Accelerating Surgical Robotics Research

A Review of 10 Years With the da Vinci Research Kit

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Robotic-assisted surgery is now well established in clinical practice and has become the gold-standard clinical treatment option for several clinical indications. The field of robotic-assisted surgery is expected to grow substantially in the next decade, with a range of new robotic devices emerging to address unmet clinical needs across different specialties. A vibrant surgical robotics research community is pivotal for conceptualizing such new systems as well as for developing and training the engineers and scientists to translate them into practice. The da Vinci Research Kit (dVRK), an academic and industry collaborative effort to repurpose decommissioned da Vinci surgical systems [Intuitive Surgical Inc. (ISI), California, USA] as a research platform for surgical robotics research, has been a key initiative for addressing a barrier to entry for new research groups in surgical robotics. In this article, we present an extensive review of the publications that have been facilitated by the dVRK over the past decade. We classify research efforts into different categories and outline some of the major challenges and needs for the robotics community to maintain and build upon this initiative.

Introduction

Robotics is at the heart of modern health-care engineering. Robotic-assisted surgery, in particular, has been one of the most significant technological additions to surgical capabilities over the past two decades [1]. With the introduction of laparoscopic or minimally invasive surgery (MIS) as an alternative to traditional open surgery, the decoupling of the surgeon's direct access to the internal anatomy generates the need to improve ergonomics and creates a favorable arrangement for robotic telemanipulator support. In MIS, the visceral anatomy is accessed through small, trocar-made ports using specialized elongated instruments and a camera (i.e., laparoscope) to observe the surgical site. Robotic-assisted MIS (RMIS) uses the same principle, but the tools and the scope are actuated by

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motors and control systems, providing enhanced instrument dexterity and precision as well as immersive visualization at the surgical console. The most successful and widely used RMIS platform, the da Vinci surgical system, is shown in Figure 1(a). To date, more than 5,000 da Vinci surgical systems have been deployed worldwide, performing more than 7 million surgical procedures across different anatomical regions [2]. Urology, gynecology, and general surgery represent the main application areas where the da Vinci surgical system has been used, although many other specializations have also developed robotic approaches, for example, in thoracic and transoral surgery [3] [Figure 1(b)].

The impact on both clinical science and engineering research of the da Vinci surgical system has also been significant, with more than 25,000 peer-reviewed articles reported, as illustrated in Figure 1(b). Many clinical studies and case reports belong to this body of literature and focus on investigating the efficacy of RMIS or its development for new approaches or specialties. In addition to clinical research, the da Vinci surgical system has also facilitated many engineering publications and stimulated innovation in surgical robotics technology. In the early years since the clinical introduction of the robot, such engineering research was predominantly focused on the development of algorithms that utilized data from the system, either video or kinematic information, or external sensors adjunct to the main robotic platform. However, relatively few institutions had da Vinci surgical systems available for research use, the majority of platforms were dedicated to clinical utilization, and kinematic information was accessible through an application programming interface, which required a research collaboration agreement with ISI. This inevitably restricted the number of academic or industry researchers able to contribute to the advancement of the field.

To address the challenges in booting surgical robotics research, the dVRK research platform was developed through a collaboration between academic institutions, Johns Hopkins University and Worcester Polytechnic Institute, and ISI in 2012 [4]. Seminal papers [5], [6] where the platform was presented for the first time, outline the dVRK and its mission. The idea behind the dVRK initiative is to provide the core hardware, i.e., a first-generation da Vinci surgical system, to a network of researchers worldwide by repurposing retired clinical systems. This hardware is provided in combination with dedicated electronics to create a system that offers researchers access to any level of the control system of the robot as well as the data streams within it. The dVRK components are the master console (the interface at the surgeon side), the robotic arms used to handle the tools and the scope at the patient side, and the controller boxes containing the electronics (Figure 2). To date, the dVRK, together with the purely research-focused RAVEN robot [7], are the only examples of open research platforms in surgical robotics that have been used across multiple research groups. The introduction of the dVRK allowed research centers to share a common hardware platform without restricted access to the underlying back- and forward control system. This has led to a significant boost to the development of research in surgical robotics during the last decade and generated new opportunities for collaboration and to connect a surgical robot to other technologies. Figure 1(d) shows the increasing number of publications citing and using the dVRK.

With this article, we aim to provide a comprehensive overview of the research carried out to date using the dVRK. We hope to help readers quickly understand the current activities of the community and the possibilities enabled by the open access architecture. It is our view that the impact of the system should be a precedent for similar initiatives between industry–academic consortia.

Search Protocol

The dVRK community is currently composed of 40 research centers from more than 10 different countries. The initiative, which began in 2012, is led by the United States. Subsequent research sites have been added in Europe and Asia, and the full timeline and list of research centers can be found at [4] and [8]. Today, the dVRK consortium includes mostly universities and academic centers within hospitals, and some companies (i.e., Surgnova [9], and of course, ISI, which supports and underpins the entire initiative with its technology [8]).

Our review focuses on only scientific publications rather than the research that resulted in patents. To identify and catalog all the available publications involving the dVRK, we followed a protocol querying three main databases: the dVRK Wiki page [4], Google Scholar [10], and https://www.dimensions.ai/ [11]. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram associated with our search and its detailed explanation can be found in "Database Search and Filtering." Only those papers published in international conferences or journals have been selected, excluding all the publications related to workshops or symposiums. Two-hundred and fifty-three publications were obtained as the final number.

In Figure 3, the dVRK community members (for which at least one publication was found) are presented. They are listed on a timeline indicating the year they received the dVRK system, following the same order of [4]. In the case of publications involving multiple centers, the publication was assigned to the principal investigator's affiliation. In the case of collaborations among dVRK community members and institutes external to the community, the publication was assigned to the dVRK community member.

Paper Classification—Research Fields and Data Types

For analyzing the body of publications, six research fields were used for clustering: automation; training, skill assessment, and gesture recognition; hardware implementation and integration; system simulation and modeling; imaging and vision; and reviews. These broadly categorize the published work, although notably, it is impossible to have solid category boundaries, and some papers may involve multiple fields or be at the interface between fields. In the histogram shown in

