

Hippocrate: a safe robot arm for medical applications with force feedback

François Pierrot^{1*}, Etienne Dombre¹, Eric Dégoulange², Loïc Urbain², Pierre Caron², Sylvie Boudet³, Jérôme Gariépy⁴ and Jean-Louis Ménégnien⁴

¹LIRMM, 161 rue Ada, 34392 Montpellier Cedex 05, France

²SINTERS S.A., Parc Basso Cambo, 5 rue P. Mesplé, 31106 Toulouse Cedex 1, France

³EDF/DER, 6 quai Watier, 78401 Chatou Cedex, France

⁴Hôpital Broussais, Médecine préventive cardio-vasculaire, 96 rue Didot, 75014 Paris, France

Abstract

We have developed a robotic system to assist doctors when they are moving ultrasonic probes on a patient's skin while exerting a given effort. The probes are used to monitor arteries for cardiovascular disease prevention, namely to reconstruct the three-dimensional profile of arteries. A preliminary feasibility study making use of an industrial robot has been made to validate the force control scheme. It has proven the interest of the robotized approach for such medical applications where force control is needed. In order to comply with safety constraints, a dedicated robotic system 'Hippocrate' has been designed. This paper describes the arm and the controller architectures, with emphasis on design strategies selected to meet safety requirements. Preliminary *in vivo* results are presented as well as a possible new application of Hippocrate as a tool for reconstructive surgery.

Keywords: echography, force control, medical robotics, safety

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1. INTRODUCTION

A lot of work has been devoted during the past decade to the development of robotic systems to assist in surgery and impressive results have already been achieved (see Davies *et al.*, 1993 or Taylor *et al.*, 1991). Following Dario's classification (Dario *et al.*, 1996), two main areas are seen: surgery based on image guidance and minimal invasive surgery. Less attention has been paid to other promising applications of robotics in medicine such as manipulation of external probes for diagnostic purposes. In this paper, we present such a system, Hippocrate, which could be used for the prevention of cardiovascular disease.

The arterial distensibility and the quantification of atheromatous plaques in the arteries provide a good index of a patient's cardiovascular risks. Up to now, doctors have

monitored the development of atheromatous plaques by scanning the arteries with ultrasonic (US) probes (Flaud *et al.*, 1990). This technique is very attractive since it is non-invasive and it can be performed on a regular basis for some patients. Besides, echography is now widespread in medical practice. However, it does not allow the quantification of the plaque volume. Other techniques such as magnetic resonance imaging (MRI) or computer tomography (CT) scanning would give comparable results, but they are very expensive.

In order to reconstruct the three-dimensional (3-D) profile of an artery and to quantify the volume of the possible atheromatous plaques obstructing it, a 3-D US probe would be necessary but such a device is not yet technically mature. An alternative solution is to move the probe in a step-by-step manner on the patient's skin while applying a programmable and constant force, and to record its successive spatial locations. Force control is necessary to provide good and reproducible conduction of the US signal, while preventing

*Corresponding author
(e-mail: dombre@lirimm.fr)

artery deformation. Images are recorded at each step and are processed off-line.

To summarize, measurements must be (i) accurate enough to ease image processing and (ii) reproducible in space (constant force along the artery) and in time (to monitor the atheromatous plaques over a long period of time). It is difficult, even for a skilled operator to achieve fine motions under force control satisfying these constraints, while these specifications can be provided by a robot.

Referring to Troccaz and Delnondedieu (1996), mechanical arms involved in medical robotics applications are of three types depending on their level of autonomy: (i) passive arms, which are unactuated and have no autonomy; (ii) active arms where all joints are actuated, and which can perform parts of the planned tasks by themselves; and (iii) in between, semi-active arms for which the power is cut-off during critical phases of the tasks, or for which the actuators are not used directly to guide the robot, but rather, for instance in PADyC in Troccaz and Delnondedieu (1996), or ACROBOT in Harris *et al.* (1997), to dynamically limit its workspace.

All these systems are relevant to enhancing doctors' capabilities in terms of accuracy and reproducibility. The justification of such a classification comes from safety reasons: any unexpected and uncontrolled motion of the arm has to be avoided at any time. Such a constraint is obviously satisfied with an unactuated arm. With an active arm, the robot has to be intrinsically safe, which means that all the failures are predicted and all the faults are handled on-line. The semi-active arm offers a good trade-off between autonomy and safety.

Force control is mandatory if clinical tests include the artery elasticity, and is necessary as well if repeatability of measurements is required; this constraint discards all passive systems which only give the probe spatial location, such as electromagnetic devices (Ganapathy and Kaufman 1992; Hodges *et al.*, 1994; Hughes *et al.*, 1996) or vision systems either passive (Mills and Fuchs, 1990) or active (Henry, 1997). This also discards mechanical systems without force sensors providing 3-D images from a series of image slices. These slices may be obtained by active mechanical scanning [single rotational or mechanical motion of a two-dimensional (2-D) US probe as proposed by Delcker and Diener (1994), Sakas *et al.* (1995) and Shiota *et al.* (1996)]. Another solution is to make use of a localizer such the three-degree-of-freedom (DOF) arm proposed by Ohbuchi *et al.* (1992) or the five-DOF arm proposed by Baba *et al.* (1989).

In conclusion, the required system must be an active mechanism, with at least six degrees of freedom, providing force control. Moreover, each measurement has to be synchronized with the heartbeat to avoid the variation of the artery diameter during the cardiac cycle.

This project was started in 1994. A feasibility study with a Mitsubishi PA-10 industrial robot allowed us to validate a force control scheme well suited for using the robot with a good level of safety. The main issues and results of this study are summarized in Section 2 of this paper. *In vivo* experiments have been run which have justified the interest of the robotized approach (see Boudet *et al.*, 1997). In order to comply with safety constraints, a dedicated robotic system, Hippocrate, was designed in 1997. Section 3 describes the arm and the controller architecture. Emphasis is put on design strategies selected to meet safety requirements: low installed power and redundancy at a system level are the keywords in the implementation. The graphical user interface (GUI) is also briefly presented.

We are confident that such a robot may be involved in many other applications where a probe or a tool has to be moved in contact with soft surfaces. A feasibility study is in progress to harvest skin in reconstructive surgery for burn patients: this application is presented briefly in Section 4.

2. FEASIBILITY STUDY

A way to obtain 3-D reconstruction of atheromatous plaques in a patient's artery would consist of using an MRI or CT scan which could provide a very accurate and regular scan of the artery. However, such systems present several drawbacks, namely they cannot be used as often as necessary due to their cost. Another way is to scan shallow arteries such as the carotid close to the neck and the femoral close to the groin. This approach is very attractive since the US beam is non-invasive. However, only 2-D US probes are available on a clinical basis, 3-D US probes being still under development.

Classical 2-D US probes are currently widely used in medical practice for image investigation (echographic probe to display arterial structure and Doppler-effect-based probes to measure the blood velocity profile). For the physician, one of the limitations for these kinds of probes arises from the fact that, at a given location, he only obtains a section of the artery. It means that for complete detection and a precise analysis of an atheromatous plaque, the doctor has to move the probe along the artery step by step with a constant force applied on the skin (ranging from 1 up to 5 N). At each step, an image must be recorded. Each record must be synchronized with the heartbeat to account for the variation of the artery's diameter during the cardiac cycle. The smaller the distance between two steps (of the order of a few tenth of a millimetre), the better the reconstruction. Accurate knowledge of the spatial location in Cartesian space of each section is required for coherent results.

