MARGE Project: Design, Modeling, and Control of Assistive Devices for Minimally Invasive Surgery

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Abstract. MARGE is a joint project in the framework of the interdisciplinary national program in Robotics, called ROBEA, launched by the French National Research Center (CNRS) in 2001. The focus is on the development of design methodologies and on the control of high mobility and dexterity assistive devices for complex gesture assistance in minimally invasive surgery, especially for coronary artery bypass grafting. This paper presents the main results of this two-year project.

1 Introduction

Minimally invasive surgery (MIS) is now widely used in abdominal operations. However, it adds several well known difficulties in the surgical procedure. Among them, the penetration point reduces the tool orientation capabilities and the amplitude of motion; the available intracorporal workspace is reduced and cluttered; the friction at the trocar level limits drastically the natural haptic feedback to the surgeon; fine and precise tasks are more difficult to realize, as compared to open surgery, due to the length of instruments, the inversion of motions induced by the trocar, the indirect vision of the scene through a screen monitor, etc. These drawbacks are strengthened in cardiac surgery, in which extremely fine and delicate structures are manipulated. Additionally the motion of the trocar is almost totally constrained by the presence of ribs. Therefore, at least two additional degrees of freedom (dof) must be provided on the distal part of the instruments, which makes the surgical tools difficult to operate manually. This has motivated the development of master-slave surgical robots such as Zeus from Computer Motion or Da Vinci from Intuitive Surgical.

However, the performance of these robots is still rather poor and many advanced functions have to be provided to enhance the surgeon dexterity. Besides, the potentialities of robotics have not yet been fully exploited: robots may be used together with new instruments in new surgical procedures aiming at performing less invasive surgery, such as beating heart surgery for instance. These objectives still require research works. The MARGE project contributes to some of them [1]. Its focus was on the development of design methodologies and the control of high mobility and dexterity devices for complex gesture assistance in MIS, especially for coronary artery bypass grafting (CABG). A first step of the project has consisted in the modeling of the CABG gesture. It is presented in section 2 of the paper. The data obtained have then been used for the optimal design of intracorporal dexterous instruments (Sect. 3). Several control algorithms have also been proposed that allows the surgeon to (tele) manipulate the instrument with a conventional robotic arm while respecting the constraint of moving it within the trocar (Sect. 4). Finally, an active trocar has been designed which cancels friction forces at the trocar level and then reflects real interaction force to the surgeon (Sect. 5).

MARGE is a 2-year joint project in the framework of the interdisciplinary program in robotics, called ROBEA (standing for ROBotics and Artificial Entities), launched by the French National Research Center (CNRS) in 2001 [2].

2 Modeling of the CABG gesture

The CABG surgery derives the blood from a healthy artery to the coronary artery downstream the lesion, so that the cardiac muscle remains irrigated. This is achieved by harvesting the internal mammary artery and by suturing it on the coronary artery. The grafting process, called anastomosis, is the most difficult and important part of the surgery. The anastomosis is described as a continuous elliptic suture around the section of the graft. The length of the incision on the artery varies from *7* to *10 mm*. The anastomosis may end with a knot between the two extremities of the thread.

In order to design an intracorporal dexterous instrument, it was necessary to collect data on the 3D motion of the needle during anastomosis as well as on the interaction forces with the coronary. Two surgical instruments have been modified (Fig. 1, left) to record 3D position data and force data, using a magnetic 3D positioning sensor (Minibird from Ascension Technologies Inc.) and a 6-axis force sensor (Nano17 from ATI). The experiments have been carried out by surgeons on sheep and pig hearts.

Fig. 1 (right) shows the interaction force (bottom) between the artery and a curved needle during the insertion in a coronary artery, as well as the corresponding position change of the needle tip (top). Position and force are given in a frame attached to the needle tip and on the axis tangential to the needle curvature. During the insertion phase, the exerted force increases due to the elastic behavior of the artery. When perforation of the artery wall occurs, the force exerted on the needle decreases rapidly due to a relaxation process. Then, viscous friction of the artery wall on the needle is observed. Elastic behaviour and sticking of the tissues on the needle create positive forces on the instrument at the end of the motion. From these experiments, it can be stated that the motion for each suture point is done in a plane, locally normal to the contour of an elliptic incision made on the coronary artery. In this plane, the motion is a rotation of the needle of about *120°*. The perforation force is up to *1.5 N*.

