First experiments with MIPS 1 (Mini In-Parallel Positioning System)

J-P. Merlet
INRIA, BP 93 06902 Sophia-Antipolis Cedex, France

Abstract: We present preliminary results of the design of a mini in-parallel 3-d.o.f. positioning system called MIPS. MIPS degrees of freedom are one translation and two orientations, which are obtained by the motions of linear magnetic actuators acting within a special in-parallel mechanical architecture. Its overall width will be about 1cm for a length of about 3cm. MIPS should be useful in medical applications and in inspection tasks.

1. Introduction

Mini positioning system have drawn a lot of interest in the recent past, especially for medical applications and inspection tasks. Building a miniature robot is not only a scaling problem. Indeed a simple scaling of a mechanical architecture like a serial robot performing well in a macro-environment will not work at a miniature scale as the friction forces (decreasing slowly with the size) will quickly take over the inertial forces (decreasing as the square of the size). Consequently a working mechanical device at small scale should rely for its motion on the deformation of its geometrical structure instead on the more classical concept of relative motion of its links. Parallel architectures rely exactly on this geometrical deformation concept and have been indeed used at different scale with good result: huge size flight simulator, large-scale positioning system, medium size robot and mini positioning system [1],[8],[13]. In these examples the height of the robot ranges from several meters to two centimeters although basically the same mechanical architecture is used. Furthermore parallel manipulators are very efficient as source of force as all the actuators are directly delivering their forces to the mobile platform (this may be seen if we consider the robot ratio L/M where L is the nominal load and M the mass of the robot: this ratio for serial arm will be at best 0.1 for 6 d.o.f. robot while this ratio may exceed 20 for parallel robots).

Broadly parallel manipulators can be divided in two classes: the first class have actuators in the legs connecting the base to the moving platform while the second class uses grounded actuators. The classical Gough-platform is an example of the first class while the HEXA robot [14] and the prototype we have presented in [11] are examples of the second class. For a miniature robot with drastic constraints on the size locating actuators in the leg is not a good solution as the interference between the legs will greatly decrease the useful workspace of the system. So a manipulator of the second class will be more appropriate.

For the applications we are considering MIPS will act as an active head mounted on some other positioning system. For example MIPS could be mounted as the end of an endoscope for insuring the fine positioning of surgical tools (as the devices proposed by Sturges [16], Wendlandt [18], which use cables and winches as actuators or the pressure-driven devices of Grundfest, Burdick [3] and Treat [17]) or as an inspection head for a mobile platform inspecting pipes. Therefore the overall mobility of the system will be insured both by the degrees of freedom of the support robot and by those of the head. A careful analysis of medical applications has shown that most of the tasks could be performed with a 3 d.o.f. robot having both translation and orientation capabilities. We will see however that MIPS may be reconfigurable to provide various combinations of d.o.f. The necessary range of motion should be in the vicinity of 5 mm for the translation part and $\pm$ 15 degrees for the orientation. The available force at the center of the platform should be around 0.15 N, but the robot should be able to withstand a larger force (especially during the travel to the point of interest). Our objectives are:

- an overall diameter of the robot in the range of 1cm
- a minimum height of the robot so that it can be used even in curved pipes
- a low stiffness: this is an element of safety especially for medical applications. But the robot should be able to withstand large forces in some configuration
- an autonomous robot with respect to the actuation: indeed an external actuation through flexible wire power transmission is a problem as soon as the length of the wire become important
- a modular robot from the control and power view point. In some mode the system should be able to perform some fixed motion autonomously without relying on any connection with the external world.
- a modular robot with respect to the provided d.o.f.: by a simple change in the mechanical architecture the operator may construct a robot with different d.o.f..

2. Mechanical architecture

Among all the possible 3-d.o.f. parallel robot one of the most promising structure has been proposed by Lee [8] which has also been used as the wrist of the ARTISAN robot of Khatib [7]. This structure is presented in figure 1. In this system each leg is connected to the base with a revolute joint and to the platform with an universal joint. A linear actuator in the leg enables to change the leg length and 3 d.o.f. of the platform could be controlled by changing the three leg lengths: a translation along the vertical direction and two orientations. We have decided to use this idea but without having the actuator in the legs: instead we use the principle presented in [11], where the joints close to the base are moving along a vertical direction while the legs have a fixed length. This

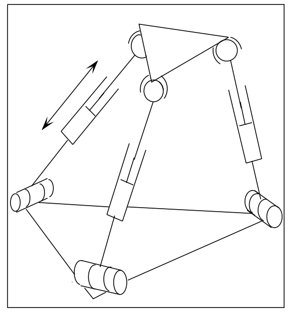

Figure 1. Lee 3-d.o.f. robot

enable to use very thin legs (leading to a very low mass of the moving elements of the robot) and therefore to decrease the risk of interference between the legs while enabling to keep the overall diameter of the robot quite small. The new architecture is presented in figure 2. This architecture is modular: for example

