A Six Degree of Freedom Micromanipulator for Ophthalmic Surgery

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Abstract

Needs which have arisen in ophthalmic research have motivated the development of a six degree of freedom parallel micromanipulator. The first application of the tool will be in the treatment of retinal venous occlusion, for which micron-scale spherical movement of a glass micropipette tip inside the eye is required. The initial operation mode will be open loop while future operation will be in a force-reflecting bilateral (macro-master / micro-slave) arrangement. Presented here are some of the design criteria, the mathematical tools used in evaluating various parallel manipulator designs, and the final kinematic configuration.

1. Background and Motivation

An active area of research is the treatment of retinal venous occlusion by delivery of anticoagulant drugs directly to blood clots in retinal vessels [1,2,4]. Shortcomings of micro manipulators currently being used in such research have motivated the development of a new tool. In order to better explain the design constraints, some steps which are included in a typical procedure are outlined here. A hypodermic needle is inserted through the wall of the eye to gain access to the interior surface. A rigid glass micropipette is inserted through the hypodermic needle far enough that its tip protrudes beyond the end of the needle. The micropipette is guided to various injection sites on the retina by pivoting the hypodermic needle about its puncture point, that is, the point of intersection between the needle and the wall of the eye. By keeping the needle nearly stationary at the point where it passes into the eye's interior, damage to the wall of the eye is minimized. A third allowable degree of freedom is movement along the axis of the hypodermic needle since it does not deform the wall of the eye at the puncture point significantly.

Most commercially available micromanipulators are not useful for guiding the hypodermic needle in the way described, since they exhibit Cartesian movements. The spherical movement needed can be found in some commercially available micromanipulators, and some have been constructed for this type of research [9], but they are circular track serial devices, (figure 1), which are mechanically constrained to move on a spherical surface.
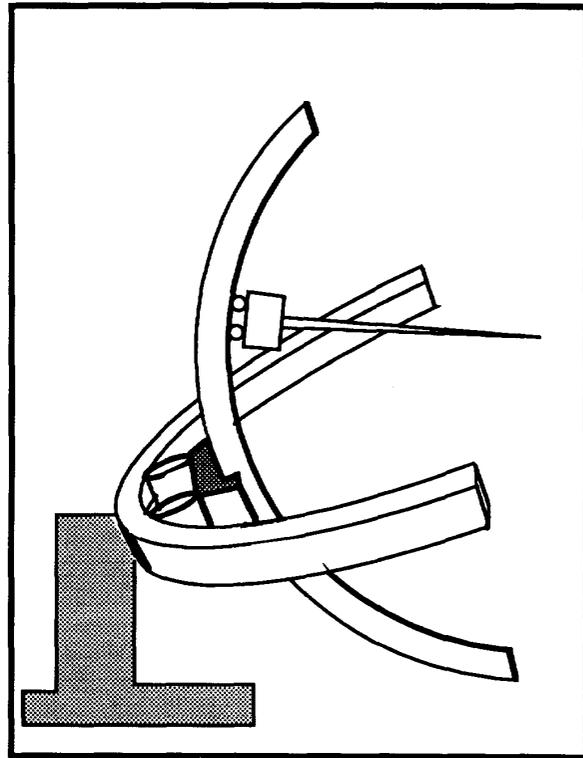

Figure 1: Schematic of a traditional spherical-movement micromanipulator.

Such micromanipulators tend to be bulky because the mechanical tracks span the entire range of motion at all times, prohibiting the accommodation of multiple simultaneous entries into the eye. Another point of functional inflexibility is that the center of spherical motion can not be moved with respect to the base of these manipulators due to the fixed radii of the mechanical tracks.

As an alternative to these gimbal-type devices which are *physically* constrained to the desired "puncture-centered" movement, the six DOF parallel device can be constrained *mathematically* by its computer controller. The advantage is not only the versatility gained by redundant degrees of freedom, but also that of compactness. A desirable size and shape for the device is that of a human wrist and hand gripping a slender tool. This will allow multiple manipulators to be used simultaneously on a single eye when necessary.

The initial operation mode will be open loop wherein the operator will watch the end effector (through the pupil with the aid of a microscope) and guide it using a multi-dimensional joystick input device connected to a computer controller. Subsequent modes of operation will include force-reflecting bilateral control arrangement (discussed later in this paper).

