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The Design of a Nine-String Six-Degree-of-Freedom Force-Feedback Joystick for Telemanipulation

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1. Abstract

This paper presents an overview of the design and controlling equations for a 6-degree-of-freedom force-feedback joystick for telemanipulation. The joystick has a parallel mechanical structure which allows all of its actuators to be fixed to a non-moving base. The low-inertia design is expected to provide an accurate force-feedback signal to the joystick operator without the need for closed-loop momentum compensation. The analysis describes the joystick's inputs and outputs in generalized Cartesian space, so the joystick can potentially be used as an interface for any 6-degree-of-freedom device.

2. Introduction

Telemanipulator joysticks are typically serial mechanisms similar to the serial manipulators they control. Serial mechanisms have the disadvantage that each joint actuator has to support its own load as well as the mass of all the other actuators higher up the kinematic chain. Serial mechanisms are therefore inherently high-mass systems. In a parallel mechanism, all of the joint actuators are fixed to ground, so the inertial mass of the mechanism will be significantly less than for a similarly sized serial mechanism. Furthermore, each actuator in a parallel mechanism shares the load; the result is a smaller torque requirement on each actuator. And since the actuators share similar loads, one design is sufficient for all the actuators. To use a parallel structure joystick to control a manipulator with a different kinematic structure, a microprocessor is required to transform information to and from the joystick actuators into Cartesian vectors which can be understood by the manipulator controller. This paper presents an overview of the design and kinematic and dynamic analysis for a parallel mechanism force-feedback joystick for telemanipulation of a 6-degree-of-freedom device.

2.1. Physical Description

The 6-degree-of-freedom force feedback joystick is shown in Figures 1 and 2. The design is based on a unilateral (no force-feedback) joystick developed by the Center for Intelligent Machines and Robotics at the University of Florida [1]. The design presented here is currently under development by Tesar and the Manufacturing Engineering Systems Group at the University of Texas at Austin. This paper is based on the author's Master's thesis [2] and summarizes some of the progress made by the research group at Texas. Implementation issues such as software development, specific design requirements, and calibration techniques are addressed in reference [2].

The 9-string design consists of a T-shaped, ambidextrous handgrip supported by nine steel cables, or "strings," and three passive, constant-force linear actuators. The cables are attached to motorized spools arranged in three triangles on three perpendicular faces of a box enclosing the joystick's working volume. By measuring the length of each cable as the handgrip moves, the position of three points on the handgrip,

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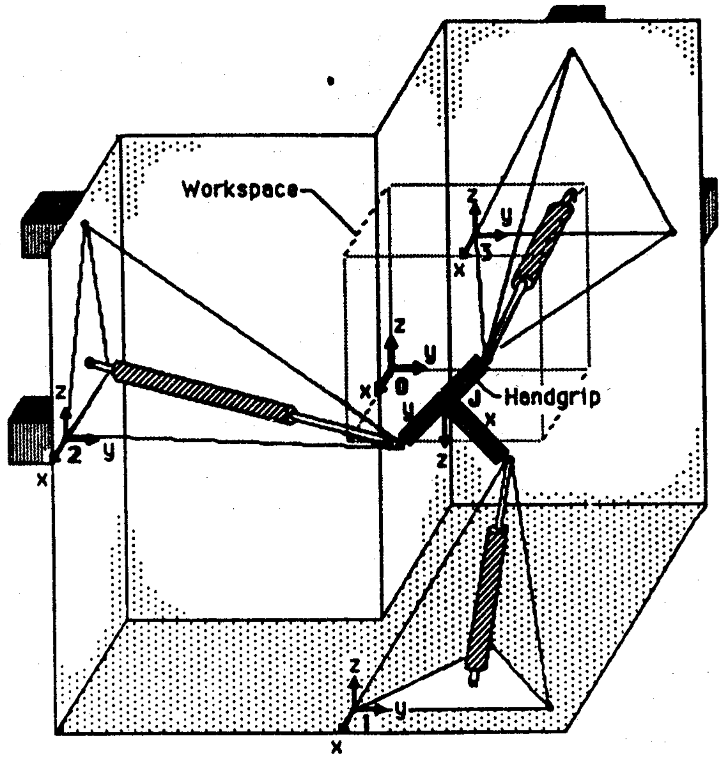

