SCALPP: A Safe Methodology to Robotize Skin Harvesting

Gilles Duchemin[1], Etienne Dombre[1], François Pierrot[1], Philippe Poignet[1], and Eric Dégoulange[2]

[1] LIRMM UMR 5506 CNRS – UM2, 161 rue Ada, 34392 Montpellier Cedex 5, France
`{duchemin, dombre, pierrot, poignet}@lirmm.fr`
`http://www.lirmm.fr`
[2] SINTERS SA, BP 1311, Parc Technologique Basso Cambo, 5 Rue Paul Mesplé, 31106 Toulouse Cedex 1, France
`eric.degoulange@tde.alstom.com`
`http://www.sinters.fr`

Abstract. This paper deals with an ongoing research program in robotized reconstructive surgery (especially for skin harvesting) with a mechanical system under force control. The constraints of the process are firstly described in terms of medical and robotic constraints. Then, we present an active mechanical structure which suits to our needs whose interesting features are a simple and closed-form solution to the Inverse Geometric Model (IGM), the ability to handle the tool without collision and a simple mechanical design. In a third part, we present the application and the controller architecture from a working point of view and the force controller chosen. Finally general and particular safety issues for medical robots are discussed and solutions are presented to turn the application intrinsically safe.

1 Introduction

This paper deals with a new robotized medical application for reconstructive surgery with an original active arm, where force control is required.

For severely burnt patients (and for patients suffering from severe orthopedic problems leading to a loss of skin), strips of skin – the thinness ranges from 1/10 to 7/10 mm – are harvested on sound locations with a “shaver-like” device called dermatome (Fig. 1) and are grafted onto burnt locations. A dermatome is a simple mechanical device offering only two adjustable parameters: the blade speed which is modified thanks to a pedal, and the maximum cutting depth which is selected on the dermatome head (Fig. 1). This depth selection does not guarantee at all the actual cutting depth: depending on the user skill, for a given depth selection, the resulting skin strip thinness may range from the selected depth down to zero.

The practitioners used to a daily practice are able to properly perform these grafts. A great discipline in the gestures performed is necessary so as to both get a regular sampling and ascertain a quick healing of the donor area. This speed factor in the epidermis reformation is crucial when the need arises to resample the same area, particularly among the severely burnt population where donor areas are scarce. Many

W. Niessen and M. Viergever (Eds.): MICCAI 2001, LNCS 2208, pp. 309-316, 2001.

surgeons having to perform these sampling gestures on an occasional basis – Orthopedic-Trauma, Surgery, Maxilla-Facial Surgery, ENT Surgery – could be interested in an automated technique avoiding such intra or postoperative hazards as skin skipping, occurring when performing a gesture at the origin of unaesthetic scars in the donor area, or else when performing too deep harvesting which entails difficult problems of late healing. The robot is designed to help these non-specialized practitioners, or those who are not performing these gestures on a daily basis.

The goal of this project[1] is then to embed part of a specialized surgeon skill in a robotic system, called "Système de Coupe Automatisé pour Le Prélèvement de Peau" (SCALPP), in order to bring this skill to other surgeons who do not practice harvesting as a routine.

2 Problem Statement

As most human motion or action, a surgeon action consisting in harvesting skin may be extremely difficult to model accurately [1]. First this is a motion in 3D space, combined with quite important forces exerted on a non-modeled environment. Moreover, there is no reason for two different surgeons to cut skin with the same motion nor the same force (we verified this fact). Finally a surgeon may change his action depending on his fatigue, and may also adapt his action according to the patient. The surgeon motion can be divided into four stages (Fig. 1). The surgeon begins to cut by pressing along z axis with the dermatome blade "not-parallel" to the skin (the orientation angle of the dermatome blade may change, phase 1); then he moves along x axis while placing the dermatome blade parallel to a plane tangent to the skin (phase 2); next, he tries to keep the blade in this plane (phase 3); finally, he frees the dermatome by a short motion of the hand (phase 4). During the third phase (cutting phase), the force normal to the skin ranges from 40 N up to 100 N, and is kept constant; moreover, the torque about x is roughly about zero, meaning that the surgeon keeps the dermatome blade completely in contact with the skin.