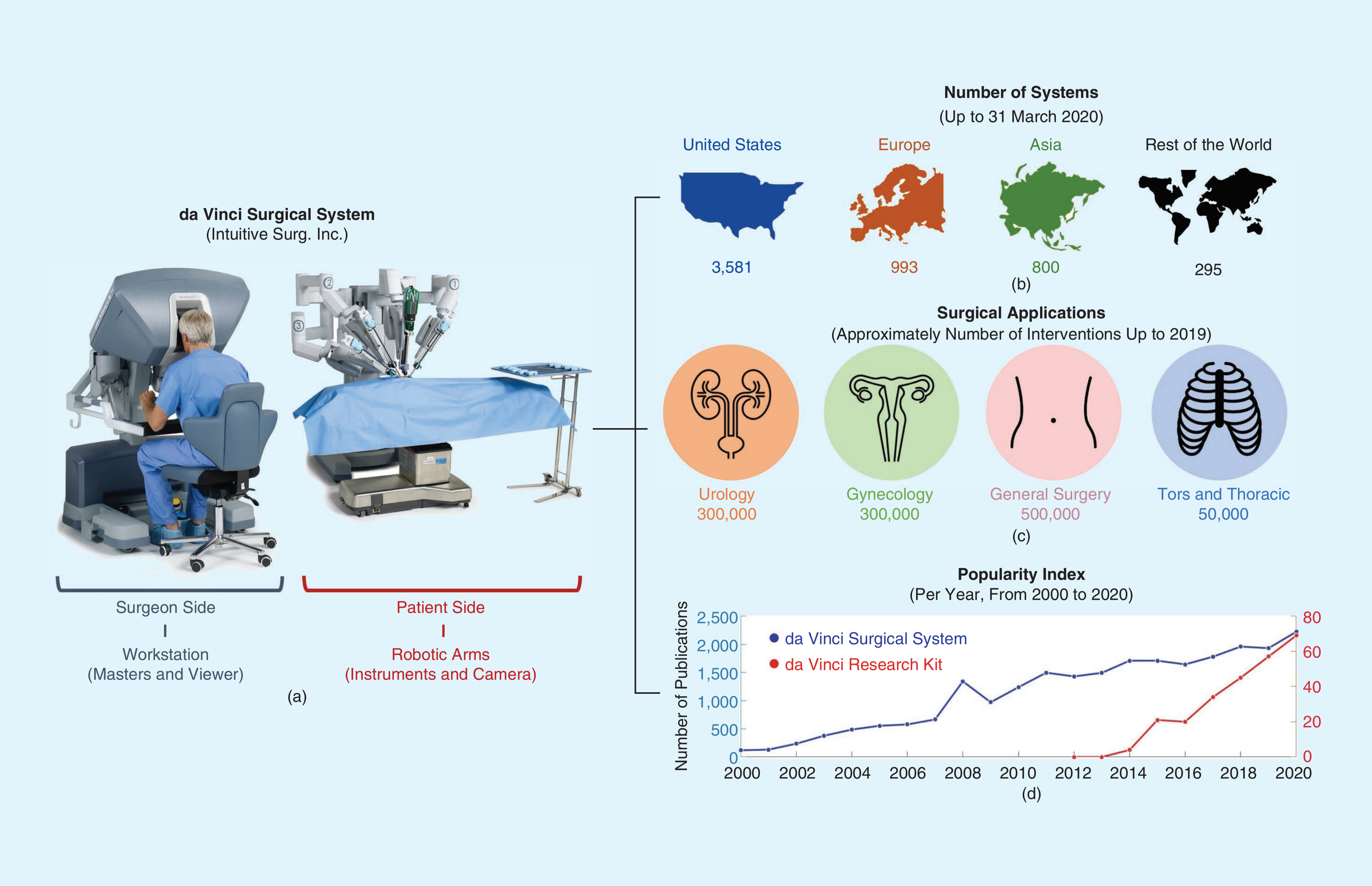
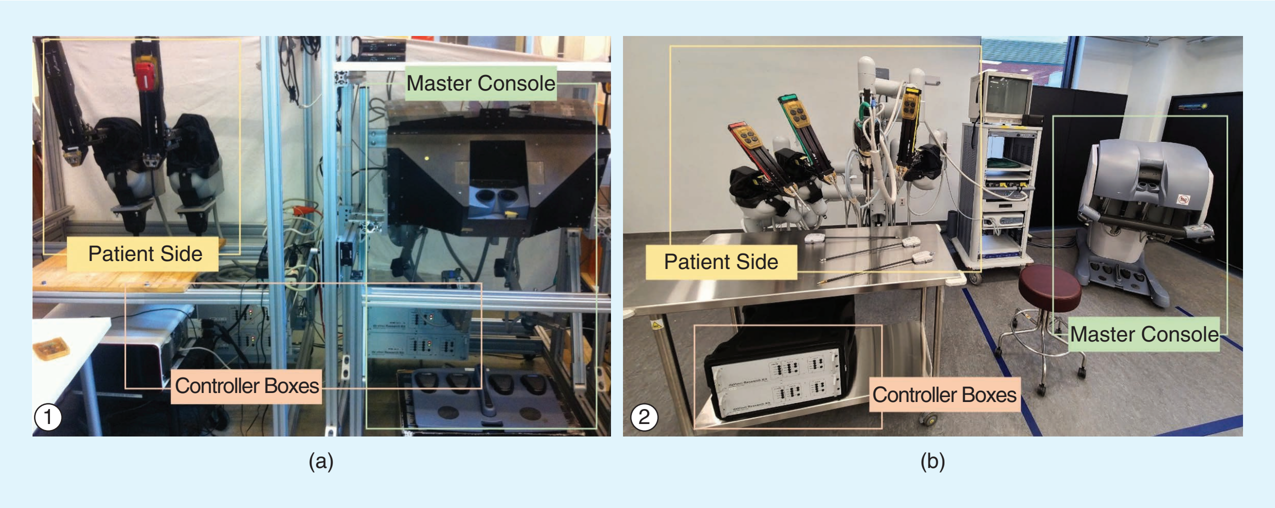


Figure 1. (a) The da Vinci surgical system is a surgical telemanipulator: The surgeon sits at a workstation and controls instruments inside the patient by handling a couple of masters; (b) the global distribution of da Vinci surgical systems in 2020; (c) surgical specialties and the total number of interventions up to 2019 using the da Vinci surgical system; [(d); blue curve] the number of publications citing the da Vinci surgical system as found in https://www.dimensions.ai/, looking for the "da Vinci surgical system" string in the medical, health sciences, and engineering fields; and [(d); red curve] the number of publications citing the dVRK as found in https://www.dimensions.ai/, looking for the "da Vinci research kit" string. (Source: [11]; used with permission from Intuitive Surgical Inc.)



(a) (b)

Figure 2. [(a) inset 1] The dVRK is available as the collection and integration of spare parts from the first-generation da Vinci surgical system or as [(b) inset 2] the fully retired, first-generation da Vinci surgical system. (Sources: Johns Hopkins University and Worcester Polytechnic Institute; used with permission.) All of the dVRK platforms feature the same main components: the patient side, i.e., the robotic arms for handling the surgical tools; the master console, i.e., the interface at the surgeon side; and the controller boxes, containing the electronics that guarantee accessibility and control of the system. [(a) inset 1] The former version does not include the endoscopic camera and its robotic manipulator at the patient side.

Figure 3, each colored box corresponds to a publication of the related research field. A second clustering criterion used to classify publications relies on five different data types, as displayed in Figure 4(b). The classes were defined based on the data used and/or collected to underpin the papers. The five different data types are: raw images (RI), i.e., the left and right frames coming from the da Vinci stereo endoscope or any other cameras; kinematic data (KD) and dynamic data (DD), i.e., all the information associated with the kinematics and dynamics of the console side of the dVRK—master tool manipulators (MTMs) as well as the instrument side—patient-side manipulators and endoscopic camera manipulator; system data (SD), i.e., the data associated with the robot's teleoperation states, as signals coming from foot pedals, the head sensor for operator presence detection, and so on; and external data (ED), a category that groups all the data associated with the additional sensors that were connected and integrated with the dVRK platform in experimental test rigs, such as eye trackers, different imaging devices, and sensors. Because of the importance of data and their utilization, especially with artificial intelligence (AI), this second categorization adds an important perspective to the work underpinned through the dVRK.

