Optimal design for the micro parallel robot MIPS

J-P. Merlet
INRIA Sophia Antipolis, France
E-mail: Jean-Pierre.Merlet@sophia.inria.fr

Abstract— **MIPS is a micro robot with a parallel mechanical architecture having three degrees of freedom (one translation and two orientations) that allow fine positioning of a surgical tool. The purpose of MIPS is to act as an active wrist at the tip of an endoscope and to provide to the surgeon an accurate tool that may furthermore offers a partial force-feedback. The current prototype has a diameter of 7mm for a length of 2.5cm and includes all the necessary hardware. We will explain why a parallel architecture has be chosen, the method of optimal design that has been used for determining the dimensions of the robot and present the current prototype.**

Keywords— **micro robot, parallel robots, optimal design, interval analysis, medical application**

I. Introduction

Among the numerous potential applications of micro-robots surgery is one of the most promising and at the same time one of the more challenging. Indeed the micro-system approach fits the trend of modern surgery which aims to *minimally invasive surgery*[3] whose purpose is to lessen the lesion on the patients that are created by the surgeon to access the operation region. Indeed in a first part of an operation the surgeon will operate the patient so that his/her hands will gain access to the operation region, thereby creating lesions that are often not in relation with the size of the zone to be accessed. In the minimally invasive approach the surgeon will use very small-sized tools that are able to reach the operating region either through small openings in the patients or through natural ways. With this approach the time for the patient for fully recovering from the operation is drastically reduced. The price is paid by the surgeon that has to deal with a more complex operating mode: no more direct access to the region, a feedback that is most of the time only visual (tactile feedback is no more provided) and of poor quality. Developing the tools that will be used for the surgeon is challenging:

- *reliability* is at premium
- *bio-compatibility* must be addressed
- *size* must be minimal
- *ergonomy issues* must be carefully addressed as surgeons are most of the time not very familiar with computer science...and not very patient

In minimally invasive surgery a classical tool is used: the endoscope. This system is basically a long flexible optic fiber that is introduced in a patient, enabling the surgeon to visually examine various critical regions within the human body for diagnosis purposes (and in some cases to perform a *biopsy*: a sample of tissue will be picked up by a small tool for further examination). Control of the motion of the endoscope is provided through a wires system that allows to modify the orientation of the last 10 centimeters of the tip of the endoscope (figure 1). But this kind of control does

Fig. 1. The motion of the tip of an endoscope

not allow for a very fine positioning of the tip of the endoscope: indeed the small wires that are used are submitted to large friction forces and act like springs that store potential energy which may suddenly be released resulting in large motion of the tip. A direct result is that the positioning accuracy of an endoscope is usually poor and does not allow to use it as an operation tool. It must also be noted that endoscopes are used in fact mostly for industrial inspection (only 20% of the endoscopes are used in medical applications). But their use in industry is limited to inspection for the same reason than for medical application: a lack of accurate mobility at the tip of the endoscope. A possible way to correct this problem is to motorize the endoscope [4], [7], [10], [16] but this leads to very complex system.

After numerous discussions with surgeons in various fields we conclude that the positioning accuracy of an endoscope may be improved by using a classical concept in robotics: the *micro-macro* approach. The idea is to have a macro system that a large workspace but a poor accuracy (in our case the endoscope) and to instrument it with a micro system that has a small workspace but a high accuracy. This approach has already been proposed by Wendlandt [17] for this application but the micro-system was driven by external wires and was suffering from the same drawbacks than the endoscope.

We end up with the following requirements:
- the micro system should have a diameter less than 1 centimeter which is the diameter of endoscope used for gastro-intestinal operation,
- the micro system must have 3 dof: two rotations along the x, y axes and a translation along the z axis (the other dof may be provided by the endoscope),
- the accuracy of the micro-system should be in the micron range
- it must be autonomous, i.e. motors and sensors must be included in the micro-robot,
- if possible force-feedback must be provided.

There is an additional requirement that deal with the forces on the micro system: although the forces that will be *exerted* by the micro robot will be small (the force necessary for cutting a human tissue is equivalent to a mass of 15 grams), it may be *submitted* to very large forces (for example when the endoscope is introduced in the human patient).