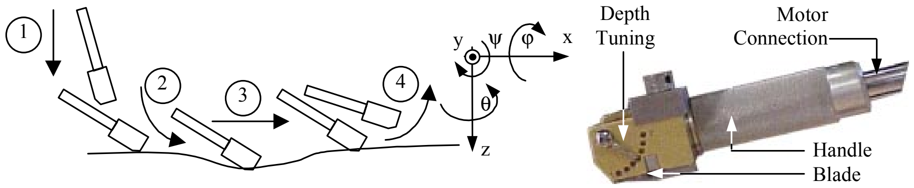

Fig. 1. Different phase of skin harvesting with a dermatome

During surgical operation, the patient is lying on an operating table. For asepsis considerations, no non-medical equipment must be closer than 400 mm from the operating table. Moreover, the robot must collide neither with the patient, nor with the medical staff, nor with the anaesthetic pipes. In our experiment, skin harvesting is

---

[1] This work has been supported partly by funds from "Ministère de l'Education Nationale et de la Recherche" and "Région Languedoc-Roussillon".

only considered on the thigh and the head. Indeed, skin harvesting is too much difficult under the armpit and the sole for a scarce result to be worth robotizing. Paths are described as follow: thighs where the path starts from the knee toward the hip or conversely; the length of the sample may vary from few mm to 400 mm (which corresponds to the whole length of a thigh); head, from the neck toward the forehead or conversely, on both sides of the skull. Therefore, due to the thigh zones, it is important to have symmetrical joint limits in order to not favor a thigh compared with the other. Since the surgeon has to manipulate the robot during teaching phase, a good accessibility to the dermatome handle is needed. Finally, note that it is mandatory to keep the robot base fixed for all paths on a given thigh (to avoid time consuming re-arrangement of the system). This motion analysis leads to robotic constraints developed below.

The robot should be able to move along a path, without crossing a singularity position, or without reaching its joints limits. Thus, the t-parcourability of the path (i.e. its continuity) has to be verified prior to start the process. Moreover, during a feasibility pre-study – achieved on pigs with a 7-dof Mitsubishi PA-10 robot, see [1] – we measured that forces involved may reached 100 N, which means that the driving motors should be quite bulky (especially on the wrist). Finally, for the sake of accuracy and safety, a closed-form solution for the IGM is preferred to a numerical algorithm, since its convergence depends on the initial conditions, leading to a non-predictive behavior. That’s the reason why redundant robots or 6-dof robots whose IGM has to be solved with polynomial or numerical methods are discarded.

3 Arm Architecture

Under the various constraints mentioned in the previous section, a suitable architecture has been designed, selecting firstly the shoulder, and secondly a convenient wrist. The complete analysis can be found in [2], as well as all the geometric equations of the models.

Two types of shoulders have been considered: anthropomorphic and SCARA (Selective Compliance Assembly Robot Arm), either moving on a track fixed to the ceiling, or fixed to a support mounted on wheels and containing the controller (which provides compactness and stability of the system). A surgery room is usually cluttered with a series of medical equipment and many of them are hung on the ceiling; consequently, the surgeons required that no device would be added on the ceiling: that’s the reason why we have discarded hung up shoulders. Anthropomorphic architectures present two main drawbacks for the application at hand: their workspace is spherical while a cylindrical one would be less wasteful; under gravity effects, the robot may collapse patient namely in case of power breakdown, which has to be avoided for safety reasons. To go further, a CAD study shown that it was easier to access all path points with a SCARA robot than with an anthropomorphic robot of equivalent link lengths. For these reasons, a SCARA architecture has been chosen as the shoulder of the robot.

Nevertheless, to avoid the classical singularity of spherical wrists when fully extended, other wrist designs have been investigated. An in-depth study [2] showed us that the non-spherical wrist presented on Fig. 2 fulfilled the four main constraints already mentioned in the previous section: absence of singularity in the workspace (the only one appears when q_5 reaches ±90°), a closed-form solution for the IGM asserted by Pieper's sufficient condition [3] (prismatic and revolute joints with collinear axis), no bulky motor, and sufficient joint position ranges (almost ±90° on the fifth joint). Theoretically, four solutions result from the IGM computation, but two of them are out of the mechanical range limits. As a consequence, SCALPP robot features a single singularity in its workspace (the "classical" elbow singularity when q_3 equals 0°) and a closed-form solution for the IGM (two configurations: "left-elbow" or "right-elbow"). Besides, it provides an easy access to the dermatome handle. Finally, with the Force/Torque (F/T) sensor, the force accuracy of the robot is 0.5 N, its maximum payload is 140 N and tool velocity is about 10 $\mathrm{mm.s^{-1}}$.

