Surgical Robotics and Computer-Integrated Interventional Medicine

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I. INTRODUCTION

Ever since their first introduction in the late 1980s [1], [2], surgical robots have played an increasingly prominent role in medical practice [3], [4]. For example, a recent study [5] found that over 15% of all general surgery procedures in 2020 were performed robotically, compared to only 1.8% in 2012. The current worldwide robotic surgery market is estimated to be $5.3 billion and is expected to reach $19 billion by 2027, with a compound annual growth rate over 21% [6].

These trends have been driven by the increasingly effective partnership comprising human physicians, technology, and information to improve the safety, efficacy, and cost-effectiveness of surgical interventions (Fig. 1). Robotic systems extend human sensor–motor capabilities by enabling extremely precise, delicate manipulation of tissue in both minimally invasive and “open” surgery. They can place surgical instruments and other devices with high accuracy relative to patient anatomy and are relatively unaffected by ionizing radiation.

This special issue provides an expert overview of the major application areas as well as the key enabling technologies in the growing field of surgical robotics.

This partnership can operate on an individual patient basis, but it can also facilitate continuous improvement in surgical processes, in much the same way that it can improve manufacturing processes. Computer-integrated systems generally can lead to more consistent task execution. Furthermore, the information used in planning and executing surgical tasks can be saved and combined with information about the surgical outcomes. Machine learning methods can then be used to improve treatment processes and workflow for future patients. Similarly, this information can be used to facilitate surgical training [7].

The overall information flow in computer-integrated surgical (CIS) systems is shown in Fig. 2. Patient-specific information from images, genetics, clinical history, and so on is combined with general information derived from multiple individual patients to develop a computationally effective *model* of the patient (i.e., a computer representation of relevant information that can be used for planning, control, and assessment of the treatment process). Treatment planning is highly dependent on the specific surgical task and the control paradigm used by the system. Essentially, the model and the planning information should provide sufficient information to enable successful task execution. Typical plans might include desired tool paths, safety barriers, “keyframe” animations of key surgical steps, specific control laws,

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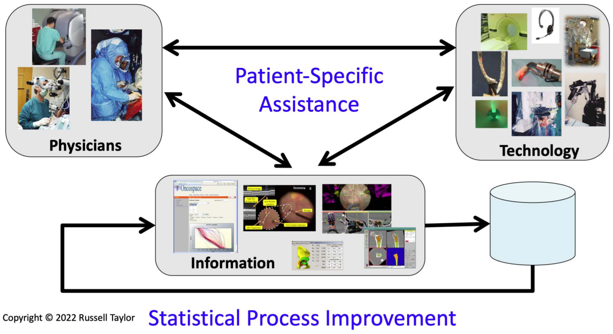

Fig. 1. *Human–machine partnership to improve the safety, efficacy, and cost-effectiveness of surgical interventions. (Figure copyright (C) 2022 R. H. Taylor.)*

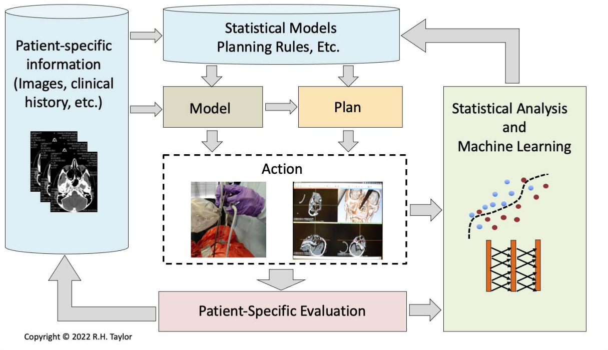

Fig. 2. *Information flow in computer-integrated interventions. (Figure copyright (C) 2022 R. H. Taylor.)*

and so on. This information is typically combined with other information gathered within the operating room to relate the "virtual reality" of the model and plan with the actual reality of the patient and equipment within the operating room. Once this registration process is completed, appropriate technology may then be used to carry out the procedure and assess the results. This process actually occurs at multiple time scales, from an entire patient treatment cycle to every second in the operating room. As discussed above, all this information can be saved, and statistical learning methods can be used to improve treatment processes for future patients.

The closed-loop paradigm described above has been described as *surgical CAD/CAM* [8] to emphasize its analogy to computer-integrated manufacturing. This nomenclature is especially apt in procedures where substantial planning is done before the procedure begins, as is often the case in orthopedic procedures (e.g., [9]), preplanned biopsies (e.g., [1]), or radiation therapy (e.g., [10], [11]). In other cases, where many or most of the surgical decisions are made interactively during the procedure, it is often more useful to think of these systems as *surgical assistants*. Teleoperated robots such as the DaVinci surgical systems (Intuitive Surgical, Sunnyvale, CA, USA) are prime examples. However, there is no sharp dividing line, and most systems will exhibit aspects of both surgical CAD/CAM and assistant paradigms, especially as more-and-more information is incorporated intraoperatively to provide feedback to the surgeon or to facilitate online modification of treatment plans. The surgeon may directly control some or all of the robot's motions in some cases, or control may be shared cooperatively, or some motions may be completely autonomous.

