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Plot of $\max_{l_1, l_2, l}(\ddot{x}_{eminminmax})$ *function of* l_2, *with* $l_1 = 2cm$ *and* $(1.03 + 1.59 \cdot l_2/l_1) \cdot l_1$

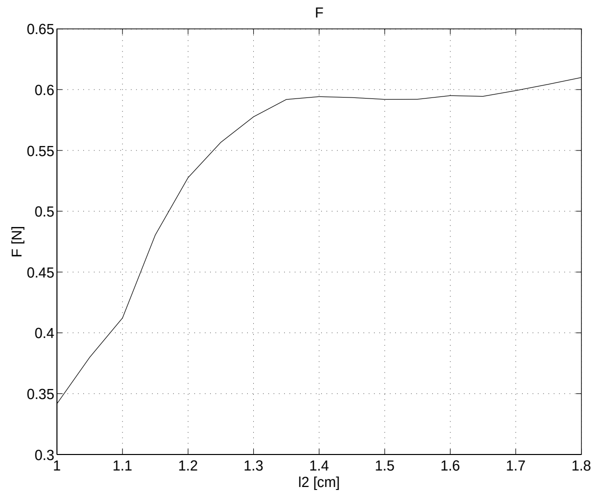

Figure 5

Plot of $F^{continuous}_{eminminmax}$ *function of* l_2, *with* $l_1 = 2cm$ *and* $(1.03 + 1.59 \cdot l_2/l_1) \cdot l_1$

may not give us the best solution of

$$F^{continuous}_{planar} \geq 0.5N$$
$$ws_{planar} \geq 1cm \cdot 1cm$$
$$\max_{l, l_1, l_2}(PI)$$

but it gives us a good solution of the problem

$$F^{continuous}_{planar} \geq 0.55N$$
$$ws_{planar} \geq 1.5cm^2$$
$$\max_{l, l_1, l_2}(PI)$$

To show it, let's assume that there is another l^{opt}, so that

$$F^{continuous}_{planar} \geq 0.55N$$
$$ws_{planar} \geq 1.5cm^2 \qquad (22)$$
$$\max_{l^{opt}, l_1, l_2}(PI) \geq \max_{l, l_1, l_2}(PI)$$

Now, for l, l_1, l_2 given by Eq (21) it is $ws_{planar} \approx 1.5cm^2$ and $F^{continuous}_{planar} = 0.55N$, so that

$$PI2(l, l_1, l_2) = 1.5 \cdot 0.55 \cdot PI(l, l_1, l_2)$$

Instead, for l^{opt}, l_1, l_2 it must be

$$PI2\left(l^{opt}, l_1, l_2\right) \geq 1.5 \cdot 0.55 \cdot PI\left(l^{opt}, l_1, l_2\right)$$

From Eq (20) it must be

$$PI2\left(l^{opt}, l_1, l_2\right) \leq PI2\left(l^{opt}, l_1, l_2\right)$$

With some substitutions we can see that Eq (22) can not be true.

CONCLUSIONS

The pen-based force display can be an effective tool for precision manipulation in virtual environment or for scaled telemanipulation. The human operator interacts with the force display in a very familiar way, using a pencil or a scalpel. This configuration can be very effective for micro-surgery.

A drawback of the design of a parallel redundant structure is the high computational requirement needed to solve the dynamic equations and to choose a torque configuration among the infinite possible. On the other hand, this parallel manipulator has a very low inertia, no backlash, almost zero friction, and the actuator redundancy can provide a homogenous force capability. We tried to measure the static friction and it was less than the resolution of our measuring devices, 1grf!

As an additional advantage of our design, multiple closed chains provide an easy way to self-calibrate the mechanical devices [Nahvi 1994]. In our case the presence of a redundant close loop allowed us to self-calibrate all the parameters of the parallel planar device, such as the position of each actuator and the length of the links. This will be the argument of another paper.
We also built a simulation virtual reality test-bed, where an operator can see virtual objects on a video display and touch them using the force display. The feeling coming from touching the virtual object confirmed us that our device is capable of high-frequency force reflection. A future research will be to determinate efficient control algorithm and real-time performance calibration technique [Buttolo & Bratthen 1994].

