INVITED PAPER

Robot-Assisted Minimally Invasive Surgery—Surgical Robotics in the Data Age

This article summarizes the state of the art in robot-assisted minimally invasive surgery and provides an overview of key emerging technologies associated with next-generation systems.

By TAMÁS HAIDEGGER, *Senior Member IEEE*, STEFANIE SPEIDEL, *Senior Member IEEE*, DANAIL STOYANOV, *Senior Member IEEE*, AND RICHARD M. SATAVA, *Member IEEE*

ABSTRACT | Telesurgical robotics, as a technical solution for robot-assisted minimally invasive surgery (RAMIS), has become the first domain within medicosurgical robotics that achieved a true global clinical adoption. Its relative success (still at a low single-digit percentile total market penetration) roots in the particular human-in-the-loop control, in which the trained surgeon is always kept responsible for the clinical outcome achieved by the robot-actuated invasive tools. Nowadays, this paradigm is challenged by the need for improved surgical performance, traceability, and safety reaching beyond the human capabilities. Partially due to the technical complexity and the financial burden, the adoption of telesurgical robotics has not reached its full potential, by far. Apart from the absolutely market-dominating da Vinci surgical system, there are already 60+ emerging RAMIS robot types, out of which 15 have already achieved some form of regulatory clearance. This article aims to connect the technological advancement with the principles of commercialization, particularly looking at engineering components that are under development and have the potential to bring significant advantages to the clinical practice. Current RAMIS robots often do not exceed the functionalities deriving from their mechatronics, due to the lack of data-driven assistance and smart human–machine collaboration. Computer assistance is gradually gaining more significance within emerging RAMIS systems. Enhanced manipulation capabilities, refined sensors, advanced vision, task-level automation, smart safety features, and data integration mark together the inception of a new era in telesurgical robotics, infiltrated by machine learning (ML) and artificial intelligence (AI) solutions. Observing other domains, it is definite that a key requirement of a robust AI is the good quality data, derived from proper data acquisition and sharing to allow building solutions in real time based on ML. Emerging RAMIS technologies are reviewed both in a historical and a future perspective.

KEYWORDS | Remote-controlled teleoperation; robot-assisted minimally invasive surgery (RAMIS); telesurgical robotics.

Manuscript received November 15, 2021; revised April 25, 2022; accepted May 25, 2022. Date of current version June 20, 2022. This work was supported in part by the Austrian Center for Medical Innovation and Technology (ACMIT), which is funded within the scope of the Competence Centers for Excellent Technologies (COMET) Program of the Austrian Government. The work of Tamás Haidegger was supported in part by the National Research, Development and Innovation Fund of Hungary under Grant 2019-1.3.1-KK-2019-00007. The work of Stefanie Speidel was supported by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany's Excellence Strategy-EXC 2050/1-Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) of Technische Universitat Dresden under Project 390696704. *(Corresponding author: Tamás Haidegger.)*

Tamás Haidegger is with the University Research and Innovation Center (EKIK), Óbuda University, 1034 Budapest, Hungary, and also with the Austrian Center for Medical Innovation and Technology (ACMIT), 2700 Wiener Neustadt, Austria (e-mail: haidegger@ieee.org).

Stefanie Speidel is with the National Center for Tumor Diseases (NCT) Dresden, 01307 Dresden, Germany, and also with the Centre for Tactile Internet with Human-in-the-Loop (CeTI), TU Dresden, 01069 Dresden, Germany (e-mail: stefanie.speidel@nct-dresden.de).

Danail Stoyanov is with the Wellcome/EPSRC Centre for Interventional and Surgical Sciences, University College London (UCL), London WC1E 6BT, U.K. (e-mail: danail.stoyanov@ucl.ac.uk).

Richard M. Satava is with the University of Washington Medical Center, Seattle, WA 98195 USA (e-mail: rsatava@uw.edu).

Digital Object Identifier 10.1109/JPROC.2022.3180350

NOMENCLATURE

AI	Artificial intelligence.
CAD	Computer-aided design.
CAM	Computer-aided manufacturing.
CE	Conformite Europeenne.
CT	Computed tomography.
DVRK	da Vinci Research Kit.
DoF	Degrees of freedom.
FDA	U.S. Food and Drug Administration.
IEC	International Electrotechnical Commission.

ISO	International Organization for Standardization.
MEE/MES	Medical electrical equipment/system.
MIS	Minimally invasive surgery.
ML	Machine learning.
MRI	Magnetic resonance imaging.
OR	Operating room.
RAMIS	Robot-assisted minimally invasive surgery.
TRL	Technology readiness level.
US	Ultrasound.

I. INTRODUCTION

Robotic surgery in the common language has become associated with the telerobotic execution of MIS, where the surgeon is physically separated from the patient—typically just a few steps away—and the surgical instruments are under the direct guidance and remote control of a human operator. This clinical approach is named RAMIS, also called robotically assisted or simply robotic MIS. The ergonomic arrangement for such systems is well suited to the modern and increasingly popular paradigm of MIS, performed through keyhole ports, which has replaced many traditionally open surgery procedures, due to the reduced tissue trauma, resulting in direct patient benefits, and offering better ergonomics for the surgeons while introducing numerous technological components for use in the OR [1]. This article focuses on linking the technical capabilities of systems to their clinical applicability, considering the regulatory environment in which they need to perform. Understanding the state of the art shall begin with looking into the current market landscape, where a single product has dominated the last two decades.

RAMIS relies on real-time imaging, using an endoscopic camera, which provides a wide-angle, high-resolution, white-light, video stream as the main sensory feedback from the surgical site. The robotically articulated instruments are maneuvered by the surgeon, through a surgical console, i.e., human–machine interface (HMI), which relies on the video stream. This synergy of the minimally invasive paradigms has been a catalyst for the use of robotic assistance and has grown rapidly over the last decade, as reflected by the annual 1.5 million procedures (with a 15% annual growth) performed using the "da Vinci surgical system" alone (from Intuitive Surgical Inc., Sunnyvale, CA, USA), making it by far the most popular RAMIS system to date [2]. The main factors that contributed to the outstanding success of da Vinci and its telerobotic concept include the followings [3], [4]:

1) advanced technology features, including better vision and instrumentation;
2) ergonomics and safety (EndoWrist for suturing, tremor filtering, and improved situation awareness);
3) strong evidence for improved patient outcome collected over the years;
4) targeting procedures, where the quality of life can be improved significantly (prostatectomy, benign hysterectomy, and so on);
5) strong training program developed over the years (including simulators);
6) no high-level autonomy introduced, therefore the legal responsibility remained with the surgeon;
7) massive marketing and promotion;
8) solution selling (consumable and service-based business model).

On the healthcare providers' side, patient benefit has been a driving factor of robotic programs, and over the years, significant clinical evidence emerged supporting various (but not all) application domains, starting with prostatectomy and benign gynecological procedures. Since 1998, over 29 000 peer-reviewed studies have been published on da Vinci surgery alone. Yet, recent studies still leave some key questions open regarding the long-term benefits of MIS versus open surgery in, e.g., in the case of radical hysterectomy [5]. It has to be noted that since separate approval is required for each intended clinical domain of a RAMIS system, the approach and timeline chosen by the manufacturer will fundamentally determine the pathway the system may take [6]. Arguably, there is a strong correlation between costs and the adoption of robotic surgery; in the United States, where healthcare expenditures account to 18% of the gross domestic product (GDP), approximately 5% of all surgeries are performed robotically, while in the European Union (EU), which spends on average 10% of its GDP on healthcare, robotic surgery adoption is only around 2% [7], and adoption remains below 1% in most of the rest of the world. Medtronic assumes that altogether, only 3% of the total addressable market of RAMIS is achieved yet. In parallel, the total market value of surgical robotics was estimated by Frost and Sullivan at \$8.3 billion in 2020, expected to reach \$33.6 billion by 2026 [8].

RAMIS in practice is predominantly represented by remote-controlled leader–follower (formerly called master–slave) robots, used exclusively in the telemanipulation mode, where the surgeon is decoupled from the direct handling of the surgical tools. In the meanwhile, several other classes of surgical or interventional robots are also in clinical use with different architectures [9]. A popular domain of application (excluded from the scope of this article) is where the robotic execution of a predefined surgical plan relies on medical imaging, thus called image-guided interventional robotics (discussed in [10]), while collaborative control is also a popular choice; especially in neuro and orthopedic applications, it is not discussed further in this article. Microsurgical systems and endoluminal robots are also excluded from this analysis, despite the fact that they share a lot with RAMIS in terms of mechatronics, control architecture, and future perspectives (sometimes even the physical platform is shared, as in the case of the da Vinci SP)—these are covered in the article by Dupont *et al.* [11].

