Automated Surgical Task Execution: the Needle Insertion Case

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***Abstract*—The paper describes a robot control and coordination framework for the automation of surgical tasks. In the proposed framework, surgeons do not interact with robots by means of teleoperation, but they are supported by autonomous robotic assistants. Such robots perform basic surgical actions by combining sensing, dexterity and cognitive capabilities. The goal is achieved thanks to rigorous assessment of surgical requirements, formal specification of robotic system behavior, including multiple arm coordination and human/system interaction, and control software development with *state-of-the-art* component-based technologies. The paper presents an experimental setup composed of two robots operating on a US-compatible phantom, demonstrating the feasibility of the approach.**

I. Introduction

Minimally invasive surgery first and, more recently, surgical robots have brought new perspectives to surgery and have significantly improved the quality of many critical surgical tasks [1], [2]. In this paper we go further by designing an architecture to control a robotic system capable of autonomously executing US-guided insertion of needles into soft bodies, i.e. emulating the surgical procedure for percutaneous cryoablation of small tumoral masses. To validate the proposed software/hardware architecture we prepared an experimental setup, involving two robotic manipulators that autonomously perform the task: one robot holds the needle and moves according to a planned trajectory to perform the puncturing, while the other robot holds an US probe which images are used to intra-operatively guide and control the needle insertion, [3]. Even the pre-operative planning is performed automatically, by means of a software that implements the algorithm proposed in [4]. Since the architecture of the system is modular and component-based by design, the same methodology can be applied to automate other simple surgical tasks. In this way, the robotic system autonomously deals with the simplest tasks and the role of the surgeon becomes that of irreplaceable supervisor. Subsequently, the surgeon can focus his/her attention on the most critical parts of the procedure. In this paper we implement the model presented in [5], where the requirements for a software-intensive and intelligent surgical robots were collected and translated into engineering specifications.

II. Case study and robotic setup

The final objective of the proposed research is to demonstrate the feasibility of robotic automation for some surgical procedures, which have been selected among those that would benefit mostly from the accuracy and repeatability levels achievable by intelligent robots. We focus on percutaneous cryoablation of small tumors, but the same methodology and design approach will be applied in a near future to automated suture of planar wounds. Percutaneous cryoablation requires the use of pre- and intraoperative images (CT, MRI/US) to insert, through the skin, one or more cryoprobe needles into the tumoral mass to be destroyed and to check the real-time position of the tools inside the patient. Trajectory misalignments are usually due to the deformation of soft tissues and organ displacement because of breathing. Thanks to real-time image registration and accurately calibrated mechanical arms, needle insertion will be executed precisely by the robots.

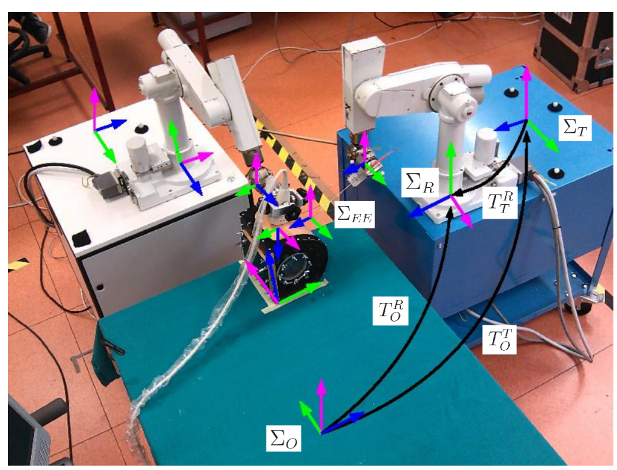

Fig. 1. Experimental setup with coordinate systems and related transformations.

To evaluate practical issues and benefits of cryoablation execution by means of automated robots, an experimental setup has been prepared, as shown in Figure 1. The setup includes two robotic manipulators: the first robot holds the needle, while the second holds the US probe. The end-effectors of both

robots are equipped with specific tool adapters that integrate 6-DOF force/torque sensor. The robots are mounted on two trolleys allowing to move them freely around the surgical bed, i.e. where the phantom replicating the human abdomen is located. Freely movable trolleys improve the setup flexibility, but, on the other hand, they require an accurate registration phase before starting the operation. For this reason an Optitrack system (NaturalPoint, Inc.) using 10 infrared cameras is used to estimate relative coordinate transformations among the robots and the phantom.

III. Control and Supervision Architecture

The autonomous system being designed in this project is composed of the following modules, corresponding also to software units deployed on different computational platforms: a *Surgical Interface*, the *Robot Controllers* and the *Sensing* system with *Reasoning and Situation Awareness* capabilities. Figure 2 shows the overall control and supervisor architecture.