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l_z has to be chosen so that a rotation of $\theta_z = \pm 20^o$ correspond to a linear motion of at least $\Delta z_e = \pm 0.5cm$, so that $ws_{vertical} = 2 \cdot \Delta z_e \geq 1cm$ is satisfied. So it has to be $l_z \geq \frac{\Delta z_e}{\sin(20)} = 1.46cm$. We choose $l_z = 2cm$, so that $ws_{vertical} = 1.37cm$.

The mass of the 2dof structure is 150gr and so, from Eq (4), we derive that a torque of about 0.03Nm is necessary to compensate the gravity force. The pair of 5.25 voice coil can provide a continuous torque of 0.12Nm and a peak torque of about 0.3Nm. Note that the mechanical structure of the robot structure provides no counter-balancing against gravity. Therefore, because 0.03 is the torque necessary to achieve 1g acceleration, our robot can achieve an upward acceleration of 9g. The peak force that can be applied by the end-effector in the up-ward direction is (0.3-0.03)Nm/0.02m = 13.50N. The continuous force is (0.12-0.03)Nm/0.02N = 4.5N.

The force applicable upward and downward is far greater than the minimum requested

$$F_{vertical}^{continuous} \geq 0.5N$$
$$F_{vertical}^{peak} \geq 1N$$

Let's solve now the optimization problem for the planar mechanism. We want to determine l, l_1, l_2 so that Eq (14) are satisfied and the performance index PI is maximum. Because of the complexity of the problem we did not look for the global maximum value, but we considered a "good" solution acceptable.

1) We tried to see if, given (l_1, l_2) it is possible to find a relation $l_{f12} = f(l_1, l_2)$ so that

$$PI(l_1, l_2, l_{f12}) \geq PI(l_1, l_2, l) \quad \forall l \neq l_{f12} \qquad (18)$$

We numerically computed $F_{planar}^{continuous}$, $\ddot{x}_{maxworstcase}$, and ws_{planar} for different values of the parameters l_1, l_2, l. We found that if

$$l = l_{f12} = 1.03l_1 + 1.59 \cdot l_2 \qquad (19)$$

an equation similar to Eq (18) is verified, but for a small error:

$$PI2(l_1, l_2, l_{f12}) \geq PI2(l_1, l_2, l) \quad \forall l \neq l_{f12} \qquad (20)$$

with

$$PI2 = \max_{l_1, l_2, l}\left(F_{planar}^{continuous} \cdot \ddot{x}_{maxworstcase} \cdot ws_{planar}\right)$$

We will prove at the end that if we choose l from Eq (19), we will find a good solution for the optimization problem.

2) We evaluated ws_{planar} for different values of (l_1, l_2) and $l = 1.03l_1 + 1.59 \cdot l_2$. We found that the planar workspace area depends mostly from l_1, while it is almost independent from l_2.
So, we choose $l_1 = 2cm$, that gives

$$ws_{planar} \approx 1.5cm^2 .$$

3) We evaluated $\ddot{x}_{maxworstcase}$ and $F_{planar}^{continuous}$. for different values of l_2, $l_1 = 2cm$ and $l = 1.03l_1 + 1.59 \cdot l_2 = 2.06 + 1.59 \cdot l_2$. The result are shown in Figure 4 and Figure 5.

$\ddot{x}_{maxworstcase}$, that is our performance index PI, is maximum for $l_2 = 1.25cm$. From Figure 4 we can see that $F_{planar}^{continuous} = 0.55N$ and so $F_{planar}^{continuous} \geq 0.5N$ is satisfied.
Now, we choose l so that Eq (20) is satisfied instead of Eq (18). This solution