Table 1 reports the proposed classification highlighting both clustering categorizations. Each of the fields is organized into three sections: an initial overview of the related research field and a brief explanation about how current research might impact future clinical practice; then, the clustering of the publications according to their applications; and finally, a summary of promising advances in the specific area and the research outcomes related to each field. A summary of this section is schematically illustrated in Figure 5.

Automation

There is a spectrum of opportunity for automating aspects of RMIS [263]: some of them may be already-existing features, such as tremor reduction; others are more forward looking, such as the automation of an entire surgical task, where a clinician must rely on the robot for the execution of the action itself. Automation in surgical robotics does not exist in clinical practice today but if realized could lead to systems that could help improve surgical workflow or optimize the performance of certain tasks. It also represents an opportunity to develop more advanced safety standardization or quality and best-practice control for specific procedures or parts of procedures. Automation in RMIS inherently requires a combination of multiple areas of robotics research: robot design and control, and the imaging/sensing and real-time signal processing currently linked to AI and machine learning. This research field includes 68 publications, representing one of the most popular research areas for dVRK efforts.

There are different approaches that can be used to automate surgical tasks; for example, involving a human in a preplanning stage, utilizing control theory to follow a human during the operation, and using unsupervised reinforcement learning or supervised machine learning to learn behaviors or motions from human-provided examples and later executing them autonomously. We decided to group efforts in RMIS automation based on the application of the proposed control strategy into the following control categories: general, instrument, and camera.

General Control

Several efforts have focused on developing new, high-level control architectures for automation in RMIS without

Database Search and Filtering

First, we manually visited the research centers' websites, as listed on the dVRK Wiki [4] (see Figure S1). Whenever the link was active, papers were collected from the laboratory's website; if inactive, the name of the principal investigator was used to locate the laboratory's website and the relative, available list of publications. This first refined research generated a cluster of 101 publications.

We then extended this collection using the results from Google Scholar [10] with the query "da Vinci Research Kit." The research time interval was set between 2012 (the origin of the dVRK community [4]) and 2021, producing 523 results. The results were further processed and refined by removing outliers where the dVRK was not actually mentioned in the "Methods" section of the work (that means it was just cited but not used in the experimental work) as well as filtering out master theses, duplicates, and the works where the full text of the paper in English was not available online. This research finally generated 247 papers.

The last paper-harvesting search was performed on https://www.dimensions.ai/ [11], looking for the same "da Vinci Research Kit" string, and generating 394 results. The same paper-filtering process, as carried out for the results from Google Scholar, was performed, resulting in 234 publications. By this stage, these three screened data sets of papers (i.e., from the dVRK Wiki, Google Scholar, and https://www.dimensions.ai/) have been cross checked to ensure no duplications in the final collection of dVRK-related papers. Two-hundred and fifty-three publications were obtained as the final number.

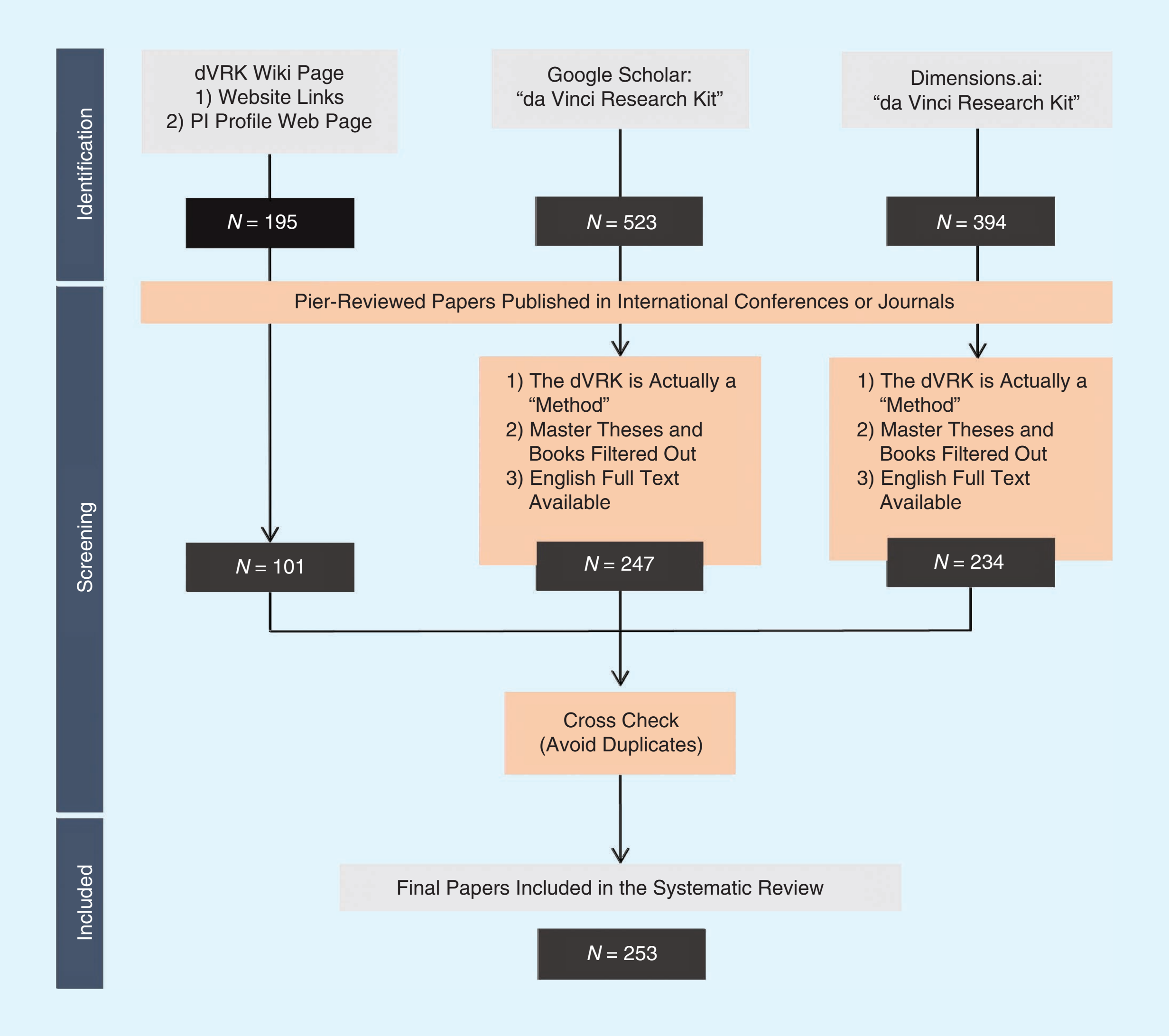
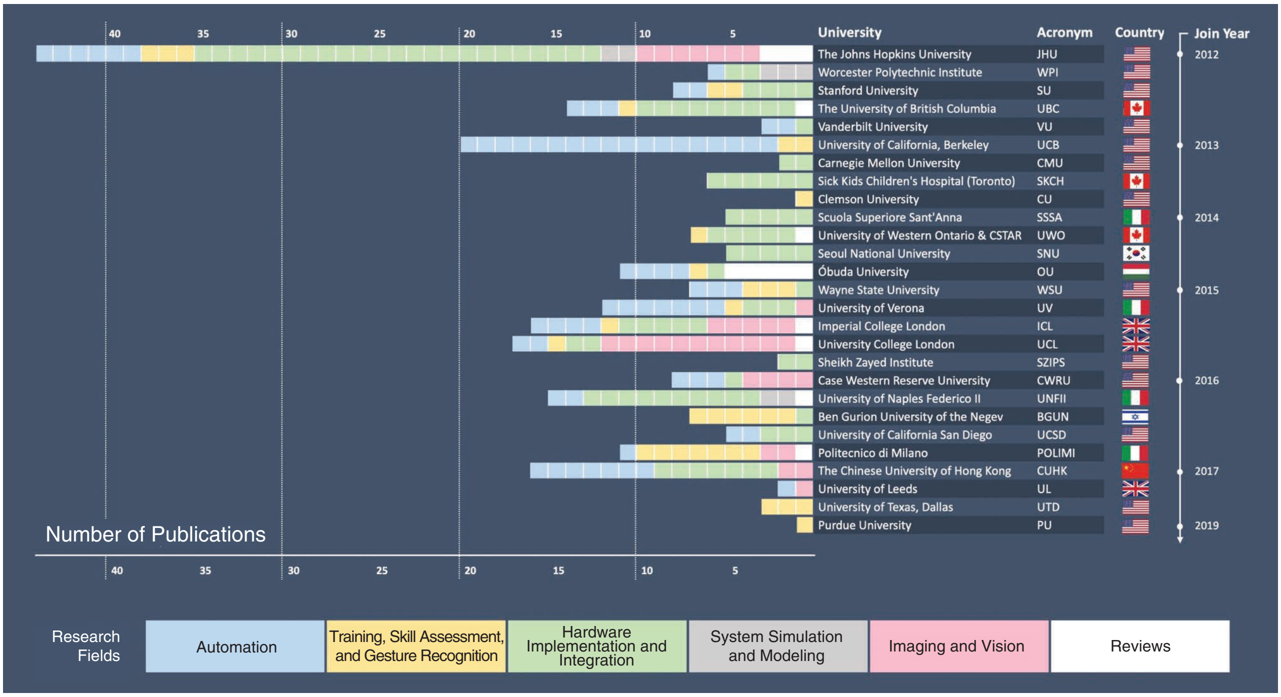