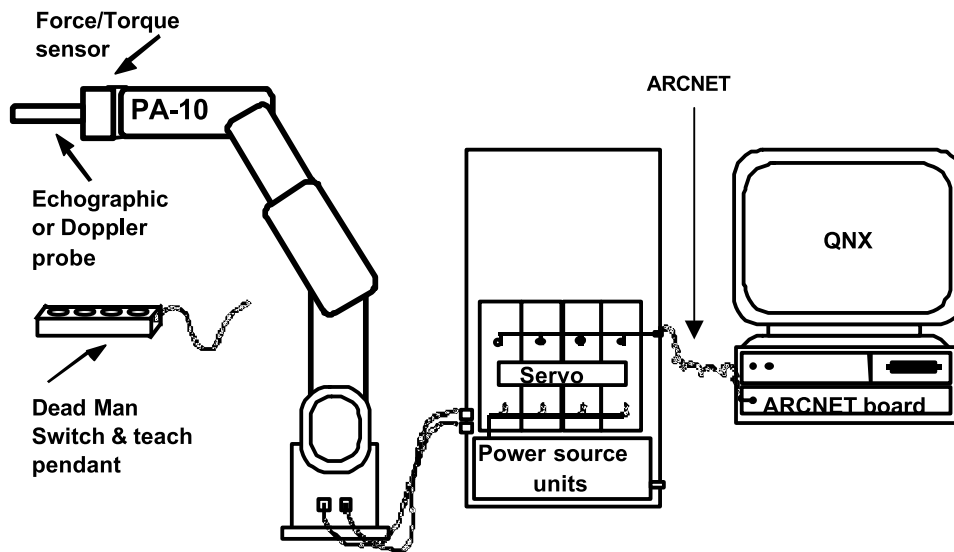


Figure 1. System used for the feasibility study.

2.1. Industrial robot arm as a testbed

During the first months of the project, several systems which were able to assist the doctor have been reviewed and evaluated. This study has led to the development of a robotic system using an active robot rather than a passive tracking mechanical device. Simulation studies have shown the feasibility of using an industrial robot, realizing both the probe placement and the measurement phase. Since medical robots must operate next to doctors and patients, the safety aspect is of paramount importance. The specification of safety constraints is not easy and depends on the application. However, a list of indispensable requirements has been established by Davies (1993), and we summarize in the following those most relevant for our application:

- the robot's behaviour has to be controlled at any given time. In particular, when a failure occurs, any uncontrolled motion must be prevented;
- when moving, only slow motions are allowed. This can be a built-in feature of the robot (high gear reduction ratios or low-power actuators);
- any automatic motion has to be run under the control of a 'dead man's switch' (DMS);
- the force applied by the robot on the patient's skin must be controlled;
- the working area of the robot must be restricted.

In this feasibility study, the solution has consisted in modifying an industrial robot to meet safety requirements. This solution was the fastest to implement and less expensive

compared to a solution where a dedicated intrinsically safe robot would have been designed from scratch.

The robot chosen for this feasibility study has been a seven-DOF, human-like industrial robot, the PA-10 from Mitsubishi Heavy Industry [see details in Dombre *et al.* (1996)]. The gear on each motor output drive has been changed (the reduction ratios have been multiplied by a factor of two) in order to slow down the robot's linear velocity to 0.5 m s^{-1} . The complete robotic system (Figure 1) includes the robot with its low-level controller, a PC running a real-time OS for the high-level controller [connected to the robot controller through a local area network (LAN) connection], a DMS and a teach pendant, and a force/torque sensor mounted at the tip of the robot arm.

2.2. Force control

As part of the medical application, several force control schemes have been evaluated. A so-called external force control scheme (De Schutter and Van Brussel, 1988) has been proved to be the best solution regarding safety constraints. Figure 2 gives an overview of this technique:

- all the robot joints are controlled in position ('position control in joint space' block) at any time, depending only on measurements of actual joint positions, q^r ;
- this low-level block receives inputs from the 'inverse kinematics model' block, which transforms the Cartesian position (i.e. the probe position, P) into joint positions;

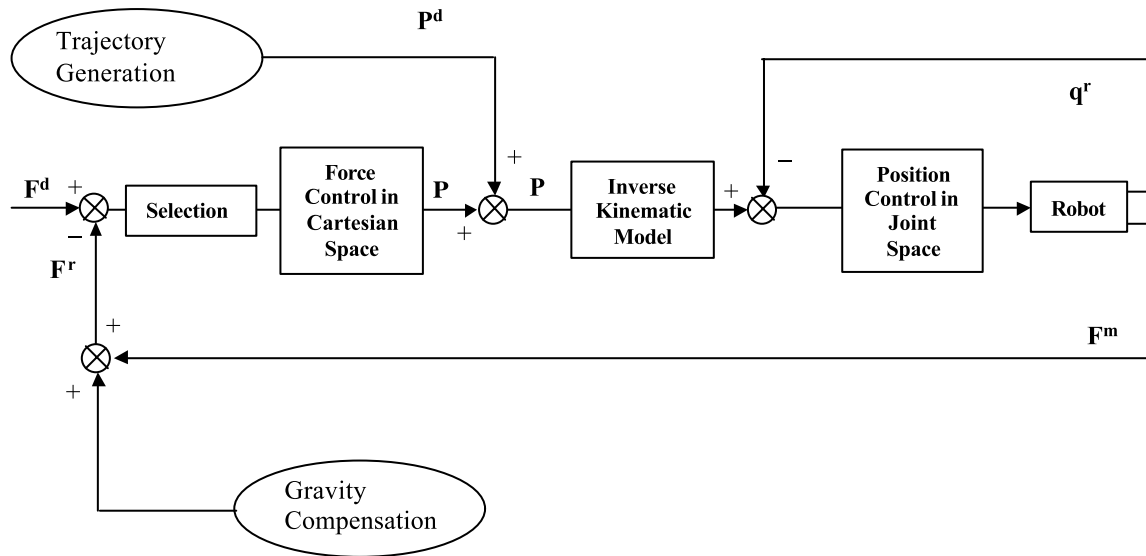


Figure 2. Block diagram of the external force control.

- as for any robot arm, a ‘trajectory generation’ module provides the desired path in Cartesian space, and then at each time the desired Cartesian position, P^d ;
- however, unlike most robots which are only position controlled, P^d can be altered thanks to an additional control loop, the external force control loop; here, the desired force, F^d , is compared to F^r , the force resulting from the force acting on the robot tip, F^m , and the gravity compensation. The difference between desired and actual forces produces a change in the desired Cartesian position in order to decrease, and ultimately to cancel out, the force error; the actual force is obtained due to a wrist-mounted force sensor and a software module dedicated to compensate for the probe weight (to be sure that the probe weight is not mixed up with the contact force);
- selecting a Cartesian direction to be sensitive to the force control system is performed in the ‘selection’ block, which simply consists in validating or not the alteration of the position by the force control loop.

The robotics literature is full of various force control schemes involving various force control laws. We have chosen the external force control scheme because of a wide experience based on studies, developments and tests performed over the last 15 years. We have implemented many kinds of control schemes on a large variety of robots including single- or dual-arm serial robots (Delebarre *et al.*, 1991), parallel robot (Pierrot, 1991), redundant robot, and we have proposed, implemented and tested classical or advanced force control laws (Fraisse *et al.*, 1992).

