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RESEARCH ARTICLE

Robotics in laparoscopic surgery - A review

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Abstract
Because of the increasing use of laparoscopic surgeries, robotic technologies have been developed to overcome the challenges these surgeries impose on surgeons. This paper presents an overview of the current state of surgical robots used in laparoscopic surgeries. Four main categories were discussed: handheld laparoscopic devices, laparoscope positioning robots, master–slave teleoperated systems with dedicated consoles, and robotic training systems. A generalized control block diagram is developed to demonstrate the general control scheme for each category of surgical robots. In order to review these robotic technologies, related published works were investigated and discussed. Detailed discussions and comparison tables are presented to compare their effectiveness in laparoscopic surgeries. Each of these technologies has proved to be beneficial in laparoscopic surgeries.

1. Introduction

Laparoscopic Surgery is a type of surgery where contrary to the conventional open surgery the surgeon makes tiny incisions that are only big enough to insert special surgical instruments and a laparoscope within a trocar [1]. These types of surgeries have grown rapidly and become more preferred by patients because of their numerous advantages [2]. They have a great impact on reducing the patient's pain, recovery time, cost as well as the scarring in the patient. However, when it comes to the surgical team, laparoscopic surgeries impose more challenges compared to conventional surgeries. These challenges include restricted area of operation, lack of depth perception due to the two-dimensional visual feedback, reduction in sensory feedback during surgery, and difficulty of instrument manipulation due to the fulcrum effect (the instrument tip moves to the opposite direction of the surgeon's hand due to pivot point) and limited number of degrees of freedom (DOFs) [2, 3]. In addition, the surgeon would lose orientation of the 3D view because of laparoscope shake if the laparoscope operator were unskilled or became tired after long operating hours [4–6].

Accordingly, many researchers have shed light on implementing technologies to reduce laparoscopic surgeries' challenges. Surgical robots have been substantially exploited in the last few decades, with the first medical robot used in 1985 [7]. Furthermore, due to the numerous advantages and challenges of laparoscopic surgeries, laparoscopic robots have became one of the most active areas for research and development of surgical robots. Robotic systems have increased the surgical dexterity in various ways [8]; increasing DOFs of the instruments greatly enhances the surgeon's ability to manipulate instruments and thus the tissues, compensating the surgeon's tremor on the end-effector motion by suitable design of robot hardware and software filters, in addition to scaling the surgeon's relatively large movements of the control grips into micro-motions inside the patient.

Surveys of laparoscopic robots are scarce [9, 10]. Most of them, however, concentrate on certain systems such as laparoscope positioners [11–14], tele-operated master–slave systems [15–18], or hand-held devices [19, 20]. The aim of this paper is to review various kinds of robots used in laparoscopic surgeries simultaneously considering different points of view with comparisons of the numerous requirements and control techniques. To achieve this aim, the following section presents several kinds of robots that are used in laparoscopic surgeries, classifying them based on application, configuration, number of DOFs, and control scheme. Then, a generalized block diagram for all robotic systems involved in the field of laparoscopy is presented. A section dedicated for the application of these robotic systems presents their experimental and clinical evaluation. Finally, a discussion is followed by the conclusion of the paper, which suggests future prospects regarding surgical robots in laparoscopic surgeries.

This paper provides a literature review of the state of art of laparoscopic robots. Contrary to the existing review papers that classify laparoscopic robots according to their application only or focus on a single category, this paper classifies the proposed systems into main categories according to their application and provides further classifications of the systems based on their configuration, DOFs, and control scheme, in addition to presenting a generalized block diagram that summarizes and compares the control scheme of each category.

2. Overview of robots in laparoscopic surgeries

2.1. Literature review methods

To provide a comprehensive review of robotics in laparoscopic surgery, general searches using online databases like Google scholar, IEEE, ResearchGate, PubMed Central, and ScienceDirect were performed. Keywords such as “Robotic assisted surgery”, “Laparoscopic robots”, “Robotic laparoscopy” were used for a general search. Then data were gathered separately for each robotic application using keywords such as “Laparoscope positioner”, “Voice controlled”, “Head movements control”, “Instrument tracking”, “Tele-operated surgery”, “Robotic training”, “record/playback”, “Robotized laparoscopic tool”, “handheld laparoscopic devices”. Clinical and experimental results of each proposed system were gathered using keywords entry such as “Clinical”, “Experimental”, “Use”, “Evaluation” along with the system’s name. Moreover, the flowchart presented in Fig. 1 depicts inclusion and exclusion criteria for the references included in the literature review.

Laparoscopic robots may be classified according to their applications, configurations, number of DOFs as well as the employed control technique. The following subsections depict these classifications.

2.2. Classification based on the application of the system

Based on the application of the robotic system applied in the laparoscopic surgeries, four main categories can be outlined, as shown in Fig. 2. The figure depicts the main categories as being handheld laparoscopic devices, laparoscope positioning systems, master–slave teleoperated systems with dedicated consoles (MSTDC), and robotic training systems. The details of these systems are presented in the following subsections.

2.2.1. Handheld laparoscopic devices

Conventional laparoscopic instruments such as forceps, needle drivers, and scissors which do not include robotic actuators may be considered very primitive. They however can be classified as the basic type of handheld laparoscopic devices. They include a simple mechanism which is responsible for transferring the motion to the end effector by simple grasping motion of the surgeon’s hand.

Moreover, handheld motorized devices [19–28] have been developed as an approach for relatively cheap, lightweight robotic systems with a short setup time and a small physical footprint, where the master and slave are integrated in one device. These systems are held and manipulated by surgeons just like how conventional instruments are handled [19]. However, they provide surgeons with more ergonomic handles, intuitive control of motorized movements of the instrument, and increased number