Technically, almost all surgical robot systems have a common feature, and they employ a robotic mechanism (robot in the widest sense [12]) to provide accurate guidance, assistance, or direct delivery of instruments or energy. Such systems can focus energy, as in radiotherapy

Fig. 1. ***Most advanced RAMIS systems, featuring only commercially available, and ready-to-launch platforms, already cleared for at least a limited set of surgical indications (presented in the order of time of appearance). (a) da Vinci Xi. (b) Senhance Surgical Robotic System. (c) Revo-i. (d) Versius. (e) Avatera. (f) Hinotori. (g) Dexter. (h) Symani Surgical System. (i) Toumai Endoscopic Robot. (j) Mantra. (k) Hugo RAS System. (l) Bitrack. Table 1 at the end provides details regarding these robots' basic engineering and clinical capabilities. (Image credit: the manufacturers.)***

or high-intensity focused ultrasound (HIFU) treatment for example, or steer needles or other tools. These rely on precise preoperative planning, performed on patient imaging information usually using 3-D modalities such as CT or MRI. We only include in our RAMIS classification full-scale, teleoperational surgical systems, where the end-effector typically does not require continuum robot-like complex (6++) DoFs articulation.

II. HISTORY AND EARLY CHRONICLE

While an exact inventor behind the idea of telerobotic surgery cannot be identified, some early pioneers at the U.S. National Aeronautics and Space Administration (NASA) and the U.S. Department of Defense, Defense Advanced Research Projects Agency (DARPA) laid the foundations of the domain already in the late 1960s, inspired by the remote manipulators employed in nuclear facilities and developed for space [13]–[15]. Given the outstanding commercial success of the first FDA cleared RAMIS system, Intuitive's da Vinci in 2000, it was evident that many other research projects and companies aimed to create their own systems, with little or no deviation from the da Vinci [16]–[19]. Intuitive overtook its former rival, Computer Motion (Goleta, CA, USA) in 2003, and discontinued their Zeus Robotics Surgical System product line immediately, therefore they remained alone on the U.S. market for 15 years. The lack of direct competitors can partially be explained with Intuitive's outstanding patent portfolio, effectively defending their technology, and also with the fact that many in-house surgical robot developments at the competitors, could not conclude in a product (due to cost, regulatory, and complexity issues) and therefore remained unreported. Only recently, we are seeing a massive wave of novel entrants, looking forward to introduce radical technological changes compared to the past decades' evolutionary development.

III. STATE OF THE ART IN RAMIS

A scoping literature review identified over 65 documented research projects aimed at developing new, complete RAMIS systems, yet only 15 managed to acquire some national clearance and only five achieved sales in more than one country (Fig. 1) [20], [21]. Table 1 includes a list of known, recognized RAMIS systems at the TRL 9+.

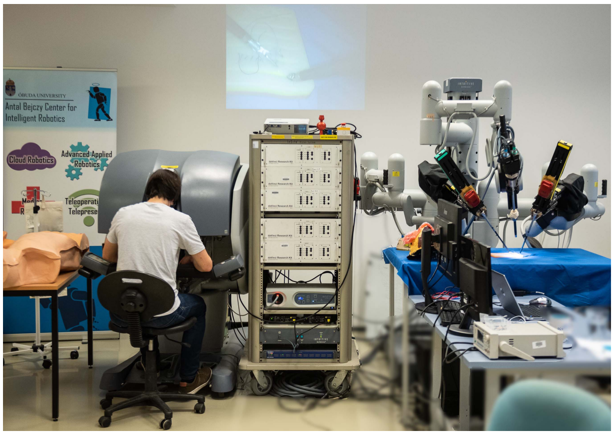


Fig. 2. ***DVRK at Óbuda University, one of the 40 sites that employs the DVRK as an advanced research platform.***

A recent review by Moglia *et al.* [22] covered the types and variations of these systems. Another recent systematic review by Dupont *et al.* [23] pointed out initial efforts on the development of surgical automation and the integration of force sensing into laparoscopic tools as probably the most important upgrade of the past decade, along with the novel robot architectures aiming to reduce procedural invasiveness.

On the research platform side, the most notable recent achievement is arguably the DVRK, an open hardware and software platform created by the Laboratory for Computational Sensing and Robotics (LCSR) at Johns Hopkins, Worcester Polytechnic Institute (WPI) and partners, supported by Intuitive Foundation (https://www.intuitive-foundation.org/dvrk/) [24], [25]. More than 40 university groups and research centers are in the program, using retired classic da Vinci surgical systems as repurposed, reassembled research platforms, capable of exploring innovative new concepts in RAMIS (Fig. 2). A recent review by D'Ettorre *et al.* [26] collected the most relevant projects with the platform (Fig. 2).

Current research efforts on the DVRK can be considered as good proxies for RAMIS development directions and can be categorized as follows (Fig. 3):

1) hardware implementation and integration;
2) system simulation and modeling;
3) imaging and vision;
4) feature automation;
5) training, skill assessment, and gesture recognition.

In most of the identified research topics, access to data with the DVRK is seen as a key enabling factor. Both kinematic and system data derived from the robot, or clinical data acquired through the vision system, are paving the way for the application of data-driven ML methods.

IV. RAMIS IN THE DATA AGE—NEW CAPABILITIES

RAMIS systems inherently provide a great platform for surgical innovation, given the fact that there is a digital data link between the surgeon console and the patient-side manipulators. While there has been a constant engineering development in all of the core components of RAMIS, i.e., the HMI, the patient-side applied surgical part, and the vision and control systems [27], radically new paradigms are emerging primarily due to the recent capability to use ML and more generic AI methods. AI has the potential to bridge the gap between the current limited application of autonomy and software capabilities already demonstrated in other industries (for example, starting with NLP and real-time annotation of scenes to anomaly detection), by combining robotics and surgical data science (SDS), and thereby, AI methods can improve therapy and patient outcome [28]–[32].

A. Autonomy Classification Framework for RAMIS

Autonomy is probably the most important feature related to the applicability of a robotic system. Medical robotics also started to employ the level of autonomy (LoA) concept (originally proposed for the automotive industry), which helps to identify and compare system functions and capabilities [33]. It builds on the classical model of analyzing tasks and decisions along the generate–model–plan–execute cycle, an overarching autonomy concept from industrial robotics [34] to image-guided interventional systems [35]. The classical surgical CAD/CAM control flowchart is technically applicable even to RAMIS systems—assuming a very high control loop frequency. This means that the fundamental concept that digital information enables accountable, measurable system engineering, and quality management concepts in CIS through medical imaging, image processing, and robotic execution is completely valid in the case of RAMIS as well.

Fig. 4 presents the most recent classification of LoA of surgical robots [36], where current RAMIS systems reside at LoA 1 and LoA 2 at the most. While the standardization experts still argue what degree of autonomy to be considered as a minimum requirement regarding "robots" in general [12], undoubtedly, the direction of development is toward achieving higher LoAs through improved autonomy, driven by a technology push and an economic pull.

Current successful approaches focus on subtask and task-level automation in RAMIS, allowing surgeons to better focus on the critical parts of their procedures [37], [38].

Meanwhile, novel RAMIS research concepts are emerging on the system side, in the form of miniaturization, and complete systems are being downsized for microsurgery, while there are other robot-ensemble and robot swarm prototypes being considered [39].

B. Advanced Communication Strategies' Influence on Telesurgery

One of the key applications of 5G communication network was thought to be telesurgery (first demonstrated in China in 2019, with the KangDuo-Surgical Robot-01), where the inherent capabilities of the network (high bandwidth, low delay, and high throughput) would enable real-time telesurgery [40], [41]. While telesurgery—up

Table 1 List of Most Advanced RAMIS Systems. Only TRL9+ Robots Are Shown, Which Have Already Achieved Regulatory Clearance in At Least One Country

No	RAMIS System Name	Old name / legacy	Year	Producer/Manufacturer/Developer	HQ	Website	Capital invested in the dev. phase (public data)	Estimated # units sold
1	**da Vinci Surgical System Xi, X**	da Vinci S, Si	FDA 2014 (FDA 2000)	Intuitive Surgical Inc.	Sunnyvale, USA	http://www.davincisurgery.com/	$250 m (1995-2004)	>7000
2	**Zeus (defunct 2003)**		FDA 2001	Computer Motion Inc.	Goleta, CA	https://en.wikipedia.org/wiki/ZEUS_robotic_surgical	n/a	<50
3	**Senhance Surgical Robotic System**	ALF-X	FDA 2017 (CE 2011)	Asensus Surgical Inc. (before: TransEnterix Surgical Inc., Sofar S.p.A.)	Morrisville, NC	https://www.senhance.com/	$263 m (2013-)	<100
4	**X-Surgical**	Surgenius	(CE 2012)	X-Surgical (prior: Surgica Robotica S.p.A)	Cambridge, MA (prior: Verona, IT)	http://surgrob.blogspot.com/2019/08/x-surgical-pres	n/a	0
5	**Revo-i,**	Eterne	Korean MFDS 2017	Meere Robot	Soeul, KR	http://revosurgical.com/	$38.8 m (2011-)	<20
6	**Versius**		CE 2019	CMR Surgical (before: Cambrdige Medical Robotics)	Cambridge, UK	http://www.cmedrobotics.com/product/	$ 947.7 m (2016-)	>100
7	**avatera**		CE 2019	avateramedical	Jena, DE	https://www.avatera.eu/start/	$ 203 m (2011-)	<10
8	**hinotori**		CE 2020 (JP 2019)	Medicaroid, Kawasaki Heavy	Kobe, JP	https://www.medicaroid.com/en/product/hinotori/	n/a	<20
9	**Dexter**		CE 2020	DistalMotion SA	Lousanne, CH	http://surgrob.blogspot.com/2018/06/distalmotion-d	$ 17m (2011 -)	<5
10	**Symani Surgical System**		CE 2020	MMI microsurgery platform	Calci, IT	https://www.mmimicro.com/	$ 20m (2015 -)	<5
11	**Toumai Endoscopic Robot**		CFDA (NMPA) 2021	MicroPort Medbot	Shanghai, CN	http://surgeniusinstruments.com/aboutus.html	$ 512 m (2014-)	0
12	**Mantra**		India temporary, 2021	SS Innovations (China: Robosurg Pte. Ltd.; Singapore: SSI Group Company)	Cambridge, MA, Hangzou	http://www.ssinnovations.org/	n/a	<10
13	**Hugo RAS System**	Einstein	CE 2021	Medtronic plc	Dublin, IE	https://www.medtronic.com/covidien/en-us/robotic-a	n/a	0
14	**Bitrack**		CE 2022*	Rob Surgical System	Barcelona, ES	http://www.robsurgical.com/bitrack.html	$ 10 m (2012-)	0
15	**Micro Hand S**	Micro Hand A	in progress	Nankai Uni. and Tianjin Medical Uni. & General Hospital	Tianjin, CN	http://www.tju.edu.cn/english/info/1011/4091.htm	n/a	0