It turns out that the external force control scheme, described for example in Perdereau and Drouin (1993) is especially well suited when simplicity, safety and implementation efficiency are of concern. Moreover, some specific drawbacks of classical hybrid control schemes have been pointed out in Perdereau and Drouin (1994) and it has been proven (in theory and with experiments) in Pujas *et al.* (1993) that a real implementation of a hybrid scheme which respects Mason’s formalism is in fact very close to external control. One can note that this implementation is simpler than the one used by Ho *et al.* (1995) because our needs regarding force control are quite simple. Indeed our implementation is very similar to the one proposed by Kazanzides *et al.* (1992) where a damping control scheme is used; in our case, we take advantage of the ‘selection’ block to provide a unique scheme working for both position and force control. In short, the key advantages of external control can be summarized as follows:

- the joint position servo loop is always activated, providing the stability of the system. There is no ‘mode switching’ between the position servo loop and the force control loop, avoiding any risk of jerking and instability [‘mode switching’ is a problem when a hybrid control is implemented on real robots; see Delebarre *et al.* (1991)];
- it is easy to handle both position and force information on the same Cartesian direction; the force information is used directly in the force control loop, while the position information is used to monitor the robot. Practically, when the doctor drives the robot by grabbing the probe, all the Cartesian directions are force controlled; when the robot operates the probe on the patient’s skin in an

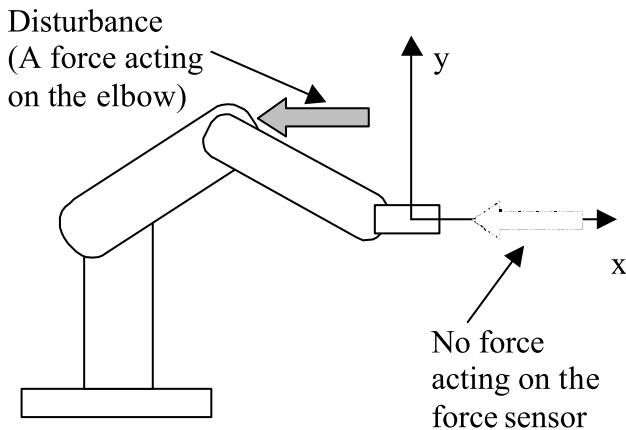


Figure 3. Hybrid control is not robust to disturbances acting on the arm.

automatic manner, only the normal direction to the skin is force controlled;

- it works well with very simple and reliable (thus safe) control laws; a PID controller at the joint level and a PI controller for the external force loop are sufficient;
- it is easy to implement on any kind of robot, even those with a complex geometry, including parallel or redundant robots. Thus the same concept can be kept for any kind of mechanism (in fact, we used a redundant robot for the feasibility study, and a non-redundant robot for the final version, and we kept the same scheme);
- unless an effort is applied on the probe (below the force sensor), the robot will not move [which is not the case with very popular control schemes such as the hybrid control tested by Reboulet and Robert (1985)]. Figure 3 helps to understand this point; let us consider a manipulator arm controlled in the (x, y) plane with a hybrid scheme and consider the case where force control has been selected on x , and position control has been selected on y . Let us imagine that the desired force (along the x axis) is set to zero, and that no force is acting on the force sensor. Thus, the force error is zero, and consequently the motors' torques are computed so that they produce no force along x (while servoing the position along y). If a disturbance occurs directly on the arm (someone may push on the elbow for instance) the hybrid control scheme is absolutely not able to overcome it, and the arm moves along x , with an acceleration profile depending on the disturbance and the arm inertia. This is definitely not the case with external force control, since the position loop is always acting.

- The external force control scheme allows us to design the control software in an incremental manner, which facilitates the tuning of the parameters and validation: a joint control loop, Cartesian space control loop and force control loop. This is a great advantage compared to more complex approaches such as hybrid control.

The external control scheme has been implemented and completely tested with the PA-10 acting on a model composed of a fake leg (made of plastic) and a piece of soft material [see Figure 4 and Théron *et al.* (1995)]. In Figure 5 force measurements are plotted for a test representing the first part of the automatic phase: the arm moves until it reaches the 'skin' and encounters the desired reaction force (here, 3 N).

2.3. Measurement procedure

First results have proven the good behaviour of the control scheme in both force space and constrained space. This is of paramount importance for us; a unique control algorithm based on a constant architecture is used for all robot motions, i.e.

- the doctor can move the robot arm by acting on the force sensor; any force he applies by pushing/pulling on the US probe is transformed into motion commands, and consequently, the robot 'follows' the doctor's motions when he moves the probe to find the best locations for US imaging (in the very same way the doctor does with a classical manual probe). This method is used to select locations on the patient's skin in a 'teaching mode'; absolutely no programming is necessary, not a single line of code has to be written: selection of convenient locations is simply done by pushing on a validation button. In this phase, all directions of motion are controlled according to force information;
- the robot performs the US measurements in an 'automatic phase' where it moves from the first up to the last location selected in the 'teaching phase'. These automatic motions require only one Cartesian direction to be force controlled: the direction normal to the skin;
- the robot can reach some pre-defined locations automatically (probe changing, homing etc.); during such motions, no direction is force controlled.

Experiments on volunteers in EDF's laboratory have clearly proved the interest of the robotized approach compared to the manual one for the 3-D reconstruction of a carotid artery. All relevant results can be found in Boudet *et al.* (1997).

The use of an off-the-shelf industrial robot has allowed us to validate the external force control scheme for US probe

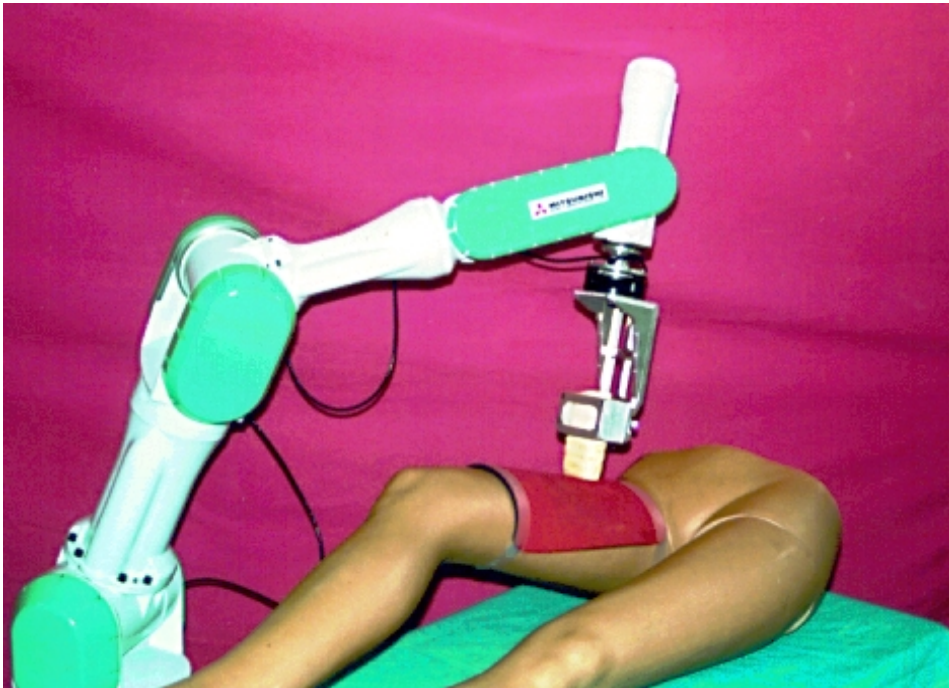


Figure 4. Testbed for force control.

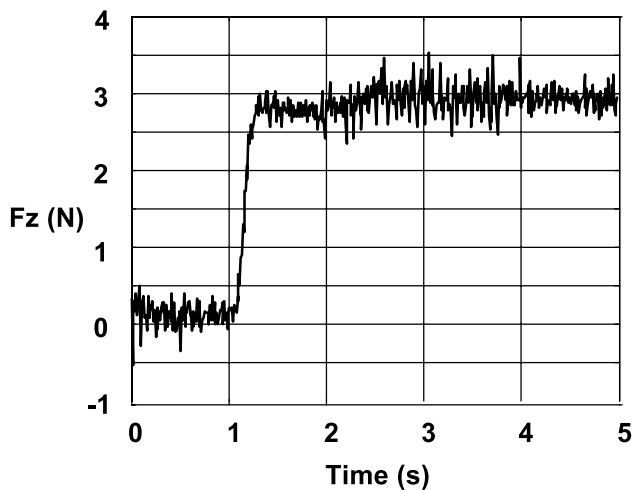


Figure 5. Force measurements. The probe moves first in 'free space' and touches the skin after 1 s. Then the desired force (3 N) is reached and kept constant. No filtering on measurements.

manipulation, but this robotic cell was not safe enough to be used on a regular basis in a hospital. Obviously, all possible software safety features were implemented as well as the DMS and other classical hardware safety features.