In the 15 years since the subject of "medical and healthcare" robots was the focus of a PROCEEDINGS OF THE IEEE special issue [13], there has been an enormous growth in active research and the range of clinical applications, accompanied by a corresponding growth in published literature (Fig. 3). Although many of the basic themes discussed in a survey article [8] included in that special issue have remained remarkably consistent over this period, a comprehensive review is no longer practical. Several recent reviews may be found in [14]–[16]. Section II provides a short overview of important and emerging clinical applications. It also provides a brief introduction of common considerations (e.g., safety, sterility, and operating room compatibility) common to these systems. Section III provides a brief technology and capabilities roadmap, with special emphasis on key emerging trends in technology and control paradigms for these systems. Section IV provides a broader discussion of how surgical robots and interventional systems fit into the larger picture of the complete cycle of care (diagnosis, treatment, recovery and rehabilitation, and home care) and related fields like prostheses, hospital logistical systems, lab automation, and the like.

II. CLINICAL APPLICATIONS AND OUTLOOK

A. Historic Clinical Drivers and Early Robotic Technology

The field of surgical robotics has grown as an extension of "computer-aided surgery," which initially provided assistance in surgical navigation, planning, and medical image registration. With the success of robotics in other domains such as manufacturing in the 1970s–1980s, researchers explored ways of extending computer-aided surgery into the realm of physical intervention by offering robotic tools as a way to

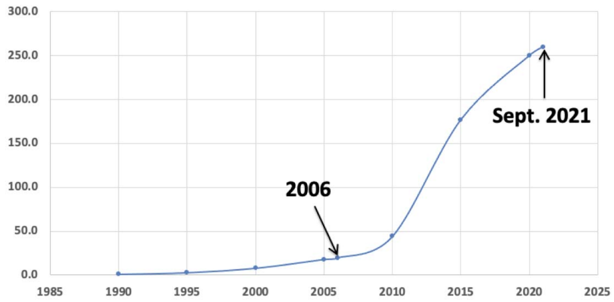

Fig. 3. ***Cumulative publications (in thousands) found with a Google Scholar search of the term "robotic surgery" [12]. The number of citations when a previous*** **Proceedings of the IEEE** ***overview article [8] appeared was 19 700; the number in September 2021 was approximately 260 000.***

achieve a more reliable and accurate coupling between preoperative surgical planning and surgical execution.

The recognition of a need for surgical robotics stemmed from advances in clinical disciplines that leveraged the availability of advanced surgical tools, but that challenged surgeons in terms of navigation, precision, dexterous reach, and perception. For example, the availability of neurosurgical interventions and radiation therapy has driven the need for stereotactic navigation aids and increased precision. In the mid-1980s, the first use of the Puma 560 robot was demonstrated for a frameless brain biopsy and followed by the clinical use of the Puma 200 for brain biopsy in 1988 [1], [17]. Driven by a similar need to localize therapy, radiation therapy has motivated innovation via robotic assistance since the 1980s and until today. Although targeted radiation delivery has been available since the first quarter of the 20th century,[1] the full potential of tumor treatment using radiation therapy manifested only when robotics became available as a tool to address the need to safely deliver localized therapy while maintaining safety for the surgeon and the patient via sweeping of the radiation source to focus energy on a localized treatment spot while avoiding trauma to surrounding healthy tissue.

The advances in laparoscopic surgery after the adoption of endoscopic instruments in the late 1970s allowed surgeons to adopt manual laparoscopic surgery in an attempt to reduce surgical morbidity. By reducing the surgical access scar size, surgeons hoped to minimize disruption to muscle layers and reduce the risk of hernia, pain, recovery time, and incision infection risk. While the use of endoscopy gathered momentum in the 1970s in gynecology, its wide adoption in general surgery was enabled by the introduction of computer chip cameras and dedicated surgical monitors in the mid-1980s [21]. Despite its advantages for patients, laparoscopic surgery introduced many challenges for surgeons. These included more difficult access, the limitation of a number of tools to as many hands as the surgeon has, the reverse kinematic mapping of the tools due to access incision constraints, lack of tool distal dexterity, and limited visual field. These challenges have created a need and an opportunity to usher in the era of robot-assisted multiport minimally invasive surgery (MIS) [22]. Along this progression of technology exploration to enable new surgical access, the possibility of natural orifice trans-urethral prostate resection was first demonstrated by Davies [23].

Most other systems in the 1990s and thereafter explored the use of robotics for multiport surgical access and the first breakthroughs were with Computer Motion's Aesop [24] and Zeus [25] systems and Intuitive Surgical's da Vinci surgical system [26] which received its first U.S. Food and Drug Administration approval in 2000.

