Theory and Method to Enhance Computer-Integrated Surgical Systems

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Ph.D. Thesis Booklet

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I. THE EMERGING FIELD OF COMPUTER-INTEGRATED SURGERY

Computer-Integrated Surgery (CIS) is the most commonly used term to cover the emerging field of interventional technologies in medicine from image processing and augmented reality applications to automated tissue ablation. CIS also incorporates surgical CAD/CAM (Computer Aided Design and Manufacturing)—analogous to industrial CAD/CAM—where digital information is used to create accurate patient models and surgical plans, while technology also improves treatment delivery.

Robotic surgery is defined as “A surgical procedure or technology that adds a computer-technology-enhanced device to the interaction between the surgeon and the patient during a surgical operation, and assumes some degree of freedom of control heretofore completely reserved for the surgeon”[1].

Minimally Invasive Surgery (MIS) originally referred to laparoscopic procedures (keyhole surgery), where the abdominal cavity is accessed through 3–5 small incisions (0.5–3 cm in size). Today, it is a generic term for the alternatives to open procedures reducing patient trauma and operation risk. On the other hand, MIS requires a highly skilled surgeon with a significant amount of practice [2]. Robot-assisted MIS is often used to characterize the complete teleoperated systems, where the robot basically serves as a replacement of the human operator’s hand by manipulating endoscopic tools.

Telesurgery (also referred to as remote surgery or telepresence surgery) enables physicians to invasively treat patients spatially separated from themselves. Unlimited bandwidth and real-time remote access to the medical site means that the surgeon is actually capable of performing operations through robots and other teleoperated devices. When the communication link is not reliable enough or the technical tools are not given, a remote surgeon can direct the local one based on semi-real-time (slightly delayed) video and voice feed from the Operating Room (OR). This technique is called telementoring (also referred to as teleproctoring), which is the spatial extension of classical mentoring and professional guiding—the monitoring and evaluation of surgical trainees from a distance. When low communication quality or latency does not even allow semi-real-time connection, consultancy telemedicine (or telehealth consultancy) can still be used. It only requires a limited bandwidth access to the remote site, however, as a consequence, the distant group cannot use real-time services or information updates. Virtual presence and remote delivery of services has great scientific and commercial potential in health care.

Image-Guided Surgery (IGS) means the accurate correlation and mapping of the operative field to a pre-operative image or intra-operative (e.g., ultrasound, fluoroscopy) data set of the patient, providing freehand navigation, positioning accuracy of equipment or guidance for mechatronic systems [3]. IGS has been primarily used in neurosurgery, pediatrics, orthopedics and also had a major impact in ear, nose, throat and maxio-facillary reconstruction surgery.

Registration is a key element of medical imaging and robotics, it means the spatial alignment of different modalities to determine the position and orientation of the patient in the operating field relative to a virtual data set of the anatomy, e.g., a pre-operative image. The registration should provide a homogeneous transformation (or similar representation) that allows the conversion of locations and control signals between different devices, i.e., mapping between the control frames [4].

A generic robot-integrated IGS system’s schematic diagram is shown in Fig. 1 where the nodes represent control frames and the lines represent homogeneous transformations. The navigation system (e.g., a camera) is able to track at least two markers. First, the position
Fig. 1. General control concept of image-guided robotic systems. The nodes represent control frames and the solid lines are homogeneous transformations connecting them.

of the Dynamic Reference Base (DRB), (i.e., a fiducial anchored to the patient) and second, the Tool Rigid Body (TRB). The navigation system is also used to register the pre-operative image of the patient to the DRB with the help of e.g., a hand-held probe and skin-mounted fiducials. Then the surgical plan can be mapped from the pre-operative image space to the robot coordinates through the chain of homogeneous transformations.

In the terms of accurate treatment delivery, it is most important to get a precise and realistic transformation between the patient anatomy and the robot end effector. While the above described registration and calibration procedures could theoretically allow for a perfect mapping, in reality, several issues arise, such as the finite accuracy of the fitting algorithms, communication latencies, the limited computational resources available and above all, the changing medical environment, most often referred to as patient motion.