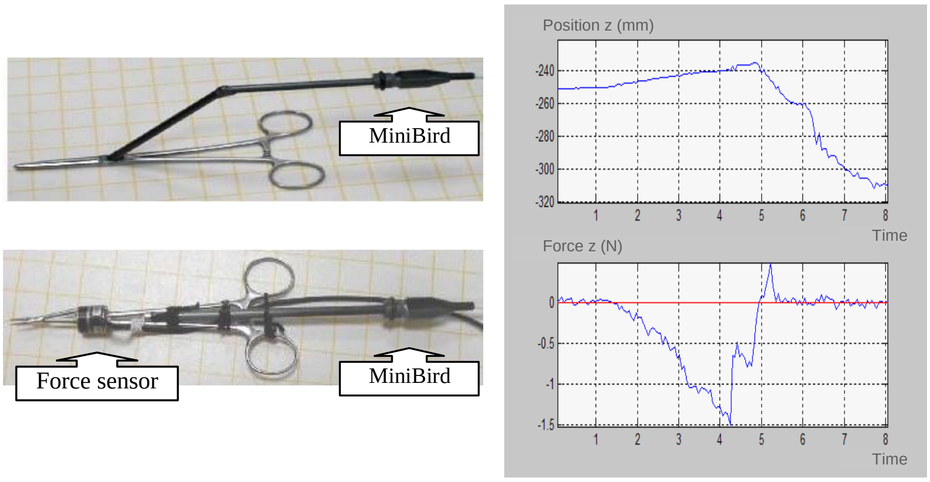

Fig.1. Modified surgical instruments (left). Perforation of a coronary artery (right)

3 Optimal design of dexterous modular instruments

Designing an instrument for MIS requires taking into account several objectives: small size; sufficient number of dof to minimize contacts with organs and circumvent dangerous areas; high resolution in velocity and force; sufficient workspace, making possible to attain all points of a given path with a desired orientation. These environmental, mechanical and control constraints are often conflicting, which make the design difficult, requiring the help of an optimization procedure. We will qualify the resulting instrument as dexterous.

An optimization procedure has been developed. It is based on evolutionary algorithms, which are well suited for optimization over large and non continuous search spaces. A multi-objective genetic algorithm has been implemented that individually evaluates the solutions with respect to every objective and returns a set of best solutions in terms of a given combination of objectives. The evaluation is performed thanks to a realistic simulation including the organs and the models of the surgical gesture (Sect. 2). From the resulting set of solutions, the designer chooses the optimal design according to *a posteriori* criteria [3].

Practically, each instrument candidate is evaluated with respect to four local criteria, calculated at every simulation step, *i.e.* at each of the n points of a given path (for instance to realize anastomosis on the intra ventricular artery). They are:

- Capability to perform the gesture (accuracy of path tracking),
- Manipulability of the instrument (resolution in force and velocity),
- Maximum joint torques,
- Minimal distance to organs.

The instruments evaluated by the optimization procedure are modular. Four kinematicaly different modules have been designed and are shown in Fig. 2 [3]. The module on the left has one dof. It consists in a micro-motor, a worm and gear transmission, a position sensor (a bipolar magnet fixed on the gear, creating a rotating magnetic field sensed by a chip including two perpendicular hall sensors rigidly mounted on the fixed part). It has a minimal length of *24 mm*, a rotation range of ± *110°*, and generates a *6 mN.m* maximum torque. Its diameter is *10 mm*.

Combining two of these modules leads to 2-dof modules, with parallel or orthogonal axes (Fig. 2, right). Their minimum length is *36 mm* with a rotation range of ± *110°*, and a maximum torque of *6 mN.m*. The module on the right shows a 2-dof module with one rotation about the main axis (more than *270°* and *8 mN.m* about this axis). A gripper using a compression spring and shape memory alloy wires has also been designed.

The dexterous instrument resulting from the optimization procedure (Fig. 3) has five dof and a total reach of *130 mm*. It is composed of three of these elementary modules (one 1-dof module, two 2-dof modules) and a gripper module.