2. Kinematic Design

2.1. Initial Choice

The Stewart Platform [10] parallel six DOF robot scheme (figure 2) was chosen as a starting point for its inherent stiffness and compactness. (Merlet has
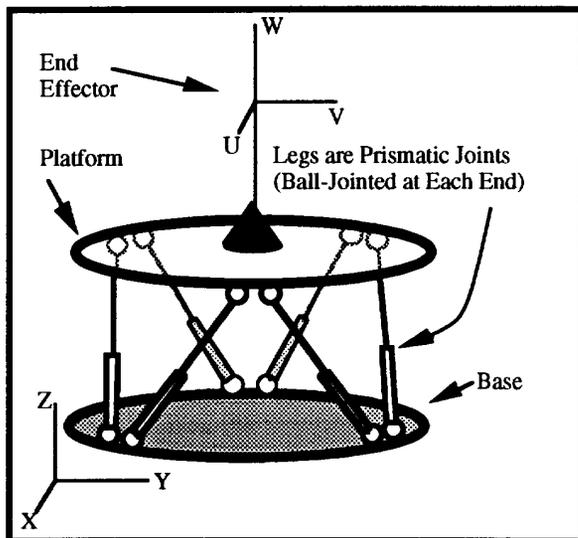

Figure 2: Stewart platform schematic

summarized several advantages not listed here [7].) Different geometries were evaluated through the definition of six quantities derived from the jacobian. Details follow.

2.2. Coordinate Systems

The traditional scheme of specifying end effector orientation with three euler angles will be slightly modified to better examine each manipulator design's suitability for the task at hand. Imagine a third coordinate system [U*V*W*] in addition to those pictured in figure 2 whose origin is always coincident with the [UVW] origin at the puncture point, and whose U*V* plane is always parallel to the XY plane. As the hypodermic end effector with rigidly attached system [UVW] is placed in some arbitrary orientation, the position of the *tip* of the needle can be projected onto the U*V* plane. (Recall that the puncture point is *not*, in general, at the tip of the needle.) The two coordinates (u^*,v^*) necessary to describe this projected tip position make up two of the three orientation variables. The third will be the angle of rotation γ of the platform about the hypodermic. The position (x,y,z) of the puncture point in the [XYZ] frame completes the set of six variables needed to fully specify the position and orientation of the end effector.

These choices were shaped by the microinjection task. During a procedure, the greatest part of the movement will be in the (u^*,v^*) coordinates, while rotation γ about the needle has little effect and therefore is of little importance for this application.

2.3. Sensitivity Parameters

One important requirement in choosing a specific kinematic design was low sensitivity of endpoint position to perturbations in leg length, because amplification of uncertainty in joint position is undesirable from the precision standpoint. Since the jacobian maps joint perturbations into endpoint perturbations, each Jacobian element can be thought of as a gain from joint to endpoint space.

$$
\begin{bmatrix} \delta x \\ \delta y \\ \delta z \\ \delta u^* \\ \delta v^* \\ \delta \gamma \end{bmatrix} = \begin{bmatrix} \dfrac{\partial x}{\partial q_1} \cdots \dfrac{\partial x}{\partial q_6} \\ \vdots \\ \dfrac{\partial \gamma}{\partial q_1} \cdots \dfrac{\partial \gamma}{\partial q_6} \end{bmatrix} \begin{bmatrix} \delta q_1 \\ \delta q_2 \\ \vdots \\ \delta q_6 \end{bmatrix}
$$

Endpoint Change	Jacobian	Joint Change

The sum of the absolute values of all Jacobian elements in a single row, (or the one-norm of each row vector) is some measure of a "worst-case" gain, mapping a

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simultaneous unit perturbation in all joints to a perturbation in one of the six endpoint coordinates. For the first row of the jacobian, define the sensitivity S1 to be

$$S_1 = \sum_{i=1}^{6} \left| \frac{\partial x}{\partial q_i} \right|.$$

The vector comprising all six such sensitivity measures will be called the sensitivity vector for convenience in this paper. Since the sensitivity vector is different for each position and orientation of the end effector of a given design, a few key positions were chosen as representative and considered across all designs. It should also be noted that comparison of sensitivity vectors is not a purely quantitative task, since one geometry might yield high sensitivity in one degree of freedom and low in another while the converse might be true in a second geometry. Knowledge of the movements that would be most critical in the microinjection application shaped the judgments of which sensitivity measures to weigh more heavily, (such as (u^*,v^*)), and which to, in some cases, ignore completely (such as γ). Yet another important point to note is that, while the vectors can be compared to one another, elements within one vector can not be directly compared. This is because the elements of the sensitivity vector corresponding to the rotational degree of freedom has units of (radians/length) while the translational DOF units are (length/length).