However, the LAN communication between the robot servo-drivers and the PC could not be regarded as totally reliable, the actuators were too powerful, and the robot could hurt patients in the case of failure of any one of the servo-drivers. In order to minimize risks (it is clear that it was not possible to cancel all of them out), extensive tests on software and hardware security systems were performed by experts in robotics before each trial, and robotics experts also had to monitor the preliminary tests (the experts were neither the designers of the prototype nor the experimenters).

In order to comply with safety constraints for a robot intended to work in hospitals, it was necessary to take them into account at early design stages of an intrinsically safe robot. This has been done by SINTERS, an Engineering Company in Toulouse, France, which has designed a dedicated robotic system called Hippocrate.

3. THE HIPPOCRATE ROBOTIC SYSTEM

3.1. Safety methodology

The main goal in designing a dedicated medical robot was to obtain an intrinsically safe system. Thanks to Sinters Company's long experience in design and control of safety and test equipment for the aeronautic industry, we complied

with the FMECA^a method at every step of the industrial project, for each sub-part of the Hippocrate system: mechanics, electronics, software and computers. Each sub-part is divided into several functional blocks and a systematic study of all possible failures is carried out in order to establish their consequences on the whole system and their level of danger (level 1, patient or operator death; level 2, patient or operator injury; level 3, patient or operator trouble). All Davies' safety suggestions (see Davies, 1993) are respected—except for the last one regarding image processing, which is not relevant here.

Since we decided at an early stage of the programme to develop as few as possible specific pieces of equipment, Hippocrate relies a lot on standard technologies (force sensor, computer, motors, drivers, control boards, position sensors etc.): it is therefore not realistic to expect reliable numbers giving good estimates of failures on these commercial products [the opposite situation is often encountered in the aeronautic industry where most critical equipment is designed to fulfil specific requirements and to provide a given MTBF: this is not critical here as recalled in Davies (1993)]. Thus we had to follow a multi-criterion approach to guarantee safety without adding local redundancy systematically (again, it is often the opposite in the aeronautic industry where computers, mechanical or electrical devices can be redundant); here, safety components (hardware or software) interact to obtain the required safety at the system level. For example, the contact between the robot end-effector and the patient (or the operator) is monitored by the force sensor; the force information is used in the control computer software, but a threshold is also built into the force sensor controller itself; in addition, the maximum force that the robot can apply is limited both at the mechanical level (torque limiters) and at the electrical level (choice of motors, total installed electrical power).

Note that Hippocrate is already compliant with EC (European Community) marking. It has been fully tested for EMC (electromagnetic compatibility) and is under the final stage of acceptance by an ethical committee in order to obtain the CCPRB^b which is now required for every new device used in a hospital for validation purpose on patients.

3.2. Arm architecture

Several criteria have been analysed in order to determine a mechanical architecture satisfying the safety constraints. These criteria are:

- the kinematics of the robot [serial, as the PA-10, parallel, as CRIGOS in Brandt *et al.* (1997), hybrid];
- the number of degrees of freedom;
- the dimension of the links;
- the position of the robot base with respect to the patient (on the ground, suspended, close to the patient);
- the technology of the position sensors (encoders, potentiometers, resolvers);
- the type of actuators and drives.

Since the interest of a redundant arm for our medical application has not been confirmed during previous experiments with the PA-10, a six-DOF serial manipulator with revolute joints has been chosen. The aim was also to design a robot smaller than the PA-10 but satisfying the rotational constraints at the tip of the probe.

A simulation study has been run to determine the best dimension of each link of the robot for three cases of base location: a standard robot fixed on the ground, a mini-robot suspended above the patient's bed and a mini-robot fixed on the patient's bed (requiring the design of a specific bed). The solution of a mini-robot suspended above the bed has proven to be the more efficient. Both the carotid and femoral zones are reachable if links 2 and 3 are ~30 cm long (see Figure 6). The advantage of this solution is that the workspace around the patient's bed is left totally free. The drawback is that the robot has to be secured on a cantilever support. This drawback has been minimized by installing the controller on the support to counterbalance the weight of the robot.

3.3. Arm technology

For safety reasons, each joint is equipped with two resolvers (except for the sixth joint which has only one resolver on the joint axis). One resolver is mounted on the motor output shaft for fine position sensing and the other is mounted on the joint axis for coarse sensing of the joint location. While improving the robot safety (both resolvers must, at any time, give consistent results; otherwise this indicates that a resolver, or the mechanical transmission, or the position acquisition board, are damaged) the combination of the two resolvers suppresses time consuming and potentially hazardous initialization procedures.

To avoid the risk of wiring wrench, all the shielded leads have been integrated inside the links of the robot arm, including the original lead for the F/T sensor located at the tip of the wrist.

In order to limit the robot velocity, a 'harmonic drive' is mounted on each motor output shaft, the reduction ratios ranging from 80 up to 160 depending on the joint. This corresponds to 1–5 revolutions/min of the link. The first four joints are also equipped with a mechanical torque limiter

^aFailure mode effects and criticality analysis, MIL-STD 1629 A, an official safety method in the aeronautic industry.

^bCertificat du comité de protection des personnes se prêtant à des recherches biomédicales.

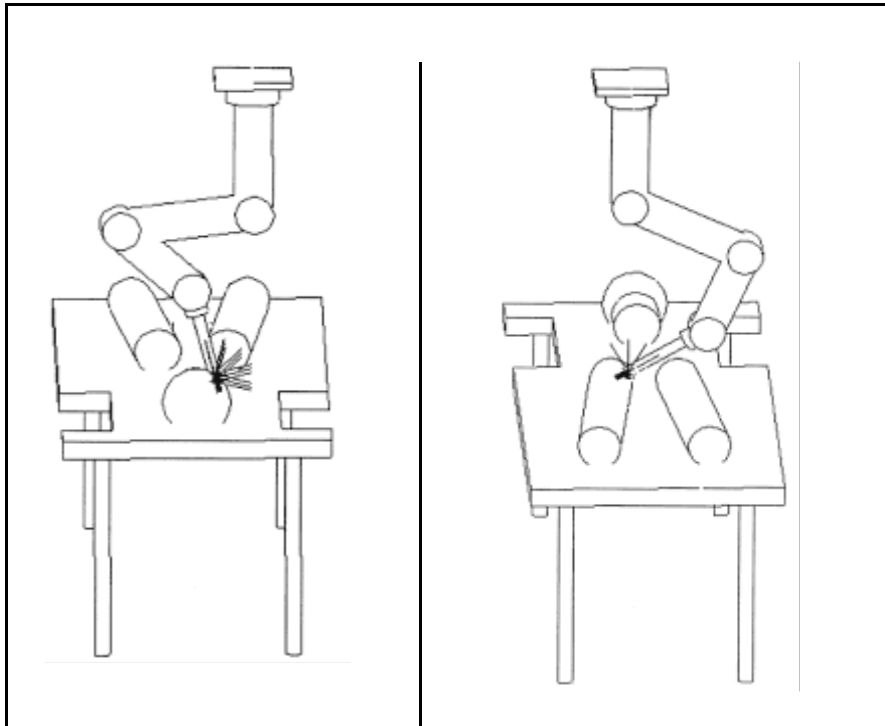


Figure 6. A single suspended arm can reach the femoral and carotid areas.

mounted between the actuator and the ‘harmonic drive’: when a link collides with an obstacle during motion, it stops moving while the motor shaft still rotates. Practically, the external force on the probe is limited to ~ 30 N (joints 5 and 6 do not require such torque limiters since the actuators are low torque, 6 and 0.4 N m respectively).

A parking brake has been mounted on joints 2 and 3 in order to prevent the robot from collapsing when the power is off. However the other joints can be moved freely, allowing the arm to be released away from the patient if necessary.