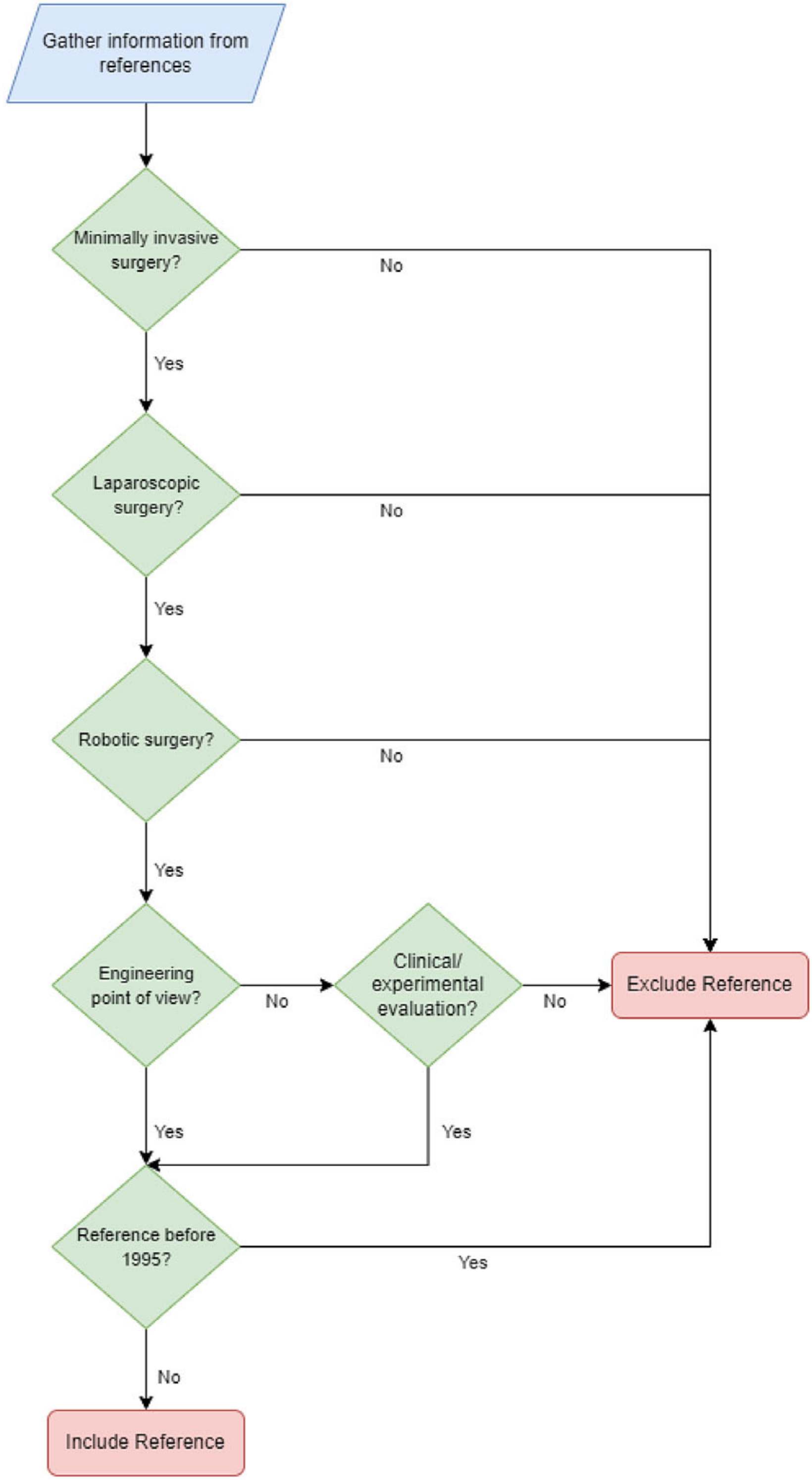

Figure 1. *Flowchart of the literature review methods showing inclusion and exclusion criteria.*

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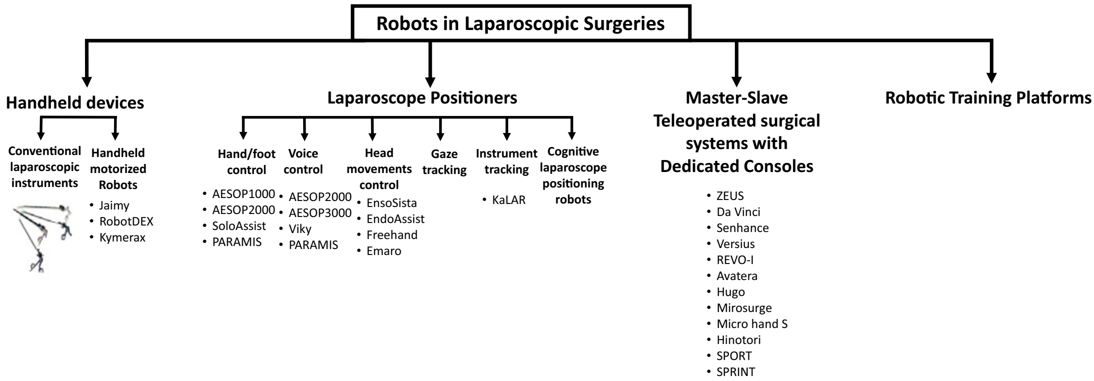

Figure 2. *Classification of robotic systems used in laparoscopic surgeries based on their application.*

of DOFs. They help surgeons with tasks that are considered challenging with manual manipulation and enhance their surgical dexterity.

A robotized needle holder Jaimy was developed by Endocontrol Medical (Grenoble, France), and its effect on ergonomics and skills has been studied in box trainers [21, 29]. Another commercialized motorized needle holder is the fully steam sterilizable Robot DEX by Dextérité Surgical (Annecy, France) [27]. A study evaluating its performance in a pelvitrainer showed that it allows precise stitching, reduces tearing, and improves the quality of cuts [30].

Kymerax by Terumo company (Tokyo, Japan) is a handheld laparoscopic system with interchangeable instruments (scissors, dissector, needle, and L-hook), driven by robotic technology [20, 23, 28]. It was clinically used in laparoscopic hysterectomy for uterine sarcoma, reporting more accurate movements and operative time that is comparable to conventional laparoscopy (80 minutes using Kymerax and 75 ± 21 minutes for conventional laparoscopy) and less than that of robotic surgery [23]. However, it was taken off the market in 2014 due to difficulties in sterilization of the motorized instruments [31].

Table I summarizes key features and experimental results of the three commercialized handheld devices (Kymerax, Jaimy, and RobotDex), and a comparison between handheld motorized devices and conventional laparoscopic instruments is summarized in Table II.

Furthermore, new prototypes of motorized laparoscopic instruments of KARL Storz SE & Co., (Tuttlingen, Germany) have been tested to compare their performance with conventional laparoscopic instruments [32]. The study showed that using the conventional instruments was faster, with fewer exercise failures in needle guidance and its usability was preferred; however, participants valued the additional DOFs [32].

Wuhan University and Harbin Institute of Technology in China developed a laparoscopic robotized needle holder consisting of a wired handle and a flexible tip mimicking da Vinci's articulated arm design to retain its 7 DOFs feature [33]. Its performance was evaluated using a force-sensing test platform, and the study showed that the use of the robotized needle holder reduced the force generated during operation; however, its learning curve was longer than that of conventional instruments [34].