Figure 1. The 9-String Force-Feedback Joystick

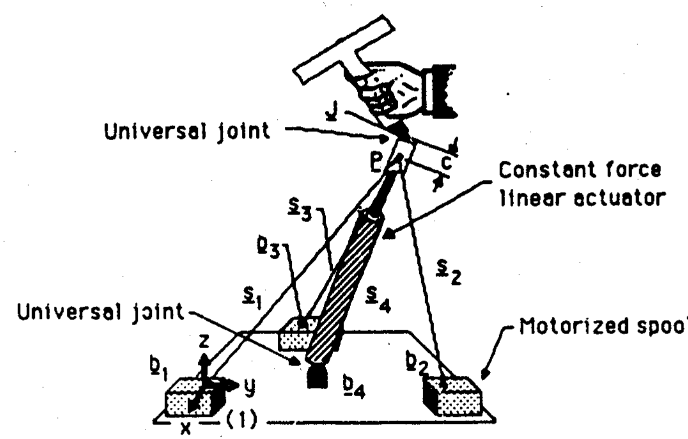

Figure 2. Detail of an Actuator Assembly

and hence the handgrip orientation and position, can be calculated. Force feedback is accomplished by controlling the tension in each cable with the motorized spools. The resultant of the force vectors from the cable tensions and the linear actuators is a force and torque vector in any desired direction at the center of the grip.

Prototypes of the motorized spools, shown in Figure 3, have been built by Houston Scientific International, Inc. The actuator design is basically an off-the-shelf position transducer with a DC servo motor rather than a spring motor for cable tension. A high-precision potentiometer attached to the spool measures cable length.

The initial design for the passive linear actuator was an air cylinder connected to a constant pressure source. The cylinders obtained for the prototype joystick had unacceptably high mass and friction, however, so other designs are being investigated. The author recommends the design shown in Figure 4, which uses constant force springs.

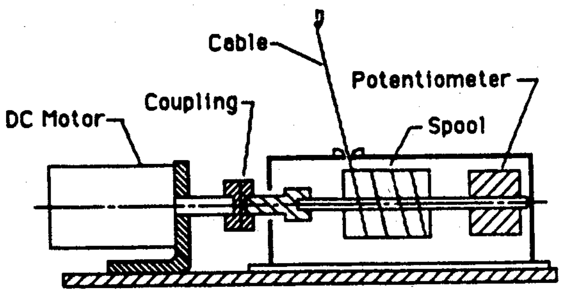

Figure 3. Detail of the Motorized Spool

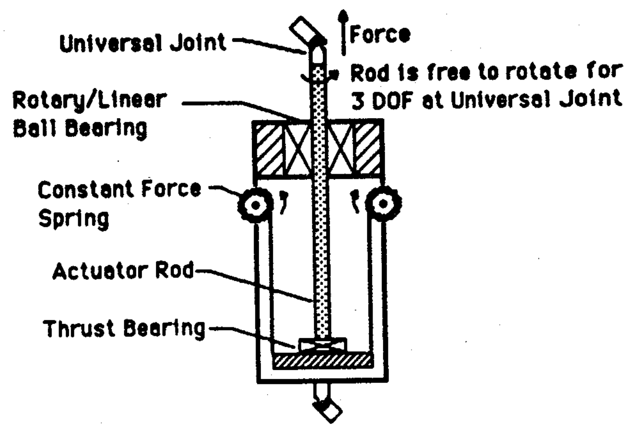

Figure 4. Detail of the Constant-Force Spring Linear Actuator

The baseline joystick controller is a DEC MicroVAX, but the research team believes it would be feasible to use a less powerful computer such as an IBM PC as a dedicated controller, and still maintain an update rate of 30 Hz or better.

The baseline 9-string joystick design parameters are as follows:

Translational Volume	16 inch cube
Orientation Range	180 degrees each axis
Force Feedback Range	9 pounds
Torque Feedback Range	2 foot-pounds

The ranges of motion and force-feedback were chosen based on human factors guidelines for comfortable manual control [3].

3. Position Analysis

This section describes the kinematic equations for determining the position and orientation of the joystick handgrip from the string lengths.

3.1. Three Intersecting Strings*

The first step in the kinematic solution is to determine the positions of the three points on the handgrip where strings intersect. Lipkin derived the solution in reference [1]. The solution is presented for one set of three strings, and can be generalized for the other two sets by a coordinate rotation. The form of the solution is simplified considerably by defining a local reference frame (frames (1), (2), and

(3) in Figure 1) parallel to the global joystick coordinate frame (0), with the origin at point $\underline{b}_1$. Point $\underline{b}_2$ lies along the y axis and $\underline{b}_3$ lies in the x-y plane. The strings s_1, s_2, and s_3 intersect at point $\underline{P}$.