Concerning the actuators, a step-by-step motor technology has been selected. The main reason for this choice is due to the fact that with conventional DC or AC motors, the rotation speed of the motor shaft depends on the output level of the servo amplifier. If a default occurs, the motor still continues to rotate: the higher the output at the time of the failure, the faster the output shaft velocity. A step-by-step motor needs pulses to rotate. If the output of a translator is stuck at a constant value, the motor shaft would receive a holding torque which prevents it from rotating. Basically, the output torque decreases as a function of the rotational velocity. Moreover, when the number of pulses per second or the acceleration are too high with respect to the motor type, the output torque is

dropped down.

Each motor has been chosen depending on the torque the joint has to generate. This minimizes the power transmitted at the joint level and thus increases the safety of the robot.

In brief, even if no safety feature were implemented in the controller (note that many software securities exist anyway; see the next section), the Hippocrate arm (see Figure 7) is intrinsically safe: the stepper motors do not suffer from an overspeed risk, their maximum torque is ‘naturally’ limited, the total installed power is small so that even at full power there is no danger, and finally, torque limiters have been installed.

3.4. Controller securities

The previous features make the Hippocrate arm an intrinsically safe mechanical device. We have implemented several additional hardware and software securities within the controller, providing very good reliability and safety to the whole system. A description in order of importance of these securities is presented in the following.

- Three emergency buttons are available (two of them are wired to the control desk, the other is wired to the controller front panel). Any action on one of these



Figure 7. The Hippocrate robot arm.

buttons immediately switches off the arm power. The arm is powered on only when a software initialization procedure and a restart button are activated.

- A watchdog board has been developed in order to manage the security from a software point of view. If anything goes wrong in the high-level controller, the cyclic signal sent to the watchdog is stopped, inactivating the watchdog and switching off the power. The time delay response of the watchdog has been tuned to 50 ms. In order to improve security, two redundant circuits have been wired on the board.
 - Five software processes are running at the same time. If one of them is stopped or blocked, the watchdog is inactivated and the power is switched off.
 - If the effort exerted on the US probe exceeds a given amount, the watchdog is immediately deactivated and the power is switched off as well.
- Software joint limits have been implemented in order to minimize the workspace, thus reduce the risk of collision. The arm cannot move outside its limits when it is servoed. The power cannot be switched on if any joint of the arm is beyond its mechanical limits.
 - When the difference between the current position and the desired position is above a defined value, a tracking error is detected, the watchdog is immediately inactivated and the power switched off.
 - The action on the DMS (a foot pedal) is necessary to authorize any motion of the robot either in the joint space or in the Cartesian space. A new motion needs a new action on the pedal. Unless the pedal is pressed down, any motion with the force control mode is not allowed.
 - The multiple configuration problem of the arm is prevented in both Cartesian and force control modes. When the robot reaches the vicinity of a singularity, any motion is stopped until it is moved away by the operator.

3.5. Controller architecture

Practically, Hippocrate consists in a six-DOF robot arm, a dedicated controller, a control desk and a DMS pedal. The control desk includes a keyboard, two emergency buttons, a restart button and a teach pendant for the learning phase. The controller is part of the cantilever support, which is mounted on wheels so that it can be moved within the hospital.

The controller is divided into four functional racks including:

- the different power supply units (+45, +24, +5, ± 15 VDC);
- the power contactors and switches, and the controller unit of the F/T sensor (from ATI, Garner, NC);
- the logical unit (I/O, resolver control board, watchdog) and the translators for the control of the step-by-step motors;
- the high-level computer, a 166 MHz Pentium PC. The control software and man-machine interface are running under QNX, a real-time, multitasking operating system. The low level of the control scheme (servo control in the joint space) is provided by an eight-axis board PMAC2 (from DeltaTau, Northridge, CA) plugged into the PC.

Due to the controller unit performance of the force/torque sensor (with respect to our acquisition method), the sampling period of the system cannot be < 10 ms. However, even with this period, the behaviour of the force controlled robot is smooth enough and a smaller period would only improve the time response. Features of Hippocrate are as follows:

- absolute accuracy: no precise information is available as yet, even if it is expected to be better than 0.5 mm;

a basic calibration has been performed to ensure the position of each axis' zero. Note that in the current application, absolute accuracy is not of tremendous importance since measurements are done inside a very small volume (few cm^3). Beside, recall that the trajectory is taught manually. Consequently, only repeatability and resolution are relevant;

- repeatability: 0.05 mm (measured in various locations of the workspace);
- resolution: $0.1 \text{ mm} \pm 0.02 \text{ mm}$;
- force accuracy: better than 0.1 N;
- weight of the moving parts (from joint 2 to joint 6): 9 kg;
- arm length/reach from joint 2 to the force/torque sensor tool plate: 837 mm;
- maximum payload: 2 kg (this is equivalent to the 20 N maximum force necessary for measurements on heart arteries, while 1–5 N is sufficient for carotid and femoral. Those values have been determined experimentally at Broussais Hospital. Note that the maximum force applied for a given procedure can be set by the physician at between 0 and 20 N);
- tool velocity: 10 cm s^{-1} .

A dedicated clip mechanism mounted on the F/T sensor allows fast and easy probe changes.

3.6. Risk analysis

When a low-level error is detected by the software, it takes 10 ms in the worst case (a sampling period) to switch off the power, plus 14 ms to apply the parking brakes. In the case of a high-level error handled through the watchdog board, the robot is stopped within 50 ms plus 14 ms.

Considering a maximum velocity of 10 cm s^{-1} , the probe motion should not exceed 2.4 or 6.4 mm, respectively. Such a small motion cannot lead to a force large enough to cause any danger to the patient or the operator. However, in any case, the mechanical torque limiters would release the arm as soon as external forces on the probe exceed 30 N.

3.7. Calibration issues

The calibration problem may be split into two sub-problems: robot registration and probe calibration. A robot registration procedure should provide the very accurate transformation between a coordinate system associated with the US probe held by the robot and a coordinate system associated with the patient. A lot of methods are available to obtain these so-called extrinsic parameters. However, for the application at hand, recall that absolute accuracy is not required. The problem is therefore much less complicated than it is for computer-aided surgery [see for instance Lavallée *et al.*

(1996) for an introduction to the topic]. In order to obtain reproducible 3-D reconstruction of atheromatous plaques, the image processing system stores a reference image of the first medical examination on which several anatomical landmarks are visible: when a new examination is done, the doctor moves the probe until the current image matches the stored one.

For the intrinsic calibration of the US probe, a classical procedure involving a calibration pattern has been set up (see for instance Henry, 1997). Incidentally, the parameters have been proven to be stationary enough to avoid running the procedure on a regular basis.

3.8. User interface

The user interface is based on three different devices:

- the robot arm itself, thanks to its force sensor and the force control scheme, lets the physician guide Hippocrate easily by grabbing the probe without any programming;
- a small teaching pendant allows the user to validate positions (during the teaching phase) without going back to the computer, that is, while staying close to the robot arm and the patient;
- a computer which runs a GUI, developed under PHOTON, an object-oriented language supported by QNX. Thanks to this technology, a single computer supports the control and the GUI.