Figure S1. The PRISMA flow diagram associated with the paper search and selection of this systematic review.



University	Acronym	Join Year
The Johns Hopkins University	JHU	2012
Worcester Polytechnic Institute	WPI	
Stanford University	SU	
The University of British Columbia	UBC	
Vanderbilt University	VU	
University of California, Berkeley	UCB	2013
Carnegie Mellon University	CMU	
Sick Kids Children's Hospital (Toronto)	SKCH	
Clemson University	CU	
Scuola Superiore Sant'Anna	SSSA	2014
University of Western Ontario & CSTAR	UWO	
Seoul National University	SNU	
Óbuda University	OU	
Wayne State University	WSU	2015
University of Verona	UV	
Imperial College London	ICL	
University College London	UCL	
Sheikh Zayed Institute	SZIPS	
Case Western Reserve University	CWRU	2016
University of Naples Federico II	UNFII	
Ben Gurion University of the Negev	BGUN	
University of California San Diego	UCSD	
Politecnico di Milano	POLIMI	
The Chinese University of Hong Kong	CUHK	2017
University of Leeds	UL	
University of Texas, Dallas	UTD	
Purdue University	PU	2019

Figure 3. This histogram shows the publications associated with dVRK community members. All of the research centers are listed in temporal order based on their year of joining. They feature the name, acronym, and country. The left side of the graph represents the number of publications for each research center. Each square represents a single publication. The color code is used to classify the topic of the paper corresponding to each square according to its research field whose legend is reported at the bottom.

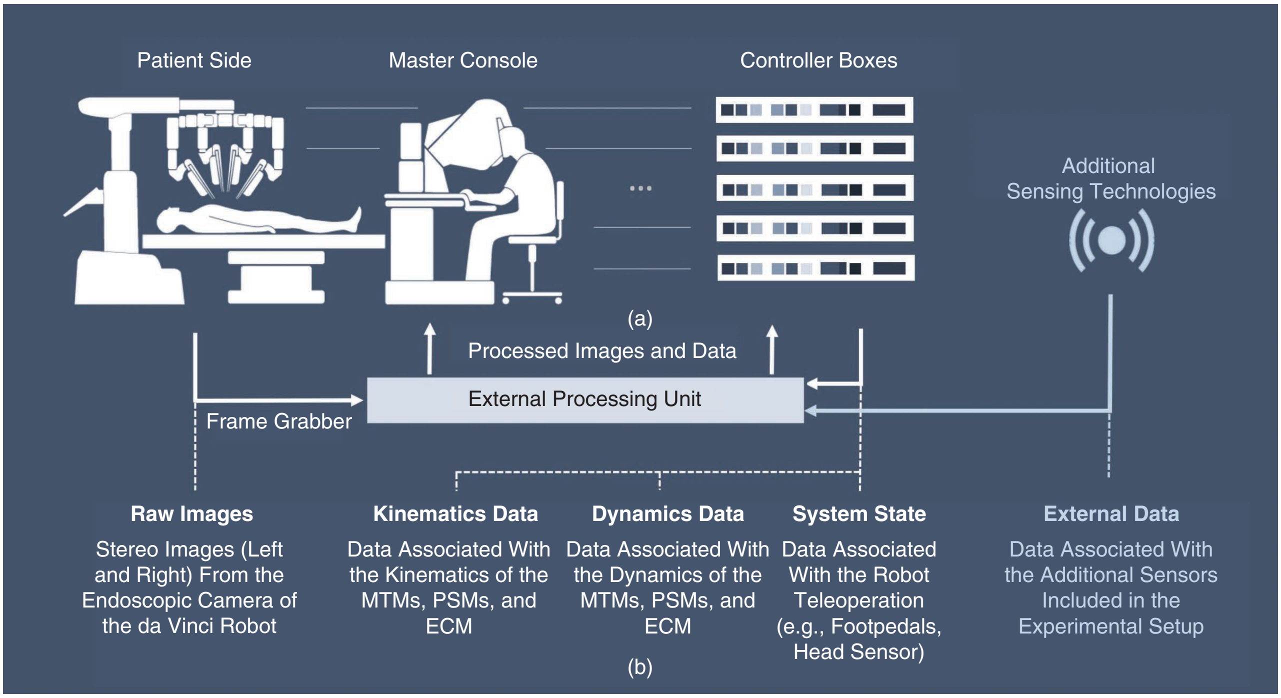


Figure 4. (a) A sketch of the dVRK components: the patient side, with the three patient-side manipulators (PSMs) and endoscopic camera manipulator (ECM); the master console, including the foot pedal tray, two master tool manipulators (MTMs), and two high-resolution stereo viewers; controller boxes; and vision elements (camera control units and a light source). (b) A description of the data types. These types of data can be read (the arrows entering the "External Process Unit") and written (the arrows exiting the "External Process Unit") using the dVRK.

