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Recent Trends in Automating Robotic Surgery

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Abstract— **Eversince computer technology entered the operating room (OR), surgery has gone through one of the greatest changes in the history of medicine, and now we are foreseeing the age of the digital OR. The range of the novel applications spans from intra-operative navigation to the development of autonomous suturing tools. More recently, after 20 years of experience with pre-programmed, image-guided and teleoperational surgical robots, a new trend is emerging: to create autonomous, or partially autonomous surgical robots. These advanced systems are intended to fit into the surgical workflow, and to help the surgeon in the least intrusive way possible. It is only the recent development of surgical–digital applications which can overcome a the barrier of the cognitive load on surgeons, to become able to completely control of the operating field. Three major trends have been identified in current products and advanced research prototypes: 1) aiming to improve camera handling 2) Sub-task automation 3) complete automation.**

I. INTRODUCTION

Minimally Invasive Surgery (MIS) is a paradigm change in modern medicine, and arguably one of the biggest revolution; in the history of surgery. The complex technical requirements of MIS calls for exceptional engineering, prototyping and surgical work. The manipulation of new tools have become cumbersome, and requires extensive skill training; even the previously simple tasks could become problematic or time consuming, due to the limited range of motion, indirect visualization, the fulcrum effect and so on. Even further, today's advancements in operating techniques can sometimes require dexterity and precision which is not achievable by a human operator. As an answer to these challenges, teleoperation robotics was developed in the early 1990s, where the surgeon's hands are replaced with remote controlled robotic arms (Fig.1) [1]. As a next step, automated methods are rapidly emerging, and a new era of surgery is rising, where the human hand is not always in full control of the surgical procedure [2], [3]. A more detailed introduction to specific systems can be found in a recent review article [4]. In this paper, the basic approaches are presented, first reviewing the function that were targeted for automation, then providing an overview of the state of the art.

II. LAPAROSCOPIC ASSISTANT ROBOTS

The most obvious area for improvement has been the camera handling in MIS. During laparoscopic surgery, when the abdomen is operated through small skin incisions, and the operating field is visualized by an endoscope, it is essential that the endoscope is adequately controlled, so it is always aimed at the surgeon's field of interest. For most cases, the endoscope is manipulated by an assistant, and the endoscope's image is visualized on a screen nearby. It is essential for the success of the operation that the constant verbal communication between the assistant and the surgeon provides a streamlined control loop, thus the visualization is acceptable for tool manipulation. Even if the surgeon and the assistant forms the perfect team, the manipulation is most likely not to be perfect, since the human operator's hand will have physiological tremor and other factors related to e.g., tiredness. Long before any automation was considered in this domain, teleoperated platforms appeared.

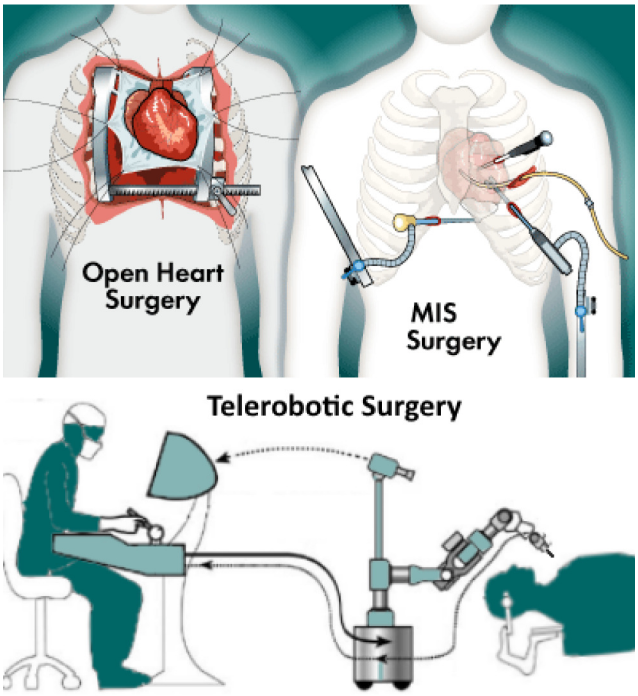

Fig. 1. The revolution in surgery, switching from open access to minimally invasive. For better accuracy and ergonomics, teleoperational robots have been developed to assist with the procedures [50]. (Image credit: *HowStuffWorks*.)