The GUI (as well as all other components of Hippocrate) has been developed in close co-operation with physicians. Every window, every button, every word of this GUI has been chosen in order to provide the physicians with user-friendly tools to communicate with the robot. The GUI, protected by passwords and ready to accept physician commands only if the system has been correctly initialized, offers in a simple package (only three windows) all the features necessary:

- to set-up the system; this menu is invoked to define parameters of the probes (length, weight, maximum authorized force etc.), to define pre-registered positions (approach of the carotids and femorals, home position etc.), and to set parameters used during the learning and automatic phases (desired step length, contact force, activation of the synchronization with the heartbeat etc.). All windows created from the configuration menu need a specific password to be opened, and all set-up data are stored in several files on the PC.
- To run Hippocrate this menu is invoked to open the user window (see Figure 8). This window allows one to select probes, pre-registered locations and motion

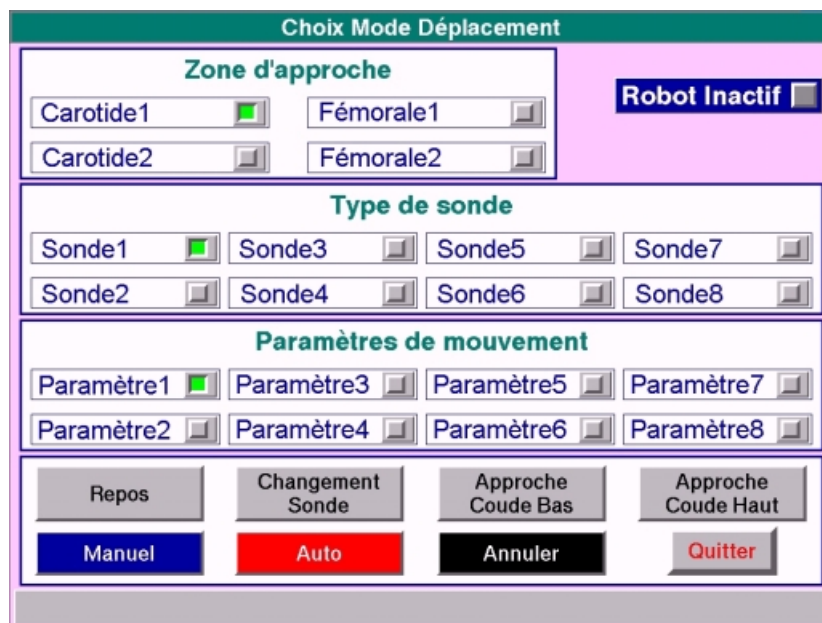


Figure 8. A view of a GUI window.



Figure 9. Hippocrate and its environment.

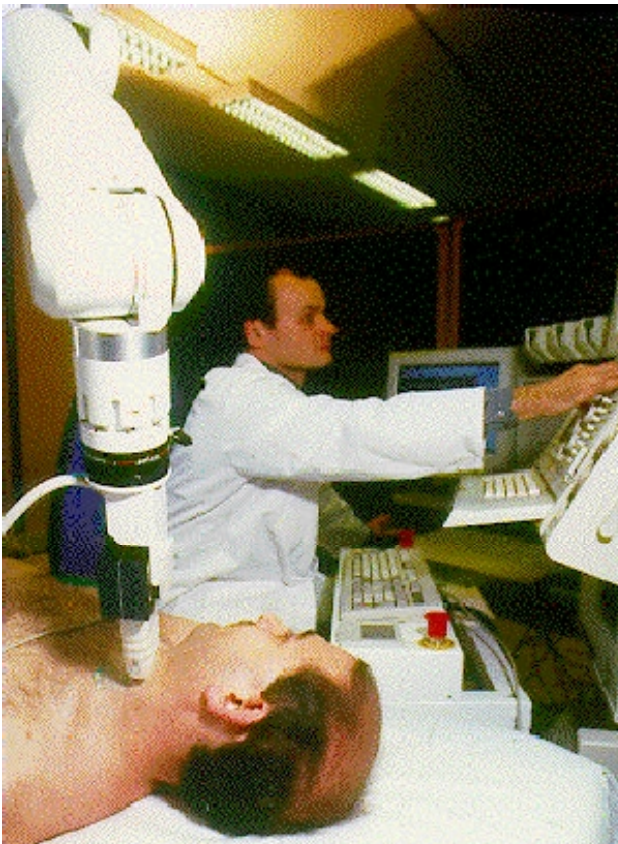


Figure 10. Another view with the physician tuning the echograph.

parameters. It is also used to activate motion toward pre-registered locations, and finally to execute the learning and the measurement phases. Some of the pre-defined parameters can be modified temporarily without having to restart the complete procedure (they are not stored after the application is stopped).

When a parameter is modified in the configuration window, a warning message is displayed in the case where the window is quitted without saving the changes. An interactive on-line help is also available via the display of messages at the bottom of each window. The doctor is guided and knows exactly what the robot is doing.

The Hippocrate robotic system was evaluated in EDF's laboratory at the end of December 1997, under real conditions of clinical experimentation. Hippocrate communicates via a serial link with a Macintosh-based image processing system, from IôDP, a Medical Engineering Company in Paris, France. This link is used at two levels:

- it allows synchronization between the robot motion, the image recording and the heartbeat (obtained from an ECG signal and sent to the Macintosh),
- it allows the transfer of the probe locations recorded at each step of the displacement during the automatic phase (these locations are used in the 3-D reconstruction).

Figures 9 and 10 show a view of the whole experimental set-up: the robot Hippocrate with its control desk, the echograph, the Macintosh, the medical bed and a patient ready for examination.

3.9. Experimental results

3-D reconstruction of a carotid artery

Robotized measurements have been performed as follows:

- the doctor moves the arm from its home position to the vicinity of the measuring zone; all the robot axes are under force control;
- the doctor selects precisely the first teaching location according to the US images (Ultramark 9 HDI ATL, 5–10 MHz probe) and stores this location;
- the doctor moves the robot to a second teaching location and stores it as well;
- then the automatic robot control mode is selected; the arm automatically goes back to the first teaching location with the axis normal to the skin under force control (5 N contact force); then it moved in 1 mm steps towards the second teaching location and waits for heartbeat synchronization. When US data acquisition was completed a new step was triggered. This was repeated until the second teaching location was reached.

Figure 11 shows preliminary results obtained with the feasibility testbed. In Figure 11a, measurements are done manually by a doctor: the slices are obtained from a flyby sequencing, during the motion of the probe, without heartbeat synchronization. In comparison, in Figure 11b (robotized measurements) the interest of force sensing is obvious despite a poor 1 mm displacement step and rough 3-D image processing.

Evaluation of the elastic properties of a carotid artery

Movements of the anterior and posterior walls of the artery are recorded during several cardiac cycles (see Figure 12, top). After processing (see Figure 12 bottom), the distension is defined as the ratio $(\varnothing_{\max} - \varnothing_{\min})/\varnothing_{\max}$, where \varnothing_{\max} and \varnothing_{\min} are the maximum and minimum distances between the walls respectively (systolic and diastolic diameters). It is used as an index of the elasticity of sclerotic arteries among hypertensive patients.

Again, it is important to perform these measurements periodically in the same experimental conditions. The

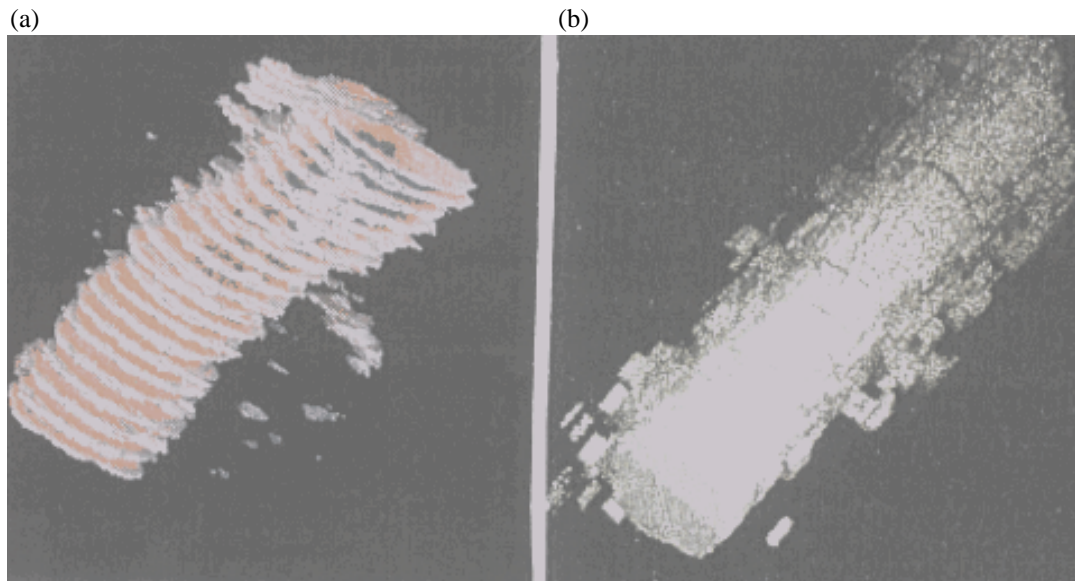


Figure 11. (a) Manual measurements; (b) robotized measurements.