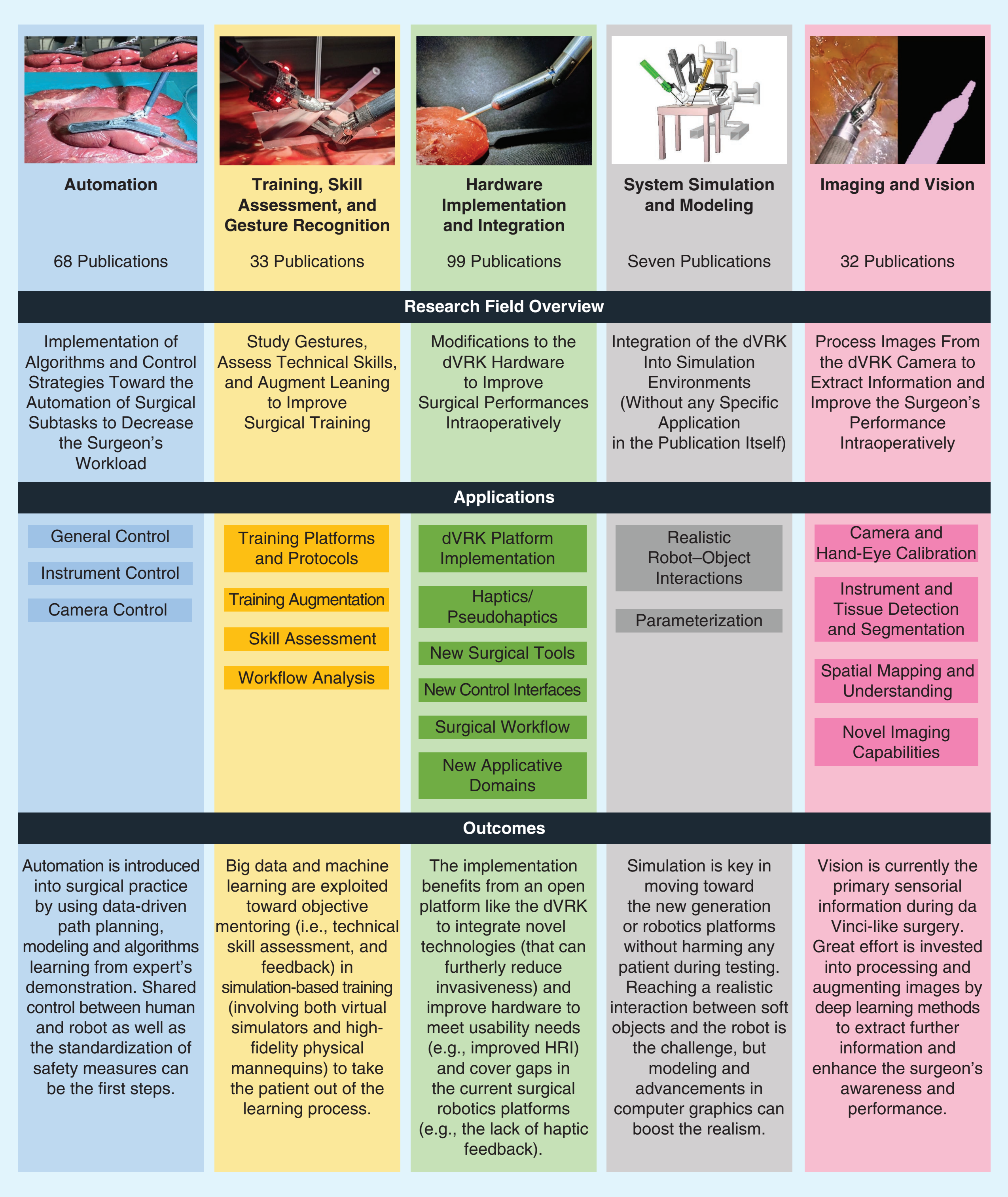
specializing on task-oriented applications [133], [150], [247]. Various applications have been explored, from focusing their attention on human–robot interaction approaches [60], [149], to general motion compensation for working in regions undergoing physiological motion [68] or control considering uncertainties [204].

Table 1. A classification of dVRK publications. On the horizontal axis, the five research macro areas are listed. Each area is to publications reviewing dVRK-related technologies.

	Automation					Training, Skill Assessment, and Gesture Recognition					Hardware Implementation and Integration		
	RI	KD	DD	SD	ED	RI	KD	DD	SD	ED	RI	KD	DD
JHU	[13]–[17]	[13]–[18]	[13]–[15]	[13]–[15], [17], [18]	[13]–[15], [17], [18]	[19]	[19], [20]	[21]		[20], [21]	[5], [6], [22]–[36], [40], [41]	[5], [6], [12], [22]–[37], [40], [41]	[5], [6], [12], [22], [25]–[38], [40], [41]
WPI		[54]	[54]								[55]	[55], [56]	[55], [56]
SU	[60],[61]		[60]	[61]		[62]	[62], [63]	[62], [63]	[63]	[62], [63]		[64]–[67]	[65]–[67]
UBC	[68]–[70]	[68], [70]			[68], [70]	[71]	[71]		[71]	[71]	[72]–[79]	[72]–[80]	[80]
VU	[82], [83]	[82], [83]									[84]	[84]	[84]
UCB	[85]–[100], [102]	[85]–[102]	[86], [93], [95]	[93]	[88]–[93], [102]	[103], [104]	[103], [104]						
CMU											[105]	[105]	
SKCH											[107]	[107]–[112]	[107], [110]–[112]
CU										[113]			
SSSA												[114]–[118]	[114]. [115], [117], [118]
UWO							[119]	[119]		[119]	[120]–[122]	[120]–[124]	[122]–[124]
SNU											[126]–[130]	[126]–[130]	[128], [129]
OU	[131]–[134]	[131]–[134]		[133], [134]	[133]					[135]	[136]	[136]	[136]
WSU	[142]–[144]	[142]–[144]		[144]		[145], [146]	[145], [146]	[146]	[145]–[147]	[147]	[148]	[148]	[148]
UV	[149]–[155]	[149]–[155]	[149]–[152], [154]	[154]	[149], [150], [153]–[155]	[156]	[156]		[156]		[157], [158]	[157], [158], [160]	
ICL	[161]–[164]	[161]–[164]		[162], [163]	[161], [162], [164]	[165]	[165]				[166]–[168]	[168]–[170]	[167], [169], [170]
UCL	[177], [178]	[177], [178]				[179]	[179]				[180], [181]	[180], [181]	
SZIPS												[193], [194]	[193], [194]
CWRU	[195]–[197]	[195]–[197]			[195]–[197]							[198]	[198]
UNFII	[203]	[203], [204]	[203], [204]		[203], [204]						[205]–[210], [214]	[205], [206] [208]–[214]	[205], [209]–[214]
BGUN						[218], [219], [223]	[218]–[223]	[222]	[222]	[223]		[224]	[224]
UCSD	[225], [226]	[225], [226]									[227]–[229]	[227]–[229]	[229]
POLIMI	[230]	[230]		[230]		[231], [232]	[231]–[237]	[231], [234], [236]	[231]–[237]				
CUHK	[241]–[247]	[241]–[247]		[241]–[243], [246]	[241], [247]						[248], [249], [254]	[248], [249], [251]–[254]	[251]–[253]
UL	[257]	[257]		[257]									
UTD						[259], [260]	[259]–[261]			[261]			
PU										[262]			

then subdivided into five subgroups according to the type of the data used in the publication. The sixth column is dedicated

