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Methodological Approach for Subtask Automation in Robot-Assisted Minimally Invasive Surgery

Részfeladatok Automatizálásának Módszertani Megközelítése a Robottal Támogatott Minimál Invazív Sebészetben

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Contents

Abbreviations and Notations

DoA	Degree of Autonomy
DVRK	da Vinci Research Kit
FLS	Fundamentals of Laparoscopic Surgery
FDA	United States Food and Drug Administration
HMI	Human–Machine Interface
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LC	Laparoscopic Cholecystectomy
LoA	Level of Autonomy
MEE	Medical Electrical Equipment
MES	Medical Electrical System
MIS	Minimally Invasive Surgery
QLA	Quad Linear Amplifier
RAMIS	Robot-Assisted Minimally Invasive Surgery
ROS	Robot Operating System
SA	Situation Awareness
TC	Technical Committee
TR	Technical Report

1 Background

In the past three decades, Robot-Assisted Minimally Invasive Surgery (RAMIS) induced a revolution in healthcare, becoming the standard of care in a number of surgical domains. This new technique kept the benefits of the traditional Minimally Invasive Surgery (MIS), including lower risk of complications and faster recovery, thus shorter hospital stay, while offering further benefits, such as 3D vision, motion scaling, hand tremor filtering, and better ergonomics for the surgeon [1, 2]. Among all the commercially available RAMIS robots, the da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA) is the most successful, by far. Currently, there are over 9200 da Vinci units installed worldwide, which perform over 2.5 million procedures per year. The 1st generation robot—referred to as da Vinci Classic—was cleared by the U. S. Food and Drug Administration (FDA) twenty-five years ago. Today, the 5th generation is available, along with the research-enhanced version of the original system, the da Vinci Research Kit (DVRK) [3, 4].

1.1 Partial Automation in Surgery

Along the benefits, RAMIS introduced new challenges to the surgeons, e.g., the execution of certain subtasks, like suturing, became tedious and time consuming. Many believe that the next step in the advancement of surgery will be partial automation. Unfortunately for the researchers, autonomy in the surgical environment affecting mostly soft tissues, and therefore presents grave difficulties. Unlike working on rigid tissues, where exact registration is possible, soft tissues are permanently in motion, and highly deformable, thus typically no pre-computed tool trajectories can be used. Another challenge of surgical automation is undoubtedly the implementation of perception algorithms usable in this complex environment. Computer vision suffers from reflections and the fact that the visual features of different organs being very similar, yet it is still the gold standard.

Currently, a number of research groups are working on subtask-level automation in surgery [LTNR1][LT5]; most of the work is being done in ex vivo conditions (rarely in vivo) [5, 6] or realistic phantom environments [7], the usage of simplified silicone phantoms is dominant [6, 8, 9, 10, 11]. During the last five years, the automation of surgical training exercises on rigid [12, 13, 14, 15, 16, 17] and deformable [18, 19] phantom environments tends to receive more attention. Within the scope of surgical training exercises, the automation of peg transfer is presented in the highest number of papers [12, 13, 14, 15, 16, 17, 20], probably due to its simplicity, making possible to build the foundations for the best algorithms and basic principles in surgical subtask automation.

1.2 Level of Autonomy for Surgical Robots

Around ten years ago, the joint International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) Technical Committee (TC) group analyzed the status of surgical robot standardization. Only one major gap was found: the Degree of Autonomy (DoA)—employed in *ISO 8373:2012 – Robots and robotic devices – Vocabulary*—was not defined properly. The discussion on the topic was concluded in a new Technical Report (TR) *IEC/TR 60601-4-1: Medical electrical equipment – Part 4-1: Guidance and interpretation – Medical electrical equipment and medical electrical systems employing a degree of autonomy*.

While the standards, mentioned above are fundamental for the assessment of the capabilities of RAMIS systems, they are not definite enough to present taxonomy to generally assess the development phases of surgical robotics, or to perform benchmarking. Surgical robotic systems should be categorized based on their advancement, relative in their field of application. A gradual mapping was presented in [21], to classify the autonomous capabilities of surgical robots. Some earlier work suggested to put the Human–Machine Interface (HMI) into the center of the classification, defining a 0–7 scale [22]. Similar concepts are also present in the field of self-driving cars; in [23], a 6-grade scale was introduced for autonomous vehicles.