B. Continued Evolution Up to Today

The historic progression of human–robot partnerships and the proper extent of robot autonomy was (and still is) not entirely clear. Modes of collaboration include teleoperated robotic manipulation driven by the surgeon (e.g., [26]); semi-active systems driven by a surgeon, but using safety zones to prevent risky excursions of the tools (e.g., [27], [28]); and fully autonomous robots carrying out a preoperative plan for a major task within a procedure under surgeon supervision (e.g., [19], [29]). Of these modes of operation, teleoperation is probably the most widely adopted in commercial systems (e.g., the da Vinci systems). However, there are a growing number of exceptions. For example, in addition to the Robodoc system shown in Fig. 4, Stryker's RIO system [30] offers semi-active assistance for orthopedic surgery, and the Cyberknife [31] is a fully autonomous robotic system for radiation therapy.

Irrespective of the mode of human–robot partnership adopted, robots have been used for augmenting manipulation, increasing distal dexterity, enhancing precision, and lowering the physiological and cognitive burden of coordinated motion. To successfully achieve widespread commercial deployment of robotic surgery systems, other desirable attributes must be addressed in addition to augmentation of surgical execution. Commercial systems must address key considerations for facilitating clinical adoption (e.g., minimal disruption to the clinical

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[1] For example, brachytherapy was demonstrated by Dr. Benjamin Barringer in 1915 [18] and an external beam radiation device was used in 1918 in Memorial Sloan Kettering Cancer Hospital.

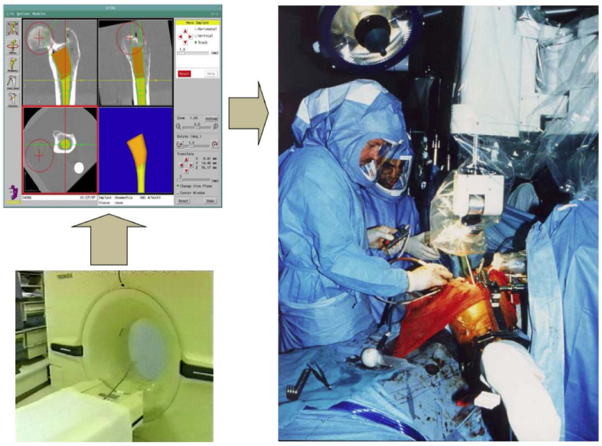

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Fig. 4. ***Robotic joint replacement with the "Robodoc" system [9], [19], [20]. The system combined CT-based planning with autonomous robotic machining of bone for cementless hip and knee implants. (Photos courtesy of Think Surgical; figure copyright (C) 2022 R. H. Taylor.)***

workflow, minimal footprint, and system reconfigurability). Teleoperated systems such as Intuitive Surgical's da Vinci have addressed many of the manipulation needs for abdominal MIS and have gradually matured to facilitate clinical deployability by addressing needs such as synchronous surgical table and robotic positioning relative to the patient (e.g., Intuitive Surgical's da Vinci Xi integrated table Motion [32]). Other systems such as Mazor's SpineAssist system [33] leverage device miniaturization to enhance portability and limit size obstruction while offering the necessary image-guided navigation and assistance for spinal implants [34]. Recent minimally invasive systems address also modularity (e.g., the Medtronic Hugo system [35] and the CMR Surgical Versius [36] system).

Surgical disciplines such as neurosurgery, urology, gastroenterology, ear, nose, and throat (ENT), thoracic, cardiac, and microsurgery continue to drive clinical needs that demand the benefits of human–robot partnership. This special issue provides an overview of the most relevant technological advances that push the boundary of what is currently possible to enable new surgical paradigms addressing the clinical needs driven by these surgical disciplines.

C. Emerging Clinical Translation

Progress in surgical robotics has been largely enabled by maturing technologies that have built upon scientific progress in the last 40 years. Nascent surgical robotics technology will enable additional new surgical interventions and expand into new surgical domains. Examples of these areas are covered by this special issue.

The success of existing commercial systems and the development of new technological capabilities over the last two decades have enabled new surgical paradigms for supporting robotic assistance in thoracic surgery, upper airway surgery, single port access, natural orifice, endoluminal and transluminal interventions, microsurgery, catheter-based interventions (e.g., cardiac, lung, and neuroendovascular), and untethered robotics (magnetic manipulation).

The commercial outlook for some of these new surgical paradigms remains unclear, but applications related to catheters are being aggressively pursued for minimally invasive lung biopsy (e.g., Intuitive Surgical's Ion [37] and Auris Healthcare Monarch [38] systems) and endovascular surgery (e.g., the Corindus CorPath [39] system). Other emerging clinical translation areas include systems for microsurgery (e.g., Preceyes system for ophthalmic surgery [40]) and systems for magnetic manipulation (e.g., the Stereotaxis Genesis system [41]).