to the extremes of intercontinental RAMIS had been demonstrated already 20 years ago [42]—5G, 5G+, and 6G may really be needed in terms of bandwidth, data load, and robustness to perform remote surgery when high fidelity, extreme resolution, multimodal information is streamed continuously [43], [44]. Even Intuitive Surgical plans to release a wireless version of the da Vinci by 2023. Edge, fog, and cloud computing technologies will allow to keep the AI-related, computationally intensive processes virtualized, therefore keeping the patient-side system component relatively simple, while there can still be a huge added value on the quality of data processing provided through the cloud. Nevertheless, the infrastructure to make remote telesurgery a commodity is missing on a global scale, and cybersecurity issues are still unsolved [45], [46]. It can be considered our luck that we have not experienced a massive cyberattack on our healthcare infrastructure, as Western hospitals are becoming massively connected and always online. Unfortunately, there is a significant rise in the recent number of incidences [47], and current RAMIS systems can claim for little or no protection [48].

C. SDS—Data and AI as Enabling Components for Democratizing RAMIS

Data in the clinical context are heterogeneous, based on multiple sources, not only intraoperative data, such as robot kinematics, laparoscopic video streams, or device data but also preprocessed clinical information and preoperative and postoperative patient datasets have to be considered [28], [29], [49]. In SDS, such high-volume information stream has to be acquired and stored, which involves several challenges, e.g., regarding interoperability or standards for storage [28]. Based on big data methods, new ML and AI applications can be developed, where possible deployment domains range from semi-automation of surgical tasks to context-aware surgical guidance [50]–[54].

Deep learning methods require large-scale annotated datasets for training, often a major bottleneck for applying such methods in robot-assisted surgery. Annotation is time-consuming, and often highly qualified human experts are required. Current approaches try to overcome this by generating synthetic datasets [55]–[57], methods to speed up annotation, such as crowdsourcing [58], [59] or active learning [60], or self-supervised learning methods that do not require detailed annotations [61]. In addition, datasets have to be representative for the task to be solved, including possible anatomical and pathological variations, preferably from multiple centers and linked to patient outcome (e.g., EQ-5D [62]), taking selection, and confounding bias into account [29]. Currently, such high-quality, highly robust clinical datasets exist only in medical imaging. This underlines the need for open challenges in the field, such as the annual MICCAI Endoscopic Vision Challenges (http://www.miccai.org/special-interest-groups/challenges/). The goal of these is to democratize surgical skills and enhance the collaboration between surgeons and robots via cyber-physical systems, by quantifying surgical experience and making it accessible to machines [31].

Experts are looking for the tight integration and assimilation of AI technologies into the domain. The term Surgery 4.0 concept was coined, meaning “the seamless integration of medical decision support systems, imaging, and automated execution” [36]. Focusing on data-driven surgery, Verb Surgical (Mountain View, CA, USA), the joint venture of Verily/Alphabet Inc. (Mountain View, CA, USA) and J&J (New Brunswick, NJ, USA), was the first in 2015 to claim developing a Surgery 4.0 compatible system, where advanced visualization, robotic instrumentation, data analytics, and ML would be combined.

D. Vision, Haptics, and HMIs

Current interfaces used in RAMIS feature an ergonomic console design allowing remote instrument manipulation and surgical site visualization. The vision systems feature high-resolution 3-D stereoscopic displays in immersive mode or through the use of open 3-D display technologies, such as polarized glasses [63]. In addition to the direct stereo camera feed, the display system may also allow the visualization of system preferences, instruments, and relevant information in areas of the display that contains additional input feed, similar to augmented reality solutions [64]. Other imaging modalities can be displayed, such as US or from preoperative planning renditions of 3-D patient-specific anatomy [65], to actively highlight information in the view using input from AI inference systems running on the video screen or to fuse multiple sources of information [66]. Coupling the robotic manipulation capabilities in a RAMIS system with new sensor probes can also lead to robotic imaging capabilities only available as prototypes today, from multispectrum fluorescence imaging to optical coherence tomography (OCT),

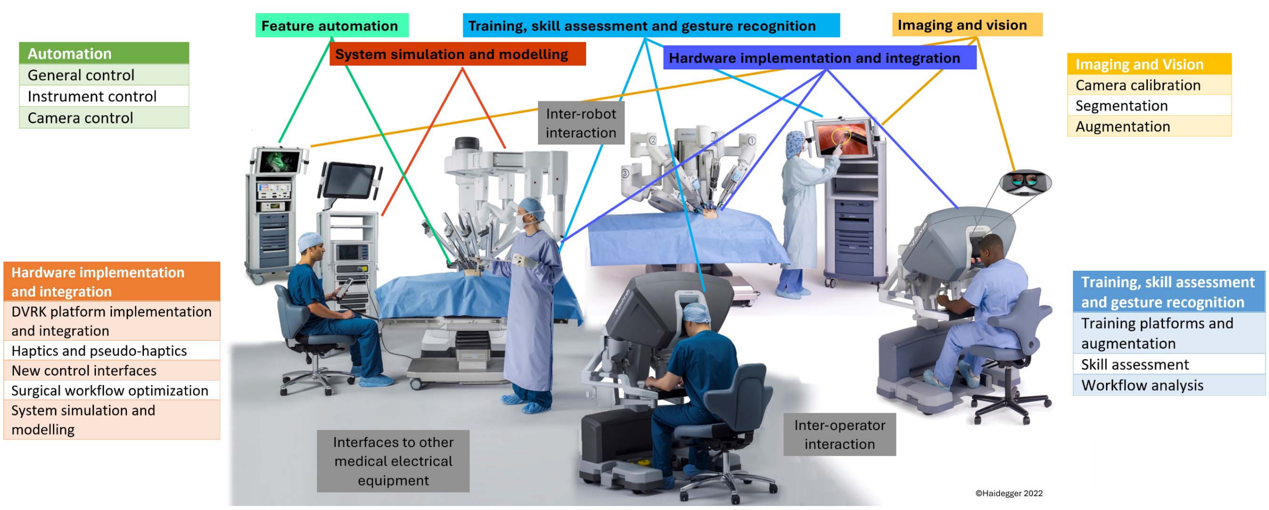


Fig. 3. *Applied research directions on RAMIS systems already established, based on the first ten years of DVRK-related projects. Initial focus was mostly on hardware capabilities and component analysis, while more recently, much attention is paid to software enhancements, decision support, and autonomous function development [26].*

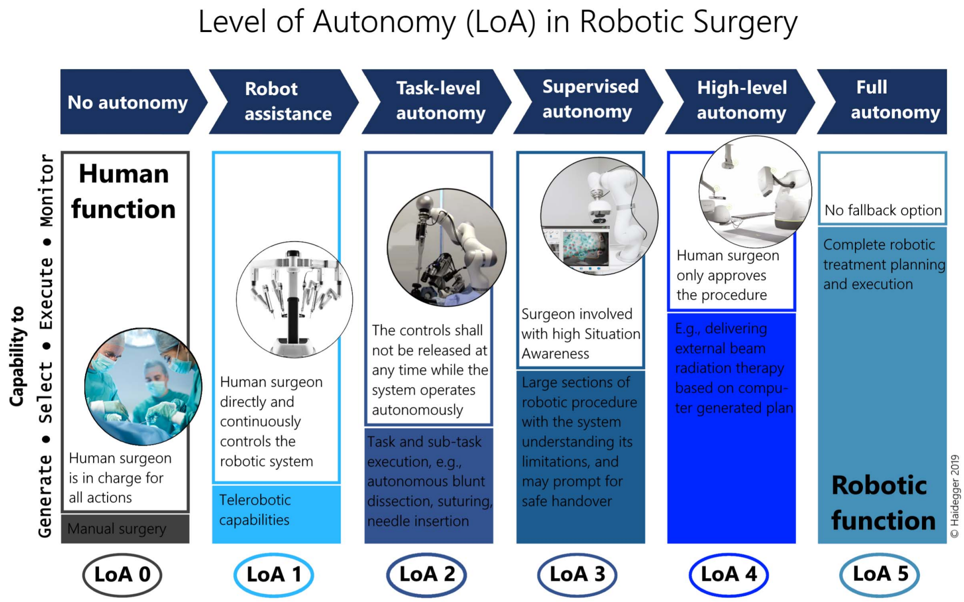


Fig. 4. ***Concept of LoA classification in RAMIS, where current teleoperational systems reach only LoA 1 typically, providing assistance with basic safety support under remote control [36].***

structured light or time-of-flight endoscopic camera, and RAMEN spectroscopy [67]–[71].