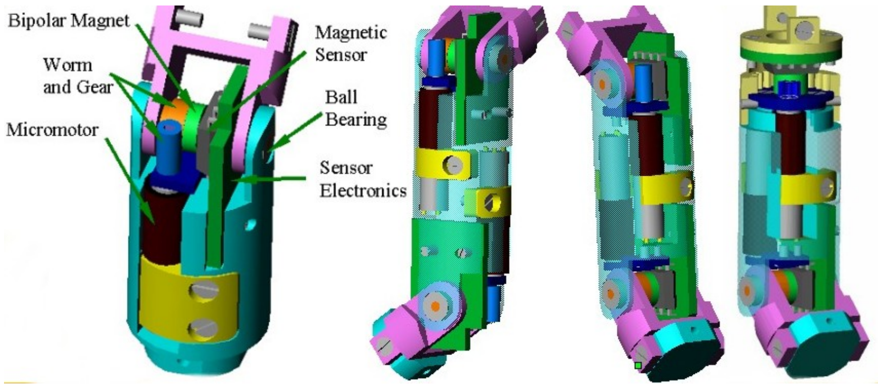

Fig. 2. 1-dof module (left). 2-dof modules (right)

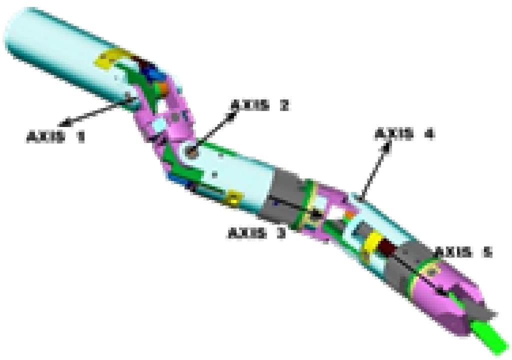

Fig. 3. An optimal dexterous 5-dof instrument for minimally invasive CABG

4 Control of assistive devices for MIS

The dexterous instrument described in section 3 is intended to be held by a robot providing enough dof to align the main axis of the first module of the instrument with the trocar axis and to control its penetration depth. Therefore, at least five extracorporal dof are mandatory (six, if we assume that the rotation about the trocar axis should also be controlled by an extracorporal joint).

Only a small number of such robots are effectively used in the operating room for MIS. They have been mainly involved so far to assessment purpose and training (few CABG operations have been reported in the literature). The main feature of these robots is to mechanically create a fixed point that coincides with the penetration point of the trocar. The Zeus robotic arm makes use of a passive universal joint. The arm holds a tube penetrating the patient through the trocar that creates the kinematic constraint for the passive joint. An additional distal wrist is fixed on the tube. The system provides 6-dof within the patient. The Da Vinci robotic arm and other prototypes such as FZK Artemis [4] and UCB/UCSF RTW [5] systems offer the same service but their kinematics are designed as remote center devices. Another way to create a fixed point is to implement an appropriate force-position control: then, the tool is position-controlled within the patient while respecting a zero force constraint on the trocar [6].

We have explored alternate algorithmic approaches to satisfy the trocar constraint, whose advantage is to not require a dedicated robot [7]. One approach is based on a geometric description of the constraint that is resolved by an optimization procedure. It states that the position of the tool tip must coincide with the desired current position $\mathbf{P}^d$, and that simultaneously the instrument must be aligned with the segment joining $\mathbf{P}^d$ and the trocar position $\mathbf{P}^{tr}$ (Fig. 4, left).

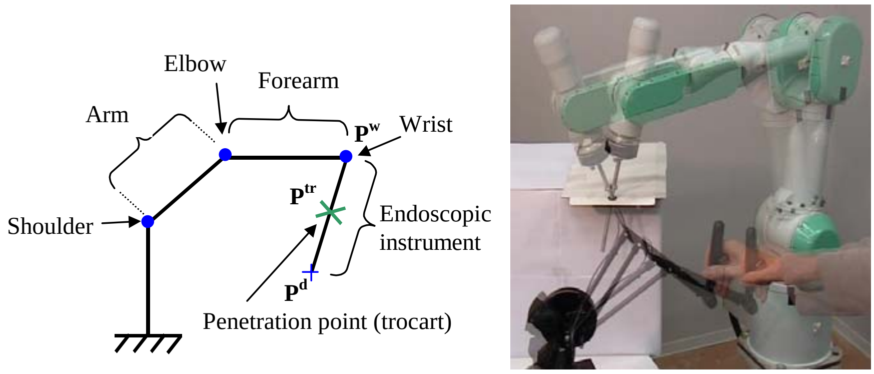

Fig. 4. Principle of the geometrical approach (left). Tele-operation under the constraint of penetration point (right)

We have validated this approach on a Mitsubishi PA-10 robot. A Phantom 1.5 arm was used as a master device to generate the desired tool tip position of the PA-10 (Fig. 4, right). The experiment is the following: the tool tip of the robot is driven via the Phantom until the contact with the trocar is reached; the instrument is inserted; then, we commute to the aforementioned control algorithm and, again via the Phantom, we realize random motions while satisfying the trocar constraint. We have verified that the distance between the trocar and the instrument shaft is smaller than a few millimeters for translation motion up to 0.3 $m.s^{-1}$. It is worth noting that this approach might be combined with force control techniques.

