Chapter 5

Silver Falcon Teleoperator Slave

This chapter presents our first teleoperator slave, the Silver Falcon. We begin by describing which of our overall goals were satisfied, and which were not. We then proceed with a general description of the design followed by a detailed description of the implementation and the appropriate differential kinematic relationships between motors and joints. We then briefly discuss the master which was used and the controller implemented on the Silver Falcon. Finally we conclude with a performance evaluation and discuss areas for improvement.

5.1 Goals Achieved

Our goal in building the Silver Falcon was to test the feasibilty of our ideas for wrist and mechanism design when applied specifically to minimally invasive surgery. The system was built around a novel cable driven wrist and actuator concept which was mounted to a remote center positioning mechanism,[1]. We control the system using a modified Phantom™ haptic interface. Below is a summary of specifications and goals achieved and not achieved in this design.

- The Silver Falcon allows positioning and and orientation of the end effector within its workspace by using 7 degrees of freedom, (6 + gripping).

[1]At the time of this writing, 3 patents were applied for: Madhani and Salisbury "Force-Reflecting Surgical Instrument and Positioning Mechanism for Performing Minimally Invasive Surgery with Enhanced Dexterity and Sensitivity", Madhani and Salisbury "Wrist Mechanism for Surgical Instrument for Performing Minimally Invasive Surgery with Enhnaced Dexterity and Sensitivity", and Madhani and Salisbury "Articulated Surgical Instrument for Performing Minimally Invasive Surgery with Enhanced Dexterity and Sensitivity"

- The system satisfies the incision point constraint by using remote center kinematics. There are no uncontrolled (passive) or redundant degrees of freedom to maintain the incision point constraint.
- The system minimizes friction by using a low friction cable drive design throughout. There are no gears, and no backlash in any of the joints.
- The wrist is designed to allow force reflection in two directions. The backdrive friction in the wrist is 0.30 N, and 0.75 N in each of these two directions measured at the tip of the end effector jaws.
- The wrist can orient +90 degrees in pitch and yaw (the exact kinematics will described herein). There are two points which are singular at the edges of the wrist workspace.
- Macro-micro control can be achieved in two of three directions, as the wrist provides redundant (micro) motions in only two of three directions.
- The stroke is 7", slightly less than the 8-10" desired.
- The maximum forces achievable at the tip of the Silver Falcon are are between 5.4 N (1.2 lbs) and 41 N (9.2 lbs) at the tip of the manipulator depending on the direction of the force and the orientation of the wrist.
- The grip force achievable is 0.48 N (1.0 lbs) at the tip of the gripper jaws.
- The system can be operated in one of two counterbalancing modes. Either we can use a spring counterbalance which is designed into the system, or we can actively add gravity compensation terms to the controller and use motor torques which are functions of position.
- The system uses electric motors, which work well within the constraints of an operating room.
- Draping and sterilization were not addressed in this design.
- Safety features such as redundant sensors were not implemented in this design.
- The tool tip (end effector) in this design is fixed and not interchangable.
- The shaft diameter is 16 mm, somewhat greater than the 10-13 mm desired.

Figure 5-1: The Silver Falcon, our first teleoperator slave prototype for Minimally Invasive Surgery. This system fixed the basic kinematics and layout of the device and allowed initial testing to determine feasability of the teleoperated MIS concept.

5.2 Silver Falcon Design

Figure 5-1 shows a photo of the Silver Falcon. The system has seven degrees of freedom (DOF) which are shown in Figure 5-2.

The Silver Falcon can be broken into two major subsystems which are designed to work together to achieve force reflecting teleoeperation. The first is a five DOF wrist unit comprising a wrist, gripper, instrument shaft, and five motors. In the descriptions, I often refer to the wrist unit as the "instrument" and the shaft which passes into the body as the "instrument shaft" in analogy with conventional surgical instruments. The wrist unit is labelled 12 in the figures, and the numbering scheme is consistent throughout all the figures in this chapter. The wrist unit is carried by a second subsystem, a two DOF remote center base positioner, 14, which allows overall pitch/yaw of the wrist unit about the incision point. Figure 5-3 shows a schematic view of the entire Silver Falcon with components labelled as described above.