2.4. Mathematical Design Search Method

The approach, using the symbolic manipulation software package, Mathematica, was to leave the Stewart Platform geometry parameters of interest and the set of endpoint coordinates as variables, and then to solve the inverse kinematics problem of finding the joint positions (leg lengths) as a function of those variables. This is straightforward for a parallel manipulator, because once the coordinates of all leg attachment points are known in a single coordinate frame, leg lengths are found by vector differences. The inverse jacobian is then obtained by symbolically differentiating with respect to the joint positions. From this state, endpoint position and geometry values can be supplied, and the inverse jacobian evaluated and inverted to give the jacobian.

Following this procedure, many geometries and endpoint positions can be examined without having to invert or differentiate with numerical methods.

Parameters to be chosen included the diameter, Db, of the smallest circle circumscribing the leg attachments to ground (base size), a similar circle diameter, Dp, for the upper end leg attachments (platform size), and a nominal value, H, for the distance between platform and base.

Two general areas of investigation into geometry effects were the ratio H:Dp (slenderness), and the ratio Dp:Db (conicalness). Table 1 shows a few examples of the effects of geometry on sensitivity vectors.

Db (in)	Dp (in)	H (in)	Sensitivity of					
			x	y	z	u*	v*	γ
2	2	2	5.94	5.21	1.07	0.71	0.77	3.01
2	4	2	7.48	7.67	1.24	0.86	0.76	1.74
4	2	2	3.42	3.81	1.28	0.86	0.80	1.61
2	2	6	12.11	12.43	1.01	0.67	0.72	8.48

Table 1: Effect of three geometry parameters on the sensitivity vector.

The u^* and v^* values, which are of primary importance for microinjection, are best when the manipulator is slender (row 4). The tradeoff is a significant degradation in x and y (using the first row as a reference). If the platform is large compared to the base (row 2), a similar but less severe tradeoff results. The third row shows a conical design in which the base is twice the diameter of the platform. The x and y sensitivities are better than in the case of the cylindrical design of row 1, and u^* and v^* are not significantly worse. This design was rejected, however, in favor of row 1 on the basis of range of motion (which always competes with low sensitivity).

3. Physical Design

3.1. Stewart Platform

Approaches to the physical design of a Stewart Platform can be divided into two classes: (1) legs either pull or push against an antagonistic force (i.e. a spring pushes the platform away from the base at all times while six variable length cables constrain it [5]), or (2) each leg is a linear actuator which can be commanded to a desired length.

In order to get a reasonable range of motion and good response characteristics using approach (1) above, a considerable amount of potential energy must be stored in the antagonistic system. Failure of a leg connection in such a system could have catastrophic results in ophthalmic surgery. With approach (2), the biggest problems are the actuator's overall length, length to stroke ratio, and diameter to length ratio. Most of these quantities are much larger than desired with commercially available linear actuators, leading to problems with leg collisions, high sensitivity values, and poor range of motion.

3.2. Variations on Initial Design

To circumvent some of these difficulties, a variation was devised (figure 3). This variation allows the linear actuators to remain fixed to ground rather than being ball jointed to ground, which in turn generates fewer problems with leg collisions and sensitivity parameter

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goals. This same variation was presented by Merlet [6] with the minor difference that Merlet's platform-end leg connections occur in three coincident pairs, while figure 3 shows six distinct platform attachment points.

It was also decided that the needle should not be mounted perpendicular to the platform in order to avoid collisions between the back end of the micropipette and the legs. (Recall that the micropipette is rigid and must pass all the way through the hypodermic needle.) Mounting at 45 degrees not only avoids collisions but makes micropipette access much more convenient yielding a more functional design.
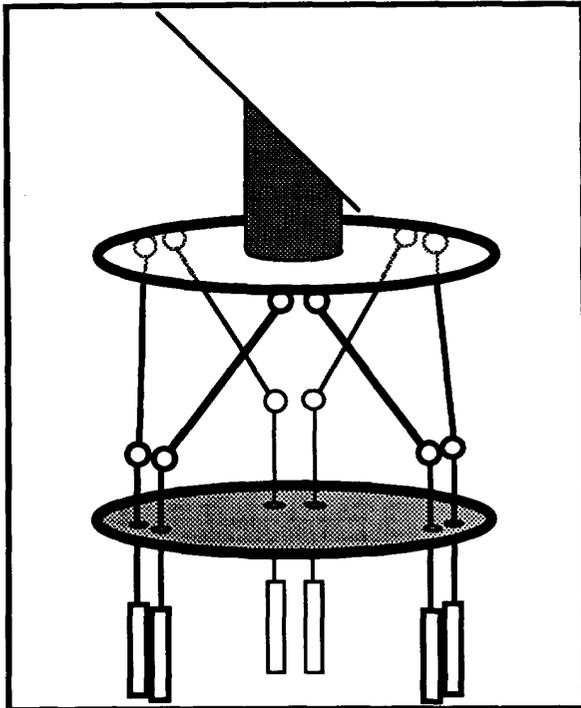
Figure 3: Schematic of the Merlet Parallel Manipulator with 45 degree hypodermic needle end effector.