II. The MIPS parallel robot

Parallel robot have the advantages of high accuracy and high load capacity and for our application their reduced workspace is not a problem. Considering these advantages we have decided to use a parallel structure for the micro-robot MIPS that will be put at the end of the endoscope. As we need only 3 dof the mechanical architecture described in figure 2 has been chosen. This architecture is a variant of the architecture proposed by Lee [11] which was using variable length legs. In this architecture the end-effector is connected through ball-and-socket joints to 3 legs with fixed length. At the other extremity of the leg there is a revolute joint. The center of this joint is put at the extremity of a linear actuator so that it may move along a vertical axis and the motion of this actuator is measured by a linear sensor. Control of the 3 linear actuators allows one to control 3 dof of the platform: motion along a vertical axis and rotation around the x, y axis. This architecture leads to a very compact design: the 3 linear actuators are co-located in a cylinder and the leg geometry is such that when the actuator
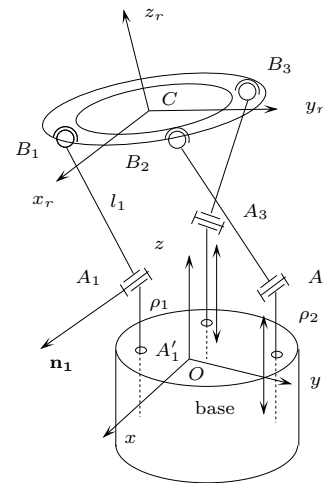

Fig. 2. The mechanical architecture of the MIPS micro-robot

are fully retracted the platform will lie on top of the cylinder: in this configuration the robot is basically a cylinder and may sustain very large forces. When the robot is close to the operating zone the linear actuators will extend but as flexible bellow joins the platform to the top of the cylinder, the inside of the robot is still isolated from the surrounding.

Note also that the platform moves only if the revolute joint center are moving: a practical consequence is that if there is a loss of current in the motors the robot will just freeze. This is an important safety advantage of the parallel structure over the serial one as even a balanced serial robot may exhibit residual motions that may be dangerous for the patient.

III. Design analysis

A drawback of parallel robot is that their performances are highly sensitive to their dimensioning. Hence for a given task it is necessary to perform an optimal design study so that the performances will be maximum. However our design will be constrained by the choice of the actuator.

A. Linear actuators

In micro-system there is a size gap in the available hardware: roughly speaking motors and sensors up to 1 centimeter are commercially available while the MEMS technology provides similar components with a maximum size of 0.1 mm. But in the range from 10 mm to 0.1 mm they are very few components available. Unfortunately for MIPS we need a pair of sensor and motor which should fit in a cylinder with a diameter at most 5mm. Furthermore some mode of actuation cannot be used in view of the application: for example piezo-electric actuator cannot be used as the high

voltage they are using may be damaging for the patient [6].

In a preliminary version of MIPS we have developed our own magnetic linear actuators. Although they were satisfactory to validate the concepts underlying MIPS, their stroke was not sufficient for the application. At the same time we were not willing to develop our own actuator as this is a full time job that will interfere with the theoretical studies that were necessary to develop the MIPS robot.

Hence with the help of the ALTRAN company we have looked at commercially available components that may be used to build a linear actuator. We have finally determined that no component providing directly a linear motion were available. Thus we have decided to use a rotary motor and a screw to convert the rotary motion into a linear one. The following motors were selected:

- the BL 1900 motor from Faulhaber with a diameter of 1.9 mm, a maximal torque of 7.5 μNm, a reduction gear of 47:1 and a maximal velocity of 100000 rpm,
- the Smoovy motor of RMB with a diameter of 3 mm, a maximal torque of 35 μNm, a reduction gear of 25:1 and a maximal velocity of 120000 rpm.

As for the linear sensor there was almost an unique choice with the Differential Variable Reluctance Transducer of MicroStrain with a diameter of 1.5 mm with a measurement range of 6 mm, a resolution of 0.06 μm and a non-linearity of $\pm$ 1%.

B. Design parameters and requirements

The following design parameters have to be determined:

- the radius r_1 of the circle on which are located the center of the ball-and-socket joints on the platform. These centers are located on a equilateral triangle and hence r_1 fully determine the location of the joints
- the length l of the leg: the three legs have the same length
- the stroke S of the linear actuator
- the pitch h of the screw

It will usually be necessary to add to this list the location of the revolute joint centers in the $x-y$ plane. But in our case we want to design a robot as compact as possible and the choice of the linear actuators impose these locations.