Before we begin the detailed description of the base unit and wrist unit, notice

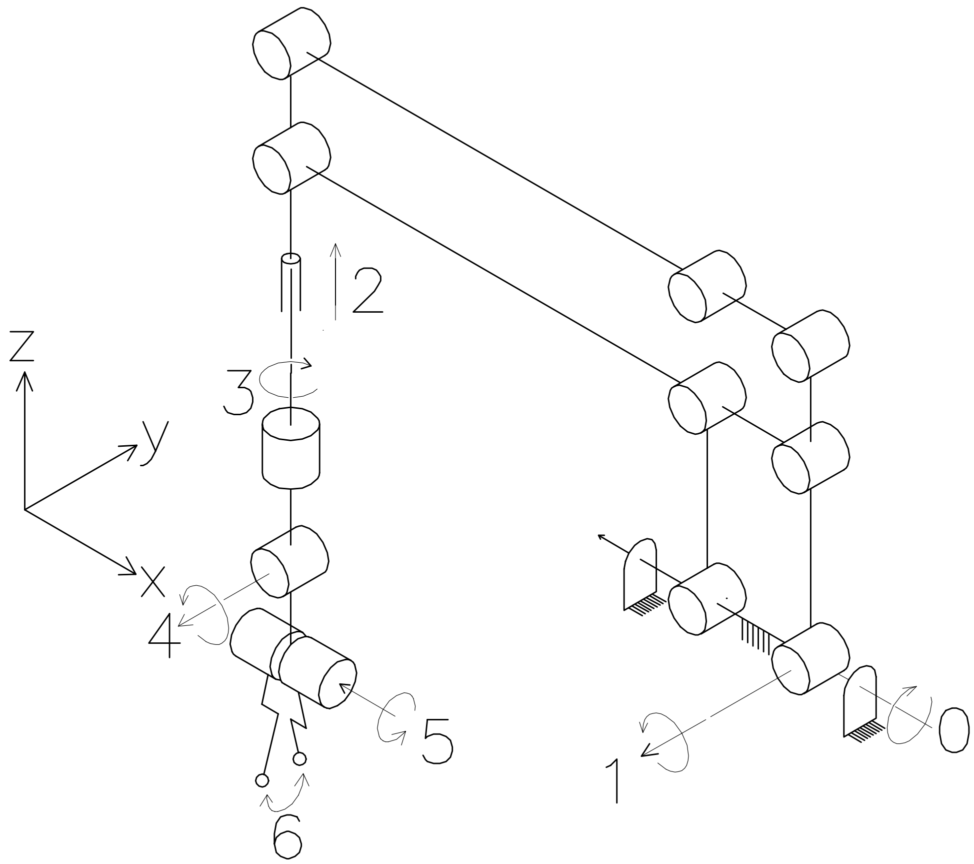

Figure 5-2: Layout of the seven DOF kinematics. The joints are labelled from 0 to 6. Note that joint 5 represents rotation of a point midway between the two fingers about the final yaw axis, and that joint 6 represents gripping motions bewteen the two fingers. Opening of the fingers is defined as positive.