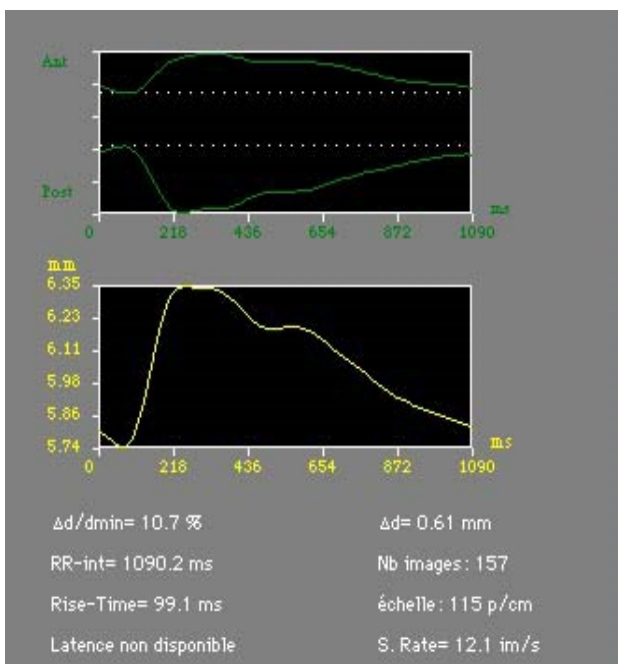


Figure 12. Evaluation of the carotid distension: movements of the artery's walls (top) and distance between walls (bottom).

force-controlled robot makes it possible to evaluate the distensibility with a reproducible pressure of the US probe on the skin (0.1 N in Figure 12), always inducing the same deformation of the artery.

4. DISCUSSION—OTHER POTENTIAL APPLICATIONS

Hippocrate has been designed to monitor cardiovascular diseases on a regular basis where accuracy and repeatability are of tremendous importance but speed is not a strong constraint; this system is thus not intended to be used in any emergency procedure, but has been designed to obtain precise measurements and requires images to be taken in synchronization with the heartbeat. This can lead to quite long measurement phases. As a matter of fact, recording an image every two or three heartbeats, along a 40 mm line, with a 1 mm step, can be done in about 2 min; but using the smallest incremental step (0.1 mm) increases this time up to 20 min. Thanks to its force control and its ability to move a probe on a predefined path with regular step, Hippocrate can help to produce fine images of small areas and other techniques should be used to produce 3-D images of complete organs. The evaluation program starting in January 1999 at Broussais Hospital, Paris, is intended to give practical answers to the question of the largest interslice distance which leads to a 3-D reconstruction precise enough to help in patient care.

Thanks to Hippocrate's capabilities a wide range of other applications are possible. An ongoing study was made in the area of reconstructive surgery. For severely burnt patients, strips of skin (thickness ranging from 0.1–0.5 mm) are harvested on sound locations with a shaver-like device (a dermatome) and are grafted onto the burnt location.

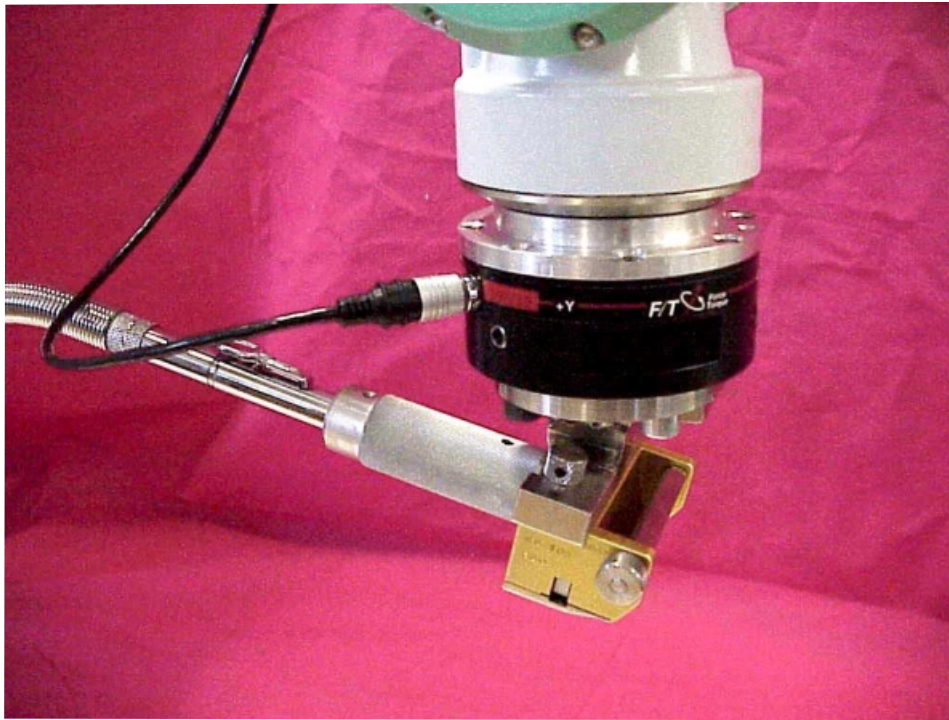


Figure 13. A dermatome can be installed on Hippocrate (this view represents the dermatome and the force sensor; they are mounted on the arm used for the feasibility study).

Depending on the area of the burn, several operations must be performed: strips of skin have to be harvested several times after healing from the same location. The goal is to robotize the process of harvesting in order to better satisfy two constraints:

- the thinner the skin strip, the better the result of the graft;
- the thickness of the removed skin has to be constant over the entire strip, which means that the pressure of the dermatome on the skin has to be constant. It is assumed that the contact area between the dermatome and the skin is constant, which makes force control possible.

Figure 13 shows a manual dermatome which has been easily adapted to be rigidly fixed on the force sensor while enabling the surgeon to hold it for teaching phases.

One of the expected outcomes is to reduce the time required for the rehabilitation process by improving the quality of the successive skin graft operations. Again, the envisioned system should be a robotics tool serving the surgeon and not a machine replacing him. To date, only preliminary studies have been carried out: we have cut thin slices of silicon with a robotized dermatome. Those experiments have already shown some challenging problems,

such as: vibration control (the dermatome produces a lot of vibration) and sensitivity to variation in material physical properties (we carried out tests with different kind of silicon, but we expect more changes with human skin, and this must be taken into account).

Funding from the 'Région Languedoc-Roussillon' together with the 'Ministère de l'Éducation Nationale, de la Recherche et de la Technologie' has been obtained to develop a Hippocrate-based new prototype. A risk analysis will be performed to take into account the safety requirements specific to the application. However, it is worth noting that the harvesting depth is adjustable mechanically on the dermatome by the surgeon prior to operating. This prevents the dermatome from penetrating more than planned under the skin if the force applied is too high. Therefore, the question of safety should not be much more demanding.

Other uses of this system include measurement of force–position relationships for various organs in order to build mathematical models to be used in augmented reality systems; one can for example apply different forces at different locations on a thigh and record the corresponding forces (and moments) to build a complete six-dimensional biomechanical model of the thigh.