Surgeons' vision may also be enhanced via semantic information, and therefore, active research is underway in the community on surgical tool identification and tracking, which may be an efficient tool not only for compensating robot inaccuracies or performing surgical skill assessment but also a necessary safety feature during autonomous task execution, replicating the surgeon's visual feedback loop [72], [73]. Computer vision-based methods are known for identifying the anatomy and providing situation awareness in the environment [74] or to provide accurate surgical phase and workflow reconstruction [75], [76].

Another feature currently not implemented profoundly in clinical RAMIS systems is the ability to sense interaction forces between instruments and tissue and enable a sense of touch through haptic feedback [77]–[79]. This could be an important development allowing fine-tuned surgical actions for instrument manipulation to adapt to various important vibrations, pressure, or texture that have clinical meaning while operating [80]. The technology to upgrade to haptic sensations on the surgeon's console needs both the appropriate sensing in the instrumentation to obtain the relevant signals and the means to relay the senses back to the surgeon, whereas significant complexity, safety, and cost challenges are present today [81].

E. Simulation and Training in RAMIS

It had been recognized that simulation and training are essential to bring surgeons up to standard when using RAMIS systems, and various physical and virtual simulators have been developed to support skill training [82], [83]. The large datasets generated through training sessions have already been fed back to improve usability and to better understand human capabilities [84]. Skill assessment has seen a tremendous research interest recently, applying classical and ML-based methods to improve outcome prediction [85]. In addition, technologies that could benefit new generations of surgical consoles may enable more sensing and interactive modalities. For example, eye-tracking system could allow an adaptive console to perform functions tailored to specific zones of the surgeons' focus [86].

Nontechnical skill assessment has been recognized as an important contributing factor to patient outcome, yet greatly understudied [87]. At a basic level, simple stress measurements can be introduced via skin dryness sensing, pupillometry, or eye tracking [88], [89], while more complex brain activation sensing systems, such as functional near-infrared spectroscopy (fNIRs), may be able to provide similar adaptation to cognitive processes or to allow the console to detect stress and risk and may monitor surgical skill development [90].

V. TRANSLATIONAL RESEARCH FROM PROTOTYPE TO PRODUCT

In the past 20 years, the success of the da Vinci robot inspired numerous groups and companies to invest into creating their own RAMIS systems. What typically was underestimated is the complexity of a commercial medical device versus a functional laboratory prototype [91]. When system design, safety, and robustness are tested against regulatory requirements, standard laboratory good research practices fall short [92]. Strict regulations apply to Class II and Class III category medical devices, which got much more rigorous in Europe, due to the recent EU Medical Device Regulation (MDR) (EU 2017/745) [93]. The two main standardization bodies, the ISO and the IEC,

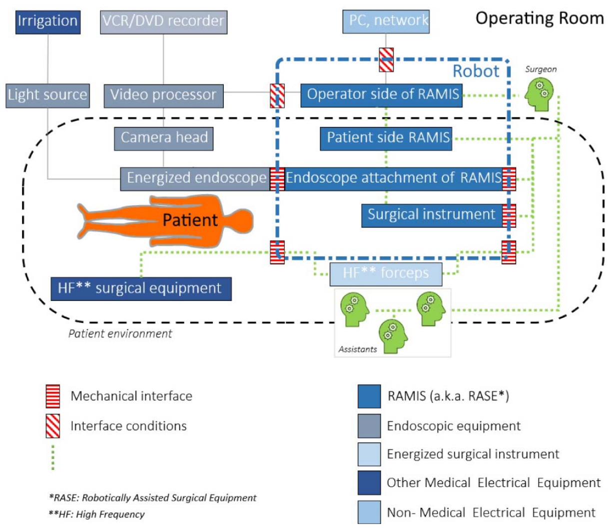


Fig. 5. ***ISO/IEC standard concept of RAMIS components and interfaces linking the robotic parts to the other medical devices (MEE/MES) in the OR. (Modified from [94].)***

have been working on these issues for over a decade. Apart from ISO 13485:2016—Quality management systems and the IEC 60601-1—Medical electrical equipment, general standards of the domain, more specific recommendations appeared recently, in the form of the 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 and the IEC 80601-2-77: Particular requirements for the basic safety and essential performance of robotically assisted surgical equipment [94]. These new standards bridge the gap between the traditional approach of treating medical devices (i.e., MEE and MES in the standard's taxonomy) separate from robots (falling under the machinery directives). It has been clearly defined that an MEE/MES can be a robot, while still being regulated as a medical device, with a certain degree of autonomy. This ends the confusion around RAMIS, which are clearly robotic systems, despite the fact that all of the known devices got cleared by FDA in the 510(k) process, providing that they are "substantially equivalent" to something already cleared and existent, such as the da Vinci being an endoscope holder, a "surgical system, computer-controlled instrument." The standards establish the necessary mappings and correlations between the robotic components and the traditional medical device nomenclature (Fig. 5).

The development and application of ML methods in robot-assisted surgeries require well-defined criteria for validation [95]. In addition, methods that can deal with data heterogeneity as well as sparsity and real-time capability are needed [28]. This requires real-time control and novel communication networks, with a low latency and a high resilience in the OR [96]. Especially in surgical applications, explainability and transparency are important aspects [97], research areas within AI that have just recently gained attention. According to the data-driven research framework for a trustworthy AI (DaRe4TAI) group [98], [99], a system shall have the properties of the following:

1) beneficience;
2) non-maleficience;
3) autonomy;
4) being just;
5) explicability.

Dealing with all of the above, the subject of AI governance is actively debated these days, not only the EU and U.S. government bodies are looking for formalized solutions but also a set of emerging standards from ISO and IEC target this domain (including healthcare and robotics among their target application areas), such as follows:

1) ISO/IEC CD 23894.2 ISO JTC 1/SC 42/WG 3 Information Technology—Artificial Intelligence—Risk Management;
2) ISO/IEC NP TS 8200 Information Technology—Artificial Intelligence—Controllability of Automated Artificial Intelligence Systems;
3) ISO/IEC TS 4213: 2021 Information Technology—Artificial Intelligence—Assessment of Machine Learning Classification Performance;
4) IEEE 7000-2021—IEEE Model Process for Addressing Ethical Concerns During System Design. Ethically Aligned Design project (https://ethicsinaction.ieee.org);
5) IEEE 7007-2021—IEEE Ontological Standard for Ethically Driven Robotics and Automation Systems [99].

Most recently, sustainability of robotics has also become a major topic, bringing together experts at the UN level to create recommendations and preferred research practices [100].

Fulfilling the regulatory requirements does costs a significant amount of time and money to the manufacturers. Table 1 presents some publicly disclosed dollar amounts invested into technology development by companies that eventually succeeded. In the current economic environment, new entrants still in the research and development phase should not be underestimated, given their rich resources. Notable funding rounds from the past years include MicroPort MedBot Company (Shanghai, China) with $512 million venture capital investment, Memic Ltd. (Or Yehuda, Israel) $127.8 million; Edge Medical Robotics Company (Shanghai, China) $309.7 million, and Activ Surgical (Boston, MA, USA) with $84.5 million capital.

Nevertheless, a significant fraction of the development efforts never achieved clinical practice level. Even Verb Surgical had difficulties, and while the mechatronics-wise complete prototype was presented at closed meeting already in 2017 [Fig. 6(a)], their envisioned Surgery 4.0 capabilities were never demonstrated, and the company was sold to J&J at around $300 million in 2019. Verb later fused their achievements to the development activities of the J&J Ottava robot. Ottava is still two years away from entering the market. Allegedly, it builds on the extended version of Auris' (now a J&J company)

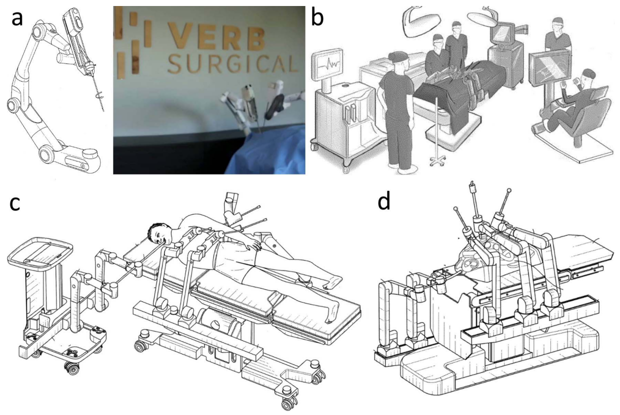


Fig. 6. ***(a) Engineering design and only visual recording on Verb Surgical's cognitive surgical robot prototype from 2017. (b) J&J Ottava RAMIS robot concept, sketched in their patent US20180078034A1. (c) and (d) Application schemes of J&J's RAMIS robot concept, built on Auris' Monarch platform, from their patent US20180078440A1.***

Monarch system [Fig. 6(b)–(d)]. In the meanwhile, other companies took up the baton, aiming to redefine MIS, such as Vicarious Surgical (Waltham, MA, USA), introducing AI algorithms and extended reality capabilities straight into the surgical workflow [64], [101].