III. TECHNOLOGY AND CAPABILITIES ROADMAP

As surgeons explore new techniques for deep access, challenges in robot design and effective partnership between robots and surgeons become more critical [22]. The next-generation surgical robotic systems will harness new technological developments and capabilities as they gradually mature and pass preclinical studies. These systems must harness advances in materials, design, sensing, image guidance, actuation, precision, and machine learning to achieve safe deep-site surgery while alleviating the surgeon's challenges in terms of sensory perception and situational awareness. We cover in this special issue the key advances in core areas related to new designs, actuation methods, sensing, image guidance, and autonomy. This section briefly discusses some of the core areas of technological advances covered in this special issue.

A. Continuum and Soft Robots

Motivated by the need for a safe and flexible way to reach into deep regions of the human body, continuum and soft robotics technologies have become clear contenders for applications requiring limited forceful interaction with patient anatomy. Existing teleoperated surgical systems rely on elongated and mostly rigid parts, gears, and tendons, thus limiting their ability to maneuver safely along sinuous paths. Both continuum and soft robots achieve complex equilibrium shapes for steering and navigation into the anatomy using a combination of passive deflection as a result of interaction with the anatomy and active deflection as part of intentional steering action meant to circumvent obstacles. Continuum robots are mostly distinguished from soft robots by using super-elastic NiTi composites for achieving their structural rigidity as opposed to soft elastomers used for soft robots.

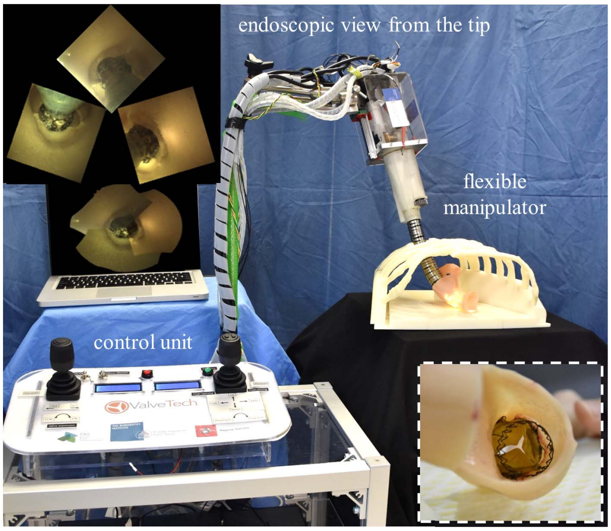

Fig. 5. *ValveTech robot: a flexible cable-driven manipulator for efficient delivery of an artificial aortic valve by the help of integrated endoscopic vision. The inset image shows the released valve in an aortic mockup [42].*

In doing this, continuum robots are capable of applying sufficient forces for surgical intervention and manipulation and offer a middle ground between rigid-link robots and soft robots. Soft robots are able to better approximate the compliance of tissue, and therefore, they offer added safety and can be used mostly for applications requiring delicate interaction with the anatomy or as implants navigating into anatomical passageways (e.g., perimodiolar cochlear implant electrode arrays). Continuum and soft robots continue to generate significant interest among clinicians (e.g., [43]–[45] and Fig. 5), and general enthusiasm for practical results, for example, based on simple, flexible, and shrinkable manipulators able to see behind the organs [46].

Both continuum and soft robots require new approaches for modeling, sensing, and control. Continuum robots require new modeling approaches that take into account the mechanics at the cornerstone of the modeling effort. Unlike rigid link robots, these robots undergo significant structural deflections to achieve their shapes. They rely on wires, push–pull actuation, or antagonistic elastic tube pairs to allow miniaturization. They present new types of singularities manifested by structural instability that is not present in traditional rigid link robots. The details of the design and modeling challenges for continuum robots are discussed in an article by Dupont *et al.* included in this special issue.

The recent adoption of soft robotics has also demonstrated that traditional design and control schemes have to be reconsidered. In soft robots, tendons, motors, and gears are substituted by pneumatic and hydraulic actuators, which deform silicone chambers with self-containing external sheets [47]. The adaptability of manipulators opens important challenges in terms of control. For teleoperating these soft devices with acceptable precision, we need to integrate sensors, but the sensorization process is not straightforward: due to the large flexibility and elongation of these devices, traditional sensing solutions cannot be applied and have to be substituted by different technologies, for example, based on fluidic sensors [48]. Last but not least, if a soft body is the best option for navigating in a safe way around organs, a rigid body is necessary for performing the task when the target has been reached. In this context, researchers have developed different solutions for tuning the stiffness of the soft robots [49], [50]. The above considerations are discussed in detail in the article by Althoefer *et al.*