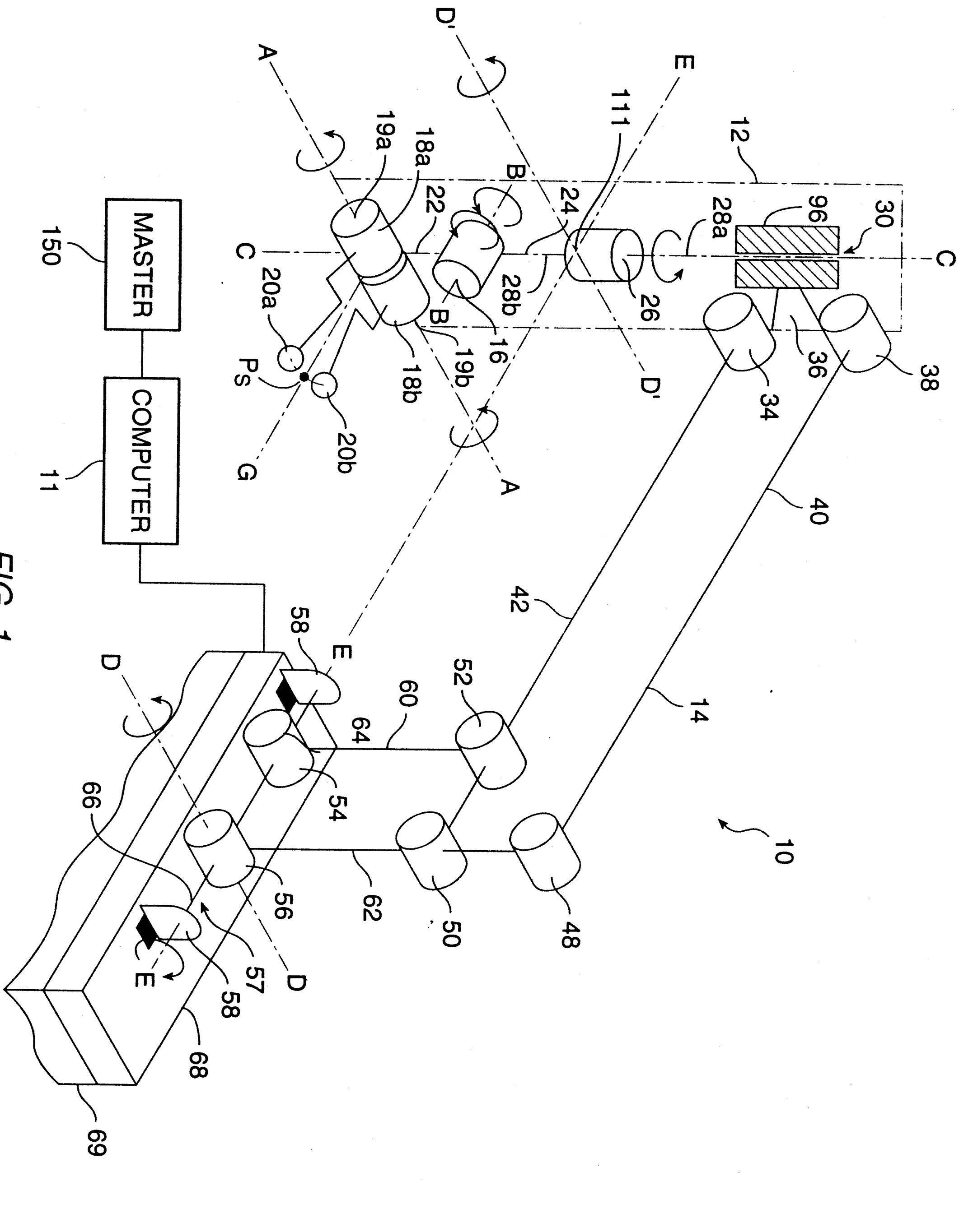

FIG. 1

Figure 5-3: Schematic view of the Silver Falcon which shows the numbering scheme used in the descriptions.

that the wrist and fingers are much lower in inertia than is the entire base positioner which must carry the wrist unit including its actuators. As a result of the low end effector inertia, the macro-micro control discussed in Chapter 3 can be applied to the Silver Falcon if we consider the wrist and fingers to be the micro freedoms and the base positioner to be constitute the macro freedoms.

5.2.1 Remote Center Base Positioner

5.2.1.1 Remote Center Kinematics

The purpose of the base positioner is to position the wrist unit with two DOF (pitch and yaw) inside the human body, without violating the constraint imposed by the fixed tissue incision point. Combined with a translational DOF which is part of the wrist unit, this provides three DOF (x, y, z) positioning for the wrist and fingers. The kinematics used to do this are shown in Figure 5-4. The parallelagram linkage shown gives the instrument shaft two rotary degeres of freedom about a remote center point. This is critical for endoscopic surgery because the center of rotation can then be placed at the tissue incision point to enable endoscopic procedures.

5.2.1.2 Cable Drives

Figure 5-5 shows the drive system for the base positioner. The drive system must operate smoothly and without backlash, because errors in this drive are amplified by the length of the instrument shaft beyond the remote center. Also vibrations or cogging introduced by the drive would excite the entire structure. The cable drives below are backlash free, have low stiction and no cogging. Referring to the figure, two rings, 32 and 42, are fixed to a spindle 57. Motor M0 is fixed to the base, 68, and is coupled to ring 32 via a cable drive as shown in Figure 5-6. This provides yaw motion of the entire remote center structure about axis E. Motor M1 is fixed to the vertical support 56 and is coupled to ring 42 in a similar manner as in the yaw drive. However, now the motor walks around the fixed ring in order to pitch the remote center mechanism forwards and backwards.

One effect of allowing motor M1 to move is that its weight partially counterbalances the entire structure. It acts as a pendulum, in effect, to countact the weight of the wrist unit and base positioner structure. Unfortunately, in this design the weight of the five wrist unit motors far outweighs that of motor M1, so that a spring counterbalance was incorporated to compensate for the remaining imbalance.