If funds were less available, companies tried to develop more simple approaches, such as a single-arm camera-holding unit [102]. Some of these simplified surgical robotic systems, such as Brainlab's Medineering (Munich, Germany), could also be transferred more easily to a complete RAMIS system, as reported development work is underway (currently CE marked for endoscope holding).

VI. DISCUSSION AND FUTURE PROSPECTS

The development of RAMIS robots requires a significant investment, especially with the rising regulatory requirements all over the world. Clinical and financial success of any new system would likely build on the advanced technological components reviewed in this article. One of the key research questions of the community is how to ensure that AI-driven new features and inherently growing complexity lead to added patient benefit and not compromising system safety. These questions can only be assessed within the overarching frames of the regulatory environment, starting with guidelines, standards, and directives.

The fact that there are over 7000 da Vinci (and few hundred other RAMIS) systems now in daily clinical use shows that this form of surgical robotics is popular among the public, helping in general the rise of new systems via new investments [103].

The volume of RAMIS procedures (over 1.5 million per year) reached a level, where the data collected during surgery have become an asset itself, paving the road for some further technological advancements. Based on large datasets, SDS techniques can be applied to many particular problems and thus improve system capabilities. Recent advances in AI hold promise and perils regarding robot-assisted surgery [104]. The use of surgical robots is still marginal, current systems are more focused on mechanical enhancements and do step up to the role of a data-driven assistant to the surgeon [101].

Autonomous quality control and safety assurance methods can largely increase the reliability of the systems, primarily through continuous supervision measures in robotics [35], [105]. Therefore, standardization organizations and clearance bodies have been looking into the classification of autonomy from a quality assurance and risk management point of view. The more recent ISO and IEEE standards put system-level safety a priority in surgical robotics as well, aiming to bring in more transparency, accountability, and trustworthiness.

Improving and rethinking the ways energy can be delivered to the tissues will fundamentally change the whole RAMIS concept. Current days RAMIS archetype, the da Vinci is then being a transition system between MIS and non-invasive surgery, providing a suitable hardware and software platform for both. It is already foreseeable that current data-driven ML and AI methods are well applicable to this domain, given the high yield of visual, spatial, tactile, and kinematic data derived from surgeries.

While traditionally, paradigm changes only occurred in a complex domain such as RAMIS over decades, the past two years of the global pandemic situation brought a tremendous gain in robot acceptance, and the rise of public robotic services, along with medical robotics also advanced significantly [106]. As RAMIS is considered to enable contact-less surgery, in the near future, it is a key technology that promises to maintain the volume of elective surgeries, even during a pandemic, while this still would require additional development to replace and automate the scrub nurse [107].

VII. CONCLUSION

RAMIS is the dominant form of surgical robotics as of today, affecting the life of millions of patients. The economic cost/benefit of RAMIS has already been demonstrated for a set of procedures, and some systems are well accepted by the general public. In its present architecture, RAMIS fundamentally builds on a safe human teleoperation control, allowing only minor technical enhancements, such as motion scaling or tremor filtering.

Current research and development trends are largely focusing on the mechatronics and surgical tools, leading to incremental, evolutionary progress. In parallel, the available sensory information is used as a growing dataset for general ML and AI solutions, aimed at improving the cognitive support to the surgeons. On the controller side, the console is a key for better HMI, and it can make the whole robot an information system, eventually changing the human to a computer. Human factors will play an increasing role in improving patient outcome through better understanding, quantifying, and training of technical and nontechnical surgical skills. Besides improving situation awareness and supporting decision-making, AI will also play a major role in quality assurance, in the evaluation and assessment of procedures, proving systematic data on human and robot-made errors. We are already seeing the rise of alternative concepts of RAMIS robots, yet the regulatory and the safety requirements toward invasive medical devices have been raised significantly recently, making additional research necessary, primarily on the software side of the systems. The present and future impact of RAMIS cannot be underestimated, yet we need to constrain it along ethical and sustainability considerations.

Acknowledgment

The authors are grateful for the support of their research teams. ■

REFERENCES

[1] R. H. Taylor, A. Menciassi, G. Fichtinger, P. Fiorini, and P. Dario, "Medical robotics and computer-integrated surgery," in *Springer Handbook of Robotics*. Springer, 2016, pp. 1657–1684.

[2] M. Azizian, M. Liu, I. Khalaji, and S. DiMaio, "The da Vinci surgical system," in *The Encyclopedia of Medical Robotics: Minimally Invasive Surgical Robotics*, vol. 1. World Scientific, 2019, pp. 3–28.

[3] V. R. Patel, "Essential elements to the establishment and design of a successful robotic surgery programme," *Int. J. Med. Robot. Comput. Assist. Surgery*, vol. 2, no. 1, pp. 28–35, Mar. 2006.

[4] P. Nicolai, J. Raczkowsky, and H. Wörn, "A novel 3D camera based supervision system for safe human-robot interaction in the operating room," *J. Autom. Control Eng.*, vol. 3, no. 5, pp. 410–417, 2015.

[5] P. T. Ramirez *et al.*, "Minimally invasive versus abdominal radical hysterectomy for cervical cancer," *New England J. Med.*, vol. 379, no. 20, pp. 1895–1904, 2018.

[6] S. DiMaio, M. Hanuschik, and U. Kreaden, "The da Vinci surgical system," in *Surgical Robotics*. Boston, MA, USA: Springer, 2011, pp. 199–217.

[7] J. Rose, T. G. Weiser, P. Hider, L. Wilson, R. L. Gruen, and S. W. Bickler, "Estimated need for surgery worldwide based on prevalence of diseases: A modelling strategy for the WHO global health estimate," *Lancet Global Health*, vol. 3, pp. S13–S20, Apr. 2015.

[8] Shanghai MicroPort MedBot (Group) Co. (2021). *Global Offering*. [Online]. Available: https://ir.medbotsurgical.com/media/u0rpu1km/2021102100011.pdf

[9] P. Kazanzides, G. Fichtinger, G. D. Hager, A. M. Okamura, L. L. Whitcomb, and R. H. Taylor, "Surgical and interventional robotics–core concepts, technology, and design [tutorial]," *IEEE Robot. Autom. Mag.*, vol. 15, no. 2, pp. 122–130, Jun. 2008, doi: 10.1109/MRA.2008.926390.

[10] G. Fichtinger, J. Troccaz, and T. Haidegger, "Image-guided interventional robotics: Lost in translation," *Proc. IEEE*, vol. 110, no. 5, pp. 1–18, May 2022.

[11] P. Dupont, N. Simaan, H. Choset, and C. Rucker, "Continuum robots for medical interventions," *Proc. IEEE*, early access, Feb. 8, 2022, doi: 10.1109/JPROC.2022.3141338.

[12] T. Haidegger, "Taxonomy and standards in robotics," in *Encyclopedia of Robotics*, M. H. Ang, O. Khatib, and B. Siciliano, Eds. Berlin, Germany: Springer, 2021, pp. 1–10, doi: 10.1007/978-3-642-41610-1_190-1.

[13] R. M. Satava, "Surgical robotics: The early chronicles: A personal historical perspective," *Surgical Laparoscopy, Endoscopy Percutaneous Techn.*, vol. 12, no. 1, pp. 6–16, Feb. 2002.

[14] A. Takács, D. A. Nagy, I. Rudas, and T. Haidegger, "Origins of surgical robotics: From space to the operating room," *Acta Polytechnica Hungarica*, vol. 13, no. 1, pp. 13–30, 2016.

[15] T. B. Sheridan, *Telerobotics, Automation, and Human Supervisory Control*. Cambridge, MA, USA: MIT Press, 1992.

[16] T. Ginoya, Y. Maddahi, and K. Zareinia, "A historical review of medical robotic platforms," *J. Robot.*, vol. 2021, pp. 1–13, Jan. 2021, doi: 10.1155/2021/6640031.

[17] M. Hoeckelmann, I. J. Rudas, P. Fiorini, F. Kirchner, and T. Haidegger, "Current capabilities and development potential in surgical robotics," *Int. J. Adv. Robotic Syst.*, vol. 12, no. 5, p. 61, May 2015.

[18] D. S. Schoeb *et al.*, "Robotik und intraoperative navigation," *Der Urologe*, vol. 60, no. 1, pp. 27–38, Jan. 2021.

[19] A. Race and S. Horgan, "Overview of current robotic technology," in *Innovative Endoscopic and Surgical Technology in the GI Tract*. Cham, Switzerland: Springer, 2021, pp. 1–17, doi: 10.1007/978-3-030-78217-7.

[20] J. Klodmann *et al.*, "An introduction to robotically assisted surgical systems: Current developments and focus areas of research," *Current Robot. Rep.*, vol. 2, no. 3, pp. 321–332, Sep. 2021, doi: 10.1007/s43154-021-00064-3.

[21] B. Millan, S. Nagpal, M. Ding, J. Y. Lee, and A. Kapoor, "A scoping review of emerging and established surgical robotic platforms with applications in urologic surgery," *Société Internationale d'Urologie J.*, no. 5, pp. 300–310, Sep. 2021.