B. Robots for Single-Port Access, Natural Orifice, and Transluminal Surgery

To address the need for minimally invasive deep intervention, emerging technologies for enabling new surgical access approaches, these systems leverage progress made in the design of wire-actuated mechanisms, continuum robots, and catheter-like systems to enable deep access (e.g., Fig. 6 shows examples for natural orifice access and Fig. 7 shows a system for single-port access). The design solutions for these systems are driven by the need for miniaturization and a high number of actuated joints (degrees of freedom) to achieve complex shapes. These robots have many more actuated joints (degrees of freedom) than the minimal necessary to achieve manipulation of their end-effector. These systems present unique challenges in terms of the resolution of kinematic redundancy and control and require ingenious design solutions that bring to bearing unique designs of wristed instruments, snake-like robots, and multiarm foldable devices. The progress made on some of these systems is presented in this special issue in an article by Kim *et al.*

C. Precise Surgery With Image Guidance

The ability of a surgical robot to place a tool onto a target with high geometric accuracy is frequently the crucial advantage offered by the system. The targeting information for these "image-guided" surgical applications generally comes from medical images acquired either before or during the procedure. Successful applications within this paradigm require methods for extracting the necessary information from medical images, typically using a combination of medical image segmentation, interactive designation by the surgeon, and (increasingly) automated

Fig. 6. *Natural orifice trans-urethral bladder access using continuum robots [51], [52].*

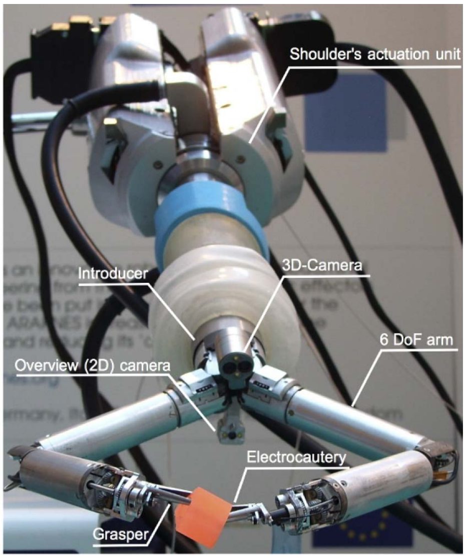

Fig. 7. *SPRINT (Single-Port lapaRoscopy bImaNual roboT) is a teleoperated bimanual robot developed in the framework of the ARAKNES European Project (FP7 grant agreement n. 224565) aimed at introducing flexibility and modularity in single-port surgery [53].*

planning methods. This information must then be "registered" to the coordinate system of the robot, and the robot must be able to execute the requisite motions to perform the task, often exploiting additional sensing or imaging of tool-to-tissue relationships or to accommodate patient motion. An example of a robotic platform guided by ultrasound and using high-intensity focused ultrasound to perform ablation and therapy is represented in Fig. 8. The article in this issue by Fichtinger *et al.* discusses the current state-of-the-art and emerging trends for such systems in greater detail.

The ability of robotic systems to use intraoperative imaging devices for on-the-spot targeting and real-time feedback during a procedure is often a decisive factor in enabling task execution. However, this has also required new robotic technologies capable of respecting the environmental constraints of the imaging modality used. Common imaging modalities include X-rays, computed x-ray tomography (CT), ultrasound, video, and magnetic resonance imaging (MRI). In some cases, these constraints are fairly easy to meet, and the use of a robot can actually offer other advantages. For example, the use of a robot with an X-ray system can enable the surgeon to avoid repeated exposure to radiation over the course of multiple procedures. Similarly, robotic manipulation of an ultrasound probe can help reduce the risk of repetitive stress injuries to the surgeon or ultrasonographer and allow easier ultrasound probe position recall for revisiting the same imaging site. The article by Salcudean *et al.* in this issue discusses the issue of robot-assisted imaging in further detail.

In other cases, the constraints imposed by the imaging modality can be much more challenging. One example is MRI imaging. MRI systems can provide exquisite tissue discrimination and functional information for targeting and monitoring during a procedure, but the strong magnetic fields and sensitive radio-frequency sensing required to form MRI images can severely restrict the materials, actuators, and sensor choices used in the design of the robot. Methods of actuation for MRI-compatible robots have included a variety of pneumatic, hydraulic, and ultrasonic motors—each of which presents unique challenges in terms of modeling, control, and system integration. Finally, the MRI's own magnetic field can be used for imaging and for actuation (a review of which was presented in [55]). The article by Fischer *et al.* included in this special issue discusses the major advances in MRI-compatible robots.