This problem was in the focus when developing several robotic platforms, such as the AESOP, EndoAssist, Free-

Fig. 2. Prosurgics' FreeHand system during an operation. An infrared receiver is employed to pick up the head motions of the surgeon for camera control. (Image credit: *Prosurgics*).

Hand, ViKY, MC2E and the da Vinci (Fig. 2). These systems utilize several types of input methods [5]. The da Vinci Surgical System allows the surgeon to switch between the manipulation of tools and the camera, the AESOP and KaLAR system use voice recognition, while other methods, such as head and eye gaze tracking were implemented as well [6]. It is also possible to benefit from the combination of robotic platforms and command options such as it was done by [7], when a 5 Degrees of Freedom (DoF) robotic arm was created by combining the MC2E and the KaLAR.

The main approach in investigating the relevance of laparoscopic assistant robots mainly consists of the comparison of the assistant to the manual method's performance. Kavoussi et al. [10] compared the human assistant and the AESOP robot's laparoscopic camera control skills during urological MIS. The results showed that the robotic device is more effective and accurate than the human operator. A similar study was presented in [11], where the AESOP was once again compared to human camera manipulation, however in theis case the authors interest was on the surgeon's motion efficiency. The study concluded that using the robotic endoscope manipulator results in less camera motion providing a more stable video stream. It was also proved in the study performed by Aiono et al. [12] that robotic endoscope manipulation results in a decrease of operating time, which is an important factor when reasoning for the cost effectiveness and efficacy of a technology. A study on the EndoAssist robotic endoscope manipulator done by Mühlmann independently concluded the same result [13].

III. CAMERA AUTOMATION METHODS, APPLICATIONS

Beyond remotely controller robotic camera handling, there is a huge potential in automated endoscope moving, since it may significantly reduce the cognitive load on the surgeon. Visual servoing is a key algorithmic tool in image-based technologies. It is defined as "*a robot control technique which combines research results from computer vision and reobotics. Information of a vision sensor is used to define the trajectory of the robot end effector*" [21]. There are numerous visual servoing applications, and the main areas in MIS are instrument tracking and motion compensation of the living tissue. Visual servoing methods can incorporate several computer vision techniques. In Krupa's work—where experiments were performed on living tissue—optical markers and feature tracking were simultaneously used (Fig. 3) [22]. However, artificial markers are not always required. Augustinos et al. proposed an image-based control on the ViKY robot for MIS. In a study done by Dockter et al., a near real-time tool tracking computer vision algorithm was presented [23]. The application used a low cost stereo webcamera and the da Vinci surgical endoscope. The algorithm used for object tracking had three steps: 2D detection of tool tips using the Hough transform, depth extraction with disparity-depth calculation and Cartesian coordinate calculation. Another approach is the utilization of a single camera. Such study was done by Shin et al. for 3D instrument tracking [24]. The presented system had two components: (1) computer vision to find laparoscopic instruments with markers, estimation of its 3D position, rolling angle and grasper angle and (2) a virtual reality part which receives data from the computer vision part and moves the laparoscopic instruments in the virtual space. Khoiy et al. presented a laparoscopic instrument tracking method for autonomous control of an endoscope holder robot [25]. Unlike the method mentioned previously, in this case, there was no need for artificial markers for tracking; the segmentation algorithm was based on color features. The accuracy rate of 97% for high quality images and 80% for those suffering from poor lighting and/or noises was achieved. In the work of King et al., the algorithm is aiming to keep the tools in the endoscope's view [26]. The viewpoint is the centroid of the tools. If both tooltips are near the center of the view, the system zooms in; and if the tooltips are near opposite edges, the system zooms out. Kumar et al. proposed a method for surgical tool attributes labelling with Bayesian filtering (the tool is open/close, stained with blood); the algorithm uses the SVM classifier [27]. Lüder et al. combine ablation with visual control during cochleostomy [28]. Ranftl et.al developed a new dynamic camera model for high performance visual servoing loop where ultrasonic actuators are used to achieve short response time [29]. Richa et al. designed a computer vision algorithm for 3D tracking of the beating heart with stereo cameras; their algorithm is based on the thin-plate splines parametric model. The recently commercialized AutoLap system (MST Medical-Surgery Technologies) is the first product to offer camera visual servoing. Powered by proprietary image analysis software, AutoLap interacts with the surgeons movements and directions within the surgical cavity providing precise laparoscope movement and positioning, and offering full and natural control (*http://surgrob.blogspot.hu/2016/01/autolap-received-fda-clearance.html*).