[22] A. Moglia, K. Georgiou, E. Georgiou, R. M. Satava, and A. Cuschieri, "A systematic review on artificial intelligence in robot-assisted surgery," *Int. J. Surg.*, vol. 95, Nov. 2021, Art. no. 106151, doi: 10.1016/j.ijsu.2021.106151.

[23] P. E. Dupont *et al.*, "A decade retrospective of medical robotics research from 2010 to 2020," *Sci. Robot.*, vol. 6, no. 60, Nov. 2021, Art. no. eabi8017.

[24] P. Kazanzides, Z. Chen, A. Deguet, G. S. Fischer, R. H. Taylor, and S. P. DiMaio, "An open-source research kit for the da Vinci surgical system," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2014, pp. 6434–6439.

[25] G. Chrysilla, N. Eusman, A. Deguet, and P. Kazanzides, "A compliance model to improve the accuracy of the da Vinci research kit (dVRK)," *Acta Polytechnica Hungarica*, vol. 16, no. 8, pp. 49–60, 2019.

[26] C. D'Ettorre *et al.*, "Accelerating surgical robotics research: A review of 10 years with the da Vinci research kit," *IEEE Robot. Autom. Mag.*, vol. 28, no. 4, pp. 56–78, Dec. 2021, doi: 10.1109/MRA.2021.3101646.

[27] T. E. T. Seah, T. N. Do, N. Takeshita, K. Y. Ho, and S. J. Phee, "Flexible robotic endoscopy systems and the future ahead," in *Diagnostic Therapeutic Procedures Gastroenterology*. Cham, Switzerland: Humana Press, 2018, pp. 521–536.

[28] L. Maier-Hein *et al.*, "Surgical data science—From concepts toward clinical translation," *Med. Image Anal.*, vol. 76, Feb. 2022, Art. no. 102306, doi: 10.1016/j.media.2021.102306.

[29] L. Maier-Hein *et al.*, "Surgical data science for next-generation interventions," *Nature Biomed. Eng.*, vol. 1, no. 9, pp. 691–696, Sep. 2017.

[30] T. Vercauteren, M. Unberath, N. Padoy, and N. Navab, "CAI4CAI: The rise of contextual artificial intelligence in computer-assisted interventions," *Proc. IEEE*, vol. 108, no. 1, pp. 198–214, Jan. 2020.

[31] E. Battaglia, J. Boehm, Y. Zheng, A. R. Jamieson, J. Gahan, and A. Majewicz Fey, "Rethinking autonomous surgery: Focusing on enhancement over autonomy," *Eur. Urol. Focus*, vol. 7, no. 4, pp. 696–705, Jul. 2021.

[32] A. Shademan, R. S. Decker, J. D. Opfermann, S. Leonard, A. Krieger, and P. C. W. Kim, "Supervised autonomous robotic soft tissue surgery," *Sci. Transl. Med.*, vol. 8, no. 337, May 2016, Art. no. 337ra64.

[33] G.-Z. Yang *et al.*, "The grand challenges of science robotics," *Sci. Robot.*, vol. 3, no. 14, Jan. 2018, Art. no. eaar7650.

[34] D. B. Kaber and M. R. Endsley, "The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task," *Theor. Issues Ergonom. Sci.*, vol. 5, no. 2, pp. 113–153, Mar. 2004.

[35] G. Fichtinger, J. Troccaz, and T. Haidegger, "Image-guided interventional robotics: Lost in translation," *Proc. IEEE*, vol. 110, no. 5, pp. 1–18, May 2022.

[36] T. Haidegger, "Autonomy for surgical robots: Concepts and paradigms," *IEEE Trans. Med. Robot. Bionics*, vol. 1, no. 2, pp. 65–76, May 2019.

[37] T. D. Nagy and T. Haidegger, "A dVRK-based framework for surgical subtask automation," *Acta Polytechnica Hungarica*, vol. 16, no. 8, pp. 61–78, 2019.

[38] T. D. Nagy and T. P. Haidegger, "Towards standard approaches for the evaluation of autonomous surgical subtask execution," in *Proc. IEEE 25th Int. Conf. Intell. Eng. Syst. (INES)*, Jul. 2021, pp. 67–74.

[39] H. Suzuki and R. J. Wood, "Origami-inspired miniature manipulator for teleoperated microsurgery," *Nature Mach. Intell.*, vol. 2, no. 8, pp. 437–446, Aug. 2020.

[40] L. B. Valdez, R. R. Datta, B. Babic, D. T. Müller, C. J. Bruns, and H. F. Fuchs, "5G mobile communication applications for surgery: An overview of the latest literature," *Artif. Intell. Gastrointestinal Endoscopy*, vol. 2, no. 1, pp. 1–11, Mar. 2021, doi: 10.37126/aige.v2.i1.1.

[41] Q. Zhang, J. Liu, and G. Zhao, "Towards 5G enabled tactile robotic telesurgery," 2018, *arXiv:1803.03586*.

[42] T. Haidegger, J. Sándor, and Z. Benyó, "Surgery in space: The future of robotic telesurgery," *Surgical Endoscopy*, vol. 25, no. 3, pp. 681–690, Mar. 2011.

[43] R. Gupta, A. Shukla, and S. Tanwar, "BATS: A blockchain and AI-empowered drone-assisted telesurgery system towards 6G," *IEEE Trans. Netw. Sci. Eng.*, vol. 8, no. 4, pp. 2958–2967, Dec. 2021, doi: 10.1109/TNSE.2020.3043262.

[44] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, "Toward 6G networks: Use cases and technologies," *IEEE Commun. Mag.*, vol. 58, no. 3, pp. 55–61, Mar. 2020.

[45] G. Lacava *et al.*, "Cybsersecurity issues in robotics," *J. Wireless Mobile Netw., Ubiquitous Comput., Dependable Appl.*, vol. 12, no. 3, pp. 1–28, Sep. 2021, doi: 10.22667/JOWUA.2021.09.30.001.

[46] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjoland, and F. Tufvesson, "6G wireless systems: Vision, requirements, challenges, insights, and opportunities," *Proc. IEEE*, vol. 109, no. 7, pp. 1166–1199, Jul. 2021.

[47] H. S. Lallie *et al.*, "Cyber security in the age of COVID-19: A timeline and analysis of cyber-crime and cyber-attacks during the pandemic," *Comput. Secur.*, vol. 105, Jun. 2021, Art. no. 102248.

[48] J.-P.-A. Yaacoub, H. N. Noura, O. Salman, and A. Chehab, "Robotics cyber security: Vulnerabilities, attacks, countermeasures, and recommendations," *Int. J. Inf. Secur.*, vol. 21, no. 1, pp. 115–158, Feb. 2022.

[49] T. P. Singh, J. Zaman, and J. Cutler, "Robotic surgery: At the crossroads of a data explosion," *World J. Surg.*, vol. 45, no. 12, pp. 3484–3492, Dec. 2021.

[50] E. D. Momi, L. Kranendonk, M. Valenti, N. Enayati, and G. Ferrigno, "A neural network-based approach for trajectory planning in robot–human handover tasks," *Frontiers Robot. AI*, vol. 3, p. 34, Jun. 2016, doi: 10.3389/FROBT.2016.00034.