$$l_1 = 2cm$$
$$l_2 = 1.25cm \qquad (21)$$
$$l = 4.05cm$$

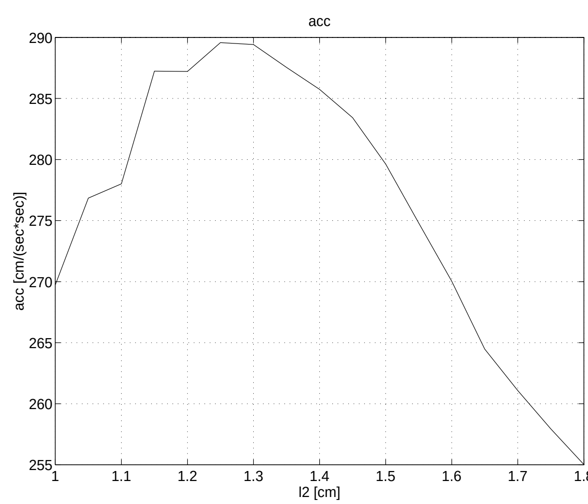

Figure 4

to actuator limits, as it is easy to prove. Because energy is not a concern for our small pen display we decided for Eq (12)

SYSTEM SPECIFICATIONS

Let's now introduce the requirements for our robot. An operator, when performing a high precision movement grasping a pencil or a scalpel with his/her finger, like a surgeon during a micro-surgery task, can move the tip of the tool in a very small workspace, about $1cm \cdot 1cm \cdot 1cm$ [Tendick 1994], [Anderson 1990]. He/She can apply through the tip of the scalpel a maximum force in the range of $0.5–1\,N$. The pen display must therefore meet the following requirements:

$$\begin{aligned} F^{continuous}_{maxworstcase} &\geq 0.5N \\ F^{peak}_{maxworstcase} &\geq 1N \\ workspace &\geq 1cm \cdot 1cm \cdot 1cm \end{aligned} \quad (13)$$

where for worst case we intend that the manipulator must be able to supply that specified amount of force from wherever inside the workspace, along whatever direction[1].

For peak force we intend the force that can to be applied for a short amount of time without burning the actuator. In a telerobotics application a high force has to be applied on the master side only for a short amount of time, usually when a collision has to be reproduced to the operator. Approximating the θ_z motion as straight vertical we can consider the motion between the 2dof parallel manipulator and the vertical approximated 1dof link to be uncoupled. So we can decompose our system specification as:

$$\begin{aligned} F^{continuous}_{planar} &\geq 0.5N \\ F^{peak}_{planar} &\geq 1N \\ ws_{planar} &\geq 1cm \cdot 1cm \end{aligned} \quad (14)$$

$$\begin{aligned} F^{continuous}_{vertical} &\geq 0.5N \\ F^{peak}_{vertical} &\geq 1N \\ ws_{vertical} &\geq 1cm \end{aligned} \quad (15)$$

where for simplicity we omitted *maxworstcase*.

ACTUATION

For mini-robotics applications, the flat coil actuators found inside the hard disk drivers are very interesting and cost-effective actuators. They come in different sizes, depending on the hard disk format, and they have very low inertia and friction. [Marbot 1991], [Marbot & Hannaford 1991], [Buttolo & al 1994].

Because of the system specifications and the flat coil mechanical properties we measured for the various devices, we decided to use the 1.8" actuators for the parallel structure, and the 5.25" size for the up and down motion. The steady state current flowing through the coil that generate a $\Delta T = 120^{o}C$ is 0.65A for the 1.8" and 0.52A for the 5.25". We observed [Buttolo 1994] some damage on the coil starting at an absolute temperature of about $150^{o}C$, at $\Delta T = 120^{o}C$. The torque generated by the actuators is 0.01Nm (1.8") and 0.06Nm (5.25"). For short amount of time we observed we could supply the actuator with up to 2A (1.8" and 5.25"), corresponding to a torque of about 0.03Nm (1.8") and 0.24Nm (5.25"). The range of motion is about 40^{o} (1.8" and 5.25").

DESIGN OPTIMIZATION

In order to choose the manipulator dimensions l, l_1, l_2, l_z we need to define a performance index to be maximized. The robotics literature contains various indices of performance [Yoshikawa 1990, Nakamura 1991], such as the manipulability index introduced by Yoshikawa:

$$w = \sqrt{detJ(q)\,J^{T}(q)}$$

Because we are mostly interested in high bandwidth force reflection, so that we can achieve a satisfactory telepresence feeling, we define the performance index as

$$PI = \ddot{x}_{maxworstcase} \quad (16)$$

that is the maximum acceleration that can be achieved in the worst case, starting from zero velocity, from any point inside the workspace, along any direction.
We can formalize our design optimization problem as the combination of the boundary equation given by Eq (14) and Eq (15) and