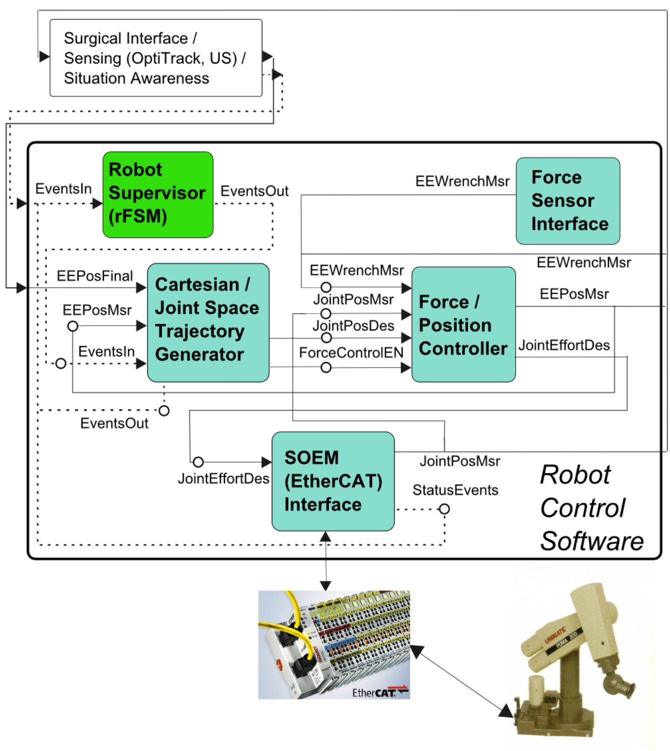

Fig. 2. Control software implementation of the robot holding US probe

In particular, the Surgical Interface is a software-intensive system allowing humans (i.e. surgeons and technicians) to drive the system during both the pre-operative and the intra-operative phase. In the first one, the focus is on detailed planning of the surgical intervention (e.g. enumeration and placement of cryoablation needles for maximal tumor coverage thans to the *cryo-planner* described in [4]). During operations, the interface should provide real-time visual navigation of the surgical scenario and, if necessary, let surgeons take control of the system (e.g. by switching to teleoperated mode).

The Robot Controllers are the units implementing control of surgical actions and tasks sequencing during the intraoperative phase. The event-driven behavior extracted from the goal model is mapped into the control logic of each robot, specified by an UML State Diagram. Safety-critical requirements put a strong demand for strict coordination of these components with both the Surgical Interface and the Sensing/Reasoning module.

Finally, the composite sub-system implementing advanced Sensing algorithms and Reasoning for Situation Awareness provides support to the planning task, during the preoperative phase, and prompt identification of anatomical changes or discrepancy between the tasks being executed and the *nominal* surgical plan. In the latter case, Situation Awareness algorithms (e.g. based on Bayesian Networks and Particle Filters) must signal the occurrence of undesired events and critical situations, so that appropriate corrective actions can be triggered. It is important to remark that even though the Reasoning and Situation Awareness module is not fully implemented in the current setup, both the behavioral specification described in the rest of the section and the distributed architecture presented above are prepared to seamlessly embed it.

The interaction among such system components has been specified with the help UML Sequence Diagrams, which represents scenarios compatible with a given collaborative behavioral specification. An UML Sequence Diagram shows a sequence of events, exchanged among a number of *object lifelines*, implicitly ordered in time from top to bottom. As an example, Figure 3 shows an admissible scenario for the cryoablation execution, focused on needle insertion under US-based monitoring. The scenario includes the adaptation required if the algorithm for needle tip detection fails to evaluate the presence of the needle in the current US image. In this case, the motion of the robot holding the needle is paused and the robot holding the US probe executes a sequence of slow rotations of its end-effector along the three orientation axes (roll, pitch and yaw). If the needle is found during these movements and the insertion can be completed with a small adaptation of motion trajectories, the surgical operation proceeds, otherwise the needle is extracted and the insertion trajectory is replanned.

