Hand-eye Coordination and Biomechanics in Cognitive Surgical Robotics

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Abstract

Computer aided surgery and computer assisted robotic surgery are having more and more impact on medical care. This paper presents the architecture and work flow of an intelligent surgical robotic system that we are developing. Our robotic surgical system is designed to augment and enhance the hand-eye coordination capability of the surgeon during operation in order to achieve the desired outcome and reduce invasiveness. By incorporating advances in surgical simulation and robot-assisted surgery, patient specific surgical plans can be derived with robot manipulation included. This highly autonomous robot is also provided high level of intelligence by cognitive engine, a key component of the system, for effective collaboration with the surgical team. A design of human-robot collaborative control is proposed in this paper as well.

1. Introduction

New surgical innovations are hitching on the band wagon of engineering technology. There are surgical innovations that can be achieved using current engineering methods. Some surgical innovations will require advanced engineering methods and materials, and more research for them to be ready for clinical use. It is predicted that the impact of computer aided surgery or computer assisted robotic surgery on medical care will be as great as the impact of computer aided manufacturing on industrial production. Computer aided surgery encompassing robotics, visualization, image and graph management, preoperative planning, training/simulation and operating room control will be the key factor for growth in demand of mechanical/electrical engineers who know biomedical science (biotraditional engineers) and biomedical engineers.

As a group of engineers who have interest in biophysics and physiology, we have been doing research and developing new devices and systems for patient care. The detachable laparoscopy system [1] that we have developed in collaboration with a general surgeon is an example of a surgical innovation that can be developed using existing engineering methods. Another example is the Measurement And Insertion Device (MAID) for in-office unsedated trachea-esophageal puncture (TEP) that is developed with ENT surgeons [2]. Bio-absorbable wound closure micro-devices [3] that we investigated with the ENT surgeons will require more work. We need new methods to accurately predict and then control the material strength and bio-absorption rate of the micro wound closure devices. The focus of this paper is on the intelligent surgical robotic system that we are developing. It is a complex computer aided surgical system that requires research in multiple fields of engineering.

2. Intelligent Surgical Robotic System

The objective of our robotic surgical system is to augment and enhance the hand-eye coordination capability of the surgeon during

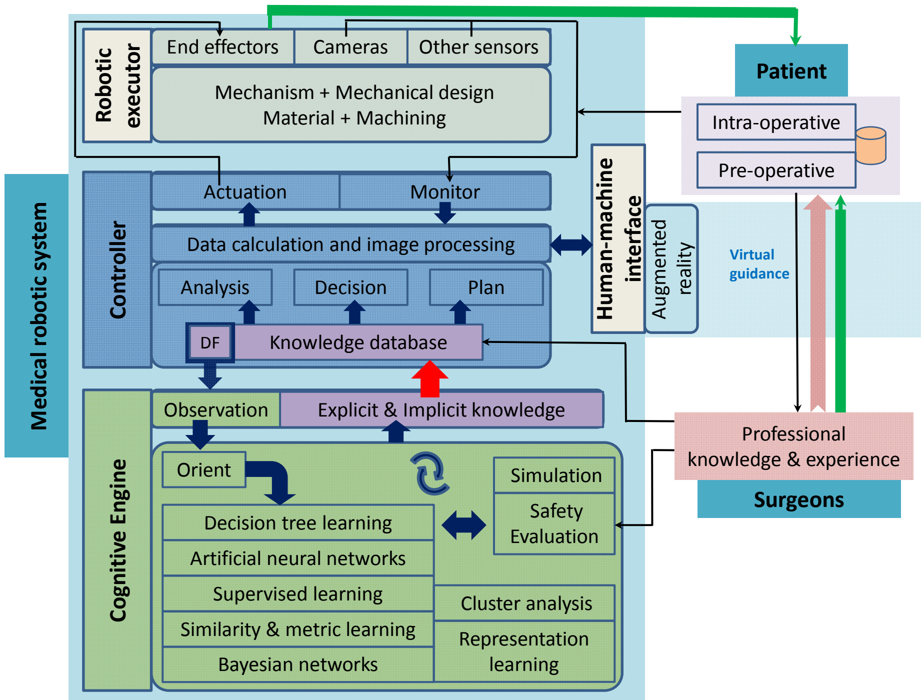

Figure 1. Architecture of an intelligent surgical robotic system with cognitive engine.

operation so as to achieve the desired outcome and to reduce invasiveness. Hand-eye coordination refers to the ability of our vision system to coordinate and process the information received through the eyes to control, guide and direct our hands in the accomplishment of a given task. We studied hand-eye coordination to build medical simulator for surgical training and to develop medical robot that will duplicate the best surgeon's hand-eye coordination skill. We also learn from our investigation on the robot hand-eye coordination to know more about human hand-eye coordination.