Another approach is based on the dynamic decoupling of the control torque into a task behavior control and a posture behavior control [8]. In fact, by minimizing the contact force or, equivalently, by forcing to zero the distance between the instrument passing through the trocar and the current location of the trocar (or the desired location, if the goal is to control it), we compute the posture behavior torque as the gradient of a cost function representing the distance. This approach allows us to dynamically control the penetration point required during MIS.

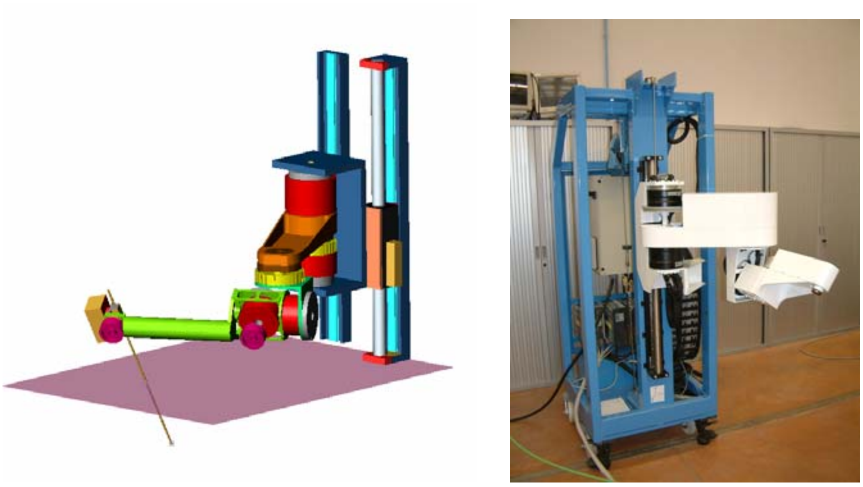

Fig. 4. The D2M2 platform: CAD view of the slave arm holding the instrument (left). The prototype of the slave arm (right)

We are currently designing a platform for development and assessment of advanced robotic functions for beating heart MIS. A 5-dof slave arm D2M2 (standing for Direct Drive Medical Manipulator) has already been designed, with a 6-axis force sensor mounted at the tip of the wrist. An intracorporal 3-dof instrument can be attached to the wrist force sensor, providing full mobility to the tool tip. To cope with the high dynamics of the beating heart together with the low friction requirements for haptic interface, direct drive actuators have been preferred. The joint ranges are such that the instrument can be manipulated as the surgeon does it manually. An open control architecture has been developed to allow several autonomous and master-slave operating modes via a Phantom 1.5.

5 High fidelity tele-operation

Force control and haptic feedback are two major functions that are still missing in master-slave surgical robots. The main reason is that in MIS the interaction forces between tool and tissues cannot be sensed by the surgeon due to the friction forces in the trocar. One solution would be to measure interaction forces with a sensor mounted very near the tool tip, but such necessarily small and sterilizable device to be inserted into the patient is not yet available. However, force control could be very useful to prevent unintentional damage of tissues or to compensate for organ motion in case of contact between instrument and organ. To compensate for the absence of haptic feedback, the surgeon naturally uses tissue deformation as a visual substitute for sensation of the remote interaction forces. This does not work when he has to perform complex interaction gesture such as knots for instance. The outcome is that MIS requires long training period.