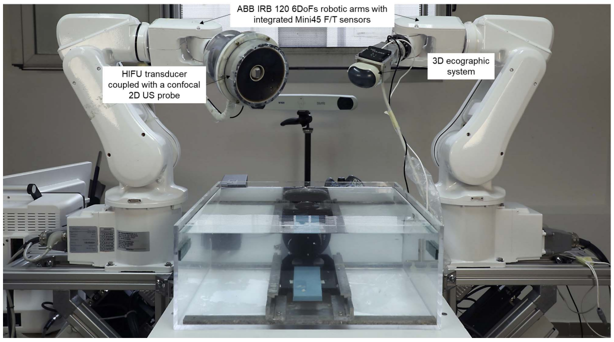

Fig. 8. ***FUTURA (Focused Ultrasound Therapy Using Robotic Approaches) platform for high-intensity focused ultrasound surgery guided by ultrasound imaging [54].***

D. System Control, Task Automation, and Autonomy

Surgical robots are not surgeons; they are surgical tools intended to help surgeons treat patients [56]. Broadly, as with any robotic system, task specification and control requires answers to two fundamental questions. First, how can the human physician specify what the robot is supposed to do? Second, how can the robot controller perform the specified task safely and reliably?

For image-guided systems whose main function is simply to place a tool or tool guide at the desired location or to move a cutter or radiation beam over a predefined path, the specification task is fairly straightforward. The surgeon interacts with a computer to define targets and paths from medical images, often with the assistance of sophisticated planning software. For task execution, the main challenges are registration of the plan to the patient, accommodation to any possible patient changes or motion (often incorporating real-time images or other sensors), and the "usual" issues of system integrity, reliability, and the like found in any safety-critical system.

For teleoperated and "cooperatively controlled" surgical robots, the specification and execution tasks are again conceptually straightforward, although there remain significant engineering challenges to ensure system safety and reliability. Typically, the surgeon manipulates control handles or other haptic interfaces to specify the desired tool motions, and the robot moves the surgical tools accordingly. The surgeon observes the tool motions visually (typically through a video display, microscope, or directly) and relies on his or her situational awareness to accomplish the desired task.

In recent years, there has been increasing interest in exploiting the potential of robotic systems to provide more active assistance to the surgeon by automating tedious or repetitive subtasks or by sharing control between the surgeon and the robot to improve the safety or accuracy of the procedure. Both the task specification and task execution components for this human–machine partnership require a shared situational awareness between the surgeon and the system of the patient anatomy, tool-to-tissue relationships, and the surgical procedure being performed [59], [60]. Fig. 9 illustrates the flow of information involved in these systems. Fig. 10 illustrates the use of direct hand-over-hand cooperative control and registered anatomic models in endoscopic sinus surgery. Here, both the robot and the surgeon hold a surgical probe tool. The robot complies with forces exerted by the surgeon on the tool while also enforcing a "virtual fixture" to prevent the surgical tool from touching critical anatomy within the sinus.

Starting from work in the early 2000s to develop a "language of surgery" based on analysis of surgical robot motion, computers are increasingly able to analyze the steps of surgical procedures (e.g., [61]–[63]). In addition to applications in surgical training and skill assessment, these techniques potentially can contribute to an enhanced situational awareness for customizing assistance and autonomy during procedures, as well as enabling the application of machine-learning techniques to relate variations in surgical techniques to outcomes [64], [65]. Recent advances in computer power, computer vision and sensor integration, machine learning, real-time modeling, and simulation capabilities have enabled significant progress in online assistance, autonomy, and safety assurance in recent years (e.g., [66], [66]–[69]). In addition to the survey articles cited above, further discussion of issues and progress in this area can be found in the articles in this issue by Fichtinger *et al.* and Fiorini *et al.*

E. Haptics and Human–Machine Interfaces

The increasing use of telerobotic surgical robotic systems has placed the surgeon's hands and eyes away from the surgical scene, providing advantages to the surgeons in terms of ergonomy, motion scaling, and enabling a direct mapping of hand and tool motion. This also creates an increased perception barrier compared to open surgery. To overcome this challenge, haptic human–machine interfaces have been designed to help recover the lost sensory presence using combinations of force feedback, vibrotactile feedback, and substitution of one sensory modality for another (e.g., use of auditory cues to indicate force levels). The factors that affect surgeon performance using a telemanipulated robotic system have been a subject of heavy study of human factors. The effects of motion scaling, force feedback, sensory substitution, and the type of visual displays have been heavily explored to discern the optimal combination that lowers the sensory