These variations on the earlier manipulator design were not without cost. The sensitivity vector suffered somewhat. After considering the sensitivities, range of motion and function, the final design now has leg length, platform diameter, and base diameter all of two inches yielding a sensitivity vector of (5.31, 5.41, 1.50, 0.48, 0.89, 1.87). The physical design is also complete, and the manipulator is being fabricated (figure 4). It will be actuated by brush-type D.C. torque motors and ball screws.

4. Future Work

Following successful open loop operation, the micromanipulator will be fitted with end effector force sensing hardware and connected to a force reflecting macro manipulandum (already developed)[8]. From this macro/micro bilateral manipulator platform, research in impedance shaping bilateral control can proceed. The goal of this research, the theory for which is described in detail in other papers [3], is to develop a computer mediated hand tool which reflects a "realistic feel" of the environment being encountered by the micromanipulator while performing a task on a level below that of human dexterity.
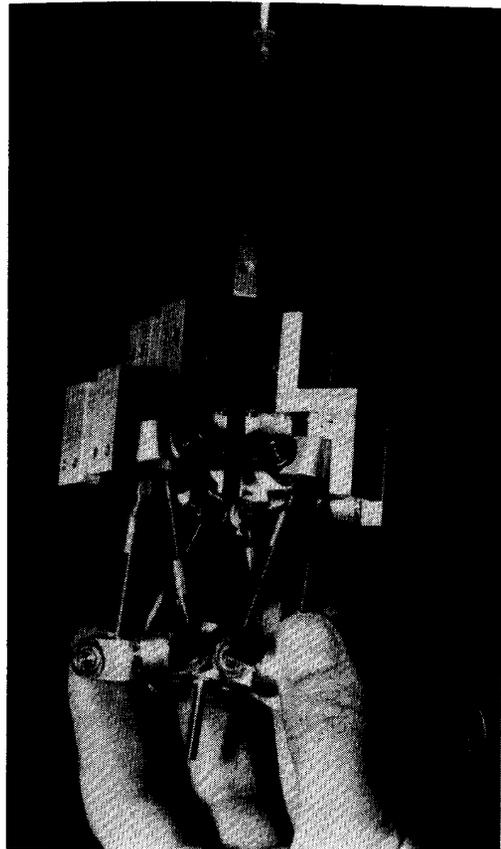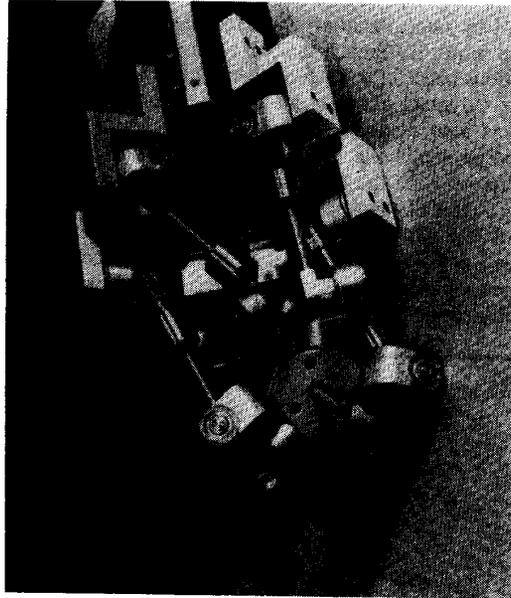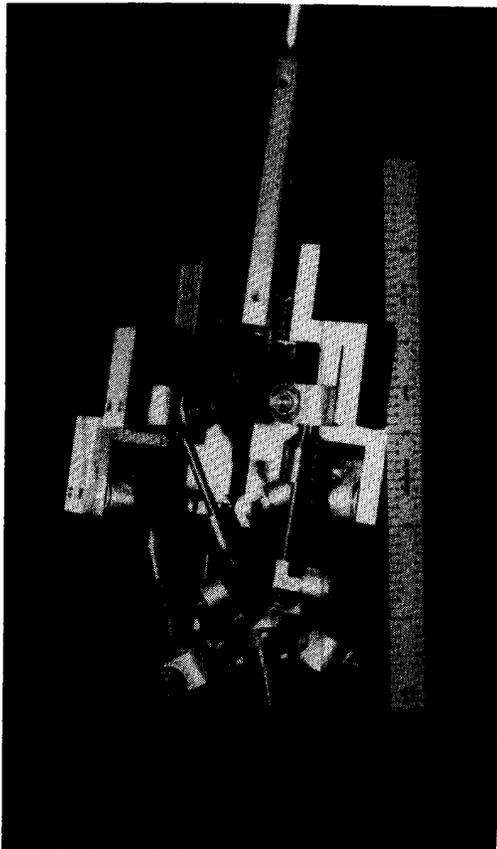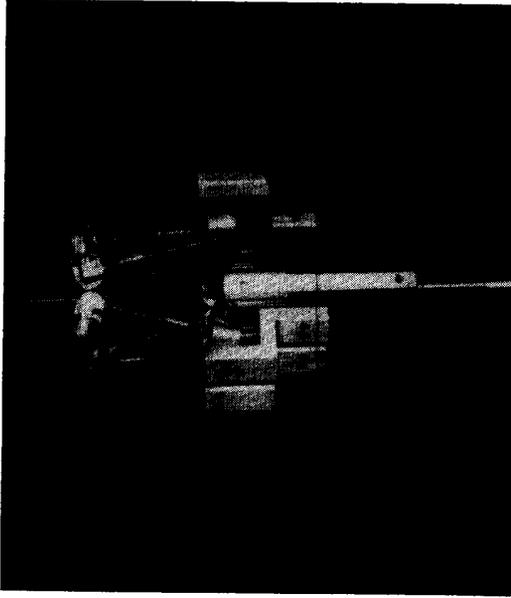
5. Acknowledgments