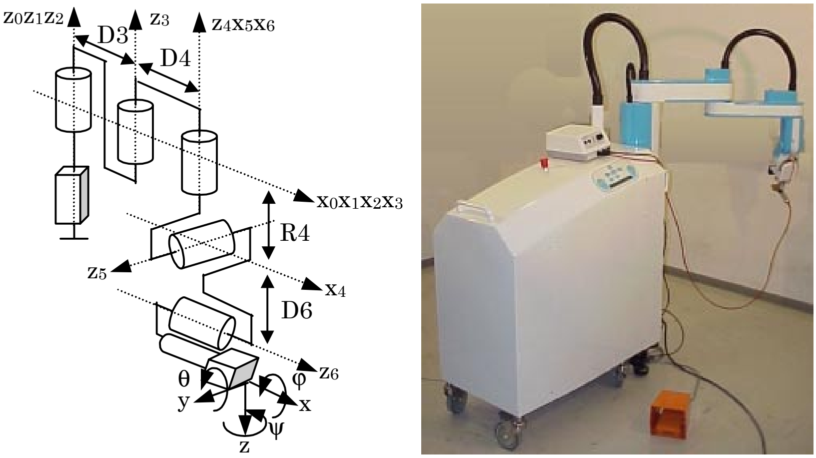

Fig. 2. Geometric architecture of the SCALPP robot

4 The SCALPP Robotic System

As mentioned earlier, SCALPP is a 6-dof SCARA arm with an User Interface (UI), a dedicated controller and a DMS foot pedal. Most of the technical devices come from our experience in specifying and designing robotic equipment [4]. The SCALPP system is fixed to a mobile support mounted on wheels and containing the controller. This last one contains 4 racks: a 550 MHz Pentium industrial PC running QNX[2] for the high level control; a rack including all the resolvers and translators boards for stepper motors control; a power supply unit; a logical unit formatting the I/O signals between user interface, switches, light signals and PC boards.

According to our experience with the Hippocrate system [4], the UI has been developed in close co-operation with physicians, in order to provide user-friendly tools to handle the robotic system. The UI consists of three main control structures. A console desk enables bilateral communications between user and robot. It is made up

---

[2] A Real Time and Multitasking Operating System (RTMOS).

of three communication sets: control buttons to cancel or validate actions, decrement or increment force applied on skin and to control the arm (respectively `esc.`, `enter`, `-` and `+`, `start`, `free` and `reconfig.`) and lights (`powered`, `active` and `default`). A LCD display indicates the current mode and the faults detected. A Dead Man Switch (DMS) pedal authorizes arm motions in `automatic` or `manual` modes (the modes where force control is required).

A detailed analysis of the robot working brought us to choose four functions modes, described bellow: a `teaching` (or `manual`) and an `automatic` modes for process constraints; a `reconfiguration` mode due to the arm architecture (i.e. its geometric structure); and for safety requirements, a `free` mode. `Teaching` mode allows physicians to teach the robot initial and final poses on skin. In this mode, the arm is compliant (the desire force is set to 0 N): the surgeon moves it by holding the dermatome handle and pushing on the DMS foot pedal. Each pose can be recorded or deleted by pressing + or − buttons. When all the points are recorded, the teaching sequence is confirmed or corrected by switching on the `enter` or `esc.` buttons. Once the teaching sequence has been recorded, the system switches in the `automatic` mode: the surgeon first selects a desired force for harvesting (from 0 to 100 N); then, as soon as he pushes on the DMS pedal, the robot begins the harvesting motion. `Free` mode enables the surgeon to move robot without force control thanks to the reversibility of the mechanism: any movement inside joint limits can be performed since no axes are controlled. This mode, activated by the surgeon by pressing the `free` button, can be used to place the arm in a "parking" position or to release the arm from the patient. Finally, the `reconfiguration` mode is selected to pass through arm singularity position: by pressing the `reconfig.` button, the user can change the arm position from a "left-elbow" to "right-elbow" configuration and conversely.