Moreover, Miyazaki et al. [26] proposed a master–slave integrated handheld robot, where the master controller (joystick) is integrated in the end of the pneumatically driven forceps (the slave). The proposed system focused on suturing using a curved needle, and the experimental results showed a favorable reduced contact force against organ models compared to conventional suturing.

Earlier studies proposed a prototype model of a master-slave combined system and confirmed its validity as a handheld robotic forceps [24, 25]. The slave forceps are cable-driven by DC servo motors mounted near the master hand grip, and the master grip is integrated at the end of the forceps' shaft [24]. Focacci et al. [22] developed lightweight robotic forceps, by separating actuators from the main body using a passive holder, and preliminary tests emphasized its use in difficult suturing procedures.

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Table I. Key features and performance evaluation of commercialized handheld laparoscopic robots.

Name	Company	DOF	Instruments	Handle	Instrument's diameter (mm)	Performance Comparison with conventional instruments in box trainer	Ergonomics Evaluation in box trainer
Kymerax [20, 23, 28] 	Terumo Medical Corporation (Currently stopped Kymerax production)	5	• Scissors • Dissector • L-hook • Needle holder	Pistol handle with buttons for controlling the instruments tip	5	• Enhanced precision in suturing tasks • Longer operative time	The handle was described as non-ergonomic
Jaimy [21, 29] 	Endocontrol	7	• Needle holder	Pistol handle with intuitive one finger control of motorized movements	10	• Better performance in ergonomically difficult exercises	Enhanced ergonomics
RobotDex [27] 	Dextérité Surgical	7	• Needle holder • Coagulation instruments • Dissector	Pistol handle with control interface on the handle for flexion and rotation of the tip	8.8	• Similar technical performance	Enhanced ergonomics

Table II. *Comparison between handheld laparoscopic robots and conventional laparoscopic instrument in terms of structure and ergonomics.*

	Conventional instruments	**Handheld robots**
Handle [20]	Scissors like handle	Pistol handle
Motorized	No	Yes
DOF [20, 21, 179]	4 + end effector	5-7
Surgeon effort [20]	High	Low
Ergonomics [20, 207]	Inadequate	Enhanced Ergonomics
Learning curve [29, 32, 34]	Steep	Requires relatively long time to master due to unfamiliarity

Moreover, handheld devices can use virtual fixtures to limit the movement of the laparoscopic instrument during surgery and prevent damaging the surrounding tissues in high-risk areas. Virtual fixtures are computer-generated constraints that limit the robot's motion into restricted pre-defined regions and/or constrain it to move along a desired path [35, 36]. A recent study proposed a human-robot interface that provides safe operation constraining the movement of a robotic forceps using virtual remote center of motion (RCM) [37].

2.2.2. Laparoscope positioning systems

There are two types of rigid laparoscopes, forward-viewing laparoscope and oblique-viewing laparoscope [38]. In oblique-viewing laparoscopes, the viewing direction has a tilt from the laparoscope cylinder axis. This allows for easily changing the viewing direction by rotating the laparoscope around its axis, providing a larger field of view. However, oblique-viewing laparoscopes require an additional DOF and a more difficult scope calibration process [38–42].

Positioning the laparoscope using motorized robotic systems can be approached with several techniques [13]. Some of these techniques require manual control of the robot. This may be effectuated using hand/foot pedals directly operated by the surgeon or assistant [43–45].

Other techniques require direct commands from the surgeon such as vocal, or head movements commands. Other methods are reactive, where sensors track data such as the surgeon's eye gaze [5] or the instrument position, and the laparoscope is moved directly according to sensor readings. Proactive strategies use higher level control, where a cognitive robot has preliminary knowledge of the surgical procedures and is able to adjust the laparoscope's view according to the prediction of the next step in the surgery.

Voice control. The AESOP robot developed by Computer Motion, is considered one of the first robots to enter the surgical arena and the first voice controlled to be approved by the Food and Drug Administration (FDA) [46]. AESOP1000 was developed in 1993 based on shared control principle. It was put in clinical use in 1994 [43] and has undergone several modifications. AESOP is a SCARA type robotic arm [12] that could be controlled manually or remotely with hand or foot control. Its newer version AESOP2000 was developed in 1996 [47] and is controlled using voice commands, which proved its excellence over older versions, as the voice control eliminated the need for human laparoscope operator [48–50]. The learning curve of the AESOP was evaluated and has shown that the use of the AESOP robot was not as fast as hand control, but the skill to use it was learned as quickly [51].

VIKY from Endocontrol Medical (Grenoble, France), another laparoscopic holder that is available for commercial use, is considered an evolutionary system of the AESOP as it is also FDA approved and

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has been used in several laparoscopic surgeries [52, 53]. It is a compact, lightweight, fully sterilizable robot. VIKY is either controlled by foot pedal or voice commands and is small enough to be placed directly on the operating room table without interfering with other held instruments.

Another laparoscope holder was developed in 2008 in Romania, the PARAllel robot for Minimally Invasive Surgery (PARAMIS). It was designed to be a laparoscope holder controlled with a keyboard, joy stick, haptic, or voice command control [44, 45]. However, the voice control mode was preferred by surgeons as it allows them to operate with both hands. The PARAMIS is a simple parallel robot whose geometric and kinematic models are described by Plitea et al. [54]. Its open architecture control system which consists of three levels; user interface, programmable logic controller (PLC), and the robot level is presented in ref. [45]. It allows fast introduction of new commands without any physical modification [45].

Head movements control. One of the oldest laparoscope holders controlled by head movements is the Endosista (Armstrong Projects Ltd.) [12, 55, 56]. It was developed as a result of modifications of the prototype unit LapaRobot that was designed and built in 1992 [57, 58]. The prototype version had only 3 DOFs corresponding to pan, tilt, and zoom motions. However, the newer version Endosista has a larger operating envelope and an extra DOF for achieving the swivel motion that is rotation about its own axis. This additional DOF is required for oblique-viewing laparoscopes [58]. Endosista was tested on a phantom, then after ethical committee approval and informed consent of patients, it was used clinically and proved its applicability [55].

Endosista's commercial version was then introduced in 1998 [11], the EndoAssist laparoscopic holder from Armstrong Healthcare Limited [59]. It is activated by foot pedal and controlled by the surgeon's head movements where the movements will only take place when the foot pedal is pressed to avoid any unwanted movements of the laparoscope. Head movements of the surgeon are detected by an infrared headset.