Figure 4: First stage of fabrication of a six degree of freedom parallel micromanipulator for retinal surgery. The end effector will hold a hypodermic needle (shown without actuators).

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References

[1] B. E. Allf. and E. De Juan Jr. In Vivo Cannulation of Retinal Vessels. *Graefe's Arch Clin Exp Ophthalmol.* 225:221-225, 1987.

[2] B. Becker and L. P. Post. Retinal Vein Occlusion. *American Journal of Ophthalmology*, 34:677-686, 1951.

[3] J. E. Colgate. Power and Impedance Scaling in Bilateral Manipulation. *Proc. 1991 IEEE Int'l Conf. on Robotics and Automation* 3:2292-2297.

[4] M. R. Glucksberg. and R. Dunn. Direct Measurement of Retinal Microvascular Pressure in the Live Anesthetized Cat. *Microvascular Research.* in press, 1992.

[5] S. E. Landsberger and T. B. Sheridan. A Minimal, Minimal Linkage: The Tension-Compression Parallel Link Manipulator. *Proceedings of the IMACS/SICE International. Symposium on Robotics, Mechatronics and Manufacturing Systems '92 Kobe*, 1:493-500, 1992.

[6] J-P. Merlet. Direct Kinematics and Assembly Modes of Parallel Manipulators. *Int'l Journal of Robotics Research*, 11 (2):150-162, 1992.

[7] J-P. Merlet. Parallel Manipulators: State of the Art and Perspectives. *Proceedings of the IMACS/SICE International. Symposium on Robotics, Mechatronics and Manufacturing Systems '92 Kobe*, 1:403-408, 1992.

[8] P. A. Millman and J. E. Colgate. Design of a Four Degree-of-Freedom Force-Reflecting Manipulandum with a Specified Force/Torque Workspace, *Proc. 1991 IEEE Int'l Conf. on Robotics and Automation*, 2:1488-1493.

[9] C. J. Pournaras, R. D. Shonat, J-L. Munoz, and B.L. Petrig, New Ocular Micromanipulator for Measurements of Retinal and Vitreous Physiologic Parameters in the Mammalian Eye. *Experimental Eye Research*, 53:723-727, 1991.

[10] D. Stewart. A Platform with 6 Degrees of Freedom. *Proc. Inst. Mech. Engr.*, 180:371-386, 1965.