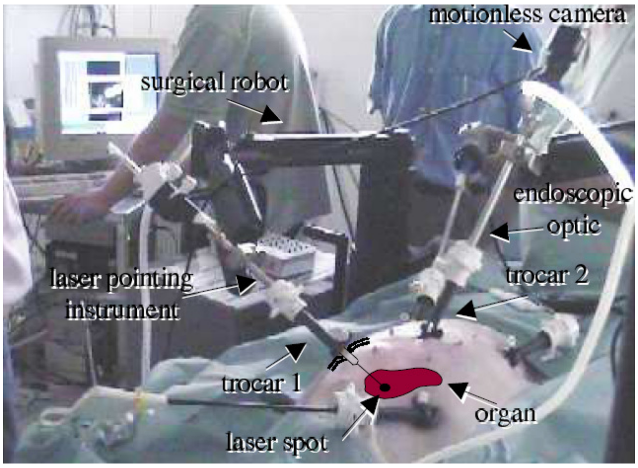

Fig. 3. Visual servoing system operative setup [22].

IV. SUBTASK AUTOMATION

While automating the decision making process in MIS is complex and challenging, the robotic execution of well defined tasks is achievable, and have been implemented in various setups. Sub-task automation has the potential to streamline a procedure, and to improve the usability of MIS systems.

A. *Needle insertion*

Needle-based techniques are widely used in MIS for both treatment and diagnosis. The applications extend to areas such as ablation, neurosurgery, biopsy, brachytherapy and others. The placement of the needle tip is crucial in these procedures, inaccuracy may result in misdiagnosis or inappropriate treatment. Nowadays, relatively stiff needles are preferred, even though those have poor steerability and cause higher tissue damage. In contrast, thinner, flexible, bevel-tipped needles cause significantly less damage and deformation to the tissue. These needles naturally bend when inserted, due to their asymmetric tip, and they move along a curved path. By rotating the needle around its axis, it is possible to steer during the insertion, avoiding obstacles, making it possible to reach the desired location more precisely. Since steering the needle manually may suffer from difficulties, robot assisted needle insertion is gaining currency in medical research, because it provides significantly better accuracy of the needle tip placement [30]. The first Ultra Sound (US) guided needle insertion on a phantom was performed by SRI's M7 robot [52].

One of the current automated needle insertion systems in research was developed by Moreira et al. (Fig. 6). In this setup, the needle is inserted into the tissue by a robotic device which is able to rotate it axially. They used offline curvature estimation using the biomechanical model of the current tissue by acoustic radiation force impulse measurement, which eliminates the need of preliminary insertions. During the insertion, the position of the needle tip is estimated by the known insertion depth and US imaging. Online curvature estimation was used to compensate the change of the Youngs modulus inside the tissue, which modifies the biomedical model real-time, and updates the steering control. Extending this system with adaptive control they were able to insert the needle into moving target in a multi-layer phantom, avoiding moving obstacle with the precision of 1–2 mm, which is in the same range as the smallest detectable object of the US images [30]. Other systems under current research are showing advanced methods for needle steering control by duty-cycled based algorithms [31], or tracking of the needle by US imaging [32]. Vancamberg et al. developed a solution for finding optimal insertion point and path for digital breast tomosynthesis biopsy without needle rotation using Rapidly-Exploring Random Tree with finite element simulation [33]. Finally, in the area of forensic medicine it is important to notice the actively used Vitrobot 2.0 prototype able to perform automatic 3D surface scanning and CT-guided robotic needle insertion [34].

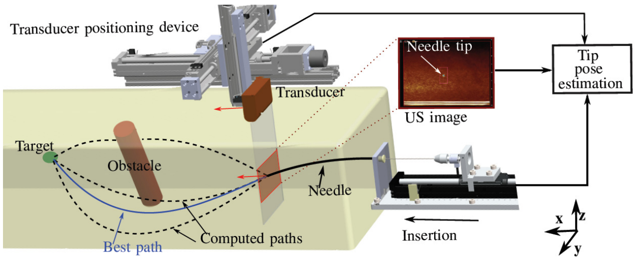

Fig. 4. The needle insertion, tracking and path planning used by Moreira et al. [30].