An integrated view on surgical simulator and robot-assisted surgery was adopted. The former is a simulation game for surgical training and treatment planning. The latter is a single or plurality of devices assisting the surgical team to operate on the patient precisely. The advancement in instrumentation, computer hardware and software as well as medical imaging is merging these two areas of engineering technologies. With computer simulator, a patient specific surgical plan can be derived with robot manipulation included. By combining patient specific simulation with robotic execution, we have highly autonomous robot(s) or micro-robot(s).

Figure 1 illustrates the architecture and workflow of the shared control cognitive surgical robotic system that we are developing. The cognitive engine is a key component to provide the high level of intelligence in the autonomous robot to be effective collaborator with the surgical team. The engine needs to represent knowledge about the relevant parts of the surgery. There is an emphasis on knowledge about the dynamics of the surgery, including the robot's own actions and the behavior of the biological tissue in response to the actions. The biological tissues within the human patient body cavity are living elements that may be preserved, repaired or destroyed using mechanical and thermal methods. The action of the surgical team

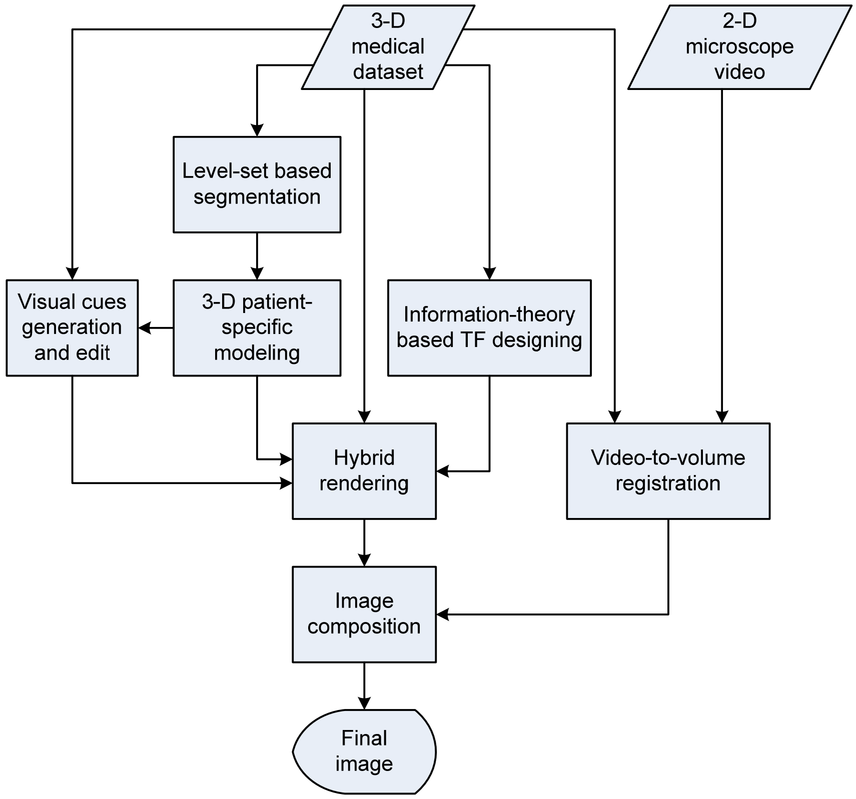

Figure 2. Flow chart of visual aid process.

has added to the dynamics and sometimes, uncertainty to the operation. The self-learning process of the cognitive engine requires inherent knowledge of tissue biomechanics. Knowledge bases of biological tissues properties and medical devices characteristics have been used in our earlier work on biomechanical simulation for designing devices and surgical methods customized for a patient [4].