Freehand from Freehand Ltd. was considered a successor to the EndoAssist. It followed its operation method, where it was also controlled by the surgeon's head movements detected by an infrared headset and activated only when a foot pedal was pressed [60, 61]. Its small, light-weight, and simple design, that includes three independent axes, offered simplified control, and has made it advantageous in laparoscopic surgeries [62, 63].

Emaro, the world's first pneumatically driven laparoscope holder robot with smooth operation [64] was launched as a result of a venture originating in universities [10, 65]. The robotic arm is a parallel manipulator with pneumatic driving mechanism that has made Emaro's movements smooth and gentle, in addition to keeping the design small and simple. Instead of using external sensors that require a clear uninterrupted space between the transmitter and the receiver, two gyroscopes are attached to the surgeon's head and body. The tracking accuracy of Emaro robot was first confirmed experimentally by Tadano and Kawashima [65], proving that it had sufficient dynamic characteristics, allowing it to quickly follow the surgeon's head movements.

Instruments tracking. Visual tracking of the surgical instruments is a more intelligent solution to maneuver the laparoscope compared to the voice and head controlled that require direct commands. The laparoscope is automatically displaced to follow areas of interest, marked by the surgical instruments. Surgical instruments are tracked by identifying significant features in them like color, shape, texture, and movement. To enhance the object tracking process, some studies attached distinguishing colored markers to the instruments [66, 67]. Kim et al. [68, 69] designed an instrument tracking laparoscope holder "KaLAR" with a bending mechanism enabling it to adjust viewing angles within a compact design. It can track the instrument 's tip identified by colored markers, adjust these views according to voice commands, and switch between the two control modes by simple "Track" and "Voice" commands. Its original version was designed for laparoscopic cholecystectomy. In order to apply it to general laparoscopy, a modified version was developed with a passive base, 2 DOF manipulator that is the lower part of MC^2E robot [70] and the same bending laparoscope [6, 71].

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However, sterilization of the colored marker would be a problem in clinical use [72]. Therefore, several studies proposed marker-free tracking frameworks, which could detect and locate the surgical instrument based solely on its features [73–77].

Learning-based systems have been beneficial to the marker-free instrument tracking process. Detection/segmentation of surgical instruments based on Machine Learning (ML) methods relied highly on hand-crafted features of the instrument [78]. Where, feature descriptors such as Histogram of oriented Gradients (HoG) [79], region Covariance [80], and Scale Invariant Feature Transform (SIFT) [81, 82] were used to distinguish surgical instruments from the background. However, due to complications in the surgical environment such as smoke, shadows/reflections, body fluid, and the dynamic nature of background tissues [83], these hand-crafted features were not robust in detection/segmentation of surgical instruments. Deep learning (DL) on the other hand can automatically extract robust image figures using well-trained convolutional neural networks (CNNs) and has shown potential in detecting/segmenting marker-free surgical instruments [78, 83–86]. There are mostly two types of studies for surgical instruments tracking using DL [83], tracking by detection using bounding box [84, 86, 87], and tracking by segmentation [78, 83, 88, 89]. In the bounding detection method, the surgical instrument is depicted by some special image features and its position is represented by a rectangle bounding box [84]. However, affected by the angle of imaging, there would be a large locating error if the end effector has occupied a small fraction of the rectangular bounding box [78]. In tracking by segmentation, the instruments can be annotated into binary (where every pixel in an image is labeled as background or instrument), parts (background, shaft, wrist, or end-effector), and categories (according to the instrument type) [83]. ToolNet [89], a holistically nested real-time instrument segmentation approach of robotic surgical instrument focused only on binary segmentation and has shown robustness and generalization ability for robotic instrument segmentation. Shvets et al. [90] segmented the instruments into binary, parts, and categories and the model has obtained better accuracy compared with other segmentation models [83, 90]. Moreover, Islam et al. [83] proposed a CNN model with adversarial scheme for real-time surgical instruments segmentation from high-resolution videos. They also segmented the instruments into binary, parts, and categories. The model surpassed performance of previous work on the MICCAI robotic instrument segmentation challenge 2017 [91] in each category of segmentation. Furthermore, Zhang and Gao [78] proposed a marker-free surgical instrument tracking framework based on object extraction via DL. The segmentation model was trained to extract the end-effector and the shaft portions of the surgical instrument in real time, and the surgical instrument joint was defined as the tracking point instead of the instrument's tip. The framework achieved accurate and fast tracking of the surgical instrument in laparoscopic videos. A novel system presented in ref. [88] allows the surgeon to perform bimanual coordination and navigation task while a robotic arm autonomously positions the laparoscope. Using a novel tooltip detection method and a new visual servoing approach for a generalized laparoscope model with support for RCM and laparoscope bending. The tooltip localization method is based on a hybrid mixture of DL and classical computer vision that ensures smooth and accurate motion of the laparoscope.

In addition to visually tracking the instruments, Eslamian et al. [92] proposed an instrument-tracking laparoscope algorithm implemented on da Vinci robot platform, where joint values of the instruments' manipulators are captured and used to set the desired joint values for the laparoscope manipulator that will enable it to point toward the centroid of the instruments.

Cognitive laparoscope positioners. Furthermore, laparoscope positioning systems that can learn/predict the desired field of view, instead of just following the surgical instruments in the field of view can offer real autonomy. In [93], traditional tracking methods are modified with prediction of the surgical instrument's motion using Markov chains based on the collected information from former interventions. KaLAR can also distinguish the procedure in progress and recognize the optimal view corresponding to each procedure, after having preliminary knowledge of the surgical procedure loaded from the database [94]. A cognitive laparoscope guidance system that learns the human assistant's surgical knowledge about suitable laparoscope position using a supervised ML algorithm is presented in ref. [95]. The system utilizes a learned knowledge-based control mechanism, where spatial surgical knowledge is extracted and learned from recorded interventions. Moreover, [96, 97] explored using learning from demonstration (LFD) to guide the laparoscope during surgery. LFD allows the robot to observe how a human performs a task then it autonomously imitates the human behavior to complete the same task. In ref. [97], the system stores the laparoscope position and its relation to the position of surgical instruments, teaching the system how the laparoscope moves depending on the instrument's position. Ji et al. [96] focused on learning viewpoint selection problem based on anatomical features, not the instrument's position.

Key features of famous laparoscope positioning robots are summarized in Table III along with representative figures.