Since the application requires force control to move the arm in the `teaching` and `automatic` modes, the wrist is equipped with a F/T sensor (a laser telemeter is added to control the distance between the wrist and the skin to improve robot behavior when harvesting on the head). Force control schemes have been widely addressed in the past and state of art can be found for instance in [5]. An usual classification consists of dividing force control into two families: passive compliance and active compliance. The first one uses a deformable structure mounted at the arm tip, without force measurement. The second one allows to adapt the robot behavior according to the contact forces; there are three classes of active compliance control laws: without force measurement; with force measurement and without (like explicit force-feedback control); with force measurement and control (active stiffness [6], hybrid [7] and external [8] controls). Due to the task constraints a force control with force measurement is needed. So, we discarded all the controls without F/T sensor. Among the remaining controls, active stiffness and hybrid control have been discarded. Indeed, the first one uses the Jacobian matrix, which could induce numerical problems, and is carried out in joint space whereas our application is a Cartesian task. The second one enables either force control or position control along a direction. The external control (called also nested or cascade structure) is the only suitable force control for our application. Here again, different schemes can be proposed depending on the space where the summation of force and position components is achieved (joint or Cartesian association) and on the position control (joint control by IGM or Jacobian matrix, and Cartesian control). External control with Cartesian summation between force and position components and joint control by IGM have been chosen (Fig. 3). Moreover, the key advantages of external control can be summarized as follow [8]: the joint position servo loop is always activated, providing stability and avoiding switching between the position servo loop and the force control; it works very well with very simple and reliable (thus safe) control laws (like a PID at the joint level and a PI for the external force loop); it is easy to implement on any kind of controller; unless an effort is applied on the dermatome (below the force sensor), the robot will not move; at last, it allows designing the control software in an incremental manner, facilitating the tuning of the parameters and validation (internal joint control, external Cartesian space control with additional force control loop).

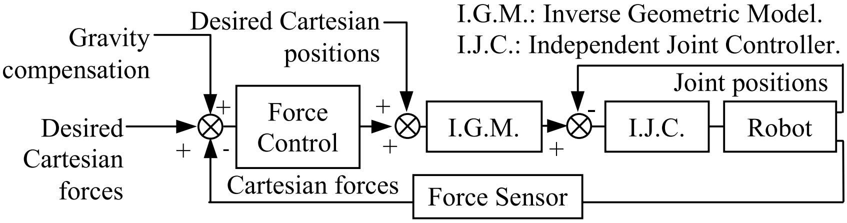

Fig. 3. External force control scheme

5 Safety Issues

A central issue when designing medical robots is safety since the robots cooperate with the surgeons and interact with patient. Consequently, introducing a robot in an operating room must fulfil some elementary rules. Most of these rules have been presented in [9] and [10]. We sum up here the most important ones: the robot should never "run away"; force applied on the patient must be well controlled; the surgeon must supervise the system at any time; the robot working area must be restricted; any automatic motion has to be run under control of a DMS pedal; it mustn't hurt patient, medical staff or instruments; it must be quickly and easily removable from the operating field. In order to satisfy these rules, special cares must be taken when designing mechanical, electrical and software components of the robot.

Thanks to a counterweight on the first axis to compensate gravity, no specific brakes are required. Moreover, the mobile support is counterbalanced to avoid any risk of falling over due to the force exerted during the operation and a locking system under the support prevents him to move once the robot has been placed. As far as actuators are concerned, a stepper technology has been selected; indeed, with conventional DC or AC motors, the rotation speed of the motor shaft depends on the output level of the servo amplifier. If a fault occurs, the motor still continues to rotate: the higher the output at the time of the failure, the faster the output shaft velocity. A stepper 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 him 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 to minimize the power transmitted at the joint level and thus increase the safety of the robot. Joints 2 to 5 are equipped with two absolute resolvers, one mounted on the motor output shaft for fine position sensing and the other one mounted on the output reduction gear for coarse sensing of the joint location. While improving robot safety, the combination of the two resolvers suppresses time consuming and potentially hazardous initialisation procedures. The use of reduction gears allows to reduce output axis speed; harmonic drives have been chosen for their low backlash and flexibility and for their high efficiency.