The pitch h of the screw is not a geometrical parameter and the manufacturing process clearly imposes a lower bound on its value. An upper bound is found by imposing that at the slowest setting of the motor velocity the motion of the leg during a sampling time does not exceed one third of the sensor accuracy.

The final design must satisfy the following requirements:

- possible rotation around the x, y axis of at least $\pm^3$ 15 degrees at least at some point of the workspace
- the possibility of providing a force on the platform equivalent to 15 grams whatever is the location of the robot in its workspace, being given the maximal torque of the rotary motors
- a positioning accuracy in the range of a few micrometers over the whole workspace of the robot, being given the accuracy on the measurements of the motion of the linear actuators
- no singularity within the workspace

IV. Optimal design methodology

A. The parameter space approach

A classical method in optimal design of mechanism is the *cost-function* approach [5]. But these methods has many drawbacks and cannot be applied in the case of the MIPS robot. Hence we have used another approach called the *parameter space* approach.

As we have seen previously we have 3 design parameters. We consider a 3-dimensional space, called the *parameter space*, with a parameter associated to each of the dimension of this space. In this space a point represent a unique geometry for our robot and the purpose of the design analysis is to determine **all** the point(s) in this space such that the design requirements are satisfied. In fact it will not be necessary to examine the whole parameter space as we have natural bounds on the values of the design parameters (given here in millimeter):

- the radius r_1 of the platform cannot exceed half the size of the robot (10 millimeters) and should be large enough to host 3 miniature ball-and-socket joints. Hence we have $r_1 \in [3, 5]$
- the stroke S of the linear actuator cannot exceed the stroke of the linear sensor (6 mm) but must be large enough to allow for relatively large change in the orientation of the platform. We have chosen $S \in [3, 6]$
- the length l of the leg cannot exceed the stroke of the actuator (otherwise the platform cannot lie on the cylinder of the robot when the actuator are fully retracted). At the same time they must be at least larger than the difference between the radius of the base and the radius of the platform (otherwise no motion of the robot will be possible). We have imposed conservatively $l \in [1, 6]$

At the same we may bound the workspace of the robot: for example the translation along the z axis cannot exceed the stroke of the actuator and must clearly be positive. Bounding the orientation angles is more complex: due to the requirements the interval for these variables must include an orientation angle of 15 degrees. Singularity analysis provide however a way to determine an upper bound for

these angles as a singularity will occur for a rotation around the x or the y axis at an angle that can be computed from the geometry of the robot (hence we have the constraints $G_x(r_1, l) \leq \theta_x \leq F_x(r_1, l)$ and $G_y(r_1, l) \leq \theta_y \leq F_y(r_1, l)$).

We thus extend the parameter space to a 6 dimensional space $\mathcal{S}$, each dimension representing one of the unknown in the list $\{r_1, S, l, z, \theta_x, \theta_y\}$ where z is the z coordinates of the platform and θ_x, θ_y its rotation angles. Due to the above constraints only some parts of $\mathcal{S}$ are of interest and can be computed as:

$$r_1 \in [3, 5] \tag{1}$$
$$S \in [3, 6]$$
$$l \in [1, \overline{S}]$$
$$z \in [0, \overline{S}]$$
$$\theta_x \in [G_x(r_1, l), F_x(r_1, l)]$$
$$\theta_y \in [G_y(r_1, l), F_y(r_1, l)]$$

where $\overline{S}$ is the upper bound for the range on S. Our purpose is now to determine all the possible values of the design parameters r_1, l, S that satisfy the following set of constraints

$$\text{Constraints} \tag{2}$$

• the workspace includes poses with $\theta_x = \pm 15$ degrees and pose with $\theta_y = \pm 15$
• in these poses:
  − the robot must be able to exert a force of 15 grams
  − the positioning errors on the platform must not exceed a given threshold

It must be noted that the above constraints are necessary to satisfy the requirements but are not sufficient as we are considering the force and accuracy requirements only for the extreme pose of the workspace.