		System Simulation and Modeling					Imaging and Vision					Reviews
SD	ED	RI	KD	DD	SD	ED	RI	KD	DD	SD	ED	
[5], [6], [12], [22], [25]–[41]	[22]–[24], [26]–[30], [32], [35], [36], [38]. [40], [41]	[42], [43]	[42], [43]	[43]	[42]	[42]	[44]–[50]	[44]–[50]	[46]–[50]	[46], [47], [49], [50]	[44]–[46], [48]–[50]	[51]–[53]
[55], [56]			[57]	[57]–[59]								
[64]	[64]–[67]											
[79]	[76]–[80]											[81]
	[84]											
	[106]											
	[107], [109], [112]											
[114], [116]	[114], [116]–[118]											
	[120], [123]											[125]
[126]–[129]	[127]–[130]											
	[136]											[137]–[141]
	[148]											
[157], [158], [160]	[158]						[159]	[159]		[159]	[159]	
[166]–[168]	[166], [168]–[170]						[171]–[174]	[172]–[175]		[173], [174]	[173]–[175]	[176]
[180], [181]	[180], [181]						[182]–[192]	[184]–[187], [192]		[192]		[266]
	[198]						[199]–[202]	[199], [202]			[202]	
	[210], [212]–[214]		[215], [216]	[215], [216]	[215]							[217]
	[224]											
							[238], [239]	[238], [239]		[238], [239]		[240]
	[248]–[250] , [254]						[255], [256]	[255]			[255]	
							[258]					



Automation	Training, Skill Assessment, and Gesture Recognition	Hardware Implementation and Integration	System Simulation and Modeling	Imaging and Vision
68 Publications	33 Publications	99 Publications	Seven Publications	32 Publications
Research Field Overview				
Implementation of Algorithms and Control Strategies Toward the Automation of Surgical Subtasks to Decrease the Surgeon's Workload	Study Gestures, Assess Technical Skills, and Augment Leaning to Improve Surgical Training	Modifications to the dVRK Hardware to Improve Surgical Performances Intraoperatively	Integration of the dVRK Into Simulation Environments (Without any Specific Application in the Publication Itself)	Process Images From the dVRK Camera to Extract Information and Improve the Surgeon's Performance Intraoperatively
Applications				
General Control Instrument Control Camera Control	Training Platforms and Protocols Training Augmentation Skill Assessment Workflow Analysis	dVRK Platform Implementation Haptics/ Pseudohaptics New Surgical Tools New Control Interfaces Surgical Workflow New Applicative Domains	Realistic Robot–Object Interactions Parameterization	Camera and Hand-Eye Calibration Instrument and Tissue Detection and Segmentation Spatial Mapping and Understanding Novel Imaging Capabilities
Outcomes				
Automation is introduced into surgical practice by using data-driven path planning, modeling and algorithms learning from expert's demonstration. Shared control between human and robot as well as the standardization of safety measures can be the first steps.	Big data and machine learning are exploited toward objective mentoring (i.e., technical skill assessment, and feedback) in simulation-based training (involving both virtual simulators and high-fidelity physical mannequins) to take the patient out of the learning process.	The implementation benefits from an open platform like the dVRK to integrate novel technologies (that can furtherly reduce invasiveness) and improve hardware to meet usability needs (e.g., improved HRI) and cover gaps in the current surgical robotics platforms (e.g., the lack of haptic feedback).	Simulation is key in moving toward the new generation or robotics platforms without harming any patient during testing. Reaching a realistic interaction between soft objects and the robot is the challenge, but modeling and advancements in computer graphics can boost the realism.	Vision is currently the primary sensorial information during da Vinci-like surgery. Great effort is invested into processing and augmenting images by deep learning methods to extract further information and enhance the surgeon's awareness and performance.

Figure 5. (From top to bottom) Each research field addressed is broken down into a general-concept overview, subdivision of approaches or methodologies, and key potential outcomes or trends. HRI: human–robot interaction.

Instrument Control

This category groups all of the contributions that have been made toward the automation of specific surgical subtasks. Six common surgical tasks appear to be widely investigated for automation. For the suturing task, including the works related to knot tying and needle insertion, we reported the following: [16], [70], [85], [88], [89], [161], [178], [195]–[197], [203], [243], and [246]. The pick, transfer, and place task was mainly characterized by experiments relying on pegs and rings from the fundamentals of the laparoscopic surgery training paradigm [54],

[69], [91], [96], [102], [151]–[153], [163], [264] or new surgical tools [177]. A lot of the remaining works focused on tissue interaction. This application category includes papers working on cutting and debridement [61], [87], [90], [92], [95], [97] as well as the retraction and dissection of tissues [101], [131], [132], [155], [257], [265] or blood suction [226]. Also included is tissue palpation for locating tumors or vessels and more general tissue manipulation, as in [13]–[15], [17], [82], [83], [86], [98], [99], [154], [164], [225], and [241], with experiments sometimes using just common fabric as a phantom for tissue [94], [100].

Camera Control

Additional literature included studies that investigated how to control the endoscopic camera or assist the surgeon in controlling it. To minimize the time lost in repositioning the camera and optimize the surgical workflow, a longstanding research effort has focused on the autonomous navigation of the endoscope [18], [93], [127], [230], [242]. Despite regulatory approval for autonomous robotic endoscope manipulation systems, clinical adoption has not been widespread, which suggests that further effort may be needed in the human–machine interfaces that can support the surgeon in using this technology.

Most of the algorithms belonging to this research field tend to rely on data-driven path planning as well as control, especially vision- and model-based approaches, and shared control between humans and robots. More recently, the papers tend to adopt learning-based approaches, often depending on the use of demonstrations from experienced surgeons [90]–[92], [96], [99], [161], [225].

Training, Skill Assessment, and Gesture Recognition

This research field encompasses all the publications that focus on gesture learning and recognition, utilizing different data sources to infer surgical processes, for a total of 33 publications. Surgical robots, like all traditional surgical instrumentation, require extensive, dedicated user training to obtain the psychomotor skills to operate them precisely and safely. Robotics, with its additional encoder information compared to normal instrumentation (specifically in an open platform, such as the dVRK), open attractive opportunities to study motor learning: robotic manipulators provide easy access to the data associated with the operator's hand motions. This information (mainly kinematics and dynamics) can be used to study gestures, assess technical skill, and improve learning by training augmentation. Depending on the way each publication aimed to optimize surgical training, they were further clustered in the following groups.

Training Platforms and Protocols

Several studies proposed the development of training platforms in either a dry lab setting [20] or in simulation [21]. The research also focused on the development of training protocols, where the data from expert surgeons were used for mentoring [71], [119], [146] or the training curriculum was automatically adapted to the trainee [233], [235], [237], [261].