[51] M. Wagner *et al.*, "A learning robot for cognitive

camera control in minimally invasive surgery," *Surgical Endoscopy*, vol. 35, no. 9, pp. 5365–5374, Apr. 2021, doi: 10.1007/s00464-021-08509-8.
[52] N. Padoy, T. Blum, S.-A. Ahmadi, H. Feussner, M.-O. Berger, and N. Navab, "Statistical modeling and recognition of surgical workflow," *Med. Image Anal.*, vol. 16, no. 3, pp. 632–641, 2012.
[53] D. Katić *et al.*, "Context-aware augmented reality in laparoscopic surgery," *Computerized Med. Imag. Graph.*, vol. 37, no. 2, pp. 174–182, Mar. 2013.
[54] D. Rivoir *et al.*, "Long-term temporally consistent unpaired video translation from simulated surgical 3D data," in *Proc. IEEE/CVF Int. Conf. Comput. Vis.*, Oct. 2021, pp. 3343–3353.
[55] M. Pfeiffer *et al.*, "Generating large labeled data sets for laparoscopic image processing tasks using unpaired image-to-image translation," in *Proc. Int. Conf. Med. Image Comput. Comput.-Assist. Intervent.* Cham, Switzerland: Springer, 2019, pp. 119–127.
[56] S. J. Wirkert *et al.*, "Physiological parameter estimation from multispectral images unleashed," in *Proc. Int. Conf. Med. Image Comput. Comput.-Assist. Intervent.* Cham, Switzerland: Springer, 2017, pp. 134–141.
[57] C. S. Ravasio *et al.*, "Learned optical flow for intra-operative tracking of the retinal fundus," *Int. J. Comput. Assist. Radiol. Surg.*, vol. 15, no. 5, pp. 827–836, May 2020.
[58] L. Maier-Hein *et al.*, "Can masses of non-experts train highly accurate image classifiers," in *Proc. Int. Conf. Med. Image Comput. Comput.-Assist. Intervent.* Cham, Switzerland: Springer, Sep. 2014, pp. 438–445.
[59] A. Malpani, S. S. Vedula, C. C. G. Chen, and G. D. Hager, "A study of crowdsourced segment-level surgical skill assessment using pairwise rankings," *Int. J. Comput. Assist. Radiol. Surg.*, vol. 10, no. 9, pp. 1435–1447, Sep. 2015.
[60] S. Bodenstedt *et al.*, "Active learning using deep Bayesian networks for surgical workflow analysis," *Int. J. Comput. Assist. Radiol. Surg.*, vol. 14, no. 6, pp. 1079–1087, 2019.
[61] T. Roß *et al.*, "Exploiting the potential of unlabeled endoscopic video data with self-supervised learning," *Int. J. Comput. Assist. Radiol. Surg.*, vol. 13, no. 6, pp. 925–933, 2018.
[62] Z. Zrubka *et al.*, "Predicting patient-level 3-level version of EQ-5D index scores from a large international database using machine learning and regression methods," *Value Health*, vol. 25, no. 9, pp. 1–12, doi: 10.1016/j.jval.2022.01.024.
[63] H. Martins, I. Oakley, and R. Ventura, "Design and evaluation of a head-mounted display for immersive 3D teleoperation of field robots," *Robotica*, vol. 33, no. 10, pp. 2166–2185, Dec. 2015.
[64] K. Moga, D. B. O. Boesl, and T. Haidegger, "Augmented/mixed reality technologies supporting digital surgery," in *Proc. IEEE 19th Int. Symp. Intell. Syst. Informat. (SISY)*, Sep. 2021, pp. 183–189.
[65] C. E. Reiley, T. Akinbiyi, D. Burschka, D. C. Chang, A. M. Okamura, and D. D. Yuh, "Effects of visual force feedback on robot-assisted surgical task performance," *J. Thoracic Cardiovascular Surg.*, vol. 135, no. 1, pp. 196–202, Jan. 2008.
[66] L. Qian, A. Deguet, and P. Kazanzides, "ARssist: Augmented reality on a head-mounted display for the first assistant in robotic surgery," *Healthcare Technol. Lett.*, vol. 5, no. 5, pp. 194–200, Oct. 2018.
[67] Y.-J. Lee, N. S. van den Berg, R. K. Orosco, E. L. Rosenthal, and J. M. Sorger, "A narrative review of fluorescence imaging in robotic-assisted surgery," *Laparoscopic Surg.*, vol. 5, p. 31, Jul. 2021, doi: 10.21037/ls-20-98.
[68] M. Balicki *et al.*, "Single fiber optical coherence tomography microsurgical instruments for computer and robot-assisted retinal surgery," in *Proc. Int. Conf. Med. Image Comput. Comput.-Assist. Intervent*. Berlin, Germany: Springer, 2009, pp. 108–115.
[69] M. Pinto *et al.*, "Integration of a Raman spectroscopy system to a robotic-assisted surgical system for real-time tissue characterization during radical prostatectomy procedures," *J. Biomed. Opt.*, vol. 24, no. 2, Feb. 2019, Art. no. 025001, doi: 10.1117/1.JBO.24.2.025001.
[70] S. Bauer *et al.*, "Real-time range imaging in health care: A survey," in *Time-of-Flight and Depth Imaging. Sensors, Algorithms, and Applications*. Berlin, Germany: Springer, 2013, pp. 228–254.
[71] A. Roberti *et al.*, "A time-of-flight stereoscopic endoscope for anatomical 3D reconstruction," in *Proc. Int. Symp. Med. Robot. (ISMR)*, Nov. 2021, pp. 1–7, doi: 10.1109/ISMR48346.2021.9661478.
[72] G. Lajkó, R. N. Elek, and T. Haidegger, "Endoscopic image-based skill assessment in robot-assisted minimally invasive surgery," *Sensors*, vol. 21, no. 16, p. 5412, Aug. 2021.
[73] Y. Wang, Q. Sun, Z. Liu, and L. Gu, "Visual detection and tracking algorithms for minimally invasive surgical instruments: A comprehensive review of the state-of-the-art," *Robot. Auto. Syst.*, vol. 149, Mar. 2022, Art. no. 103945, doi: 10.1016/j.robot.2021.103945.
[74] A. Attanasio *et al.*, "A comparative study of spatio-temporal U-Nets for tissue segmentation in surgical robotics," *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 1, pp. 53–63, Feb. 2021.
[75] C. R. Garrow *et al.*, "Machine learning for surgical phase recognition: A systematic review," *Ann. Surg.*, vol. 273, no. 4, pp. 684–693, Apr. 2021.
[76] M. Kawka, T. M. Gall, C. Fang, R. Liu, and L. R. Jiao, "Intraoperative video analysis and machine learning models will change the future of surgical training," *Intell. Surg.*, vol. 1, pp. 13–15, Jan. 2022.
[77] T. Haidegger, B. Benyó, L. Kovács, and Z. Benyó, "Force sensing and force control for surgical robots," *IFAC Proc. Volumes*, vol. 42, no. 12, pp. 401–406, 2009.
[78] A. Takács, I. J. Rudas, and T. Haidegger, "The other end of human-robot interaction: Models for safe and efficient tool-tissue interactions," in *Human-Robot Interaction*. London, U.K.: Chapman & Hall, 2019, pp. 137–170.
[79] A. K. Golahmadi, D. Z. Khan, G. P. Mylonas, and H. J. Marcus, "Tool-tissue forces in surgery: A systematic review," *Ann. Med. Surgery*, vol. 65, May 2021, Art. no. 102268, doi: 10.1016/j.amsu.2021.102268.
[80] T. B. Sheridan, "Human supervisory control of automation," in *Handbook of Human Factors and Ergonomics*, 5th ed. Hoboken, NJ, USA: Wiley, 2021, pp. 736–760.
[81] A. M. Okamura, "Haptics in robot-assisted minimally invasive surgery," in *The Encyclopedia of Medical Robotics: Minimally Invasive Surgical Robotics*, vol. 1. World Scientific, 2019, pp. 317–339.
[82] D. Julian, A. Tanaka, P. Mattingly, M. Truong, M. Perez, and R. Smith, "A comparative analysis and guide to virtual reality robotic surgical simulators," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 14, no. 1, Feb. 2018, Art. no. e1874.
[83] A. Kirubarajan, D. Young, S. Khan, N. Crasto, M. Sobel, and D. Sussman, "Artificial intelligence and surgical education: A systematic scoping review of interventions," *J. Surgical Educ.*, vol. 79, no. 2, pp. 500–515, Mar. 2022, doi: 10.1016/j.jsurg.2021.09.012.
[84] S. S. Vedula and G. D. Hager, "Surgical data science: The new knowledge domain," *Innov. Surgical Sci.*, vol. 2, no. 3, pp. 109–121, Apr. 2017.
[85] R. N. Elek and T. Haidegger, "Robot-assisted minimally invasive surgical skill assessment-manual and automated platforms," *Acta Polytechnica Hungarica*, vol. 16, no. 8, pp. 141–169, 2019.
[86] N. Ahmidi, G. D. Hager, L. Ishii, G. Fichtinger, G. L. Gallia, and M. Ishii, "Surgical task and skill classification from eye tracking and tool motion in minimally invasive surgery," in *Proc. Int. Conf. Med. Image Comput. Comput.-Assist. Intervent*. Berlin, Germany: Springer, 2010, pp. 295–302.
[87] R. N. Elek and T. Haidegger, "Non-technical skill assessment and mental load evaluation in robot-assisted minimally invasive surgery," *Sensors*, vol. 21, no. 8, p. 2666, Apr. 2021.
[88] A. Ohnishi *et al.*, "A method for estimating Doctor's fatigue level in operating a surgical robot using wearable sensors," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshops Other Affiliated Events (PerCom Workshops)*, Mar. 2021, pp. 38–43.
[89] C. Wu *et al.*, "Eye-tracking metrics predict perceived workload in robotic surgical skills training," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 62, no. 8, pp. 1365–1386, Dec. 2020.
[90] K. Izzetoglu, M. E. Aksoy, A. Agrali, D. Kitapcioglu, M. Gungor, and A. Simsek, "Studying brain activation during skill acquisition via robot-assisted surgery training," *Brain Sci.*, vol. 11, no. 7, p. 937, Jul. 2021.
[91] P. Barattini, F. Vicentini, G. S. Virk, and T. Haidegger, Eds. *Human-Robot Interaction: Safety, Standardization, and Benchmarking*. Boca Raton, FL, USA: CRC Press, 2019.
[92] T. Haidegger and I. J. Rudas, "From concept to market: Surgical robot development," in *Human-Computer Interaction: Concepts, Methodologies, Tools, and Applications*. Hershey, PA, USA: IGI Global, 2016, pp. 484–522.
[93] G. Guerra, "Evolving artificial intelligence and robotics in medicine, evolving European law. Comparative remarks based on the surgery litigation," *Maastricht J. Eur. Comparative Law*, vol. 28, no. 6, pp. 805–833, Dec. 2021, doi: 10.1177/1023263X211042470.
[94] K. Chinzei, "Safety of surgical robots and IEC 80601–2–77: The first international standard for surgical robots," *Acta Polytechnica Hungarica*, vol. 16, no. 8, pp. 171–184, 2019.
[95] A. J. Navarrete-Welton and D. A. Hashimoto, "Current applications of artificial intelligence for intraoperative decision support in surgery,' *Frontiers Med.*, vol. 14, no. 4, pp. 369–381, 2020, doi: 10.1007/s11684-020-0784-7.
[96] F. H. Fitzek, S. C. Li, S. Speidel, T. Strufe, M. Simsek, and M. Reisslein, Eds., *Tactile Internet: With Human-in-the-Loop*. New York, NY, USA: Academic, 2021.
[97] *Ethics and Governance of Artificial Intelligence for Health: WHO Guidance*, World Health Organization, Geneva, Switzerland, 2021.
[98] P. Stone *et al.*, "Artificial intelligence and life in 2030. One hundred year study on artificial intelligence," Stanford Univ., Stanford, CA, USA, Tech. Rep. 2015-2016, Sep. 2016. Accessed: Sep. 6, 2021. [Online]. Available: http://ai100.stanford.edu/2016-report
[99] E. Prestes *et al.*, "The first global ontological standard for ethically driven robotics and automation systems," *IEEE Robot. Autom. Mag.*, vol. 28, no. 4, pp. 120–124, Dec. 2021.
[100] D. B. Boesl, T. Haidegger, A. Khamis, V. Mai, and C. Mörch, "Automating the achievement of SDGs: Robotics enabling & inhibiting the accomplishment of the SDGs," in *Proc. IATT, Emerg. Sci., Frontier Technol., SDGS, Perspect. UN Syst. Sci. Technol. Communities*. New York, NY, USA: United Nations Interagency Task Team on Science, Technology and Innovation for the Sustainable Development Goals, 2021, pp. 122–126.
[101] D. Sorid and S. K. Moore, "The virtual surgeon [virtual reality trainer]," *IEEE Spectr.*, vol. 37, no. 7, pp. 26–31, Jul. 2000.
[102] Z. Li and P. W.-Y. Chiu, "Robotic endoscopy," *Visceral Med.*, vol. 34, no. 1, pp. 45–51, 2018.
[103] P. H. Pucher, M. H. Sodergren, A. C. Lord, J. Teare, G.-Z. Yang, and A. Darzi, "Consumer demand for surgical innovation: A systematic review of public perception of NOTES," *Surgical Endoscopy*, vol. 29, no. 4, pp. 774–780, Apr. 2015.
[104] D. A. Hashimoto, G. Rosman, D. Rus, and O. R. Meireles, "Artificial intelligence in surgery: Promises and perils," *Ann. Surgery*, vol. 268, no. 1, pp. 70–76, Jul. 2018, doi: 10.1097/SLA.0000000000002693.
[105] P. Nicolai, J. Raczkowsky, and H. Wörn, "A novel 3D camera based supervision system for safe human-robot interaction in the operating room," *J. Autom. Control Eng.*, vol. 3, no. 5, pp. 410–417, 2015.
[106] A. Khamis *et al.*, "Robotics and intelligent systems against a pandemic," *Acta Polytechnica Hungarica*, vol. 18, no. 5, pp. 13–35, 2021.
[107] P. Garcia *et al.*, "Trauma pod: A semi-automated telerobotic surgical system," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 5, no. 2, pp. 136–146, Jun. 2009.