The role of Situation Awareness (SA) may be crucial to distinguish the cognitive level up to which the human may be able and shall be allowed to perform take-over; described as human-on-the-loop control [24]. Coherent to the current standardization efforts, yet fitting to the commonly used terms, the following scale of LoA is suggested [LT5]:

- **LoA 0 — No autonomy:** all system-level functions (generating, selecting, executing and monitoring actions) are performed by the human operator.

- **LoA 1 — Robot assistance:** the surgical robot performs specific, low level functions only.

- **LoA 2 — Task-level autonomy:** the system is trusted to complete certain tasks or sub-tasks in an autonomous manner.

- **LoA 3 — Supervised autonomy:** the system is able to autonomously complete large sections of a surgical procedure, while making low-level cognitive decisions. All actions are performed under human supervision, assuming the operator's full SA.

- **LoA 4 — High-level autonomy:** the robotic system executes complete procedures based on human-approved surgical plans, while the human only has the capability to emergency stop (e-stop) the procedure.

- **LoA 5 — Full autonomy:** a full-time performance of the robotic system, handling all environmental and adverse conditions.

2 Research Goals

RAMIS often involves time-consuming and monotonous subtasks. Automating these subtasks can reduce the surgeon's cognitive load, allowing them to focus more on critical aspects of the procedure. Recent technological advancements, like deep learning or smart mechatronics, offer an increased capability in the automation of surgical subtasks; and consequently, it became a prevailing topic in the research community. Meanwhile, several challenges remain, including operating in a continuously changing soft tissue environment, difficulties in anatomical and pathological recognition due to visual limitations, such as glare and the complexity of both the procedures and the instruments used.

To address these challenges, my research aimed to:

1. **Develop a standardized methodology to support the automation of surgical subtasks in RAMIS.** The field of RAMIS automation is highly fragmented, with most systems being far from clinical translation. A unified, transparent framework is necessary to support the development of autonomous RAMIS systems.
2. **Establish robust validation metrics for clinical applicability.** Many developed systems lack proper validation and adjacent metrics, making comparisons difficult. A standardized methodology is required to assess and compare the clinical applicability of autonomous surgical systems.
3. **Monitor and quantify situational awareness in surgical automation.** Increased automation may reduce the operator's SA, potentially affecting performance. It is essential to monitor and quantify this effect to ensure safe and effective human–machine interaction.

3 Materials and Methods

3.1 Software Tools and Environment

To realize the data collection and processing for surgical subtask automation, complete research platforms have to be built and constructed, bringing computer technology to the operating room. Within the academic domain, the Robot Operating System (ROS) [25] platform is widely used in the research of robotics, and also preferred by many in the medical robotics domain; most of the research centers, working on the two dominant platforms presented below, rely on ROS. ROS is undoubtedly a powerful, modular tool with already implemented solutions for most of the frequently occurring problems of the field, such as stereo-camera calibration or acquisition of sensory data. ROS 2, released in 2017, improves real-time support and scalability for industrial applications, though the transition from ROS 1 is still ongoing. This thesis remains version-independent, with some implementations already ported to ROS 2.

3.2 Open Research Platforms for Automating Surgical Subtasks

The research projects on surgical subtask automation were utilized a number of robotic devices during the last decade, including medical, industrial or custom-built robots. However, two RAMIS research platforms—the DVRK and the RAVEN Platform—are dominant in the field, easing the future translation of the developed methods to the clinical practice. During my research I had access to the DVRK in the Antal Bejczy Center for Intelligent Robotics, making possible to work on this cutting edge research platform presented in the followings.

The da Vinci Research Kit

Over ten years ago, when the 1st generation da Vinci robots (da Vinci Classic) was sent to retirement due to the discontinued manufacturer's service and supply, the old systems found another purpose. The robots that were still functional could be utilized in applications more tolerant to malfunctions. At the Johns Hopkins University, the development of a research platform for those robots—DVRK—was concluded, and only in a few years, an active community was built with more than 40 setups worldwide [26].

The DVRK is a fully open-source platform, consisting of custom hardware and software elements, in order to open the possibility of programming the da Vinci arms. The controllers—developed to operate the arms—are built on custom boards: an IEEE-1394 FPGA board for computational power and low latency communication and a Quad Linear Amplifier (QLA) for high-frequency low-level robot control. The controllers are connected to PC using IEEE 1394a (FireWire). On the PC side, the open-source *cisst* libraries are responsible for the handling of FireWire communication and the mid-level control of the robot. The cisst libraries offer the functionality to program the arms themselves. Additionally, cisst is also interfaced with ROS, which interface is currently used to program the da Vinci arms at more than half of the DVRK locations [26, 27].