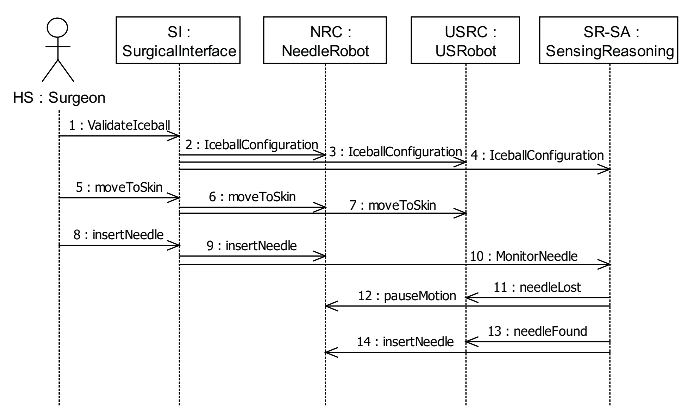

Fig. 3. UML Sequence Diagram of the interaction among system components during cryoprobe needle insertion: scenario in which the US image processing module fails to detect the needle position

IV. RESULTS

In this section the time series of forces and the states of the robots control logic recorded during the experimental phase are reported (see Figures 4 and 5). The proposed experimental setup goes through the following steps triggered by the surgeon through the user interface:

1) The surgeon pushes the Ready button. Both robots move from their nest position to the ready position where the needle and the US probe are mounted.
2) The surgeon pushes the Start button. The robots receive their nominal trajectories and move the needle and the US probe in contact with the phantom.
3) When the surgeon pushes the InsertNeedle button, the robot holding the needle starts the insertion until it reached the target point. In this case the state of its control logic is WaitCryoCycle. However if the surgeon decides to stop the procedure (Stop button) because the needle is not visible in the US image any more, the robot holding the needle performs a sequence of movements of the US probe to bring the needle back on the US images.
4) Since the cryoablation is not available in the current setup, the final step is for the surgeon to push the button Finish to bring the robots back in the Ready state.

Figure 5 shows the force measured by the F/T sensor located on the robot holding the needle along the main axis of the needle. The dashed vertical lines and the numbers help to understand which states of the control logic (Figure 4) are activated.

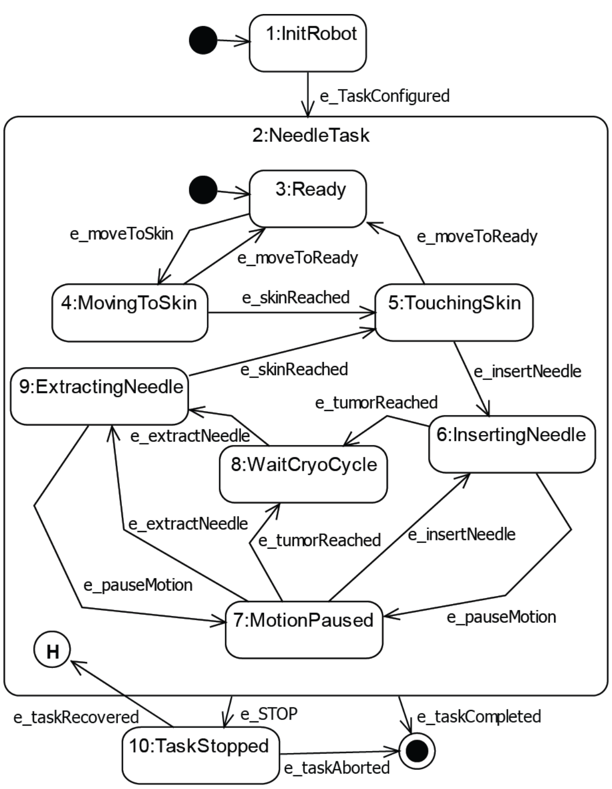

Fig. 4. UML State Diagram of robot control logic for needle insertion in a cryoablation task.

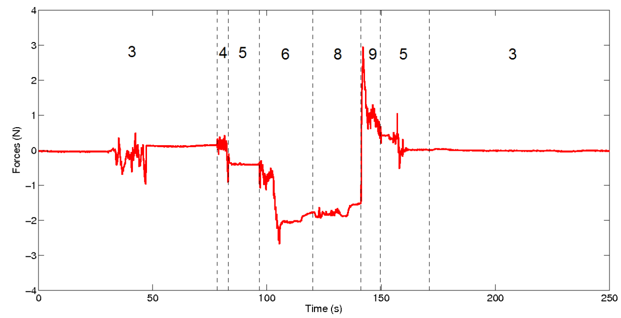

Fig. 5. Force applied to the needle during the emulated cryoblation task.

V. CONCLUSION

In this paper we presented a robot control and coordination framework for the automation of simple surgical tasks. We formalized the design specifications using a requirements engineering approach and derived the state machines for the control of the robots involved in the operation. Then, we implemented the proposed architecture using component-based design tools, i.e. Orocos framework and rFSM, in order to handle properly the distributed nature of our system.

The goal of these experiments was to show that the technology to execute autonomously basic surgical tasks is available and could be used to improve accuracy. To better reach this critical objectives, a Situation Awareness module that takes care of the uncertainty and manages unexpected events has been implemented on top of the control architecture.

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