Artificial Cognitive Supervision during Robot-Assisted Laser Surgery

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***Abstract*—This abstract focuses on the role of artificial cognition in the context of robot-assisted laser microsurgery. The issues related to the use of a laser as surgical tool are identified and contrasted against the possibilities offered by a cognitive system. The concept and progress in the development of a cognitive supervisory system for laser microsurgery are presented. This system is intended to supervise laser-tissue interactions occurring during surgery, controlling the incision process and generating alarms when potentially dangerous situations are detected.**

I. Introduction

Applications of cognitive systems in robotics vary widely. By definition, these systems exhibit a set of properties [1] that are desirable when tackling problems that require high-level reasoning capabilities i.e., similar to those of humans. Examples of such problems include planning and executing actions in real-world environments, dealing with high-dimensional or uncertain information and coping with situations that were not considered or cannot be taken for granted at design time.

Surgical robotics constitute a promising field of application for cognitive systems. Recent trends in this area point towards the development of special-purpose robots [2] to attain surgical procedures that would be difficult or impossible otherwise. The purpose of developing robots for surgery is to provide the surgeon with highly specialized tools that extend his/her performance, therefore improving the overall quality of the surgical treatment [3]. Nevertheless, sometimes interposing a robot between the surgeon and the patient increases the complexity of the procedure, which is usually due to the physical constraints of the robot. For instance, the robot may have many degrees of freedom in order to adapt to the shape of specific anatomical parts, making it difficult to control. Additional constraints appear in minimally invasive surgery, where a limited access to the surgical site implies a poor perception of the area of interest, demanding additional mental workload to the surgeon, who plan and execute movements on the tools by looking at images provided by a camera located inside the body of the patient. An extended list of open problems related with the use of robots in the operating room is reported in [4].

Thus, it seems that classic robot control strategies are not sufficient to handle the complexity of the scenarios presented above. Cognitive approaches are currently being investigated to turn surgical robots into smart tools. Recent results in this context cover the development of advanced control algorithms for robots with many degrees of freedom, automatic movement of surgical tools, obstacle avoidance, navigation aid and simultaneous localization and mapping [4].

In the case of laser surgery of the vocal cords, i.e., laser phonomicrosurgery (LP) [5] surgeons cannot rely on their sense of touch to control the incision process. Rather, they are required to develop a different kind of dexterity, built around the capability of predicting the effects of laser irradiation of tissue.

This abstract discusses the issues related to the use of lasers as surgical tools and how systems based on cognitive approaches can help in mitigating them. The concept and the current state of development of a cognitive supervisory system for laser phonomicrosurgery is presented.

II. Laser Phonomicrosurgery

The interaction between the laser and the tissue is the elemental building block at the core of laser-based surgery. It is through this interaction that incisions and resections are performed. The control of the incision process relies on the experience and dexterity of the surgeon, who intrinsically establishes the state of the interaction and thereby decides the laser actions to perform. The mental workload is intensified by an inadequate perception of the surgical site, as LP is performed through a microscope [6]. Acquiring the skills needed to conduct LP requires extensive training.

Improper operation of the laser may hinder the surgical procedure. Furthermore, it may lead to undesired and potentially dangerous effects. Carbonization is one of those. It occurs when the temperature of tissue increases, due to the energy transferred from the laser [7], beyond 100°C. Carbonization causes pain and longer healing times, diminishing the quality of surgery [6]. Also, it may influence the patient ability to speak normally again.

Nowadays there are no technical solutions for the automatic supervision of the incision process during laser-based surgery. To this end, a predictive model would be necessary, predicting the outcome of the process and analyzing its state. Analytical models of laser-tissue interaction (LTI) are well known [7]. They depend mainly on tissue temperature and water content. At the same time, these variables depend on laser properties as beam focus and power, as well as on laser exposure time and pulse rate. The laser wavelength, and its corresponding absorption and scattering coefficients on the

tissue also determine the emergence of undesired effects like tissue carbonization. Accurate and real-time measurement of some of these variables during LP is not straightforward.

Thus, if a system is supposed to supervise the state of the LTI, it should rely on inputs similar to those used by surgeons (laser location and history of actions) and not on analytical models based on tissue properties.

III. Cognitive Systems for Laser Surgery Supervision

Using a forward model to predict the state of LTI during LP leads to formulate a solution in which analytical modeling is neither convenient nor viable. Accordingly, we propose to use models motivated by the capacity of humans to map and fuse diverse sets of information and infer the state of events.

A. *Cognitive Model*

Length and depth of an incision depend on the treatment parameters, such as the laser power and the total exposure time. Skilled surgeons have developed the ability to finely configure these parameters in order to get the incision they have planned. The thermal state of the tissue plays a major role during the incision process [7], driving its outcome. We may hypothesize that surgeons have an internal, and probably not explicit, estimation about the thermal state of the tissue. Developing an autonomous system able to predict this state without using a deterministic model can be seen as the design of an artificial cognitive model.

A *cognitive model* generally denotes the combination of a knowledge set with a given cognitive architecture [8]. Such knowledge encapsulates the experience about certain process or entity, while the cognitive architecture specifies how this knowledge is represented, acquired, and processed in order to obtain some specific behaviour.

We have developed a thermal model of tissue based on high-level information such as laser activation, power and pulse mode [9]. The change in temperature due to heat transfer and diffusion are modeled as functions of laser exposure time. The model is parameterized with respect to laser power and assumes constant tissue properties. This model has been extracted using machine learning techniques.

Initial results demonstrated the concept of an artificial cognitive system able to predict the tissue thermal state during laser exposure and it is based on simulated data, generated with a Monte Carlo-based algorithm complemented by a finite difference method for the resolution of heat diffusion [10].