$$\max_{l, l_1, l_2, l_z} (PI) \quad (17)$$

1 $$F^{continuous}_{planar} = \min_{(x_e, y_e)}\left(\min_{\alpha}\left(\max_{\substack{\tau_1, \tau_2, \tau_3 \\ |\tau_1|, |\tau_2|, |\tau_3| \leq \tau_{max}}}\left(\|\bar{F}_e\| \,|\, \angle\bar{F}_e = \alpha\right)\right)\right) \qquad F = J_e^{-T}(\bar{\theta})\,\bar{\tau}$$

$$\bar{F}_e = J_e^{-T}(\bar{\theta}) \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} \frac{c_{1_{\theta_{12}}}}{l_1 s_{1_{\theta_2}}} & \frac{c_{2_{\theta_{12}}}}{l_1 s_{2_{\theta_2}}} & \frac{c_{3_{\theta_{12}}}}{l_1 s_{3_{\theta_2}}} \\ \frac{s_{1_{\theta_{12}}}}{l_1 s_{1_{\theta_2}}} & \frac{s_{2_{\theta_{12}}}}{l_1 s_{2_{\theta_2}}} & \frac{s_{3_{\theta_{12}}}}{l_1 s_{3_{\theta_2}}} \end{bmatrix} \bar{\tau} \quad (3)$$

Given a desired $\bar{F}_e$ there are an infinite set of torque vectors $\bar{\tau}$ that solve the above system of equations. In the next section we will briefly introduce the criterion we choose to solve the redundancy, that will be more completely treated in a successive paper.

The equation for the third dof is approximately given by

$$\tau_z = l_z (mg + F_z) \quad (4)$$

where τ_z is the torque given by the pair of vertical actuators, m is the mass of the planar 2dof mechanism, and F_z is the external force applied along the vertical axis.

Now we determine the equation for the dynamics. If we break the parallel manipulator at the end-effector, and no force is applied from outside, the equation for the i-th serial chain is

$${}^i\tau = {}^iM({}^i\bar{\theta})\,{}^i\ddot{\bar{\theta}} + {}^iV({}^i\bar{\theta}, {}^i\dot{\bar{\theta}}) + {}^iG({}^i\bar{\theta}) \quad (5)$$

and in the cartesian frame[1]:

$${}^i\bar{F}_e = {}^iM_e({}^i\bar{\theta})\ddot{\bar{x}}_e + {}^iV_e({}^i\bar{\theta}, {}^i\dot{\bar{\theta}}) + {}^iG_e({}^i\bar{\theta}) \quad (6)$$

Now we consider the interaction forces between the serial chains. We are assuming the gravity force to be zero, because the parallel manipulator works in or close to the horizontal plane, but the same procedure can be applied also in presence of gravity forces. The equations are:

$$\begin{cases} {}^1\bar{F}_e = {}^1M_e({}^1\bar{\theta})\ddot{\bar{x}}_e + {}^1V_e({}^1\bar{\theta}, {}^1\dot{\bar{\theta}}) + \bar{F}_{21} + \bar{F}_{31} \\ {}^2\bar{F}_e = {}^2M_e({}^2\bar{\theta})\ddot{\bar{x}}_e + {}^2V_e({}^2\bar{\theta}, {}^2\dot{\bar{\theta}}) + \bar{F}_{12} + \bar{F}_{32} \\ {}^3\bar{F}_e = {}^3M_e({}^3\bar{\theta})\ddot{\bar{x}}_e + {}^3V_e({}^3\bar{\theta}, {}^3\dot{\bar{\theta}}) + \bar{F}_{13} + \bar{F}_{23} \end{cases} \quad (7)$$

Where $\bar{F}_{ij}$ is the force exerted by the i-th manipulator on the j-th. Because they are endogenous forces they must have zero sum:

$$\bar{F}_{21} + \bar{F}_{31} + \bar{F}_{12} + \bar{F}_{32} + \bar{F}_{13} + \bar{F}_{23} = 0 \quad (8)$$

Adding together the three dynamic equations and considering an external force F_{ext} we get the dynamics of the 2dof parallel structure in the cartesian frame:

$$\sum_i {}^i\bar{F}_e + \bar{F}_{ext} = \sum_i M_e(\bar{\theta})\ddot{\bar{x}}_e + \sum_i V_e(\bar{\theta}, \dot{\bar{\theta}}) \quad (9)$$

The equation for the third dof is approximately given b

$$\tau_z = l_z mg + l_z F_z + I_z \dot{\omega}_z \quad (10)$$

where $\dot{\omega}_z$ is the angular acceleration of the θ_z joint.