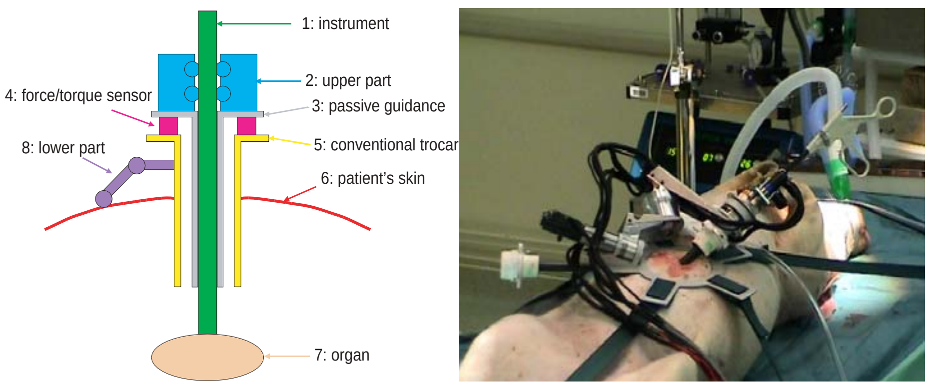

Fig. 5. Active trocar principle (left). *In vivo* tests with the MC^{2}E device (right)

An original solution has been proposed in which the sensor is integrated to the trocar, but fixed outside the patient [9]. The instrument is placed inside a passive guidance tube (Fig. 5, left), which increases the rigidity of the system. The passive guidance tube is attached to the upper part of the force/torque sensor. The lower part of the sensor is placed on a conventional trocar. This set up makes it possible to measure the tool-tissue interaction forces by adding mobilities to the trocar. Writing the generalized forces on the different moving parts, it can be shown that the interaction forces may be easily inferred from the force sensor data if the gravitational forces are known and if the forces due to dynamics are known or negligible. A dedicated device, called MC^{2}E (a French acronym for compact manipulation for endoscopic surgery) has been designed. It is lightweight and can be mounted directly on the patient. It is a 4-dof actuated mechanism providing an invariant center at the fulcrum point, a rotation and a translation respectively about and along the instrument axis. An animal experiment with the active trocar is shown in Fig. 5 (right).

6 Conclusion

This paper has summarized major results of a French national two-year project aiming at the improvement of robotized minimally invasive surgery. The results obtained in modeling of the CABG gesture have clearly shown the need for dexterous motion and high-fidelity tele-operation; we have addressed those need by proposing on one hand a design methodology for intra-corporal devices, and on the other hand the concept of active trocar. Moreover, we have shown a new way for guiding MIS tools inside a trocar without resorting to dedicated robot arms; the proposed method is based on algorithms only, and thus is compatible with multi-purpose (then versatile) arms. Additional work is now required to integrate all the above mentioned technologies into a single system.

References

1. Dombre E. et al.: Projet MARGE: Modélisation, Apprentissage et Reproduction du Geste Chirurgical. Proc. Journées Robea. Toulouse, France (2004) 17-25
2. http://www.laas.fr/robea
3. Sallé, D., Bidaud, P., and Morel, G.: Optimal Design of High Dexterity Modular MIS Instrument for Coronary Artery Bypass Grafting. To appear in Proc. IEEE Int. Conf. on Robotics and Automation (ICRA). New Orleans, USA (2004)
4. Rininsland, H.: ARTEMIS : a Telemanipulator for Cardiac Surgery. European J. of Cardio-Thoracic Surgery, Vol. 16: S106-S111 Suppl. 2 (1999)
5. Cavusoglu, M.C., Williams, W., Tendick, F., and Sastry, S.S.: Robotics for Telesurgery: Second Generation Berkeley/UCSF Laparoscopic Telesurgical Workstation and Looking Towards the Future Applications. Proc. 39th Allerton Conf. on Communication, Control and Computing, Monticello, USA (2001)
6. Krupa, A., Doignon, C., Gangloff, J., de Mathelin, M., Soler, L., and Morel, G.: Towards Semi-autonomy in Laparoscopic Surgery Through Vision and Force Feedback Control. Proc. Int. Symp. on Experimental Robotics, ISER'00. Waikiki, USA (2000) 189-198
7. Michelin, M., Poignet, P., Dombre, E.: Geometrical Control Approaches for Minimally Invasive Surgery. To appear in Proc. Workshop on Medical Robotics Navigation and Visualization (MRNV), Remagen, Germany (2004)
8. Michelin, M., Poignet, P., Dombre, E,: Dynamic Task / Posture Decoupling for Minimally Invasive Surgery Motions. Submitted 9th Int. Symp. on Experimental Robotics (ISER). Singapore (2004)
9. Zemiti, N., Ortmaier, J., Vitrani, M.-A., Morel, G.: A Force-Controlled Laparoscopic Robot Without Distal Force Sensing. Submitted 9th Int. Symp. on Experimental Robotics (ISER). Singapore (2004)