B. *Suturing*

The motivation behind the automation of suturing is different from needle insertion, its main purpose is to save time. Suturing, especially knot-tying is one of the most time consuming operations in robot-assisted MIS. E.g., in the case of cardiovascular disease treatment, the repair of the mitral valve requires about 12 independent sutures with as many as 6 overhand securing knots [35].

One approach for the automation of knot-tying was presented by Kuniholm et al., developing a suture cartridge prototype. This device contains a pre-tied knot and able to secure the suture, what reduced the time spent with tying knots by 25% without the redesign of the robot [35].

Another aspect is the autonomous completion of the task by the robot itself, however there is no complete solution for this problem yet, due to it's main complexity.

Recently, a group at Children's National Hospital achieved the first semi automated reconnection of bowel segments (intestinal anastomosis) during a live pig surgery. Shademan et al. designed and programmed their Smart Tissue Autonomous Robot (STAR) platform (based on a KUKA iiwa robot) to perform the suturing, combining smart imaging technologies and fluorescent markers to navigate and adapt to the complexities of soft tissue (Fig. 5). The STAR

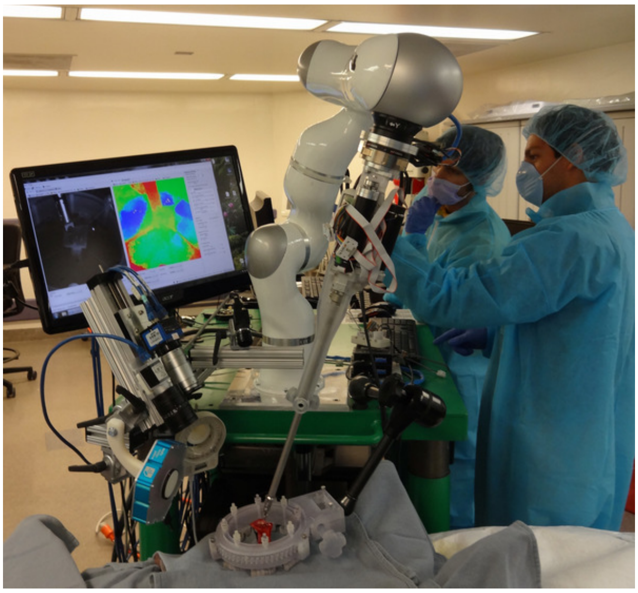

Fig. 5. A recent example of automated suturing: anastomosis on a big by the STAR robot at Children's National [53].

was tested against manual surgery, laparoscopy and robot-assisted surgery with the da Vinci. It was shown that under supervision, STAR proved superior outcome in suturing and anastomosis both ex vivo and in vivo in pigs [53].

The next step in this research is probably to study the surgeons' movement during the suturing task. The proper tools for this purpose can be ontologies; it is believed that human cognitive understanding can be translated into robotic reasoning using ontologies and these ontologies will be able to give the robot a detailed description of the surgical task [36]. Furthermore there is already a great amount of surgical data stored in machine-readable format as ontologies, however those are not standardized yet.

The area of surgical ontologies is under intensive research, which mostly aims the evaluation of the surgical skill, or to help the surgeon during the planning or the executing of the operation [37]. Morineau et al. showed that expert and novice surgeons can be separated by the work-domain ontological model of their activity [38]. Several studies presented applications aiming to help the surgeons in the operating room e.g., in instrument recognition, decision making and performing complex processes, which also seems to be helpful in robotic applications [39], [40], [41], [42]. It is important to highlight the work of Vedula et al., who captured the movement of surgeons during the suturing and knot-tying, divided it into hierarchical subtasks and created a vocabulary to analyze the workflow and evaluate the surgeons' skill level. The database they created is freely available for download [43]. Another approach was followed at Johns Hopkins University, where the formal language description of suturing was achieved within the cisst-saw project, employing Hidden Markov Models [9].