Training Augmentation

Haptic guidance and virtual fixtures (i.e., the application of forces to the trainee's manipulators to guide and teach the correct movement) have been of particular interest for augmenting the available information during training and in turn support more effective learning [221], [222], [234]. A recent systematic comparison of training augmentation in multiple sensorial domains was carried out using the dVRK [236].

Skill Assessment

As a fundamental component of training, skill assessment has received attention, especially in automation through data analysis. Some studies focused on proficiency analysis [19], [147], [156], [223], [231], [259], [260] as well as addressed the mental and physical workload of the user [135], [262] or the influence of training on haptic perception [62].

Workflow Analysis

Surgical gesture analysis [63], [145], [220] and fine gesture segmentation [103], [104], [113], [145], [165], [179] have also been widely investigated, with a particular interest in combining image/video analysis and kinematics.

As described in the "Automation" section, the majority of efforts in optimizing surgical training focus on the use of kinematics and video data to develop algorithms to automatically assess or understand surgical skills and propose augmentations to training protocols accordingly. The general paradigm being investigated appears to center around personalizing training experiences to the trainee and tailoring protocols and feedback. Further efforts are needed to fully understand how such systems will impact current clinical training for robotic surgery, especially with more advances in AI and objective mentoring support systems [267].

Hardware Implementation and Integration

Hardware implementation and integration is quite a heterogenous category. It includes the works that have contributed to the development of the dVRK system and further modifications of the software and hardware as well as new instruments that make the surgery more affordable and capable of interface with other surgical equipment. Hence, the highest number of publications (99) belong to this group. We subdivide the section according to which components were modified and the goals of these modifications.

dVRK Platform Implementation and Integration

This category includes papers published during the development of the dVRK. Both the hardware and software components are described in [5], [6], [12], [22], [25], [33], [34], and [37]–[40]. Recently, a few integrations were published in [253], where a new control strategy for gravity compensation of the MTMs was proposed to compensate for nonlinear disturbance forces. This gravity compensation strategy was then integrated into the software architecture of the dVRK and publicly released.

Haptics and Pseudohaptics

Several research groups investigated how to overcome the lack of haptic feedback in the current da Vinci system. Numerous hardware and software developments [65]–[67], [79], [80], [106], [107], [114], [124], [193] worked on implementing haptics or force-sensing integration with the dVRK. The researchers also explored how such systems can link to automation [118], [212], [213], [224], [228]. The use of virtual fixtures, previously mentioned in the "Training, Skill Assessment, and Gesture Recognition" section as an intraoperative guidance tool, were investigated in [26]–[28], [77], [84], [167], [168], [205], [208], and [209] by providing constraints on the instruments' workspace. The use of force information within augmented reality to provide the surgeons with visual feedback about forces (the so-called pseudohaptics) was also explored [29], [30], [32], [105], [227], [254].

New Surgical Tools

In this category, publications include works focusing on the design and integration of new tools compatible with the dVRK: new surgical instruments [108]–[112], [115], [116], [123], [129], [130], [160], [194], [206], [207], [214], [249], [250], [252], and new sensing systems [73], [74], [180], [198], [248]. New flexible endoscopes and vision devices have also recently been proposed in [244] and [245].

New Control Interfaces

Some articles reported the development of novel control interfaces of the endoscopic camera by using head-mounted displays [127], [148] as well as integrating the console viewer [126] or the manipulators [128] with additional sensing technologies to simultaneously control the surgical tools and the camera. Additional studies tried to improve' the ergonomics and the portability of the master console [166], [169], [170].

Surgical Workflow Optimization

The final category of publications relates to technologies that can enhance the surgeon's awareness [31], [211] and perception from a visual point of view; for example, using eye-gaze trackers [76], [78] to personalize a surgeon's experience or combining different imaging techniques, such as ultrasounds [72], [181], to provide more intraoperative visual information but also from tactile sensing [120]–[122], [160], [251]. A significant research effort also targeted improving the teleoperation capabilities of the dVRK, taking into account time delay [23], possible master-slave misalignment [64], constrained workspace [35], shared control [41], or incorporating virtual environment guidance [55].

Other

Additional works investigated the use of the dVRK as a means of exploring clinical indications beyond its current intent or for nonsurgical applications. For example, retinal surgery [24], heart surgery [75], and portable simulators [210] were addressed. Several studies included using the master controllers to drive vehicles in simulations [136] or cutting the satellite insulation [36].

In summary, this research field highlights how research teams are taking advantage of an open platform like the dVRK to easily integrate and test novel technologies. Modified end effectors, such as flexible instrumentation and devices like new imaging probes or tools interacting with tissue using ultrasound, can benefit from the dVRK by using it as a platform that allows for rapid testing in user studies. The main advantage of the dVRK controllers is the potential to break the master-slave link and the capability to use and control each one of the components independently, thus enabling experimentation with new applications.

System Simulation and Modeling

This smaller field of seven publications contains studies that focused on the integration of the dVRK into surgical simulation environments. We note however that the small size of this grouping is partly due to our approach of dividing the fields and that many papers using simulation have been classified in previous categories.

Realistic Interaction With Objects

A few works focused on the integration of the dVRK into simulation environments to obtain realistic robot interactions with rigid and soft objects [42], [58], [215]. This is due to the fact that simulation is achieving an increasingly important role for both surgeon education and for developing algorithms that enable robots to autonomously execute tasks.

Parameterization

The identification of the kinematic and dynamic properties of the robotic arms were addressed in [43] and [216] for external forces estimation, in [57] to know the kinematics of each link instead of the serial chain, and in [59], where an entire open source package was released with the capability of modeling all the tendon couplings, springs, and counterweights.

The use of simulation also identified in the previous sections highlights that simulation environments are likely to be fundamental for the development of new robotic platforms, both in terms of technical developments and in user studies without complex laboratory needs. High-fidelity simulators are also key to effective clinical training programs and the development of robotic surgery skills. Despite the availability of advanced simulation environments as commercial systems used in clinical training, research simulation platforms are currently not as well developed and do not feature advanced realism of instrument tissue interaction. This would be a prime area for further development to complement the dVRK and enable additional research stimulus, which could link to some of the exciting developments in unsupervised, self-supervised, and reinforcement learning.

Imaging and Vision

This research field includes 32 publications related to the processing of the images acquired by the dVRK endoscopic camera. Vision and image processing are essential building blocks of computer-assisted interventions, and surgical robotics that feature intelligent decision support or link to surgical data science [268], [269]. This is a very active category of research due to recent advances in AI and the utilization of rich data sources like video, which forms the main signal from the surgical site used for clinical decision making and postoperatively contain a unique record of events during the procedure.

Camera and Hand-Eye Calibration

This first category includes publications investigating approaches registering the coordinate systems of the endoscope and the robotic surgical tools (i.e., hand-eye calibration) [45], [159], [173], [174], [184], [185], [202], [255] as well as possibly determining the camera-intrinsic parameters using dVRK information about the instruments [44]. Calibration is important for building systems that can combine information from the robot kinematics and the surgical field of view.

Instrument and Tissue Detection and Segmentation

A wide range of papers have reported algorithms aimed at detecting, segmenting, and tracking important elements in the surgical scene, such as surgical instruments [172], [182], [183], [186], [188], [189], [191], [192], [199], [219], [256], tissues [258], suturing needles [201], and threads [200]. Detecting and tracking image structures or instruments is important for various applications, for example, avoiding instrument interaction with certain tissues or automating surgical subtasks.