Knowledge of biomechanics is inherent in the simulation system. The processes are modeled after human hand-eye coordination with the visual stimulation and motor commands in the parietal lobe handled by the tightly coupled controller-executor pair, and planning and thought process in frontal lobe represented by the cognitive engine.

Understanding the biomechanics of biological soft tissue is important for surgery planning and subsequent autonomous execution of surgical tasks by the robots. Advancement in biomechanical system research provided us with tools to develop virtual organ models for realistic simulation of tool-tissue interactions. However, the application of biomechanics to routine clinical care remains a great challenge. The heterogeneity and dynamism of living things and the complexity of their mechanical responses make it difficult to create biomechanical theories that could correlate well with the empirical data in medicine.

3. Human-Robot Collaborative Control for Microsurgery

Microsurgery which requires an operating microscope is used as an example of human-robot collaborative control design in our cognitive robotic surgical system. Microsurgery

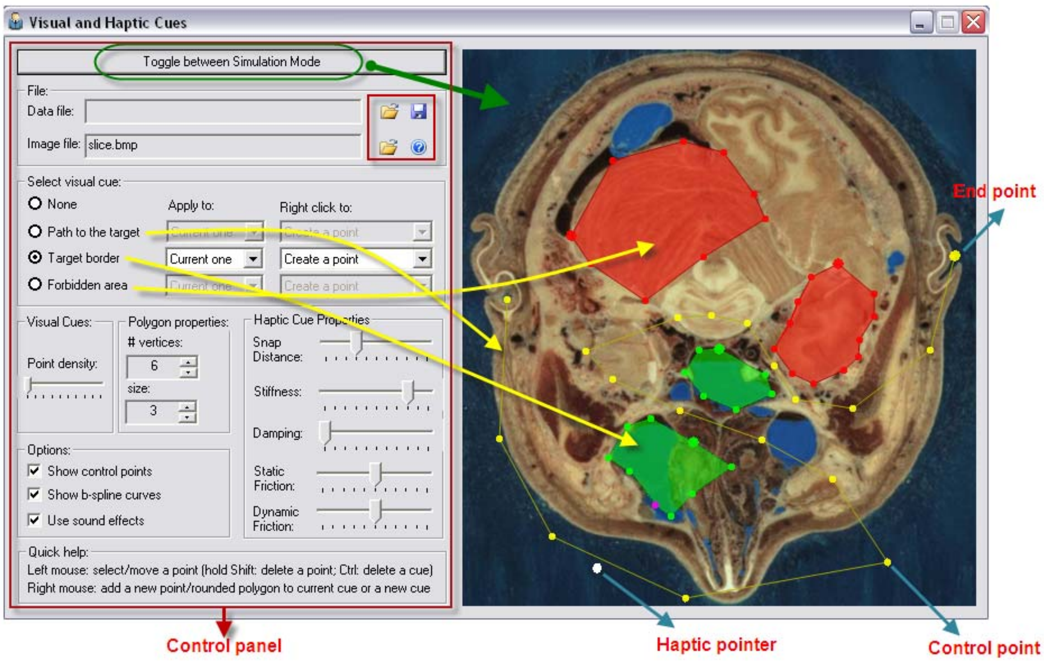

Figure 3. GUI of the visual cues editor.

can be performed using micro-robots. The autonomous micro-robots may remove the clinician from decision-making role due to poor information feedback. As microsurgery is dominantly visual, an augmented reality system based on micro-robots with image overlay, importance-driven focus of attention and adaptive visual cues may compensate for the lack of haptics in microsurgery.

Figure 2 presents the visual aid process in our framework. A level-set based method is first applied to segment the larynx from preoperative MRI/CT data. After the segmentation of laryngeal structures is completed, an accurate 3-D patient-specific model of the larynx for surgical path planning is constructed. During the planning step, visual cues are introduced by the computer or by the clinicians using a customized-software developed in-house to briefly define the operating regions, critical regions and suggested paths of surgical devices (Figure 3). These visual cues which are represented using control points are further refined using computational intelligence methods based on records of past surgeries and clinicians' input. They can be adjusted interactively. Based on the analysis using information theory, region-of-interests such as tumors or primary vessels, will be detected and the corresponding visual cues for surgical guidance are generated automatically. The diagram of the visual cues generation and edit is illustrated in Figure 4.