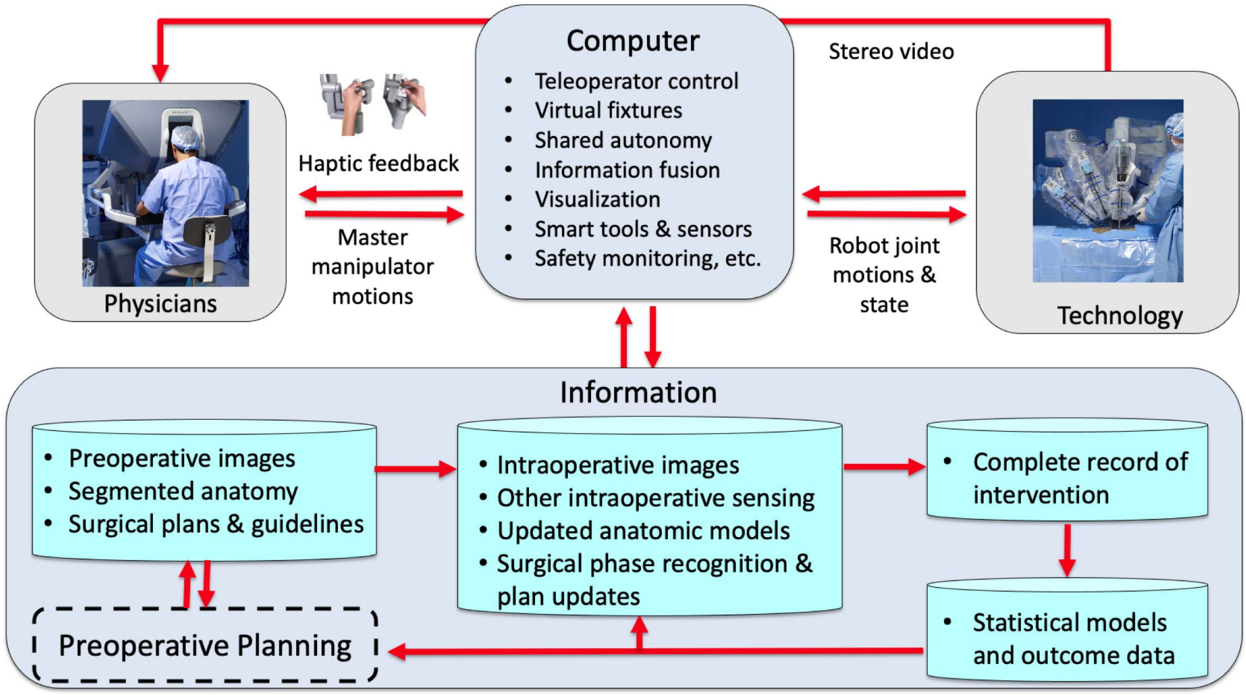

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Fig. 9. ***Information-enhanced interactive surgery. This figure illustrates the information flow in an emerging class of highly interactive surgical systems in which the robot provides assistance to the surgeon going well beyond traditional teleoperation or hand-over-hand cooperative control. (Figure copyright (C) 2022 R. H. Taylor.)***

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Fig. 10. ***Hand-over-hand cooperative control with virtual fixtures for sinus surgery. In this experiment, (a) the surgeon manipulates a pointer tool held by the robot while (b) observing the tool through endoscopic video. (c) The system uses a registered model of the tool-to-anatomy relationship to help guide the tool to its desired target while ensuring that it does not collide with delicate structures [57], [58]. (Figure copyright (C) 2022 R. H. Taylor.)***

barrier without undue distraction or cognitive burden to the surgeon. The areas of information-augmented displays, 3-D displays, and augmented reality have also been extensively explored as a means to help surgeons better identify surgical targets and discern the surgical interaction characteristics such as force and stiffness of the manipulated anatomy. More recently, exploration of virtual reality and augmented reality for complex anatomy (e.g., spinal neurosurgery and retinal microsurgery) have been presented (e.g., [70], [71]). The article by Patel *et al.* included in this special issue discusses the key advances made in the area of haptics.

F. Robot-Assisted Imaging

In addition to *using* medical images in surgical applications, robots can also be used to help *acquire* images used for diagnostic or interventional purposes. These applications exploit the ability of robotic systems to accurately position an imaging sensor relative to a patient's anatomy, move the sensor in a precisely controlled path, or combine sensing with other forms of tissue manipulation. Although most commonly found in ultrasound, X-rays, or computer vision applications, there are also beginning to be with other modalities, as well (e.g., [72]). The article by Salcudean *et al.* in this special issue discusses the current state of the art and potential avenues of research in this area.

G. Microsurgery Systems

Surgical interventions on delicate structures such as the eye, ear, nerves, or very small blood vessels often pose significant challenges for human surgeons, because of human sensory-motor limitations. Human hand tremor limits a surgeon's ability to manipulate surgical tools with the submillimetric precision required, and tool-to-tissue interaction forces are often well below human perceptual thresholds. The potential of robotic systems to address these limitations has long been recognized (e.g., [27], [73]), and microsurgery has been an increasingly important focus for both research and commercial development. Robotic systems can be controlled to make very precise, tremor-free micrometer-scale motions. Furthermore, information from extremely sensitive force and other sensors can be incorporated into the robot control system. These capabilities are especially important for ophthalmic applications, and the article by Iordachita *et al.* in this issue discusses current research and commercialization activities in this area. Magnetically manipulated microrobots also show promise for extremely fine-scale, minimally invasive interventions in the eye and other parts of the body. Additional discussion of this technology may be found in the article by Nelson *et al.* in this special issue.