2.2.3. Master–slave teleoperated systems with dedicated consoles

Master–slave tele-operated systems with Dedicated Consoles (MSTDC) have become very common in laparoscopic surgeries [9, 98–105]. They offer significant advantages, including eliminating the surgeon's hand tremor and reducing his/her fatigue in dealing with restricted area of operation, due to limited DOFs provided by the trocar. The surgeon controls the laparoscope and the surgical instruments using a master device at a separate dedicated console while monitoring the surgical view. A slave robot at the patient side maps the master's movements and manipulates the laparoscope and the instruments following the surgeon's lead [101, 106]. The concept of master–slave tele-manipulation system was introduced in the early 1990's, where it was urged by the goal to perform surgical procedures on patients from remote places, like battlefields or outer space [107]. Several systems are now available with different configurations regarding the surgeon console (including hand controllers and vision display), patient console, and endoscope control.

The first two MSTDCs to be commercialized were Zeus by Computer Motion, introduced in 1998 [9, 102, 108], and the da Vinci surgical system by Intuitive Surgical. Zeus was initially developed for cardiac operations [109–113]. However, several clinical trials have been reported using it in abdominal surgery [114–118], gynecology [119, 120], and urology [121, 122]. The da Vinci was the first to gain FDA approval in 2000 followed by Zeus in 2001 [9, 104, 123, 124]. After Intuitive Surgical had bought out Computer Motion and discontinued the sale of Zeus system [17], the da Vinci system monopolized the market of MSTDC, with different versions for multi-port laparoscopic surgeries including da Vinci SI, da Vinci XI, and da Vinci X [104]. The da Vinci family has become well adapted for cardiac, urologic, gynecologic, pediatric, and general surgeries [125].

With the expiry of some key patents of Intuitive Surgical in 2019, competitors were allowed to adopt their technologies, introduce new robotic platforms, and apply for approval for clinical use [16, 126]. The Senhance system from Transenterix Surgical Inc. initially named "ALF_X" became FDA approved in 2017 [104, 127, 128], making it the only market cleared competitor with Intuitive Surgical in the USA [16]. It has several unique features compared to da Vinci including haptic feedback, gaze control of the endoscope, and independent robotic arms capable of holding reusable laparoscopic instruments. Moreover, Transenterix recently received 510 (k) clearance for its machine vision system which will automatically move the laparoscope according to instrument movements and recognition of learned landmarks in the field of view [16, 129].

The REVO-I system was developed in 2015 and has received Ministry of Food and Drug Safety (MFDS) approval. Its configuration is similar to that of da Vinci including single patient cart with 4 arms, 3D stereoscopic display, and similar hand controls at the surgeon's console [104, 130].

Versius system that was unveiled by CMR Surgical in 2018 is not yet FDA approved but has received Therapeutic Goods Administration (TGA) approval for use in Australia [16]. The system's slave arms are human-like robotic arms, enabling them to hold the laparoscopic instrument more like how a surgeon would hold it, thanks to the multiple wrist V – wrist™ technology (as named by CMR surgical). The robotic arms are of relatively small size compared to other systems, with a footprint of only 38 cm x 38 cm each, offering an easy setup [103].

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Table III. *Comparison of laparoscope positioning robots. The table shows key features of the systems including degrees of freedom, weight, control method, FDA approval, and fixture type in the operating room.*

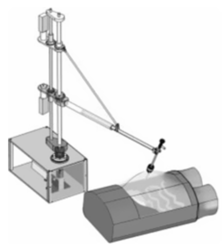
Name	DOF	Weight (Kgs.)	Control	FDA approved	Fixture	Figure
AESOP [12, 43, 46–51]	6	> 22.7	Voice control(Older versions controlled manually or remotely by hand or foot control)	Yes (1996)	Table mounted with cart	
VIKY [52, 53, 208]	3	1.41	Voice control	Yes (2008)	Clamped to operating table	
PARAMIS [44, 45, 54]	3	–	Voice control	Not FDA approved	Portable base	
Endosista [12, 55, 56]	4	–	Head movement (gesture sensor)	–	Placed on a trolley	

Table III. Continued.

Name	DOF	Weight (Kgs.)	Control	FDA approved	Fixture	Figure
EndoAssist [11, 59]	3	–	Head movement (Infrared headset)	Yes (but currently with-drawn)	Wheeled free standing	
Freehand [60–63]	3	7	Head movement (Infrared headset)	Yes	Clamped to operating table	
Emaro [10, 65]	4	–	Head and body movements (Gyroscopes)	No	Wheeled free standing	

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Table III. *Continued.*

Name	DOF	Weight (Kgs.)	Control	FDA approved	Fixture	Figure
KaLAR [6, 68–71, 94]	5(3 + 2M)	1	Visual tracking (using coloured tapes on instruments) + voice commands	No	Clamped to operating table	

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Avatera system by Avateramedical (Jena, Germany) has been in development since 2011 and has received Conformité Européenne (CE) certification in 2019 [16]. It shares a similar configuration to the da Vinci multi-port family [131]; however, it uses single-use disposable instruments [18]. Mirosurge system was developed by the DLR Institute of Robotics and Mechatronics in Germany with the MIRO robotic arm as its main component [132]. The system is considered versatile as it fulfils the requirements of a broad range of surgical applications and enables the implementaion of different control modes [133]. Since all joint units of MIRO integrate both position and torque sensors, it can be used in impedance-controlled mode. Therefore, a soft ("hands on") robotics feature is integrated into the system's workflow, allowing sensitive movements of the robot affected by the surgeon. In addition, the end-effector's orientation remains constant due to programmed high stiffness, enabling the surgeon to easily insert the surgical instrument into the patient by touching and moving the robotic arm [134]. Medtronic (Dublin, Ireland) has been developing Hugo system since it acquired Mirosurge system in 2013 [16, 135]. Hugo was unveiled in 2019 [136] and is expected to receive CE in 2021 [135]. It is unique for its modular, wheeled design, and cost-effectiveness [16]. Medicaroid Cooperation (Kobe, Japan) was established in 2013 as a result of collaboration between Kawasaki a Japanese Industrial Robotics Company and Sysmex a Medical Manufacturer [16]. It developed Hinotori system that has recently (August 2020) received regulatory approval from the Japanese Ministry of Health, Labor, and Welfare [18]. In 2013, Central South University in collaboration with Tianjin University developed Micro hand S system [137, 138]. The system's slave manipulator is based on the folding principle of the laminated double parallelogram mechanism allowing it to have a compact design and wide range of motions [139, 140].