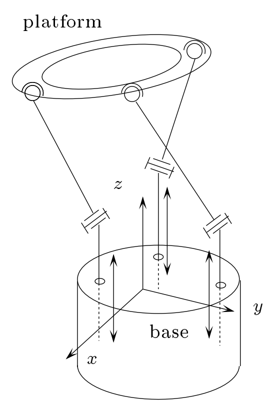

Figure 2. The mechanical architecture of the proposed robot

by changing the axis of the revolute joints we may modify the rotation axis of the platform or by connecting the platform with a rigid link fixed on the base with a ball-and-socket joint we will get a wrist with 3 rotational d.o.f.

In our basic design the revolute joint axis of leg 2 and 3 is the x axis while the joint axis of leg 1 is the y axis. With this disposition the platform may perform a translation along the z axis and rotations around the x, y axis. Note that with this architecture simple motion can be performed with very simple control laws for the actuators. For example:

- a similar periodic inputs on the three actuators will create an up and down motion of the platform

- a periodic input on leg 1 and a similar input with a phase shift of 180 degree on leg 2 and 3 will create a rotation of the platform around the y axis

- a periodic input on leg 2 and a similar input with a phase shift of 180 degree on leg 3 will create a rotation of the platform around the x axis

2.1. Kinematics

A reference frame $O, (\mathbf{x}, \mathbf{y}, \mathbf{z})$ is defined. Similarly we define a moving frame $C, (\mathbf{x_r}, \mathbf{y_r}, \mathbf{z_r})$ where C is an arbitrary point of the moving platform. The location of the moving platform will be defined by the coordinates of C in the reference frame and by a rotation matrix R relating the two frames (a vector whose components is expressed in the moving frame will be denoted by a superscript ^{r}).

Let define A_i as the connecting point of leg i to the revolute joint, B_i its connecting point to the universal joint on the moving platform, A'_i a reference point on the linear actuator axis. The axis of the revolute joint is $\mathbf{n_i}$, the leg length l_i and λ_i will be the height of A_i with respect to A'_i.

In order to solve the inverse kinematics consider the constraint equation on the leg length:

$$||\mathbf{A_i B_i}|| = l_i$$

or:

$$|| - \lambda_i \mathbf{z} + \mathbf{A'_i O} + \mathbf{OC} + R\mathbf{CB^r_i}|| = l_i$$

squaring the previous equation leads to:

$$\lambda_i^2 - 2\lambda_i \mathbf{z}.(\mathbf{A'_i O} + \mathbf{OC} + R\mathbf{CB^r_i}) + ||\mathbf{A'_i O} + \mathbf{OC} + R\mathbf{CB^r_i}||^2 - l_i^2 = 0 \qquad (1)$$

Hence the articular coordinates are obtained as solution of a second order equation. One solution will have a height greater than B_i and will be discarded. As expected not all possible motions can be performed as we have the constraint equation:

$$\mathbf{A_i B_i}.\mathbf{n_i} = 0$$

The direct kinematics problem may be reduced to the direct kinematics of Lee prototype. For given heights of the actuator there may be up to 16 different configurations for the moving platform. The configurations can be determined by solving a 16 order polynomial in the tangent of the half angle of one of the revolute joint [10].

A software tool has been designed to simulate the motion of the robot, estimate its workspace and find the optimal design according to the task at hand.

3. Actuation

According to our basic design the three linear actuators will be disposed side by side in the main body of the robot. For a miniature device the actuation scheme may be: electrical motor, piezo-electric linear actuators, wires actuation, shape memory alloy (SMA), polymeric gels and films, or magnetic actuation. Although small electric motors (with a diameter of 8mm) are available we have not retained this solution. Indeed they need a reduction gear and a mechanism to transform the rotary motion into linear motion. Their diameters are such that they have to be put on top of each other in the body, leading to a robot with an important height.

Piezo-electric linear actuators are interesting for their low weight and high force and have been used in the past for micro parallel robot [1] or serial robot [2],[5]. Their main drawbacks are their rather limited range of motion (even with stacked actuators the range of motion is about 2 mm) and their cost.

Wire cable robots have also been used in the past [16],[18]. They have the advantage of compacity as soon as the winches are external to the robot (internal winches lead to the use of electrical motors) but one our objective prohibit the use of external power transmission.