Spatial Mapping and Understanding

In [47], image segmentation was used to control a four-degrees-of-freedom laparoscopic instrument. In [190], images were used to learn how to estimate the depth of the workspace. In [171], images were processed to automatically remove smoke from the surgeon's field of view.

Novel Imaging Capabilities

dVRK research has tried to keep up with advancements in different imaging techniques, like ultrasound (miniaturized probes) or photoacoustic imaging [46], [50]. Some of these efforts were dedicated to implementing image guidance [49], especially to enhance patient safety during operations [48], [187], [238], [239].

New imaging modalities or systems used to interpret imaging information during procedures are likely to be important new additions to future robotic surgery systems. The dVRK has provided a platform to develop and validate such technologies through its stereo endoscope. With the rapidly evolving capabilities in supervised AI and deep learning architectures, the dVRK has also become a platform capable of generating data for AI model training and validation. Building on this and generating open data sets that combine image/video data synchronized with kinematics and other sensor signals is likely to be important for the development of cognitive robotic features or AI systems that can link to the robotic hardware.

Reviews

Several major review publications cite the dVRK and study the literature in RMIS-related topics. Comprehensive reviews on the state of the art of RMIS and future research directions were presented in [52], [53], [125], [138], [140], [141], and [240]. Works like [137] and [139] reviewed the general aspects of autonomy in robotic surgery, while [81] and [217] focused on the human aspects in control and robotic interaction. In [176], the legal implications of using AI for automation in surgical practice are discussed, while virtual and augmented reality in robotic surgery are reviewed in [51]. A recent review of gesture analysis in surgical robotics summarized the state of the art in this field [266].

Discussion

This review article summarized the research facilitated throughout the first decade of the dVRK by providing a comprehensive collection of the papers that have been published thus far in a wide range of research topics. Overall, 253 papers have been classified into five different categories based on their application paradigms. In each category, the publication was then grouped, based also on the type of data it relied on, and Figure 6 depicts the percentage use of a given type of data for each research field.

Starting from the automation research category, nearly all of the papers we reviewed rely on the use of endoscopic images and/or KD from the encoders as the primary data sources. A similar trend can be observed in the imaging and vision classes, even if research items based on KD are slightly fewer. For training and skill assessment and gesture recognition, most of the papers rely on KD, using any other type of data in fewer than 50% of the cases or exploiting external-sensor ED. When it comes to hardware implementation and integration, nearly all of the types of data cross the 50% threshold, preserving a good balance, except for the KD. For system simulation and integration, it is possible to notice how KD and DD are used in the vast majority of publications, leaving the other data types to fewer than 25%. In general, the correlation between the type of data and each application area shows the increasing importance of images in RMIS, because in nearly all of the categories, raw image (RI) crosses 50%. The extensive use of KD and DD also highlights the significance of having a research platform, such as the dVRK, which facilitates the ability to exploit the robot as a haptic interface and to make use of the systems' data-generation capabilities. Furthermore, the open access design of the dVRK incentivizes and enables researchers to integrate it with different types of hardware and software, as demonstrated by the extensive usage of external data in nearly all of the classes we covered.

These considerations on data usage and research fields in the work facilitated by the dVRK can be an interesting stimulus for reflecting on the optimization or acceleration of surgical robotic research. Despite the nonexhaustive nature of this

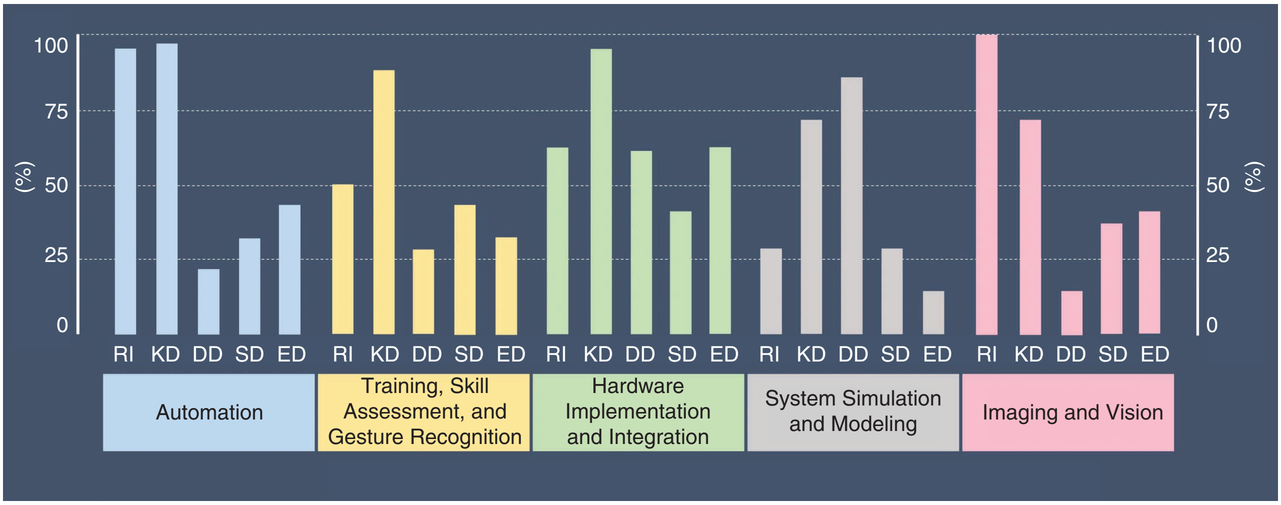


Figure 6. A histogram of data usage (in percentage) for each category based on the publications listed in Table 1. The percentage refers to the number of publications involving a certain data type out of the total number of publications in a certain research field.

review and analysis, we believe that the information collected provides a useful basis of the research directions explored by and enabled through the dVRK. It offers adopters of the dVRK a comprehensive overview of the research outputs and a synopsis of activity of the different consortium stakeholders across the globe.

This article highlighted the importance of data accessibility. A future improvement for the dVRK platform would be enabling researchers to collect and store data with minimum effort so that it can be reused for different applications. For example, all of the experiments carried out in papers around the category of surgeon training and skill assessment could be recorded in centralized data storage and used as a demonstration to train algorithms for task automation. This links to areas of active development with research institutions under research agreements with ISI where data can be recorded from the clinical setting (using custom recording tools such as the dVLogger by ISI, as in [270]). Another interesting addition to the dVRK considering the recent developments in the automation area, would be to integrate a fully enabled simulation environment, giving researchers the possibility to test algorithms that require a vast number of learning iterations or to look at user studies with a large number of known scenes or environment parameters.

In summary, the trend toward more effective data utilization in surgical robotic research is related to the possibility of making research platforms more compliant and open to the integration of different systems to facilitate data collection, storage, sharing, and use. The work facilitated by the dVRK highlights this current area of development. However, the dVRK also does much more, including examples of significant effort and development facilitated by the platform in new hardware, integration with imaging or other nonrobotic capabilities, and human factors studies. It is the authors' opinion that the platform has been a huge catalyst for research acceleration in RMIS and hopefully for the transition of research efforts into clinically meaningful solutions.

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