Our first purpose is now to compute the possible values of the design parameters such that the corresponding robot satisfy the above constraints, or in other words, the region(s) $\mathcal{R}$ of the parameter space that include all the possible values for the design parameters. An *approximation* of $\mathcal{R}$ will be calculated using interval analysis.

B. Optimal design regions

B.1 Validation step

In our method $\mathcal{R}$ will be approximated by a list of element, each element being constituted of 3 ranges, one for each design parameter. For computing this approximation it will necessary to have an algorithm that enable to check if the requirements are satisfied. For this purpose we consider a set T of 6 elements in $\mathcal{S}$: the four first elements will be a range for the variable r_1, S, l, z while the last two elements (corresponding to

the θ_x, θ_y) will have a numerical value. The possible[4] values for these elements will be ± 15 degree or 0: hence we will consider in turn the pair (15,0), (-15,0), (0,15), (0,-15). Hence a set T is constituted of a set T_d of range for the design parameters and a mixed set T_X which describe the possible pose of the platform. For a set T, T_d will be a solution of the optimal design problem if for any value of the design parameters in their ranges:
• the minimal value of the force that the robot is able to exert is greater than the threshold $F_s = 15$ grams whatever is the pose of the robot in the set T_X
• the maximal positioning errors on the platform must not exceed a given threshold ϵ whatever is the pose of the robot in the set T_X

Being given the maximal force τ_{max} that an actuator can provide the maximal force F_z^{max} on the platform can be computed as:

$$F_z^{max} = \sum_{i=1}^{i=3} |J_{F_z, i}^{-T}| \tau_{max} \tag{3}$$

where $J_{F_z}^{-T}$ is the row of the transpose of the inverse jacobian matrix J^{-T} matrix corresponding to the vertical force. Similarly being given the maximal sensor error $\Delta \rho_{max}$ the maximal positioning error ΔX_{max} of the platform can be be computed as:

$$\Delta X_{max_j} = \sum_{i=1}^{i=3} |J_{ji}| \Delta \rho_{max} \tag{4}$$

Thus for a set T, T_d will be a solution of the optimal design problem if

$$\Delta X_{max} \leq \epsilon$$
$$F_z^{max} \geq F_s$$

for any pose in the set T_X. Computing exactly the extremum of ΔX_{max} and F_z^{max} will be difficult. But by using interval analysis we are able to compute bounds for this extremum. Interval analysis used on the equations (3,4) will provide two range $U_1 = [\underline{u_1}, \overline{u_1}]$, $U_2 = [\underline{u_2}, \overline{u_2}]$ such that:

$$\underline{u_1} \leq \Delta X_{max} \leq \overline{u_1}$$
$$\underline{u_2} \leq F_z^{max} \leq \overline{u_2}$$

The bounds provided by the interval analysis may be overestimated, but are guaranteed (even with respect to numerical round-off errors). Hence if for a set T we have:

$$\overline{u_1} \leq \epsilon \qquad \underline{u_2} \geq F_S \tag{5}$$

then T_d is a solution of the optimal design problem: verifying if the above constraint is satisfied is called the *validation step* for a set T.

B.2 Algorithm

We may now design an algorithm that enable to compute the approximation of the region. In this algorithm we use a list $\mathcal{L}$ of set T that is initialized with the set T_0 that bounds all the unknowns as presented in (1). At some time in the process $\mathcal{L}$ will have n elements and an index i is used to denote the set T_i that is currently examined (hence at the start we have $i=0$ and $n = 1$). The algorithm proceed along the following step:

1. if $i = n$ then **EXIT**
2. compute $U_1(T_i), U_2(T_i)$
3. if T_i satisfy the constraints (5) store T_{d_i} in the list of valid solution, $i = i + 1$, goto step 1
4. if $\underline{u_1} > \epsilon$ or $\overline{u_2} < F_s$ then there is no solution in T_{d_i}, $i = i + 1$, goto step 1
5. otherwise choose a variable j in the set T_i and bisect its range $[\underline{x_j}, \overline{x_j}]$. Affect to T_{n+1} the same range than for T_d except for the variable j that has the range $[\underline{x_j}, (\underline{x_j} + \overline{x_j})/2]$. Affect to T_{n+2} the same range than for T_d except for the variable j that has the range $[(\underline{x_j} + \overline{x_j})/2, \overline{x_j}]$. Then $n = n + 2$, $i = i + 1$, goto step 1

To avoid having to consider set for which the ranges will be reduced to a point we also discard all the set T_i in which all the ranges have a width lower than a fixed threshold β (usually corresponding to the manufacturing errors). Note also that this algorithm can be designed for a distributed implementation: the processing of a given set T_i is independent from the processing of the other set and therefore it can be done on an independent machine.