B. *Supervising Laser-Tissue Interaction*

The cognitive supervisory system is meant to support surgeons, enhancing their perception about the state of LTI, thus facilitating their decision making. This model is not supposed to replace the surgeon perception but to complement it. Fig. 1 shows a diagram describing this concept.

The purpose of this system is to predict the continuous appearance changes of the surgical site that can be observed during LP, by means of image processing (e.g., laser localization, carbonization detection) and artificial intelligence techniques. This functionality will be used to automatically supervise the surgical procedure, generating alarms in case unexpected or unforeseen situations are detected. The focus of the supervisory system falls on the undesired and potentially dangerous situations that may arise during LTI. In this context, tissue carbonization and incision quality are recognized as potential targets for automatic supervision.

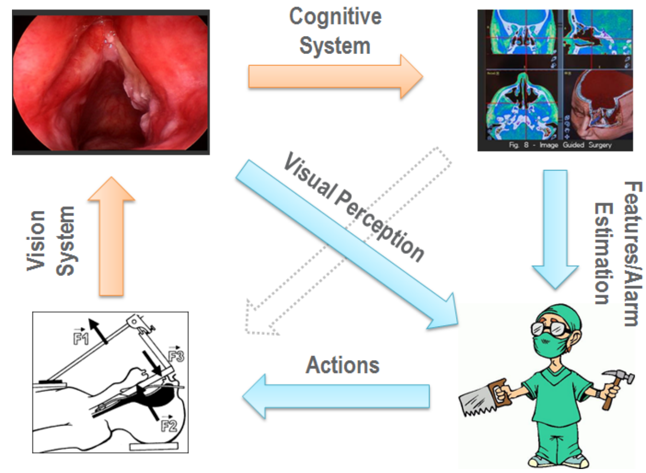


Fig. 1. Cognitive System for supervision of laser surgery. The system provides additional information to the surgeon enhancing the perception on the laser-tissue interaction

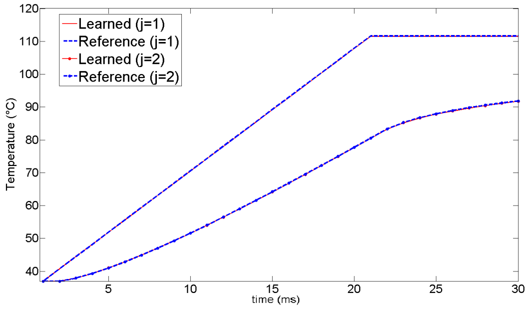
At the core of the supervisory system lies the developed model of temperature during LTI [9]. Based on the model of temperature dynamics and the history of laser actions, an autonomous system to avoid tissue carbonization and to supervise the quality of the incision can be implemented. Given the location of the laser beam, the temperature model can be mapped onto the area of interest, activating the input when the surgeon triggers the laser, generating and tracking an estimation of tissue temperature.

IV. Preliminary Results

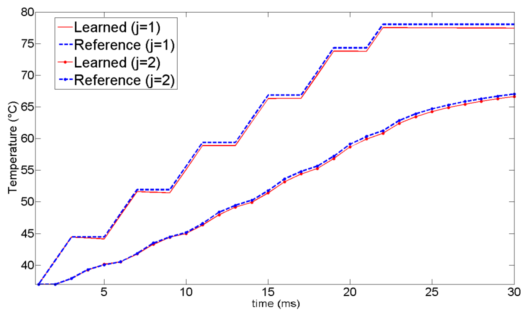
Initial studies demonstrated that a model based on ML can be obtained mapping the same inputs that surgeons use (i.e, laser actions) to the resulting thermal state of the tissue [9]. Nevertheless input/output data for the model was obtained through simulation, given an analytic description of the temperature dynamics [7],

$$\dot{T} = \kappa \nabla T + \frac{1}{\rho c} S, \tag{1}$$

where T, and $\dot{T}$ represent the tissue temperature and its temporal derivative, while ∇T is the Laplacian operator, describing the spatial change of temperature along the tissue, which conductivity, κ, is approximately the same for liquid water and most tissues ($\sim 1.4 \times 10^{-7} \frac{\mathrm{m}^2}{\mathrm{s}}$). The source of heat per unit of volume and time, S, contributes to the change in temperature weighted by the density (ρ) and the specific



(a) Continuous Laser Mode



(b) Pulsed Laser Mode

Fig. 2. Temperature dynamics at the center of the tissue at the surface ($j = 1$), and at $z = 0.025$mm, ($j = 2$) for continuous/pulsed type of laser modes. Time response of the reference (blue) and learned (red) models are shown.

heat capacity (c). In pursuance of proving initial concepts in [11], [9], Eq.(1) was solved using Finite Differences (FD) approximation whereas a Monte Carlo approach was used to properly simulate the heat of rate generation (S).

The results presented in Fig. 2 demonstrated that a learned system can reproduce the dynamics of tissue temperature obtained through the solution of the partial differential equation presented in Eq. 1.

V. Conclusion

In this abstract, the concept of cognitive supervisory system for robotic laser surgery was discussed. The system is intended to supervise the laser-tissue interactions that occur during surgery. A model of tissue temperature during laser irradiation is at the core of the system. The model is inspired by the cognitive process that surgeons do when map visual information i.e., location of the laser spot, together with the history of laser actions, to the estimation of temperature in the tissue to avoid carbonization. This is, they decide what actions to do in order to avoid increasing the temperature of the tissue beyond 100°C.

Further investigation and developments are needed to bring the system into a real surgical scenario. Current efforts are focused on the validation of the temperature model. Also, a model able to predict the properties of laser incisions, in terms of depth and width, is being developed. These developments are supported through the collection of experimental data from real laser-tissue interaction.

VI. Acknowledgments

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