REDUNDANCY

Because we have 3 actuators for 2 dof there are an infinite number of possible torque vectors (τ_1, τ_2, τ_3) that provide the same force $\bar{F}_e$. Two possible choices are those that minimize

$$\sqrt{\tau_1^2 + \tau_2^2 + \tau_3^2} \quad (11)$$

or minimize

$$max(|\tau_1|, |\tau_2|, |\tau_3|) \quad (12)$$

If we choose the Eq (11) we minimize the energy spent by the system, if we choose the Eq (12) we maximize the force that can be applied by the end-effector subject

1

$${}^iM_e({}^i\bar{\theta}) = \begin{bmatrix} 2m_1 + 5m_2 + 2m_1 c_{2^i\theta_{12}} + m_2\left(\left(-c_{2^i\theta_1} - 3c_{2^i\theta_1} + 3\frac{c_{2^i\theta_{12}}}{s^2_{i_{\theta_2}}}\right)\right) & \frac{2m_1 s_{2^i\theta_{12}} + m_2\left(-s_{2^i\theta_1} + 3s_{2^i\theta_{12}}\right)}{s^2_{i_{\theta_2}}} \\ \frac{2m_1 s_{2^i\theta_{12}} + m_2\left(-s_{2^i\theta_1} + 3s_{2^i\theta_{12}}\right)}{s^2_{i_{\theta_2}}} & 2m_1 + 5m_2 + 2m_1 c_{2^i\theta_{12}} + m_2\left(\left(-c_{2^i\theta_1} - 3c_{2^i\theta_1} + 3\frac{c_{2^i\theta_{12}}}{s_{2^i\theta_2}}\right)\right) \end{bmatrix}$$

$${}^iV_e({}^i\bar{\theta}, {}^i\dot{\bar{\theta}}) = \frac{m_1}{s^2_{i_{\theta_2}}}\left(l_1 c_{i_{\theta_2}}\,{}^i\dot{\theta}_1^2 + l_2\left({}^i\dot{\theta}_1 + {}^i\dot{\theta}_2\right)^2\right)\begin{bmatrix} c_{i_{\theta_{12}}} \\ s_{i_{\theta_{12}}} \end{bmatrix}$$

manipulators, connected together at the end-effector. Each serial chain is composed of an inner and an outer link, as shown by the bold line in Figure 2. Between the two links there is no actuator; however it is possible to introduce a fictitious actuator with null mass and null output torque. From now on:

- A superscripts on the upper left corner of any symbol refers to the i-th serial chain. Otherwise the symbol represents the global parallel structure.
- $s_\alpha = \sin(\alpha)$, $c_\alpha = \cos(\alpha)$
- ${}^i\theta_1, {}^i\theta_2, {}^i\theta_{12} = {}^i\theta_1 + {}^i\theta_2$ are the angles formed by the two links of the i-th serial chain, as shown in Figure 2.
- $\left({}^ix_o, {}^iy_o\right)$ is the position of the origin of the i-th serial chain expressed in the cartesian reference frame (x,y).
- $\left({}^ix_{in}, {}^iy_{in}\right)$ is the position of intermediate joint of the i-th serial chain expressed in the cartesian reference frame (x,y).
- (x_e, y_e) is the position of the end effector expressed in the cartesian (x,y) frame.