ABOUT THE AUTHORS

Tamás Haidegger (Senior Member, IEEE) received the Engineering degree from the Budapest University of Technology, Budapest, Hungary, the M.S.E.E. and M.S.B.M.E. degrees, in 2006 and 2008, respectively, and the Ph.D. degree in medical robotics, in 2011.

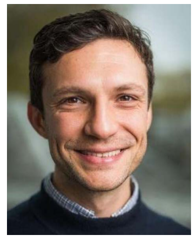
He is currently an Associate Professor with Óbuda University, Budapest, where he is also the Director of the University Research and Innovation Center and the Technical Lead of medical robotics research. He is a Bolyai Fellow of the Hungarian Academy of Sciences, Budapest. Besides, he is also a Research Area Manager at the Austrian Center of Medical Innovation and Technology (ACMIT), Wiener Neustadt, Austria, working on surgical simulation and training. He is the author or coauthor of over 250 scientific articles, books, and articles across the various domains of biomedical engineering, with over 2000 independent citations to his work. His main fields of research are medical technologies, control/ teleoperation of surgical robots, image-guided therapy, and digital health technologies.

Dr. Haidegger is an active member of the IEEE Robotics and Automation Society (serving as an Associate Vice President), IEEE System Men and Cybernetics Society (SMCS), IEEE Engineering in Medicine and Biology Society (EMBS), IEEE Standards Association (SA), and euRobotics aisbl, holding leadership positions in the IEEE Hungary Section as well. He is the Co-Editor-in-Chief of *Acta Polytechnica Hungarica* and an Associate Editor of the IEEE TRANSACTIONS ON MEDICAL ROBOTICS AND BIONICS and the *IEEE Robotics and Automation Magazine*. For his merits, he received the Gabor Dennis Award and the Hungarian Academy of Sciences (MTA) Bolyai Plaque and the Kalmar Award, among other recognitions. He has been running a professional blog on medical robotic technologies for over 15 years: http://surgrob.blogspot.com.

Stefanie Speidel (Senior Member, IEEE) received the Ph.D. (Dr.Ing.) degree from the Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, in 2009.

She has been a Professor for "Translational Surgical Oncology" at the National Center for Tumor Diseases (NCT) Dresden, Dresden, Germany, since 2017, and a Deputy Speaker of the DFG Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) since 2019. She was a Junior Researcher with the Computer-Assisted Surgery Group, KIT, from 2012 to 2016. Her current research interests include image- and robotic-guided surgery, sensor-based surgical training, and intraoperative workflow analysis based on various sensor signals in the context of the future operating room.

Dr. Speidel regularly organizes workshops and challenges, including the Endoscopic Vision Challenge@MICCAI as well as the Surgical Data Science Workshop and has been the general chair and the program chair for a number of international events, including Information Processing in Computer-Assisted Interventions Society (IPCAI) and Medical Image Computing and Computer Assisted Interventions Society (MICCAI) conferences.



Danail Stoyanov (Senior Member, IEEE) received the Ph.D. degree from the Hamlyn Centre for Robotic Surgery, Imperial College London, London, U.K., in 2006.

He was the Director of the Wellcome/EPSRC Centre for Interventional and Surgical Sciences (WEISS) and the Chair in Emerging Technologies, Royal Academy of Engineering, London, from 2019 to 2029. He joined the Centre for Medical Image Computing, UCL, in 2011. He is currently a Professor of robot vision with the Department of Computer Science, University College London (UCL), London. His research focuses on robotics and artificial intelligence applied to surgery, especially around surgical video analysis and understanding. This research has been translated into several companies, including Digital Surgery, London (acquired by Medtronic in 2020), where he was a Chief Scientist, and Odin Vision Ltd., London, which he co-founded in 2019.

Dr. Stoyanov is a Fellow of IET. He was awarded a Royal Academy of Engineering Research Fellowship for the term 2009–2014 and an EPSRC Early Career Research Fellowship for the term 2017–2022. He has been a program and general chair for the IPCAI and MICCAI conference series. He was an Associate Editor of IEEE ROBOTICS AND AUTOMATION LETTERS. He is an Associate Editor of IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING and a Deputy Editor of *International Journal of Computer Assisted Radiology and Surgery*.

Richard M. Satava (Member, IEEE) received the B.A. degree from Johns Hopkins University, and the M.D. degree from the Hahnemann University Medical School, Philadelphia, PA, USA, in 1968, internship at Cleveland Clinic, surgical residency at Mayo Clinic with a Master of Surgical Research.

He is currently a Professor Emeritus of surgery with the University of Washington Medical Center, Seattle, WA, USA. Prior positions include a Professor of surgery at Yale University, New Haven, CT, USA; military appointment as a Professor of surgery (USUHS) at the Walter Reed Army Medical Center, Bethesda, MD, USA; a Program Manager at the Defense Advanced Research Projects Agency (DARPA), Arlington, VA, USA; and a Senior Science Advisor at the U.S. Army Medical Research and Materiel Command, Frederick, MD, USA. During 23 years of military surgery, he has been an active flight surgeon, an Army astronaut candidate, a MASH surgeon for the Grenada Invasion, and a hospital commander during Desert Storm, all the while continuing clinical surgical practice. He was a surgeon on the project that developed the first surgical robot, which later became the da Vinci Surgical Robot. He has served on the White House Office of Science and Technology Policy (OSTP) Committee on Health, Food and Safety. He has been continuously active in surgical education and surgical research, with more than 250 publications and book chapters in diverse areas of advanced surgical technology, including surgery in the space environment, video and 3-D imaging, plasma medicine, directed energy surgery, telepresence surgery, robotic surgery, virtual reality surgical simulation, objective assessment of surgical competence and training, and the moral and ethical impact of advanced technologies.

Dr. Satava is a Fellow of the American College of Surgeons (ACS). He serves on numerous committees of ACS and the editorial board of numerous surgical and scientific journals and is active in numerous engineering societies. He is the past president of many surgical societies. His awards include the Smithsonian Laureate in Healthcare and the Department of Defense Exceptional Service Award.