Moreover, several systems have been developed for single port laparoscopic syrgery, such as the da Vinci SP [141–143], the SPORT surgical system [144–147], and SPRINT system [148–151]. They all utilize a single robotic arm, with the instruments having additional articulated joints for enhanced dexterity within a single incision [17].

Table IV summarizes comparison points of MSTDCs along with representative figures in Table V.

2.2.4. Robotic training systems

Traditionally, surgical training was carried out by observational learning, and refining the surgical skills by practice during live operations under experts' supervision. However, this process is considered time consuming and risky. An alternative to this risk of training under real-life situation is the use of simulated surgical environments, such as physical box trainers [152], virtual reality [153–156], and augmented reality simulators [157, 158]. However, none of these solutions mimic the conventional hand-over-hand guidance that surgeons use to teach their trainees.

Robotic training systems can actively teach trainees the skilled motion of master surgeons and evaluate the trainee's performance by comparing his/her motion with that of the master surgeon [159]. The expert surgeon's manipulation of the surgical instrument is either recorded and played back to the surgical trainee, or using a master–slave system, the expert surgeon remotely instructs surgical trainees by manipulating the master robot that is imitated by the slave robot holding the trainee's laparoscopic instrument [159–163].

Chui et al. [159] proposed a robotic box trainer with a 5 DOF manipulator that can record, play back movements carried out by the master surgeon, guide the trainee, and evaluate his/her performance. In record mode, the master surgeon performs surgery while his/her manipulation of the instrument is tracked (using cameras to acquire the 3D coordinate location of the instrument) and recorded. In replay mode, the robot is in full control, driving the surgical instrument by mimicking the recorded trajectory and the trainee is holding onto the instrument's handle to learn the master's skilled motion. In the guiding mode, the robot guides the trainee to follow the recorded trajectory by preventing his/her motion form varying excessively from that of the master's using force feedback. In the evaluation mode, the trainee performs the surgical tasks while the motion of the surgical instrument is being recorded and compared with that of the surgeon.

Table IV. *Comparison of Master–Slave Teleoperated surgical systems with Dedicated Consoles (MSTDCs), showing differences in their structures, type of approval received, and the manufacturer of each system.*

Name	**Manufacturer**	**Approval**	**Type of surgeon console and control interface**	**Vision Display**	**Patient console**	**DOF**	**Instruments Number of Uses**	**Unique Features**
Zeus [9, 102, 108–122]	Computer Motion (No longer commercially available)	FDA (2001)	• Open • Loop like handles	3D flat panel + polarized glasses	3 table mounted arms	5	–	Uses AESOP for camera positioning
da Vinci X da Vinci Xi [9, 17, 104, 123, 124, 209]	Intuitive surgical	FDA (2000)	• Closed • Loop-like handles	3D stereoscopic	4 arms on a single cart	7	10	Binocular endoscopic vision for the surgeon's console creating a truly 3D vision experience
Senhance [16, 104, 127–129, 210, 211]	TransEnterix	US FDA (2017)	• Open • Manipulator based on traditional laparoscopic instruments	3D HD flat panel+ polarized glasses	3-4 arms on individual carts.	7	∞	• Gaze control of camera • Haptic feedback. • Unlimited reusability of instruments
Versius [16, 103, 130, 212]	CMR Surgical Ltd.	TGA (2020)	• Open surgeon console • Manipulator resembling game controller	3D HD flat panel+ polarized glasses	4-5 arms on individual carts	7	–	• Relatively small slave robotic arms • Haptic feedback

Table IV. *Continued.*

Name	Manufacturer	Approval	Type of surgeon console and control interface	Vision Display	Patient console	DOF	Instruments Number of Uses	Unique Features
REVO-I [104, 130, 213–216]	Meere company, South Korea	MFDS (2017)	• Closed • Loop like handles	3D stereoscopic	4 arms on a single cart	7	20	Haptic feedback
Avatera [16, 18, 131, 217]	Avateramedical	CE (2019)	• Semi-closed • Loop like handles	3D stereoscopic	4 arms on a single cart	7	1	Haptic feedback
Hugo [16, 135]	Medtronic	CE expected in 2021	• Open. • Hand grip controllers	3D flat panel + polarized glasses	4 arms on individual wheeled carts	7	–	
Mirosurge [132–134]	DLR	–	• Open • Loop like handles	3D flat panel + polarized glasses	3 MIRO arms on individual carts (mounted to the table)	7	–	• Haptic feedback • Impedance-controlled mode
Micro Hand S [137–140]	Collaboration between Central South and Tianjin Universities in China	–	• Open • A series of 3 rotary joint manipulator	3D stereoscopic image on a flat panel	3 arms on a single cart	–	–	Slave manipulator is based on the folding principle of the laminated double parallelogram mechanism

Table IV. *Continued.*

Name	Manufacturer	Approval	Type of surgeon console and control interface	Vision Display	Patient console	DOF	Instruments Number of Uses	Unique Features
Hinotori [16, 18, 218]	Medicaroid	Regulatory approval from the Japanese Ministry of Health (2020)	• Semi-closed • Loop like handles	3D HD microscope like ocular lens	4 arms on a single cart	8	–	
SPORT [17, 144–147]	Titan Medical	–	• Open • Loop like handles	3D Flat panel + polarized glasses	Single manipulator	6	1	
SPRINT [17, 148–151]	ARKANES	–	• Open • Haptic device	3D flat panel+ polarized glasses	Single manipulator	6	–	Haptic feedback

Table V. *Representative figures of MSTDCs.*

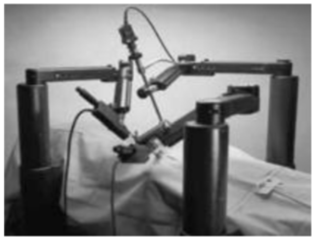
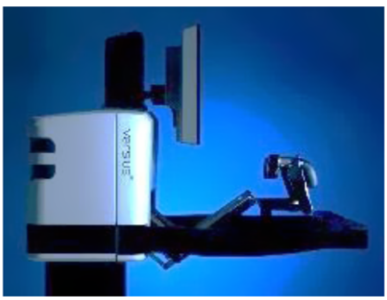
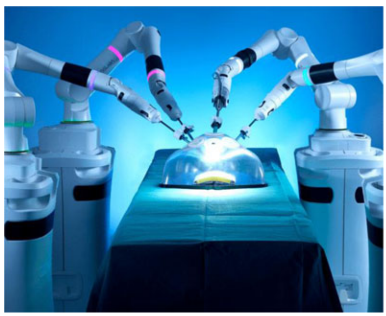
Name	**Surgeon console figure**	**Patient console figure**
Zeus [9, 102, 108–122]		
da Vinci X **da Vinci Xi** [9, 17, 104, 123, 124, 209]		
Senhance [16, 104, 127–129, 210, 211]		
Versius [16, 103, 130, 212]		