A. Surgical robotic concepts

Robots can be involved in medical procedures with various level of autonomy [5]. Some of them serve as a robust tool holding equipment once directed to the desired position, while others are able to perform fully automated procedures, such as CT-based biopsy or cutting. The later ones are called autonomous or supervisory controlled devices, as a human supervisor would always be present to intervene if deviations from the surgical plan are noticed. This can be combined with the classic tools of IGS, when the surgeons are only using the images to gain additional information to better position their tools. When the planning is completed, the physicians have to match the robot’s coordinates with the patient’s anatomical points, registering the physical space to the robot’s working frame. Once appropriately registered, the robot can autonomously perform the desired task by exactly following the pre-programmed plan.

On the other hand, if the robot is entirely teleoperated or remote-controlled (robotic telesurgery system) the surgeon is absolutely in charge of its motion. These complex systems (such as the da Vinci) consist of three parts: one or more slave manipulators, a master controller and a vision system providing feedback to the user. Based on the gathered visual
(and sometimes haptic) information, the surgeon guides the arm by moving the controller and closely watching its effect. In most of the cases, mechatronic systems and cameras are the remote hands and eyes of the surgeon, and therefore key elements of the operation.

Modifying the teleoperation control paradigm we can introduce cooperative control (also called shared control or hands-on surgery). It means that the surgeon is directly giving the control signals to the machine through a force sensor. It is possible to read and process these signals in real-time to create the robot’s motion. The human is always in contact with the robot, as the master and the slave devices are physically identical. In this case, the robot is the extension of the doctor’s hand, equipped with special features and effectors. This approach keeps the human in the control loop, and still allows the surgeons to use their senses throughout the procedure. It is often employed in the case of micro-manipulation operations, such as micro-vascular, urologic, eye or brain operations.

B. Advantages of surgical robots

Robot-assisted procedures offer remarkable advantages both for the patients and the physicians [6]. The main features of robotic surgery systems are the following:

- superior 3D spatial accuracy provided by the robot,
- stabilization of the instruments within the surgical field,
- improvement of manual dexterity, motion scaling,
- physiological tremor filtering,
- integrated 3D vision system with high resolution,
- specific design for maximum performance (including miniature robots),
- advanced ergonomics supporting long procedures,
- high fidelity information integration,
- stable performance,
- invulnerability to environmental hazards,
- patient advantages (reduced blood loss, less trauma, shorter recovery time),
- decreased costs (per treatment) due to shorter hospitalization,
- possibility to provide better and more realistic training to physicians.

C. Further improvements for CIS

Despite their success in various applications, there are some concerns that prevent CIS technologies from becoming dominant in health care. While there is a clear need for accuracy and robust operation for many procedures, the associated high expenses are not welcomed. Technology can only conquer the OR gradually, as it takes a long time and a significant amount of training to change the general way procedures are performed. Many surgeons are reluctant to use novel devices or protocols that they do not completely understand or control.

Image guidance at the same time is a steadily emerging field; physicians recognize the value of better imaging, more precise tools and smarter devices. Currently, the leading direction of development is to provide incremental updates to existing protocols and instruments. This means the enhancements of already deployed navigation devices, better simulation, accurate modeling, information coupling and error-resistant control. The working environment of a surgical robot is not entirely predictable and cannot be modeled completely, therefore complete automation of the procedures is extremely hard. Safety concerns delayed or prevented the approval of many automated interventional systems, and streamed the
research community towards human-integrated control solutions, such as telesurgery and hands-on surgery. Cooperative control is a promising way to provide highly integrated robotic support for procedures while applying all the necessary safety standards. It is believed that this method currently provides the highest effectiveness according to the criteria hierarchy for surgical robots [7].