Finally, one could even consider the use of Hippocrate for tele-applications and obtaining US 3-D imaging from a remote site, for example to monitor astronauts' arteries during long missions in a space station.

5. CONCLUSION

We have presented Hippocrate, an intrinsically safe six-DOF medical robot with force control capabilities and a user-friendly graphical interface. It is an active arm in the sense that it is actuated but its power is limited. The main features are a maximum linear velocity at the probe tip of 10 cm s^{-1} , a resolution of 0.1 mm and a maximum payload of 2 kg. The complete system has shown its efficiency for accurate 3-D reconstruction of arteries from US data. Clinical evaluation at Broussais Hospital is scheduled to start in January 1999 to study the changes of the atheromatous plaques volume over a long period of time.

Hippocrate offers clear advantages when force control is needed together with a pre-defined trajectory in six-dimensional space and thus could help in other medical or biomechanical applications.

REFERENCES

- Baba, K., Satch, K., Satamoto, S., Okai, T. and Shiego, I. (1989) Development of an ultrasonic system for three-dimensional reconstruction of the foetus. *J. Perinat. Med.*, 17, 1924.
- Boudet, S., Gariépy, J. and Mansour, S. (1997) An integrated robotics and medical control device to quantify atheromatous plaques: experiments on the arteries of a patient. *Proc. IROS, Grenoble, France*, pp. 1533–1538.
- Brandt, G., Radermacher, K., Lavallée, S., Staudte, H.-W. and Rau, G. (1997) A compact robot for image guided orthopedic surgery. *Proc. CVRMed-MRCAS'97, Grenoble*, pp. 767–776.
- Dario, P., Guglielmelli, E., Allota, B. and Carrozza, M. C. (1996) Robotics for medical applications. *IEEE Robot. Automation Mag.*, 3, 44–56.
- Davies, B. L. (1993) Safety of medical robots. *Proc. 6th ICAR, Tokyo*, pp. 311–317.
- Davies, B. L., Ng, W. S. and Hibberd, R. D. (1993) Prostatic resection: an example of safe robot surgery. *Robotica*, 11, 561–566.
- Delcker, A. and Diener, H. C. (1994) Quantification of atherosclerotic plaques in carotid arteries by three-dimensional ultrasound. *Brit. J. Radiol.*, 67, 672–678.
- Delebarre, X., Bouffard-Vercelli, Y., Dégoulange, E. and Dauchez, P. (1991) Force control of a two-arm robot manipulating a deformable object. *Proc. 2nd Int. Symp. on Experimental Robotics, Toulouse*, pp. 1–12.
- De Schutter J. and Van Brussel, H. (1988) Compliant robot motion: II. A control approach based on external control loop. *Int. J. Robot. Res.*, 7, 18–13.
- Dombre, E., Théron, X., Dégoulange, E. and Pierrot, F. (1996) Robot-assisted detection of atheromatous plaques in arteries. *Proc. IARP Int. Workshop on Medical Robots, Vienna*, pp. 133–140.
- Flaud, P., Bensalah, A., Counord, J.-L., Levenson, J. and Simon, A. (1990) A new geometric procedure for *in vivo* pulsed Doppler evaluation of velocity distribution inside the diametric section of large arteries in human. *Ann. Biomed. Eng.*, 18, 519–531.
- Fraisse, P., Dauchez, P. and Pierrot, F. (1992) Robust control scheme for a 2-arm robot: performance analysis. *Proc. IECON'92, San Diego, CA*, pp. 676–681.
- Ganapathy, U. and Kaufman, A. (1992) 3-D acquisition and visualization of ultrasound data. *Visualiz. Biomed. Comput., SPIE Conf.*, Vol. 1808, 535–545.
- Harris, S. J., Lin, W. J., Fan, K. L., Hibberd, R. D., Cobb, J., Middleton, R. and Davies, B. L. (1997) Experiences with robotic systems for knee surgery. *Proc. CVR Med.-MRCAS '97, Grenoble, France*, pp. 757–766.
- Henry, D. (1997) *Outils pour la Modélisation de Structures et la Simulation D'examen Échographiques*, Ph.D. Thesis, Université Joseph Fourier, Grenoble, France (in French).
- Ho, S. C., Hibberd, R. D., Cobb, J. and Davies, B. L. (1995) Force control for robotic surgery. *Proc. ICAR 1995, Vol. 1*, pp. 21–31.
- Hodges, T. C., Detmer, P. R., Burns, D. H., Beach, K. W. and Starned, D. E. (1994) Ultrasonic three-dimensional reconstruction: *in vivo* volume and area measurement. *Ultrasound Med. Biol.*, 20, 719–729.
- Hughes, S. W., D'Arcy, T. J., Ruff, C. F., Maxwell, D. J. and Saunders, J. E. (1996) Measurement of organ volume using 3-D US. *Proc. Comput. Assisted Radiol.*, pp. 210–215.
- Kazanzides, P., Zuhars, J. F., Mittelstadt, B. D. and Taylor, R. H. (1992) Force sensing and control for a surgical robot. *Proc. IEEE ICRA'92, Nice*, pp. 612–617.
- Lavallée, S., Troccaz, J., Sautot, P., Mazier, B., Cinquin, P., Merloz, P. and Chirossel, J.-P. (1996) Computer-assisted spinal surgery using anatomy-based registration, In Taylor, R. H. *et al.* (ed.), *Computer-Integrated Surgery: Technology and Clinical Applications*, pp. 425–449. The MIT Press, Cambridge.
- Mills, P. H. and Fuchs, H. (1990) 3-D ultrasound display using optical tracking. *Proc. 1st Conf. on Visualization for Biomedical Computing*, pp. 490–497.
- Ohbuchi, R., Chen, D. and Fuchs, H. (1992) Incremental volume reconstruction and rendering for 3-D ultrasound imaging. *Vis. Biomed. Comput.*, 312–323.
- Perdereau, V. and Drouin, M. (1993) A new scheme for hybrid force-position control. *Robotica*, 11, 453–464.
- Perdereau, V. and Drouin, M. (1994) About kinematic local instability and stabilization of hybrid control schemes. *Proc. ISRAM'94, Hawaii*, pp. 525–530.
- Pierrot, F. (1991) *Robots Pleinement Parallèles légers: Conception, Modélisation et Commande*, Ph.D. Thesis, Université Montpellier II, Montpellier, France (in French).
- Pujas, A., Dauchez, P. and Pierrot, F. (1993) Hybrid position/force control: task description and control scheme determination for a real implementation. *Proc. IROS, Yokohama*, pp. 841–846.

- Reboulet, C. and Robert, A. (1985) Hybrid control of a manipulator with an active compliant wrist. *Proc. 3rd ISRR*, Gouvieux, pp. 76–80.
- Sakas, G., Schreyer, L.-A. and Grimm, M. (1995) Preprocessing and volume rendering of 3-D ultrasonic data. *IEEE Comput. Graph. Appl.*, 15, 47–54.
- Shiota, T., Sinclair, B., Ishii, M., Zhou, X., Ge, S., Teien, D. E., Gharib, M. and Sahn, D. J. (1996) Three-dimensional reconstruction of colour Doppler flow convergence regions and regurgitant jets: an *in vitro* quantitative study. *J. Am. Coll. Cardiol.*, 27, 539–542.
- Taylor, R. H. *et al.* (1991) Taming the bull: safety in a precise surgical robot. *Proc. 5th ICAR*, Pisa, pp. 865–870.
- Thérond, X., Dombre, E. and Pierrot, F. (1995) Arteries diseases detection: a cooperative robot solution. *Proc. ICAR*, Sant Feliu de Guixols, Spain, pp. 43–50.
- Troccaz, J. and Delnondedieu, Y. (1996) Semi-active guiding systems in surgery. A two-DOF prototype of the passive arm with dynamic constraints. *Mechatronics*, 6, 399–421.