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Table V. *Continued.*

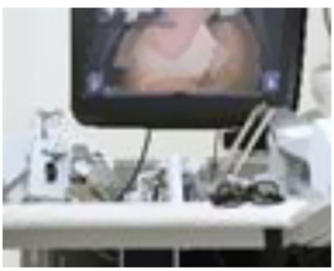
Name	Surgeon console figure	Patient console figure
REVO-I [104, 130, 213–216]		
Avatera [16, 18, 131, 217]		
Hugo [16, 135]		
Mirosurge [132–134]		

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Table V. *Continued.*

Name	Surgeon console figure	Patient console figure
Micro Hand S [137–140]		
Hinotori [16, 18, 218]		
SPORT [17, 144–147]		

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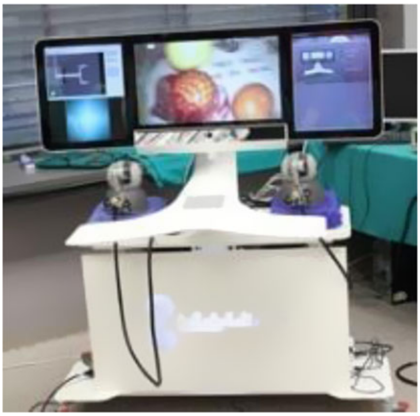
Table V. *Continued.*

Name	Surgeon console figure	Patient console figure
SPRINT [17, 148–151]		

Other systems record the manipulator's joints' angles during the record stage. Garudeswaran et al. [161] proposed a 6 DOF robotic arm, with its servomotors acting as potentiometers during the recording stage when they are not energized. The expert surgeon manipulates the surgical instrument, moving the robotic arm. The joints' angles are recorded, stored, and then played back to the servomotors in the training stage. A system of two surgical manipulators with 5 DOF each, providing a similar range of motion as in conventional laparoscopic instruments, is proposed by Lee et al. [162]. With one manipulator being controlled by the surgeon, recording joints' angles measured by encoders, and the other follows its recorded movements to guide the trainee. Abdelaal et al. [160] proposed a record/playback system that utilizes the tele-operated da Vinci surgical system as the training platform. The proposed system records joint angles of both the master tool manipulators (MTMs) and the patient side manipulators (PSMs) during the performance of a tele-operated laparoscopic surgery by an expert surgeon. These motions are then played back to either the MTMs for robotic laparoscopic surgery training or the PSMs for conventional laparoscopic surgery training.

A more recent work by Prince et al. [163] proposed the LapaRobot, a laparoscopic surgical system for tele-mentoring training, composed of an expert station and a trainee station. The joints' angles in the expert station are measured by optical encoders and sent as joint commands to the trainee station. The expert and trainee stations can also be used as standalone record/playback devices without tele-operation.

Features of developed robotic training systems are summarized in Table VI.

2.3. Classification based on configuration

Generally, laparoscopic manipulators which exist in clinical use can be classified into two main categories: serial manipulators and parallel manipulators.

2.3.1. Serial manipulators

Surgical serial manipulators depend on wires or rod and gear-based systems to transmit the mechanical movement to the robot joints since no actuators are allowed to be inside the patient body. Most of the commercially available MSTDCs utilize serial manipulators, such as da Vinci, Senhance, REVO-I, Avatera, and Hinotori [16, 18, 104, 127, 164, 165]. In addition to several laparoscope positioners including the AESOP [43], Endosista [12], Endoassist [59], and Freehand [60, 61]. Some handheld devices

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Table VI. Summary of robotic training systems, including key features and experimental results.

Reference	Structure	Function	Experimental evaluation	Offer training for tele-operated robotic laparoscopic surgery
[159]	• Box trainer with cameras to visually track the surgeon's movements • 5 DOF robot trainer that follows the surgeon's instrument's trajectory	• Record and playback	Development and experimentation are on-going	No
[161]	Robotic arm with 6 DOF	• Record and playback	–	No
[162]	Two 5 DOF manipulators (master and slave)	• Record and playback	Showed better performance than passive training • Reduced cumulative deviation of the instrument tip by 8.5% • Reduced joints displacements by 15.4%	No
[160]	The da Vinci MSTDC with additional record/playback buttons	• Record and playback	Enhanced accuracy when combining both record-playback and discovery training	Yes
LapaRobot [163]	Expert station (master) and trainee station (slave)	• Tele-mentoring • Record and playback	Improved performance of trainees by 55% compared to 19% without LapaRobot	No

also have serial configuration [22, 33]. A number of serial laparoscopic robots have spherical configuration to mechanically constrain the instrument with respect to the incision, but this may come with a tradeoff of inadequate workspace. To solve this problem, a redundant serial spherical multi-robot system was proposed in ref. [166]. Moreover, snake-like wire-driven devices are proposed, where a snake-like device with multi-backbone has been introduced by Simaan et al. [167], with three super elastic wires responsible for performing pull and push modes.

However, wire-driven laparoscopic manipulators have many downsides. The wires might rupture during the operation, or be slacked, requiring pre-tensioning mechanism [168]. In addition, the sterilization

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process may also be troublesome. Therefore, researchers have started to propose parallel manipulators that offer further advantages over the serial manipulators.

2.3.2. Parallel manipulators

Parallel manipulators are considered closed-chain mechanisms that have a movable platform connected with the fixed base platform through several independent kinematic chains. This configuration has offered multiple advantages over the serial configuration, including higher structural stiffness and payload capacity, accurate positioning with high speed, and easy sterilization process.