Lipkin's solution is shown below. The $^{(1)}$ superscript indicates that coordinates are in coordinate system (1) (vectors without a superscript are in the global coordinate system (0)), and the trailing superscript indicates the vector component. s_i is the length of string i.

$$ {}^{(1)}p^y = (s_1^2 - s_2^2 + ({}^{(1)}b_2^y)^2) / 2\, {}^{(1)}b_2^y \tag{3.1.1} $$

$$ {}^{(1)}p^x = (s_1^2 - s_3^2 + ({}^{(1)}b_3^x)^2 + ({}^{(1)}b_3^y)^2 - 2\, {}^{(1)}p^y\, {}^{(1)}b_3^y) / 2\, {}^{(1)}b_3^y \tag{3.1.2} $$

$$ {}^{(1)}p^z = \pm\sqrt{(s_1^2 - ({}^{(1)}p^x)^2 - ({}^{(1)}p^y)^2)} \tag{3.1.3} $$

Equation 3.1.3 has two solutions, one above and one below the x-y plane. The correct choice is obvious from the physical constraints of the joystick; the positive solution is correct for all three sets of strings.

Since the reference frame (1) is parallel with the global frame (0), point $^{(1)}\underline{P}$ can easily be translated into the global frame.

Because of physical design constraints, the strings intersect at points on the linear actuator rods, rather than on the arms of the joystick. However, point $\underline{J}$ on the joystick can be found from point $\underline{P}$, since they both lie in the direction of the vector $\underline{s}_4$, a fixed distance c apart, as shown in Figure 2. First we define $\underline{s}_4$ as the free vector:

$$ \underline{s}_4 \equiv \underline{P} - \underline{b}_4 \tag{3.1.4} $$

where $\underline{b}_4$ is the position of the bottom universal joint axis of the linear actuator. $\underline{J}$ is:

$$ \underline{J} = (s_4 + c)\, \underline{s}_4 + \underline{b}_4 \tag{3.1.5} $$

where s_4 is the magnitude of $\underline{s}_4$ and $\underline{s}_4$ is the unit vector in the direction of $\underline{s}_4$.

3.2. Orientation of the Joystick

After determining the positions of three points on the joystick grip, we must find its orientation and the position of the center of the grip. We can do this by deriving the rotation matrix from the local (J) reference frame fixed in the center of the grip to the global (0) reference frame, shown in Figure 5. The points $\underline{J}_{1-3}$ are equidistant from $\underline{J}_0$, located at the corners of an equilateral triangle. This arrangement results in an equal distribution of the force-feedback load to the actuators and minimizes errors in the orientation solution, as recommended by Lipkin [1]. The unit vectors $\underline{i}$, $\underline{j}$, and $\underline{k}$ are defined as the direction cosines of the (J) system x, y, and z axes in the global frame (0). The arms of the joystick lie in the x-y plane of the (J) system, with the top of the T parallel to the $^{(J)}y$ axis, and these properties are used to find the direction cosines as follows:

$$ \underline{j} = (\underline{J}_2 - \underline{J}_3) / \left| \underline{J}_2 - \underline{J}_3 \right| \tag{3.2.1} $$

$$ \underline{k} = ((\underline{J}_1 - \underline{J}_3) \times \underline{j}) / \left| (\underline{J}_1 - \underline{J}_3) \times \underline{j} \right| \tag{3.2.2} $$

$$ \underline{i} = \underline{j} \times \underline{k} \tag{3.2.3} $$

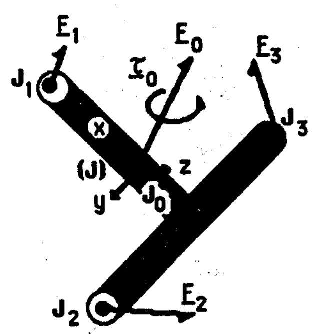

Figure 5. Forces on the Handgrip

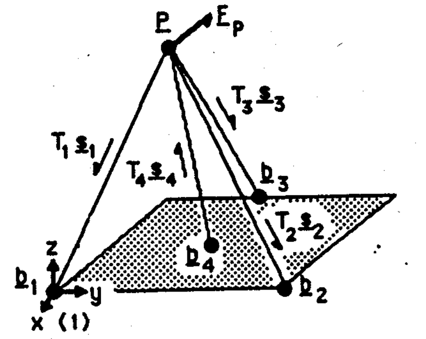

Figure 6. Actuator Force Vectors

The 3x3 rotation matrix from the (J) to the (0) system is simply:

$$[R_J{}^0] = [\underline{i}\ \underline{j}\ \underline{k}] \tag{3.2.4}$$

Since we know the position of at least one point on the grip in global coordinates, the vector from that point to the center of the grip in local coordinates, and the (J) to (0) rotation matrix, the center of the grip $\underline{J}_0$ can be calculated in global coordinates:

$$\underline{J}_0 = \underline{J}_1 - [R_J{}^0]\ {}^{(J)}\underline{J}_1 \tag{3.2.5}$$

${}^{(J)}\underline{J}_1$ is the vector from the origin of the (J) frame, $\underline{J}_0$, to point $\underline{J}_1$ in local coordinates.