Now we derive the static equations. We first consider the planar manipulator and then the vertical motion. Considering only ${}^i\theta_1$, that is the i-th actuator displacement, we get:

$$ {}^i\dot{\theta}_1 = \begin{bmatrix} \dfrac{c_{{}^i\theta_{12}}}{l_1 s_{{}^i\theta_2}} & \dfrac{s_{{}^i\theta_{12}}}{l_1 s_{{}^i\theta_2}} \end{bmatrix} \dot{x}_e , \qquad (1) $$

and for the overall planar manipulator

$$ \dot{\bar{\theta}} = \begin{bmatrix} {}^1\dot{\theta}_1 \\ {}^2\dot{\theta}_1 \\ {}^3\dot{\theta}_1 \end{bmatrix} = J_e^{-1}(\bar{\theta})\,\dot{x}_e = \begin{bmatrix} \dfrac{c_{{}^1\theta_{12}}}{l_1 s_{{}^1\theta_2}} & \dfrac{s_{{}^1\theta_{12}}}{l_1 s_{{}^1\theta_2}} \\ \dfrac{c_{{}^2\theta_{12}}}{l_1 s_{{}^2\theta_2}} & \dfrac{s_{{}^2\theta_{12}}}{l_1 s_{{}^2\theta_2}} \\ \dfrac{c_{{}^3\theta_{12}}}{l_1 s_{{}^3\theta_2}} & \dfrac{s_{{}^3\theta_{12}}}{l_1 s_{{}^3\theta_2}} \end{bmatrix} \dot{x}_e \qquad (2) $$

But, we know that

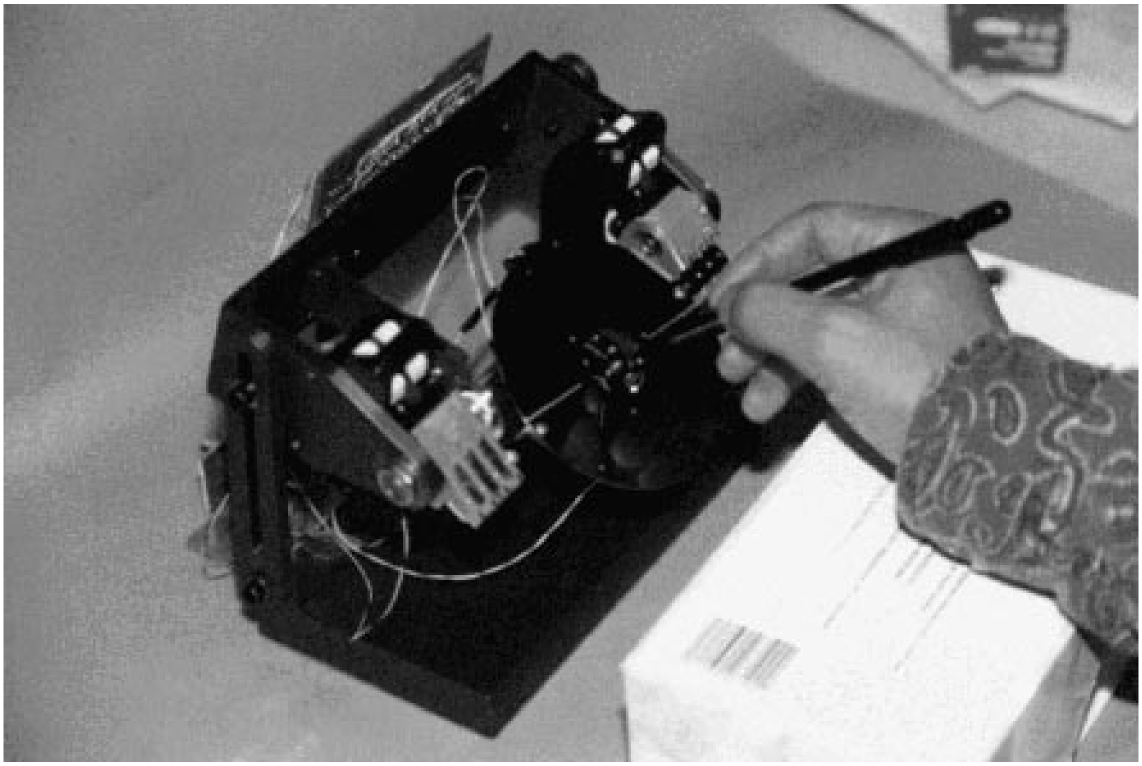

Figure 3

The Pen Based Force Display

manipulators. For this reason serial direct drive manipulators are characterized by a very high inertia. We decided, therefore, to provide the 2 dof motion in the horizontal cartesian space using a parallel structure. We found a number of 2 dof parallel manipulator in literature. One of the most used structure [Millman & Colgate 1991, Ramstein & Hayward 1994] is the one in Figure 1 where the 2 actuators sometimes are on the same axis, sometimes not:

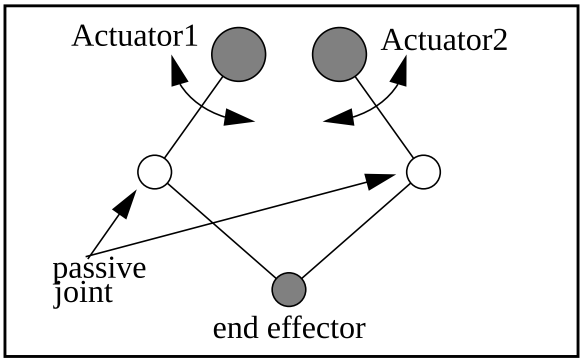

Figure 1

Schematic representation of a typical 2dof parallel manipulators.

We decided to add a third actuator to obtain a more symmetrical workspace and to provide more force to the end-effector. The resulting planar structure, see Figure 2, is a redundant actuation system, with 3 actuators and 2 dof.

The third degree of motion is given by a more powerful pair of rotational actuators which rotate the planar mechanism around the axis shown in Figure 2 and Figure 3. Because we are interested in rotation of about $\theta_z = \pm 10°$ across the horizontal plane, it is possible to approximate the rotary motion with a linear motion along the vertical z axes

STATIC AND DYNAMIC

The evaluation of a parallel manipulator dynamic behavior can be an extremely complex mathematical problem. Because the robot is not an open chain we can not use directly the Newton-Euler approach, and to derive the Hamiltonian is quite complex too. Various approach can be found in the literature [Nakamura 1991, Hayward & al 1994], [Asada & Toumi 1987]. To simplify the problem we decided to consider the 2dof parallel structure as composed of three serial 2 link