IV. BROADER PICTURE

Over the past 30 years, the development of surgical robots has enjoyed a steady growth in clinical applications, largely driven by increasing healthcare demand, patient acceptance, and the maturity of allied technologies. However, in the future, patients and healthcare providers will become more critical about the postoperative quality, cost-effectiveness, and unique niche that robotics technologies can offer, in addition to how they can be seamlessly integrated with the overall surgical workflow.

With rapid advances in imaging and diagnostic technologies, as well as our improved understanding of different disease progressions and their impact at a system level, surgery is moving toward greater precision and earlier intervention. This itself poses challenges to the future development of robotic surgery. New systems need to deal with smaller, earlier lesions with unprecedented accuracy, linking imaging, cellular, and molecular biomarkers with consideration of system-level function and ensuring quality of life after surgery in the long term. Increased longevity and survival after major illnesses means that many surgical patients are likely to have comorbidities and become octogenarians. Comorbidity means isolated surgical treatment will be suboptimal as local intervention can have inevitable transient or persistent metabolic, hemodynamic, and neurohormonal consequences. In this regard, we need to consider not only minimizing invasiveness and surgical trauma, but also potential system-level complications.

As many diseases originate and develop within lumens, endoluminal interventions will be increasingly performed and many of the technologies mentioned earlier will become clinically important. Future surgical robots will be smaller, smarter, and more agile, offering truly superhuman dexterity and vision [74]. As we move toward earlier, smaller-scale and more targeted intervention, close integration with imaging is key to the future success of surgical robots. We have already seen the effective use of both pre- and intra-operative imaging for surgical navigation via MRI, CT, or ultrasound imaging modalities [75]–[77]. Microscopic imaging will be increasingly used in the future, particularly by leveraging developments in biophotonics to bring cellular and functional imaging to an *in situ–in vivo*, surgical environment. This alters the planned surgical pathways, for example, tissue biopsy, by streamlining intraoperative surgical decision-making, hence mitigating postoperative complications and risks for revision surgeries.

One fundamental shift of future healthcare is that surgical intervention must not be done in isolation and limited only to the operating theater. Smart implants are likely to be increasingly used for continuous monitoring and regulation of a patient's health. Pervasive sensing and rehabilitation robots will play an increasingly important role throughout the entire treatment cycle. Neurosurgical procedures need to be supported by postoperative rehabilitation for "recovering musculoskeletal function or as prosthetics for daily assistance, providing dexterity, natural mobility, and sensation to missing or paralysed limbs... augmenting missing movements and sensing, supporting motor function and independence" [78]. It is important to consider functional level restoration at all levels: organ, system, and physical functions, as well as perceptual and cognitive implications.

The recent and ongoing COVID-19 pandemic has completely changed our society, not only in terms of dealing with the resulting disruption, but also in searching for a new norm during and after the pandemic [79]. Historically, the use of surgical robots for managing patients with infectious diseases has not been a major focus of the medical robotics community. However, this is likely to change as it has now become clear that the effective use and innovative development of robotics can play a vital role in mitigating infection risks. In addition, patients infected with coronavirus may also have other implications that require intervention that could be assisted by surgical robots. In a recent review, Gao *et al.* summarized how robotic technologies could be used to combat infectious diseases in a range of different scenarios and explained the need to further develop related technologies [80]. These include better sensing and imaging, improved teleoperation and navigation, intuitive human–robot interaction, more effective machine-learning techniques, as well as the need for technically mature, application-centered robots. In addition, a greater focus on laboratory automation and logistics, improved user experience, and coordinated, globally sustained efforts are required. These are in reflection of the current "last-minute" prototypes that have been rapidly developed during the COVID-19 pandemic, in an attempt to respond to the emergency demand and the terrible experience of many patients who are deprived of normal surgical care.

As we still see, few signs of the pandemic-relenting health services must establish long-term sustainable solutions, rather than immediate fixes, to cope with unexpected surges of newly infected patients while maintaining routine service provision at all levels. In this regard, there are certainly further challenges for the surgical robotics community to consider in the development of future generation robots.

Acknowledgment

Under a license agreement between Galen Robotics, Inc and the Johns Hopkins University, Russell H. Taylor and Johns Hopkins University are entitled to royalty distributions on technology that may possibly be related to that discussed in this publication. Russell H. Taylor also is a paid consultant to and owns equity in Galen Robotics, Inc. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict-of-interest policies. Dr. Taylor's patents on surgical robot technology have also been licensed to other commercial entities and both Dr. Taylor and Johns Hopkins University may be entitled to royalty distributions on this technology. Also, Dr. Taylor receives salary support from separate research agreements between Johns Hopkins University and Galen Robotics and between Johns Hopkins University and Intuitive Surgical, from the Multi-Modal Medical Robotics Centre in Hong Kong, and from various U.S. Government agencies. ■

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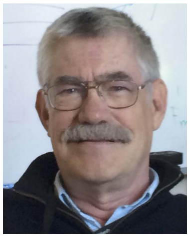

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