SMA [9] have also been considered: by changing their temperature they have the property to come back to a given geometry. They have the advantages of compacity and low weight but their control is far from simple and it is difficult to predict their behavior in a surrounding where the temperature may be varying. Furthermore their bandwidth is usually very low.

Some polymers like the perfluorosulfonic acid polymer are able to bend when a low voltage is applied onto its surface [4],[15]. The amplitude of bending is usually very low (less than 0.1 mm) and consequently these actuators will need to be stacked to get the necessary range of motion.

Magnetic actuation is interesting and has been considered in the past [6],[12]. A permanent magnet which can slide into a solenoid leads to a very simple linear actuator. The force that can be exerted by such an actuator is sufficient as long as the range of motion is not too large and the control is basically simple while the stiffness of the actuator is low. The mechanical efficiency of these actuators are good (no reduction gear and the friction of the magnet in the solenoid is reduced with the centering effect of the system). Note also that the leg inputs we have presented for performing simple motions can be easily produced with on-board simple electronic hardware and battery power source.

We have build a first version of a magnetically driven linear actuator (figure 3). The plunger is constituted of three iron mini-magnets coated with Teflon connected by two aluminium cylinders. This plunger slides into a cylinder fixed to the base with two coils along the main axis. The current in each coil is controlled independently so that the resulting magnetic fields of the coils create two forces enabling the motion of the plunger or its station keeping.

Each extremity of the plunger is topped by a miniature head so that the motion is limited. The mass of the actuator is about 20 grams, the diameter is about 6 mm, the total length about 55 mm and the stroke is about 5 mm. The first tests have shown that the actuator force is in the range 0.3-0.5 N for a peak current of 2A and is therefore sufficient. However to improve the design we will like to decrease the actuator length and be able to use a lower peak current. Hence we are currently designing a second version of linear actuator with the following changes:

- we plan to use either Neodymium Iron Boron (NdFeB) or Samarium-Cobalt (SmCo) magnets instead of iron magnet. Their energy product coils magnets

Figure 3. Principle and first version of the magnetic linear actuator

is about 20 to 60 times higher than the low-cost iron magnet.

- to increase the magnetic field produced by the coils they will be disposed on a 0.2 mm thick film of FPC (ferrite polymer composite) with permeability 9.
- we will investigate the use of only one coil, the plunger being held by a spring. This will enable to simplify the control scheme, reduce the power consumption and actuator length. The lower force provided by a lone coil will be compensated by the higher force provided by the FPC/SmCo coil/magnet.

The initial and potential versions of MIPS are presented in figure 4. To in-

Control

Energy

Control

Energy

$\oslash \leq 1.3cm$

Figure 4. Two possible versions of MIPS: the first one uses the early version of the linear actuator while the second will use the improved version of the actuator

crease the autonomy of the end-effector we intend to have a modular energy cell which can be attached to the mechanism and will provide the necessary power. Similarly a control cell could also be attached to the end-effector: pre-defined motion of the mechanism will be stored in this cell and they should be triggered by an external input sequence (via ultrasound waves for example). This modularity will enable to change the level of autonomy of the robot according to the task to be performed (from a completely autonomous robot with on-board control and power to a teleoperated robot with external power and control).

4. Position sensing

The linear motion of the actuators should be measured for the close-loop control of the robot. Currently we are investigating three possible methods:

- optical measurement: a tilted mirror will be fixed to the bottom magnet and will deflect the light of a laser diode toward a light sensor array: the position of the spot on the array is a function of the height of the mirror
- LVDT measurement: two auxiliary coils will be fixed at the bottom of the actuator. One of them will be connected to an AC source and the tension in the second coil will be a function of the position of the magnet
- Hall effect measurement: a fixed Hall effect sensor will be put at the bottom of actuator and the current in this sensor will enable the measurement of the distance between the sensor and the bottom magnet.

5. Design of the passive joints

The passive joints are the revolute joint at A_i and the universal joint at B_i. A miniature revolute joint is not difficult to manufacture. Thus remains the problem of constructing the joint at B_i. Three possible solutions are possible: elastic joints constituted of miniature flexible coupler which can be obtained by drilling appropriate holes in a metal block[13], or more classical miniature joints. In an early design each leg has been made of a needle with a sphere as end point. This sphere will be disposed in a hole of the mobile platform which will then closed by a small ring whose hole diameter will be slightly less than the diameter of the sphere.

6. Conclusion

We have presented the preliminary result of the design of a micro in-parallel magnetically actuated 3 d.o.f robot. Our main task has been to test the linear actuator. Our early version exhibit interesting properties that we hope to improve in a second version by using more sophisticated materials.

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