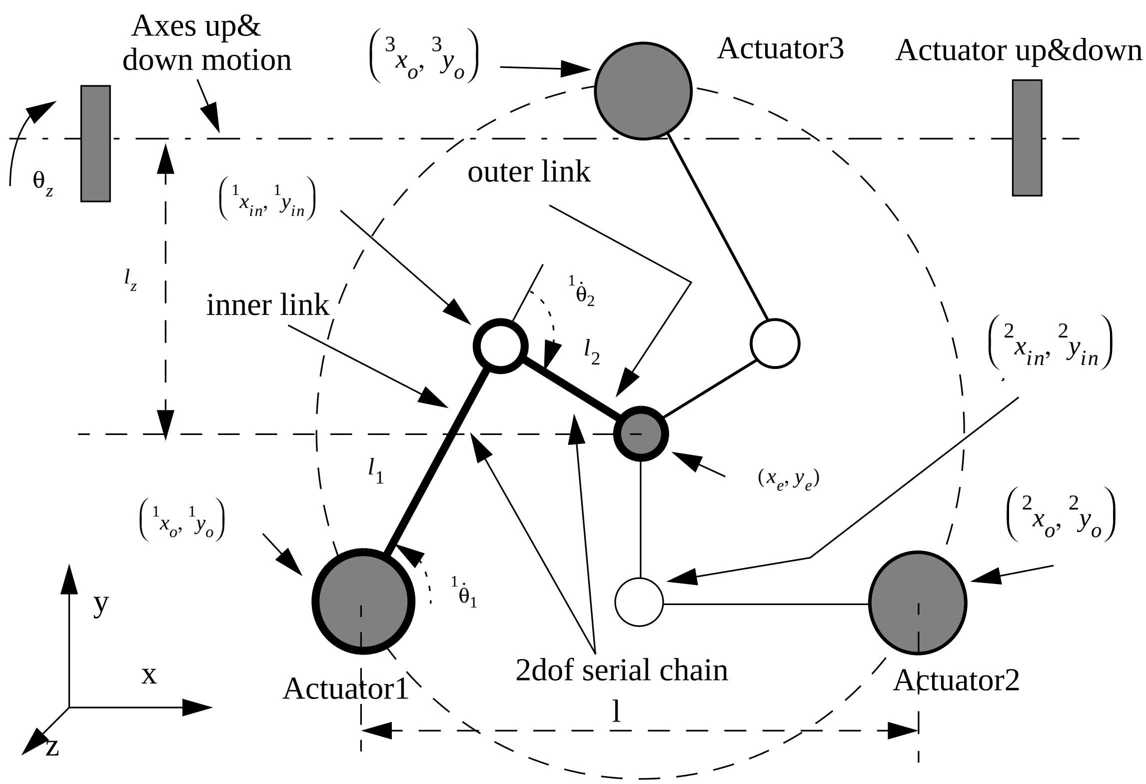

Figure 2

Schematic representation of the pen-based force display. For the notation refers to the Symbolic Notation paragraph. The shaded circles represent actuated joints. The non-shaded circles represent non-actuated joints. The gridded circle represent the end-effector joint.

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Pen-Based Force Display for Precision Manipulation in Virtual Environments

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ABSTRACT

In this paper we describe the structure of a force display recently implemented for precision manipulation of scaled or virtual environments. We discuss the advantages of direct-drive parallel manipulators over geared serial manipulators for human-robot interaction application and introduce the serial-parallel structure we chose for our robot which interfaces with the human operator either at the fingertip or at the tip of a freely held pen-like instrument. We derive the statics and the dynamics, and then introduce the optimization criteria that allowed us to choose the dimensional parameters for the force display. Finally we show some of the potential application for this device that will be the subject of following papers.

KEYWORDS: force display, haptic interface

INTRODUCTION

A force display is a manipulator designed to provide and receive kinaesthetic information to/from an human operator. Master manipulators used in telerobotics systems are an example of such devices. Using a master an operator can perform remote manipulation feeling simulated contact with the remote site. A force display can also reproduce feeling coming from a virtual environment, providing in this way a mechanical interface for virtual reality applications.

In the literature it is possible to find various examples of force-display and master devices; parallel mechanism [Ramstein & Hayward 1994], [Hayward & Kurtz 1984], [Millman & Colgate 1991], magnetically-levitated devices, [Salcudean & Yan 1994], [Hollis & al 1990], and others as [Hirota & Hirose 1994], [Sato & al 1994], [Iwata 1994].

The sensation of contact with the real site while operating in a remote station is often referred in the telerobotics literature as telepresence. The same concept can be easily adapted to virtual reality applications. To achieve telepresence the human has to interact with the telerobotics/virtual reality system in a natural way. In an ideal case he should not be able to tell if he/she using the force display or his/her natural tool. For example, a surgeon interacting with a force display should feel as he/she is grasping a scalpel. Therefore, the physical characteristics of the force display must be as close as possible to those of the natural tool. For micro-surgery applications the force-display must have no backlash or lost motion; friction and inertia must be as low as possible.

In this paper we describe the force display we have recently implemented. The design satisfies some specifications required to perform micro-surgery tasks, like high resolution, low inertia and low-friction.

DESIGN

Let's imagine a surgeon performing a precise incision using a very sharp scalpel. If the surgeon is not trying to use the scalpel as a lever, the force interaction between the tip of the scalpel and the tissue that is being cut is in a 3 dof cartesian space. This is because the contact surface can be approximated by an infinitesimal point. Hence, we designed a 3 dof force display. We decided also that the operator should interact with the manipulator using the tip of a real scalpel or other pointed tool. The main goal was to design a manipulator with very low inertia and friction. In this way the operator does not feel a burden while the scalpel is in free motion, and he/she can feel the high frequency force components generated by the interaction of the scalpel with different kind of tissues.

Geared manipulators do not fit this objective very well. They do not have very high bandwidth, so force information with high frequency components cannot be satisfactory reproduced. In addition backlash and friction phenomena are always present. On the contrary, direct drive manipulators are characterized by very high force generation bandwidth, low friction and no backlash.

The drawback is that direct drive manipulators usually have a higher mass/torque ratio compared to geared