The previous features make SCALPP arm an intrinsically safe mechanical device. We have added several hardware securities, providing very good reliability and safety to the whole system. A description of these securities is presented in the following. On the robot base, an emergency button allows to switch off the arm power in emergency case. The arm is powered on only when the software initialisation procedure is carried out and the emergency button is switched off. A watch-dog 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 watch-dog is stopped, inactivating it and switching off the power. Besides, in order to improve security, two redundant circuits have been wired on the card. Each external module – F/T sensor, laser telemeter and motors – is controlled by a specific board. Each of these boards is separately initialized and can detect a fault on the module: respectively disconnection, saturation, or incoherent data of the F/T sensor; laser measure out of range; tracking error during the arm motion, excessive velocity on a motor, translator or amplifier failure, arm close to the limit of workspace. Moreover, several working LEDs are present on the console desk and on the arm itself and signal to the user any working fault during the motion. Finally, an action on the DMS foot pedal is necessary to authorize a motion of the robot in `automatic` or `teaching` modes; besides, a new motion needs a new action on the pedal.

In addition to the mechanical and electrical securities, the high-level program has been built thanks to a software analysis based on security. The different solutions implemented are presented in this section. We chose the RTMOS QNX dedicated to real-time running on PC. Five processes are running, one for each specific function: security, function modes, force, communication and translators controls. They ran according to a Round-Robin mode and communicate thanks to shared-memory variables in data bases, each one can be read or written only by authorized processes. Of course, all the safety variables are taken into account with higher priority than the other ones. The sampling period of a process is tuned to 1 ms. As we have five processes, if the execution time constraint is respected (i.e. if the five processes are executed in 1 ms or less), the final sampling frequency correspond to 1 KHz. Moreover, every time a fault occurs, all the software and the hardware systems are initialized. Besides, in addition to the above mentioned hardware watch-dog, the dedicated security process checks the activity of the others ones. If anyone of these processes is locked, then the emergency procedure is switched on. In addition, in order to detect jamming of the dermatome blade which can occur during the skin harvesting (due for example to a bad lubrication of the mechanism), an algorithm based on a Fast Fourier Transform (FFT) has been implemented. It relies on the analysis of the dermatome noise, namely on the tracking of the resonance frequency of the blade. Finally, in case of a fault or if the DMS pedal is switched off during the `automatic` mode, different phases of clearing have been planed depending on whether blade is in contact with the skin or not.

6 Conclusion and Perspectives

In this paper, we have described our methodology to design and develop a safe active arm dedicated to skin harvesting. Taking into account several constraints, we designed a SCARA robot with a non-spherical wrist. The robot is force controlled. It is easy to operate thanks to a user-friendly interface. A particular care has been devoted to security at mechanical, electrical and software levels. We are currently at the experimental phase of the project: tests on silicon and on foam rubber (which roughly simulate skin) will be carried out, as well as validation on animals, cadavers before later in vivo graft harvesting.

References

1. Pierrot, F., et al.: Robotized reconstructive surgery: ongoing study and first results. Proc. IEEE Int. Conf. on Robotics and Automation, San Francisco, CA (2000) 1615-1620.
2. Duchemin, G., et al.: SCALPP: a 6-dof robot with a non-spherical wrist for surgical applications. Advances in Robot Kinematics, Piran-Portoroz, Slovenia (2000) 165-174.
3. Pieper, D.L.: The kinematics of manipulators under computer control. Ph. D. Thesis, Stanford University (1968).
4. Pierrot, F., et al.: Hippocrate: a safe robot arm for medical applications with force feedback. Medical Image Analysis (1999) **3**(3) 285-300.
5. Yoshikawa, T.: Force Control of Robot Manipulators. Proc. IEEE Int. Conf. on Robotics and Automation, San Francisco, CA (2000) 220-226.
6. Salisbury, K.: Active Stiffness Control of a Manipulator in Cartesian Coordinates. Proc. of the 19th IEEE Conf. on Decision and Control, Albuquerque, New Mexico (1980) 95-100.
7. Pujas, A., et al.: Hybrid position/force control : task description and control scheme determination for a real implementation. IROS'93, Yokohama, Japan (1993) 841-846.
8. Perdereau, V., and Drouin, M.: A New Scheme for Hybrid Force-Position Control. Robotica, **11** (1993) 453-464.
9. Davies, A.: Safety of medical robots. Proc. of 6th ICAR, Tokyo, Japan (1993) 311-317.
10. Dombre, E., et al.: Intrisically safe active robotic systems for medical applications. Proc. of 1st IARP/IEEE-RAS Joint Workshop on Technical Challenge for Dependable Robots in Human Environments, Seoul, Korea (2001).