After running this algorithm we get a list of design solution such that:

- the constraints defined in (2) are satisfied
- for the solutions with size β if we take as nominal values for the design parameters the center of the ranges in T_d the robot can be manufactured and even if due to manufacturing errors the real robot differs from the theoretical one the constraints defined in (2) will still be satisfied

C. Optimal design solutions

At this point of the method we have determined all the regions of the parameter space than can include the point(s) corresponding to the optimal design solutions. But not all the points in the region will correspond to a robot satisfying the requirements as we have used only a restricted version of these requirements to determine the regions.

We will now sample the regions and for each robot in the sampling we will verify if it satisfy the full list of requirements by using the *verification step*

C.1 Verification step

The purpose of the verification step is to determine if a robot of given geometry satisfy the complete list of requirements. This is usually a complex problem as it implies in most cases to solve a constrained optimization problem. To solve this problem we have developed specific tools: verification of the worst case accuracy [14], verification of the absence of singularity within the workspace [15] and worst case value for the joint forces [13].

C.2 Optimal design of MIPS

The previous methodology has been applied to the design of the MIPS micro-robot. After running the algorithm for 24 hours on a set of 6 computers we have obtained a list of 12843 potential design boxes. The verification step performed on 48290 possible robots among thses boxes has run for about 12 hours and has led to a list of 10 robot geometries. Among these 10 solutions we have chosen the one which was the easiest to manufacture. Fortunately the same design can be used if we use either the BL 1900 motor or the Smoovy motor: the only difference is that the diameter of the robot with the Smoovy motors will be 8.6mm instead of 7 mm.

V. THE MIPS ROBOT

The final theoretical version of the MIPS robot has been designed with the help of the LMARC laboratory in Besançon and its manufacturing has been done by the company DG Création in Besançon in the framework of the "Factory of the Future" collaboration contract funded by AFIRST. Preliminary experiments have shown that the open-loop motions were very good but that after a few hours of use the reduction gear of the BL 1900 motor was beginning to present failure. This has been corrected by Faulhaber and the motors are now working perfectly.

We have also some concern about using a magnetic linear sensor in close proximity to a motor. Preliminary experiments have shown that the magnetic field induced by the motor was too small to influence the motor but that the sensor was very sensitive to change in temperature. We are now currently starting the integration of the sensors in the robot.

A closed-loop controller based on a PC running RT-linux has been designed. It includes an AD board for processing the sensor signal while the motors are controlled through a sinus amplifier connected to the parallel port of the PC.

VI. CONCLUSION

Adding an accurate extra mobility to the tip of an endoscope is necessary to enlarge its field of applica-
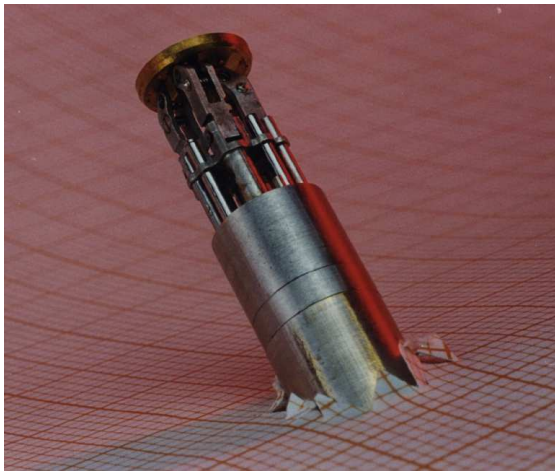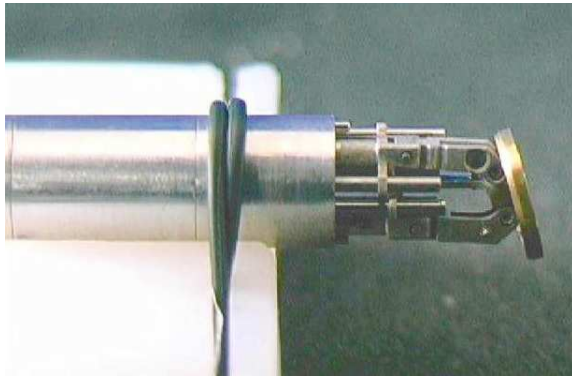
Fig. 3. MIPS prototype

Fig. 4. MIPS prototype

tion from inspection-only purpose to operational goals. Parallel mechanical structures are appropriate in this case as they allow for small device having a small workspace but high accuracy and load capacity.