4. Force-Feedback Analysis

The desired force and torque vector on the handgrip is a signal generated by the telemanipulator controller, representing forces felt by the telemanipulator. These vectors are assumed to be expressed in a coordinate frame parallel to a local frame fixed to the handgrip. This section describes the transformations which relate cable tensions to a desired force on the handgrip.

4.1. Transformation from the Force and Torque at the Center of the Handgrip to Three Forces

This transformation is easier to think about by posing it backward. Given three force vectors on a body as shown in Figure 5, the resultant force and torque at point $\underline{J}_0$ is:

$$^{(J)}\underline{F}_0 = \Sigma\ ^{(J)}\underline{F}_i \tag{4.1.1}$$

$$^{(J)}\underline{\tau}_0 = \Sigma\ (\ ^{(J)}\underline{J}_i \times\ ^{(J)}\underline{F}_i\ ) \tag{4.1.2}$$

where i is summed from 1 to 3. Note that all vectors throughout this transformation are in the local (J) coordinate frame, fixed to the grip. Equations 4.1.1 and 4.1.2 can be rewritten in matrix form as

$$\underline{c} = [G_c{}^f]^T\ \underline{f} \tag{4.1.3}$$

where $\underline{c}$, $[G_c^f]^T$, and $\underline{f}$ are defined as:

$$\begin{bmatrix} F_0^x \\ F_0^y \\ F_0^z \\ \tau_0^x \\ \tau_0^y \\ \tau_0^z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & J_2^y & 0 & 0 & J_3^y \\ 0 & 0 & -J_1^x & 0 & 0 & -J_2^x & 0 & 0 & -J_3^x \\ 0 & J_1^x & 0 & -J_2^y & J_2^x & 0 & -J_3^y & J_3^x & 0 \end{bmatrix} \begin{bmatrix} F_1^x \\ F_1^y \\ F_1^z \\ F_2^x \\ F_2^y \\ F_2^z \\ F_3^x \\ F_3^y \\ F_3^z \end{bmatrix} \qquad (4.1.4)$$

The reference frame superscript $^{(J)}$ has been omitted in the equation above for readability, but the vectors are still in the (J) coordinate system.

Now the problem is to invert equation 4.1.4 and solve for $\underline{f}$. Since there are more unknowns than knowns, we will choose a cost function and use classical optimization to find the solution. A logical choice is to minimize the force on each arm of the grip, which will minimize the tension on each string, reducing each actuator load. The cost function q is defined as:

$$q = \underline{f}^T \cdot \underline{f} \qquad (4.1.5)$$

which is the sum of the squares of the force components. q is minimized subject to the set of constraints $\underline{r}$, which in our case is equation 4.1.3, rewritten as:

$$\underline{r} \equiv \underline{c} - [G_c^f]^T \, \underline{f} = 0 \qquad (4.1.6)$$

We can now form the Lagrangian:

$$L = q + \underline{\lambda}^T \cdot \underline{r} \qquad (4.1.7)$$

where $\underline{\lambda}$ is the 6 element vector of Lagrange multipliers. Partial differentiation of the Lagrangian with respect to $\underline{f}$ and $\underline{\lambda}$ yields 15 equations and 15 unknowns, which is sufficient to solve for $\underline{f}$ in terms of $\underline{c}$. The result is:

$$\underline{f} = [G_c^f] \left([G_c^f]^T [G_c^f] \right)^{-1} \underline{c} \qquad (4.1.8)$$

Since $[G_c^f]([G_c^f]^T[G_c^f])^{-1}$ is derived from constant geometric parameters (the shape of the joystick handgrip), it is constant and needs to be calculated only once. Now the solution for $\underline{f}$ is a straightforward matrix multiplication. For this design's particular grip geometry (an equilateral triangle with sides of length L), the solution is:

$$\begin{bmatrix} F_1^x \\ F_1^y \\ F_1^z \\ F_2^x \\ F_2^y \\ F_2^z \\ F_3^x \\ F_3^y \\ F_3^z \end{bmatrix} = \begin{bmatrix} 1/3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/3 & 0 & 0 & 0 & \sqrt{3}/3L \\ 0 & 0 & 1/3 & 0 & -2\sqrt{3}/3L & 0 \\ 1/3 & 0 & 0 & 0 & 0 & -1/2L \\ 0 & 1/3 & 0 & 0 & 0 & -\sqrt{3}/6L \\ 0 & 0 & 1/3 & 1/L & \sqrt{3}/3L & 0 \\ 1/3 & 0 & 0 & 0 & 0 & 1/2L \\ 0 & 1/3 & 0 & 0 & 0 & -\sqrt{3}/6L \\ 0 & 0 & 1/3 & -1/L & \sqrt{3}/3L & 0 \end{bmatrix} \begin{bmatrix} F_0^x \\ F_0^y \\ F_0^z \\ \tau_0^x \\ \tau_0^y \\ \tau_0^z \end{bmatrix} \qquad (4.1.9)$$

Finally, keeping in mind that $\underline{f}$ in equation 4.1.9 is in the (J) coordinate frame, we need to rotate the force on each arm of grip into the global coordinate frame with the rotation matrix derived in Section 3.2:

$$\underline{F}_i = [R_J^0] \cdot {}^{(J)}\underline{F}_i \qquad (4.1.10)$$

4.2. Transformation from the Force on a Grip Arm to Cable Tensions

The cables exert a force vector at point $\underline{P}$ on the linear actuator rather than at point $\underline{J}$ where we have calculated the desired force. However, if the distance between $\underline{P}$ and $\underline{J}$ is small relative to the distance from $\underline{P}$ to the linear actuator's bottom pivot, a force vector at $\underline{J}$ will be approximately equal to the same vector applied at $\underline{P}$. We will assume this is true to proceed, although the transformation from a force at $\underline{P}$ to a force at $\underline{J}$ is derived in reference [2]. The solution for the tensions in one set of cables is presented here. The solution can be generalized for the other two sets by a coordinate rotation. The force vectors from the actuators are shown in Figure 6.

If it were not for the linear actuator, the resultant force $\underline{F}_P$ would be constrained to point inside the tetrahedron formed by the strings, and force-feedback in an arbitrary direction would not be possible. A constant force linear actuator is desirable because it reduces the computation load on the joystick controller. Given the three vector components of the force at P, the controller has to calculate only three, rather than four, actuator forces. Also, constant force can be implemented with a passive actuator, simplifying the design task. The force from the linear actuator can be chosen off-line to optimize performance parameters, such as the force-feedback range [2].

As in Section 4.1, it is easier to state the transformation from force to string tensions backward and then invert it to solve for the unknowns. The vector $\underline{F}_P$ is the sum of the actuator force vectors. The actuators act in the directions of unit vectors $\underline{s}_j$, defined as $(\underline{P} - \underline{b}_j)/s_j$ (s_j is the string length). The strings act with tensions T_{1-3} (tensions are negative) along $\underline{s}_{1-3}$, and the linear actuator acts with compressive force T_4 (positive) along $\underline{s}_4$. $\underline{F}_P$ can be written in matrix form as:

$$\underline{F}_P = [\, \underline{s}_1 \; \underline{s}_2 \; \underline{s}_3] \, [\, T_1 \;\; T_2 \;\; T_3]^T + T_4 \, \underline{s}_4 \qquad (4.2.1)$$

Solving 4.2.1 for T_{1-3} yields:

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = [\, \underline{s}_1 \; \underline{s}_2 \; \underline{s}_3]^{-1} \, (\underline{F}_P - T_4 \, \underline{s}_4) \qquad (4.2.2)$$

Rather than performing a matrix inversion three times per loop of the joystick controlling software (one inversion per set of three strings), the inversion is done symbolically off-line, and the controlling software merely plugs values for $\underline{P}$ and $\underline{F}_P$ into the equation to calculate the string tensions.

5. Conclusions

The 9-string force-feedback joystick presented in ~~this paper~~ is an innovative approach to man-machine interface design. By taking advantage of the powerful microcomputers available for real-time control, telemanipulator design is no longer constrained to the replica master-slave systems of the past. This paper presented an overview of the design and the analytic feasibility for the joystick. It is now a matter of mechanical development to build and demonstrate the concept.

6. Acknowledgments

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7. References

[1] H. Lipkin, J. Duffy, and D. Tesar, "Kinematic Control of a Robotic Manipulator with a Unilateral Manual Controller," Report to the United States Department of Energy, The University of Florida, 1983.

[2] M. Agronin, "The Design and Software Formulation of a 9-String 6-Degree-of-Freedom Joystick for Telemanipulation," Master's Thesis, The University of Texas at Austin, 1986.

[3] W. E. Woodson, **Human Factors Design Handbook**, McGraw Hill, New York, 1981.