3.3 Description of Surgical Subtasks

This thesis focuses on two surgical subtasks as models to support the developed concepts and methodologies. These two subtasks presented below—blunt dissection and peg transfer—, are simple enough to enable work on the very fundamentals of surgical subtask automation, yet relevant from the clinical aspect.

The Blunt Dissection Surgical Subtask

Blunt dissection is a surgical subtask, where the surgeon carefully separates two tissue layers without using the instrument's cutting edges in an effort to avoid any damage to sensitive tissue structures (e.g., vessels, nerves). During blunt dissection, the retractor holds the tissues, and the dissector is inserted between the two layers, then by opening of the dissector it forces the two layers apart. This surgical subtask is recurring element in multiple procedures, where automation could ease the cognitive load on the surgeon by relieving him/her from concentrating on the manual handling of the instruments, so the surgeon may pay full attention to the patient-specific details of the surgery. Furthermore, robotically executed procedures can provide an increased accuracy compared to the human operator, therefore it can take effect the success of the operation. During Laparoscopic Cholecystectomy (LC) procedures, blunt dissection is a typically employed subtask to expose the Calot triangle.

The Peg Transfer Training Exercise

Peg transfer is probably the most frequently used exercise in MIS and RAMIS training to improve hand–eye coordination and motor skills. It is also one of the five tasks of the Fundamentals of Laparoscopic Surgery (FLS) exam [28]. The training task consists of a pegboard, with two sets of 6 pegs and 6 blocks. Once all six block have been transferred to the opposite side of the board, reverse the process and first grasp each block with the dominant hand, transferring mid-air to the non-dominant hand, and place it on the original side of the pegboard. FLS scores the task as follows: a penalty is applied if a block is dropped outside of the field of view; there is no penalty for dropping the block within the field of view, if the block can be retrieved; also, the task needs to be performed within a certain time limit (300 seconds for FLS proficient-level exam).

4 New Scientific Results

Thesis 1

I developed a method to support the automation of surgical subtasks in RAMIS. The presented methodology is based on the hierarchical decomposition of human surgical motions, enabling high modularity. Additionally, based on the developed method, I have designed a system architecture and implemented a software framework, capable of realizing autonomous surgical applications effectively.

Related publications: [LT1, LT2, LT3, LT4, LT5, LT6]

Thesis 2

I developed a method for the validation of autonomous applications in the field of surgical subtask automation, originating from the human surgical skill assessment techniques. I created a model to represent the capabilities of autonomous surgical systems. I have reviewed, organized, and graded the metrics from the field of capability and performance evaluation in surgical subtask automation and related research areas, like autonomous robotics or surgical skill assessment. Additionally, I compiled a method to choose the metrics best describing the performance of applications performing surgical subtasks autonomously.

Related publications: [LT7, LT8]

Thesis 3

I addressed the objective monitoring and quantification of Situation Awareness (SA) and evaluated its impact within the context of partial automation.

Thesis 3/I: I conceived a measurement framework for the quantitative analysis of vehicle driver's SA during LoA 3 handover scenarios using the DVRK-enhanced da Vinci Surgical System. I showed that the proposed framework effectively enables the objective measurement of SA through the combination of methods during the handover process.

Thesis 3/II: I analyzed the effect of SA on the handover performance during LoA 3 emergency situations in the proposed measurement framework. I showed that the success of such handover maneuver highly depends on the driver's SA. Furthermore, I showed that SA exhibits an increasing trend across successive scenarios, suggesting that the subjects' ability to assess and respond to the environment improved with exposure to the task.

Related publications: [LT9, LT10, LT11]

Other publications related to the Ph.D. thesis and the accompanying research work: [LTNR1, LTNR2, LTNR3, LTNR4, LTNR5, LTNR6, LTNR7, LTNR8, LTNR9, LTNR10, LTNR11]

5 Applicability of the Results

The presented results fall into the category of applied sciences, targeting future clinical use. However, the research of subtask automation in RAMIS is still at a very early stage globally, and true clinical applications are still far ahead. The conducted work aims to answer some of the current research questions of the field, to make incremental steps and to establish basic principles. The presented software framework will hopefully benefit the research community, potentially serving as a basis for novel implementations of autonomous applications in RAMIS. Additionally, the proposed methodology for validation and benchmarking may add to the quality of future publications in the area and help to make the results comparable. The importance of SA in partial automation was also emphasized, advising extra attention to this aspect during the development of such systems.

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