D. The JHU image-guided neurosurgical system

I was given the unique chance to be involved in a neurosurgical project as a visiting scholar at the Center for Computer-Integrated Surgical Systems and Technology (CISST ERC) at the Johns Hopkins University (JHU, Baltimore, MD) in 2007/08. We have developed an integrated surgical robotic system to support skull base drilling. The system consists of a modified NeuroMate robot (Integrated Surgical Systems Inc., Sacramento, CA; currently owned by Renishaw plc., Wotton-under-Edge, UK), a StealthStation (SS) surgical navigation device (from Medtronic Navigation Inc., Louisville, CO) and adequate network and control equipment. The goal of the project was to improve the safety and quality of neurosurgery while reducing the operating time. The robotized solution is only used for the removal of the bone tissue, to gain access to the anatomical region affected by a tumor or other lesions. Our technical approach was to use pre-operative imaging, allowing the medical professional to identify the region of the skull base that could be safely drilled. We chose a cooperative control implementation, in which the surgeon applies forces to move the robot and the robot enforces the safety boundaries [8].

The JHU system has three major advantages. First, it offers advanced visualization features typical used in stereotactic surgery; the tool’s position can be followed on the 3D model of the patient, acquired from pre-operative CT scans. Second, the surgical tool is mounted on the rigid robot, thereby improving its stability. The surgeons still hold the classic drill and directs its movement, but they can release the tool any time. Finally, the most important advantage—and the novelty of the application—is that the physicians can define virtual boundaries on the patient’s model prior to the operation. This spatial constraint is called Virtual Fixture (VF), and once registered to the robot, it is strictly enforced, thus preventing the tip of the tool from going beyond the defined safe area. These features together can
greatly increase the safety and the reliability of the procedure, facilitate task execution and potentially reduce operating time.

The JHU setup was an excellent platform to prototype and test my results, and to perform realistic simulations along with phantom and cadaver trials to acquire relevant data.

II. METHODS OF THE RESEARCH

The goal of my research was to create new methods and algorithms to support image-guided systems, to increase their accuracy and safety with intra-operative tracking, develop error reduction and advanced control. Three specific areas have been targeted for improvement, each addressed with a research project.

Within the areas of my work I conducted a profound literature review to assess the state of the art, and the results are thoroughly reported in my Thesis, incorporating over 280 references. Next, long discussions and planning phase proceeded, followed by the invention, implementation and verification of new models. Classical mathematical apparatus was employed including linear algebra, statistics and classical control theory. New ideas were prototyped and tested on a physical setup and in a simulation environment under MATLAB (Mathworks Inc., Natick, MA). Extensive data collection was performed to acquire relevant input data set for the algorithms. Further, the results connected to patient motion compensation and error modeling in integrated IGS systems were verified on the JHU system through laboratory trials and tests on the actual data derived from the neurosurgical robot. Telesurgery control experiments were simulated based on previously verified models and properly identified system parameters.

III. RESEARCH PROBLEM STATEMENT

There is a clear trend in medicine to shift towards less invasive treatment solutions. In the case of robot-assisted IGS or radiation therapy, accuracy is paramount, therefore precise positioning of the surgical tools is required. Typical practice is the rigid and invasive fixation of the patient, and the employment of additional hardware to ensure safety. Beyond the inherent precision of the system components, accuracy of treatment delivery can also be affected by the many changing factors in the OR. There are several people in the room moving around the numerous medical devices surrounding the patient. Further problems arise with teleoperation. Long distance telesurgical applications require adequate control algorithms to support the operator and to handle latency. Effective emergency medical care in space requires additional considerations and innovative solutions.

Three specific problem descriptions have been formulated and grouped around outstanding challenges of the field of CIS.

Problem 1: Patient motion in the Operating Room

There is an urgent clinical need to improve treatment delivery precision and to reduce invasiveness solely relying on the existing hardware in the OR, as further costs and consuming too much space should be avoided. Integrated IGS systems must provide increased safety and accuracy features.

