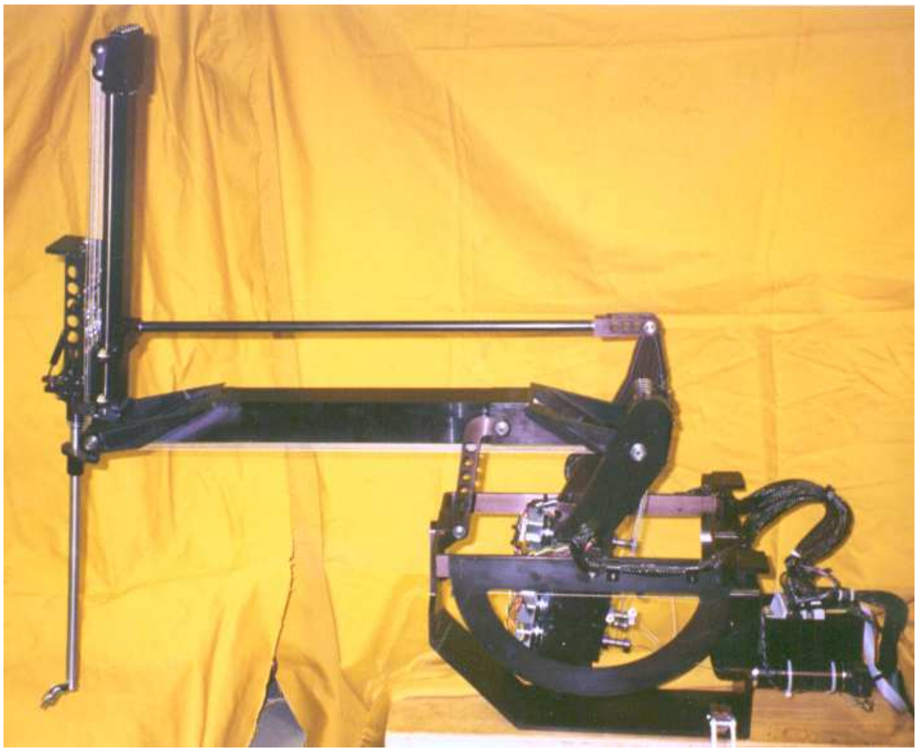

Figure 6-1: The Black Falcon