In order to provide an informative diagnosis and operating image, we develop a hybrid rendering method to combine the surface model of the targeted objects, visual cues and the volumetric context of the surrounding anatomy. This rendering technique is based on our previous work on automatic design of transfer function (TF) for medical image visualization [5].

During surgery, image registration between 2-D microscope video and the 3-D patient-specific model is needed. Our method of multimodal image registration [6] and time-series image registration have to overcome challenges on the differences of the larynx appeared in the microscope from that of the 3-D

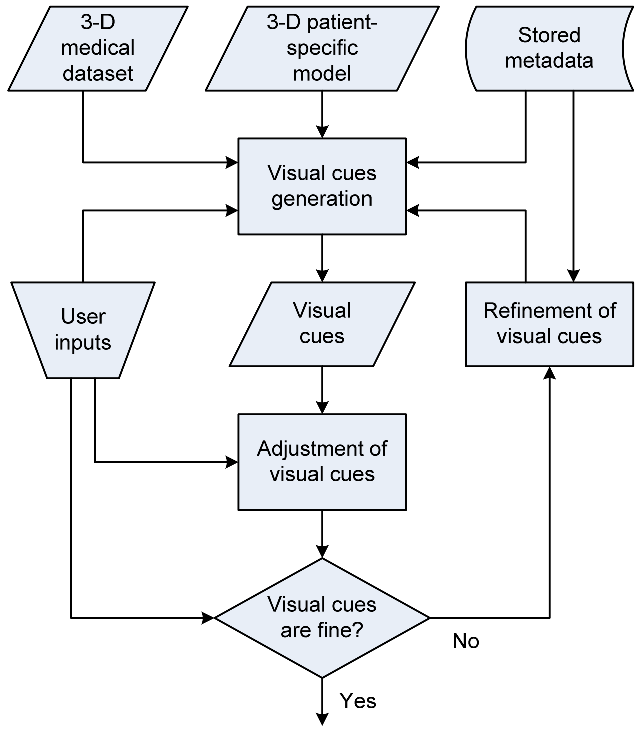

Figure 4. Flow chart of visual cue generation and edit process.

model as well as non-rigid deformation of the laryngeal structures.

The modeled human internal environment is updated during surgery. Hybrid rendering combines the surface model of the device and volumetric model of the patient's anatomy which is reconstructed from medical images. In order to model the complex physics between the device and surrounding organs, a judicious binding of finite element (FE) methods that model deformation of bodies, with multi-body dynamics (MD) methods which model the kinematics and dynamics of a multitude of bodies [7]. Important-driven rendering [5] will be used to provide the visual aid to the clinician that allows automatic focus of attention on interesting objects. Both viewpoint setting and visual parameters which are controlled by an importance distribution which is created using information theory, among objects within the volumetric data are modified to put emphasis on the object in focus.

Importance-driven computer graphical rendering based on information theory for provision of visual cues, can be extended to haptic rendering. Haptic cues may provide motion guidance to the surgeon in controlling the micro-robot towards the targeted tissue with a high standard of safely not possible without robotic assistance.

Necessary visual and/or haptic cues have to be provided to the surgeon in a timely manner so that he/she can intervene in a speedy manner. This is achieved via utilization of parallel computation using multi-core CPU and GPUs.

4. Discussion and Conclusion

This paper describes an intelligent surgical robotic system that we are developing, and introduces our investigation on balancing human control and automation for robotic surgery. It is easier to communicate with an “intelligent” robot; however, it is just as important to have an effective “control” over the robot within the highly complex and heterogeneous surgical environment. Hand-eye coordination of an operator was enhanced with the provision of visual and haptic cues in our application on microsurgery.

The study on human centricity in a collaborative human-robot setting will provide unique insights on human perceptual, cognitive, and motor skills. Interesting scientific questions include to what extent an individual learn and how the individual learn the hand-eye coordination skill with external guidance. Findings on “operator engagement” are also useful to research and development of robotic systems, for example, underwater monitoring device that can replace the dangerous and important role a diver undertakes during dry docking inspection in marine industry.

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