Image-guided surgery requires trackable markers used as references (or perfect immobilization of the body), as it is based on the principle that the real-world setup does not change unpredictably over time; therefore the registration to the pre-operative image space
remains valid. IGS is sensitive to spatial changes, when the patient is unintentionally moved relative to the marker that tracks their motion. The event of patient motion occurs when the body’s position moves relative to the base frame of the device executing the surgical plan. (Physiological tissue motion is not addressed here, as its tracking requires different techniques and methods.) The fundamental problem with patient motion is that without proper identification and compensation, the whole surgical plan may become obsolete, and the treatment potentially harmful. From the clinical point of view, a few millimeters of error could be tolerated at the most. Depending on the speed of the tool, this translates to a maximum of a few seconds of latency. If it is noticed in time, re-registration is demanded to avoid damaging the patient. However, re-registration is usually time consuming, thus it should be avoided, whenever possible. From the technical point of view, many sources of errors can be handled as patient motion, having the same degrading effect on performance.

**Problem 2: Inadequate modeling of system error propagation**

On the way towards having more robotic technology involved in the OR, a major problem is the proper modeling of system noises and their propagation. Even a semi-autonomously guided machine with a misaligned image-overlay can be the source of malpractice. Effective mapping of spatial error based on a priori information is necessary to support the operation of integrated medical tools. Currently, generalized error values and the experience of the medical staff determines the use of a system under different conditions. As a consequence, worst case safety margins have to be applied all along the procedure, while more thorough analysis of the distribution of spatial error would allow for optimized approach, leading to better treatment delivery and faster execution.

Surgical procedures and integrated medical devices relying on patient imaging should provide a clear indication of the system’s error at the Point of Interest (POI) and the expectable distribution of it. Generally accepted metrics should be applied to make the current systems comparable. Deterministic spatial accuracy analysis of image registration and surgical robot systems was performed by many research groups [9, 10, 11]. However, stochastic analysis has mostly been avoided due to the fact that it is computationally demanding and can lead to extremely complex solutions [12]. Without effective and easy means of assessment, it is utterly difficult to verify IGS systems’ accuracy. Even today, the most successful surgical robot system (the da Vinci) relies on the direct control of the surgeon. The human-in-the-loop control strategy allows for more flexible (and less autonomous) hardware solutions, where the surgeon is entirely responsible for patient safety. It is believed that development is towards improved machine intelligence and automation, and as a major step forward, the inherent precision of the future systems has to be improved.

Most of the previous methods developed for error assessment do not deal with the orientation error at a target, and do not provide any information about the error distribution. Originally, the concept of coordinate frame registration handled accuracy as a norm of the deviation in $x, y, z$ from the target point—entirely disregarding the orientation uncertainty. In several applications, such as an IG interventional robot employing a Virtual Fixture (VF), it is critical to consider angular errors as well.

**Problem 3: Difficulty of telesurgery over large distances**

While pilot experiments have been conducted for distant telesurgery around the globe and between continents, regularly performed remote operations have many practical obstacles
and limitations. Primarily, these systems need robust and stable controllers to deal with technological issues deriving from the latency in the communication, and also to incorporate an adequate model of human–machine teleoperation.

Space application of telerobotic surgery has been a major focus of the research community since the early days of the field. While advanced internet-based communication theoretically enables terrestrial telesurgery, serious technological problems arise in the case of long distance operations or space exploration missions. These days, it still seems inevitable to have a flight surgeon on board of the spacecraft for long duration missions, as robots do not have enough autonomy to adapt to unpredictable events.

A realistic teleoperation system suffers from time delays during communications between the master (controller) and slave side (effector system). Unless the process is significantly slower than the latency, the control lag time can cause the deterioration of the control quality and instability can occur due to unwanted power generation in the communications. Time-varying delay poses further difficulty to classical PID controllers, while on the other hand, model predictive control is extremely hard to apply due to the human operator’s complex behavior. Scalable empirical methods, such as Kessler’s Extended Symmetrical Optimum (ESO) method could provide better solution for these problems [13].

Beyond these points, there are many other challenges within the field of CIS, and researchers are exerting great effort to answer these, resulting in the continuous flow of technical breakthroughs and theoretical achievements. The problems identified above summarize three areas covering an important set of interconnected issues, and addresses scientific problems relevant to the clinical practice.