Another approach for the automation of suturing is to teach the robot by imitation, impressive results can be found in this area [44], [45]. Ghalamzan et al. presented an incremental learning approach able to reproduce the demonstrated tasks successfully even with different start and end positions with previously unknown obstacles [46]. A novel Human Machine Collaborative system was developed by Padoy et al. using the da Vinci surgical robot, which learns from surgical demonstration (Fig. 6). In this solution, the fine movements are done by the operator, and tasks with no environmental interaction are done by the robot automatically. The switch between manual and automatic mode is triggered by Hidden Markov Model based task recognition [47]. Osa et al. also presented algorithms for surgical subtask automation, especially in knot-tying. The system they developed can learn the gestures of knot-tying subtasks, such as the two-handed looping of the thread by demonstration, and reproduce it with different initial conditions (Fig. 7) [48], [49].

V. TOWARDS FULLY AUTOMATED SURGICAL ROBOTS

Arguably, current robotic technology and artificial intelligence is not there yet to completely take over both the decision making and the execution from the human surgeons. However, the rapid development of synergistic areas (e.g., self-driving cars) forecasts a rise of autonomous platforms. For some limited complexity procedures, the literature already covers some experiments.

Reportedly, a remotely-controlled catheter guiding robot was used in Milan in 2006 to automatically perform cardiac ablation, initiated and supervised by a group of professionals from Boston, MA. The robot used high magnetic fields to insert the catheter to the desired location, taking advantage of the pre-operative CT scans of the patient and real-time EM navigation. As the only (questionably authentic) report claimed, initial trials had been performed on 40 patients before the telesurgical experiment took place. The novelty of the system was that it could create the surgical plan on its own relying on an anatomical atlas built on 10,000 patients data [54].

It made headlines last year when Google announce that it has joined forces with Johnson & Johnson to develop the new generation of MIS telesurgical robotics. Verb Surgical Inc. was founded with technology, expertise, and funding from Verily (formerly Google Life Sciences) and Ethicon, a medical device company in the Johnson & Johnson family of companies. he new robot is planned to have cognitive capabilities beyond of any existing system, it will offer advanced data analytics in the OR, workflow dynamic, and even reduced cost to serve. Verb's system is anticipated to hit the market in 2019 as earliest (*http://surgrob.blogspot.hu/2015/12/verb-surgical-name-for-google-and-jnjs.html*).

VI. CONCLUSION

Surgical automation is a rapidly developing field, and various approaches have been explored in the past two decades, starting with the less invasive camera handling to the more critical needle biopsies. Computer vision offers great tools for endoscope manipulation during minimally invasive surgery, and the advantages of these algorithms

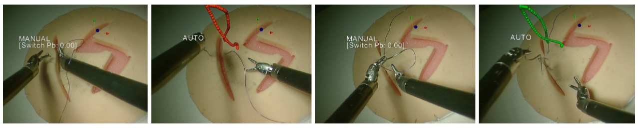

Fig. 6. An example task performed using the Human Machine Collaborative system on the da Vinci surgical robot developed by Padoy et al. [47].

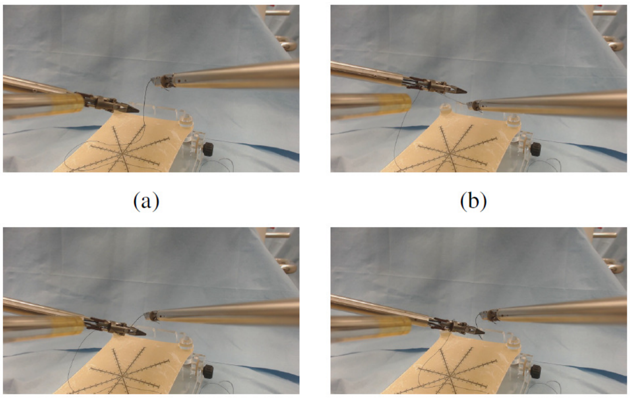
(a) (b)
(c) (d)

Fig. 7. Autonomous thread looping executed by the da Vinci surgical robot learnt from demonstration achieved by Osa et al. [49].

are already shown when the quality of the surgery or the operational time is investigated. Gradual automation of time consuming and delicate operations immediate benefits for both surgeons and patients. Automation proposes legal and ethical risks for the operation therefore full task automation remains questionable, however subtask automation can also significantly increase the surgeon's performance, keeping the surgeon in full control of the procedure.

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