After the integration of the sensors in the current prototype we will start a clinical validation in the framework of an "Action Concertée Incitative" funded by the ministry of Research: an endoscopic surgeon in Marseilles will start using the device on animals and will provide the necessary user feedback.

REFERENCES

[1] Arai T., Stoughton R., and Jaya Y.M. Micro hand module using parallel link mechanism. In *Japan/USA Symp. on Flexible Automation*, pages 163–168, San Francisco, July, 13-15, 1993.

[2] Charentus S. and Renaud M. Calcul du modèle géométrique direct de la plate-forme de Stewart. Research Report 89260, LAAS, Toulouse, France, July 1989.

[3] Cohn M.B., Crawford L.S., Wendlandt J.M., and S.S. Sastry. Surgical applications of milli-robots. *J. of Robotics Systems*, 12(6):401–416, 1995.

[4] Dario P. and others . A micro robotic system for colonoscopy. In *IEEE Int. Conf. on Robotics and Automation*, pages 1567–1572, Albuquerque, April, 21-28, 1997.

[5] Erdman A.G. *Modern Kinematics*. Wiley, New-York, 1993.

[6] Fukuda T. and others . Characteristics of optical actuator-servomechanisms using bimorph optical piezo-electric actuator. In *IEEE Int. Conf. on Robotics and Automation*, volume 2, pages 618–623, Atlanta, May, 2-6, 1993.

[7] Fukuda T. and others . Micro active catheter system with multi degrees of freedom. In *IEEE Int. Conf. on Robotics and Automation*, pages 2290–2295, San Diego, May, 8-13, 1994.

[8] Gough V.E. Contribution to discussion of papers on research in automobile stability, control and tyre performance, 1956-1957. Proc. Auto Div. Inst. Mech. Eng.

[9] Griffis M. and Duffy J. A forward displacement analysis of a class of Stewart platform. *J. of Robotic Systems*, 6(6):703–720, 1989.

[10] Ikuta K., Tsukamoto M., and Hirose S. Shape memory alloy sensor actuator system with electric resistance feedback and application for active endoscope. In *IEEE Int. Conf. on Robotics and Automation*, pages 427–430, Philadelphia, April, 24-29, 1988.

[11] Lee K-M. and Arjunan S. A three-degrees-of freedom micromotion in-parallel actuated manipulator. *IEEE Trans. on Robotics and Automation*, 7(5):634–641, October 1991.

[12] Merkle R.C. A new family of six degree of freedom positional devices. http://nano.xerox.com/nanotech/6dof.html, 1994.

[13] Merlet J-P. Efficient estimation of the extremal articular forces of a parallel manipulator in a translation workspace. In *IEEE Int. Conf. on Robotics and Automation*, pages 1982–1987, Louvain, May, 18-20, 1998.

[14] Merlet J-P. A formal-numerical approach to determine the accuracy of a parallel robot in a 6D workspace. In *13th RoManSy*, Zakopane, July, 3-6, 2000.

[15] Merlet J-P. and Daney D. A formal-numerical approach to determine the presence of singularity within the workspace of a parallel robot. In F.C. Park C.C. Iurascu, editor, *Computational Kinematics*, pages 167–176. Seoul, May, 20-22, 2001.

[16] Suzumori K. and Abe A. Applying flexible microactuators to pipeline inspection robots. In *IMACS/SICE Int. Symp. on Robotics, Mechatronics, and Manufacturing Systems*, pages 631–636, Kobe, September, 16-20, 1992.

[17] Wendlandt J.M. and Sastry S.S. Design and control of a simplified Stewart platform for endoscopy. In *33nd Conf. on Decision and Control*, pages 357–362, Lake Buena Vista, December, 14-16, 1994.