IV. NEW RESULTS

1. Thesis Group: Algorithm for Patient Motion Detection and Compensation

I have developed a new tracking-based Minimally Invasive Surgery concept for patient motion compensation to support systems with less rigid fixation setup or limited surgical navigation capabilities.

Related publications: [HT-1, HT-2, HT-3, HT-4, HT-5, HT-6, HT-7, HT-8, HT-9, HT-10, HT-11, HT-12, HT-13].

1.1 Optimal determination of Surgical Cases

I developed a general framework for patient motion tracking that is applicable to various Image-Guided Surgery setups. I proposed a decision-tree based event recognition algorithm that allows to choose the best control option for any pre-defined Surgical Case. IGS events have been categorized and defined as patient motion, camera motion, robot motion and the arbitrary combination of these. The control sequences can be transformed to any arbitrary frame to ensure safe operation even during patient motion. A measurement-based method was constructed to identify the actual Surgical Case, and to perform the desired action to enhance patient safety.

1.2 Extending window adaptive filtering

I proposed extending window averaging to be applied to compensate for the inaccuracies in the control frames and transformations of an integrated IGS system. This ensures more reliable and accurate estimation of the surgical tool, thus increases the safety of the operation.
Discussion of the thesis: The new approach uses the intra-operative navigation device’s internal coordinate base frame to better estimate the possible changes in the environment. The base frame for the computations can be chosen arbitrarily as long as it is registered to the robot frame (and possibly to other control frames, such as the navigation systems) through known homogeneous transformations. The advantage of the method is that it is scalable to fit various surgical setups without additional hardware requirements. The general nomenclature and definitions of the subfield were founded.


I developed a stochastic approach for the assessment of spatial errors of an integrated IGS system. It can determine the probability density function of the location of the Point of Interest. By combining computation and simulation, error distribution for a given setup can be derived. Once the spatial constraints are defined and transformed into the POI’s coordinate system, it is possible to derive the exact probability of the tool entering the Virtual Fixture.

Related publications: [HT-14, HT-15, HT-16].

2.1 Better expression of transformation errors

I demonstrated that since the overall homogeneous transformation connecting the patient’s space and the robot can be expressed as the function of the ideal and noise terms:

\[
P_{\text{PAT}} T = f(t) + f(\Delta t), \text{ where } t = [x, y, z, \phi, \theta, \psi],
\]

the probability \( P(\text{POI} \notin \text{VF}) \) that the POI is in the forbidden region can be analytically calculated as:

\[
P(\text{POI} \notin \text{VF}) = \int_{t \in \text{VF}} f(t) \, dt.
\]

Then stochastic approach can be applied to determine the location of the tooltip. This is a simple and effective way to express \( f(\Delta t) \), the error of the transformation.

2.2 Describing a scalable solution for enhanced safety

With the help of differently chosen VF segments and \( w \) weighting factors, any complex penalty function can be built and applied to the IGS system in real-time during the execution of the operation. Significant errors occurring with lower probability can be considered as:

\[
\eta = w_1 P(\text{POI} \notin \text{VF}_1) + w_2 P(\text{POI} \notin \text{VF}_2),
\]

where \( w_1 > w_2 \), if \( \text{VF}_1 \) is more limiting than \( \text{VF}_2 \). This enables faster and safer task execution for any integrated systems using a pre-operative surgical plan combined with an intra-operative interventional tool.

2.3 Improving treatment delivery precision in the Operating Room

The new approach allows for the a priori estimation of the POI’s distribution. Based solely on the devices’ known intrinsic accuracy parameters and the registration (acquired before the surgical procedure), thorough error distribution estimation can be performed. This simulation leads to better approximation of the surgical tool’s position.
Discussion of the thesis: I formulated the general extension of Wiles’ approach [14], taking into consideration rotational uncertainties as well. The angular error distribution can also provide information about the probability that the POI is moving toward the VF, which is crucial in the case of certain surgical tasks. The method does not overload computationally current hardware setups, as the most recent devices allow for the handling of these functions. It is able to manage a previously challenging case: critical errors with low probability, and the method can be extended and arbitrarily scaled to incorporate more regions. The exact calculation of the probability of the error gives a much stricter control over the motion of the tool, resulting in higher accuracy and safety. With known error distribution, it is possible to determine which directions are more dangerous from the application point of view. The robot can be allowed to move faster towards directions with lower error deviation.

3. Thesis Group: Control Method for Long Distance Telesurgery

I proposed a three-layered space mission architecture to achieve the highest degree of performance by combining robotic and human surgery. A suitable teleoperation control architecture was defined, and its limitations presented. I proved the effectiveness of Kessler’s Extended Symmetrical Optimum method in telesurgical applications and drawn conclusions on the optimal parameters to be chosen.


3.1 Framework to design controllers for telesurgery

I presented the limitations of different telemedicine technologies, and developed a concept for the application of telesurgery, enabling the support of a future space exploration missions. It contains the simplified human and machine representations derived to accommodate long distance telesurgical applications. I proposed a method for controller design that relies on the adaptive and continuously updated modeling and identification of the communication system, and on empirical controller design.

3.2 Cascade control structure with empirical design method

I proposed a cascade control structure employing empirical controller design to address the challenges of a system with large and probably varying latencies. I focused on Kessler’s Extended Symmetrical Optimum method and showed the feasibility to use it embedded in the broader domain of robotics. I demonstrated the capability of the method to deal with latencies up to 2 seconds. Optimal $\beta$ design parameter settings were derived based on the requirements and assumptions for an effective space telesurgery system.

Discussion of the thesis: Different telepresence technologies may provide the best performance in space medicine. The effectiveness of real-time control strategies and communication techniques decreases significantly with the increase of latency. Considering the challenges, I defined the pre-control context for telesurgery, based on what an adequate control method was formulated. I focused on classical control options to provide a simple, universal and scalable solution. The use of empirical design methods is justified with the need for simple and quick algorithms in cases when model predictive control may be cumbersome to apply.
V. Application of the Results

A. First Thesis Group

The Surgical Case identification concept was tested on the neurosurgical robot system developed at the Johns Hopkins University. The setup serves as a testbed for various technologies that can be prototyped and tested under realistic circumstances. The patient motion algorithm has the universality and applicability to be employed beyond laboratory conditions. One of the future target applications is patient immobilization at ion therapy, a solution that the Austrian Center for Medical Innovation and Technology (ACMIT) is investigating. Negotiations for future applications with Renishaw plc. (current developer and distributor of the NeuroMate robot) are also scheduled.

B. Second Thesis Group

The proposed stochastic approach has several advantages, as it can be applied to IGS systems during the setup phase to verify the performance of the devices in the actual OR arrangement. It could easily be incorporated into commercially available navigation systems, fitting into the surgical workflow. At the beginning of the procedure—when the devices are roughly positioned around the patient—simple readings of the actual position information can serve as the input for the simulation. The stochastic method provides the error distribution based on the Monte Carlo simulation within a few seconds, and with that knowledge, the surgeon can decide to re-arrange the setup or to proceed with the operation.

C. Third Thesis Group

The simulation results derived for delayed teleoperation may help to better understand human adaptation to visual feedback latency, and new experiments are proposed to be conducted on our laparoscopic training box setup for that purpose.

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VII. REFERENCES


VIII. Publications


IX. FURTHER SELECTED PUBLICATIONS


Summary of publishing activity:

- Total number of publications: 52
- Peer reviewed publications: 27
- Patent: 1 (pending)
- All known citations (including self-citation): 36
- All known independent citations: 2
- Independent recensions: 1
- Total Impact Factor: 3.681

Summary of advisory activity:

- Total number of students supervised: 16
- Student’s Scientific Circle (TDK) papers: 3
- Successful B.Sc. defenses: 2
- Successful M.Sc. defenses: 1 (4 pending)