Several designs of laparoscopic parallel manipulators have been proposed in the last decade, including laparoscope positioners such as the voice-controlled parallel manipulator PARAMIS [44, 45, 54], and the pneumatically driven laparoscope positioner Emaro [65]. Parallel configuration has also been introduced in robotic forceps that can be used in handheld devices or teleoperated systems. A robotic forceps with complex rigid link mechanism has been developed by Arata et al., allowing bending in two directions and grasping. But the bending angle is limited to $\pm 70^{\circ}$. Yamashita et al. [170] introduced another laparoscopic forceps manipulator with 2-DOFs bending mechanism by multi-slider linkage mechanisms and 1-DOF wire-driven grasping mechanism; however, troubles about precision and power consumption have been reported. Ishii et al. [171] developed new dual screw drive (DSD) forceps, but the manufacturing accuracy needs to be improved. A novel actuator driven handheld laparoscopic instrument is introduced by Rose et al. [172] having a parallel kinematic instrument tip to overcome the workspace restrictions of classic laparoscopic instruments. However, the largest bending angle of the manipulator is not equal in every direction because of the distinctive design of its limbs. A parallel hybrid surgical robot PARASURG-9 M is introduced by Pisla et al. [173], consisting of a surgical robotic arm, PARASURG whose kinematics and singularity analysis are studied in refs. [174, 175] and an active robotized surgical instrument PARASIM. A significant drawback is its limited range of the orientation angles. Elastostatic model of a novel hybrid laparoscopic robot has been introduced [176], having two identical spherical-prismatic-universal (SPU) limbs and a 3 revolute (RRR) limb to enable spherical movements of the end effector. The robot possesses four active joints, 3 for the parallel mechanism and 1 for the translational movement along the axis of the surgical instrument. However, its maximum bending angle was $\pm 60^{\circ}$ in any direction. A 4-DOF laparoscopic parallel manipulator has been designed and implemented [177], with two prismatic-universal-universal (PUU) and two prismatic-universal-spherical (PUS) limbs, capable of reaching $\pm 90^{\circ}$ in all directions. However, a thorough singularity analysis is required to discover why the movable platform could not resist forces in some configurations. Moreover, the kinematics of the general 3-prismatic-revolute-spherical (PRS) parallel mechanism that owns 2R1T DOFs is investigated by Li and Xu [178]. Table VII shows kinematic structures of developed parallel manipulators along with their limitations. Novel laparoscopic parallel manipulator with 3-PUU architecture that also owns 2R1T DOFs is presented by Khalifa et al. [168]. It can achieve a bending angle of more than $\pm 90^{\circ}$ in any direction. Unlike the 3-PRS mechanism, this manipulator does not need precise, troublesome spherical joints. Therefore, from a practical point of view, 3-PUU manipulator owns better orientation capability and is also cheaper and easier to produce [168].

2.4. DOFs of laparoscopic robots

A minimum number of 3 DOFs is required to maneuver the laparoscope providing insertion/withdrawal, pitch, and yaw movements. Moreover, additional roll motion may be required to correct the top and bottom of image for forward-viewing laparoscope and to observe the back of the organs for oblique-viewing laparoscope [14]. Furthermore, conventional laparoscopic instruments require 4 DOFs and an additional DOF if there is a grasping action [179]. Developed laparoscope positioning robots offer a wide range of DOFs starting from 3 up to 6 DOFs [6, 10, 43, 53, 54, 71]. Additionally, a robotic system developed by ref. [180] for positioning oblique-viewing laparoscopes has 8 DOFs including the Franka

Table VII. *shows kinematic structures and degrees of freedom of different surgical parallel manipulators along with their reported drawbacks.*

Reference	Kinematic structure	DOF	Reported drawbacks
[169]	3 parallel links with active prismatic joints mounted in a rotating housing for grasping	3	Bending angle is limited to $\pm 70^{\circ}$
[170]	2 sets of sliding linkages and wire driven grasping mechanism	3	Precision and power consumption problems
[171]	3 links with DSD bending mechanism	3	Poor accuracy
[173, 174]	• PARASURG 5 M: 3 links with translational active joints connected to a kinematic chain containing 2 cylindrical, 2 prismatic and 3 rotational passive joints • PARASIM parallel active robotized surgical instrument	54	Limited range of orientation angles
[176]	1 RRR and 2 identical SPU links	4	• Bending angle is limited to $\pm 60^{\circ}$ • Costly spherical joints
[172]	4 links with active prismatic joints and passive spherical joints connected in a distinctive manner,2 links are directly connected to the instrument platform, (one of them is the main kinematic chain) the other 2 are connected to the main kinematic chain between the base and instrument platform	4	Non-even maximum bending angles in all directions
[177]	2 identical PUU and 2 identical PUS links	4	Failure to resist forces in some directions
[178]	3identical PRS links	3	Costly spherical joints
[168]	3 identical PUU links	3	No reported drawbacks

Emika Panda manipulator (7 DOFs) and a rigid 30 degree oblique-viewing laparoscope with mono vision (1 DOF).

Industrial master–slave systems provide the surgeon with either 5,6,7, or 8 DOFs [9, 16, 108, 130]. Handheld devices also offer the surgeon enhanced dexterity with 5 and 7 DOFs [20, 21]. Published works of robotic training systems proposed a variety of 5 to 7 DOFs robotic trainers [159–162]. Figure 3 classifies laparoscopic robots according to their DOFs.

2.5. Classification based on the control technique employed in the system

Further to the above subdivision, Fig. 4 classifies laparoscopic robots according to their type of control technique used as being open or closed loop. All systems have visual feedback to the surgeon. However, systems are considered to have closed loop control if the robot's path is continuously monitored and adjusted according to feedback of the desired position. Therefore, gaze/instrument tracking, cognitive laparoscope positioning robots, MSTDCs, robotic training systems, and handheld systems with virtual

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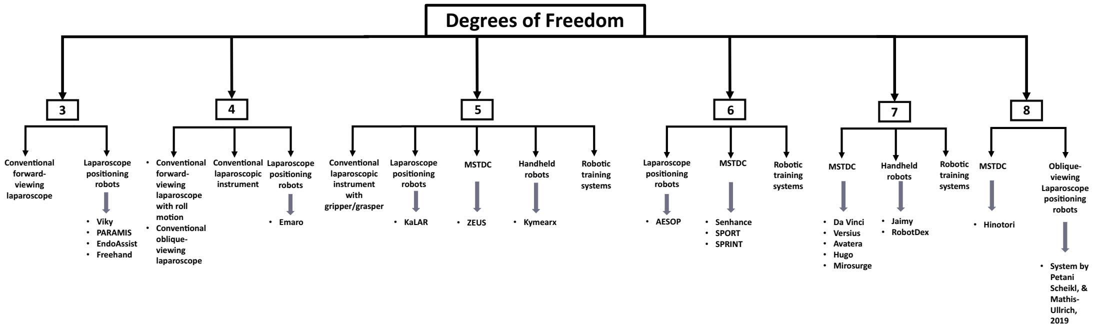

Figure 3. *Shows degrees of freedom of conventional laparoscopic robots.*

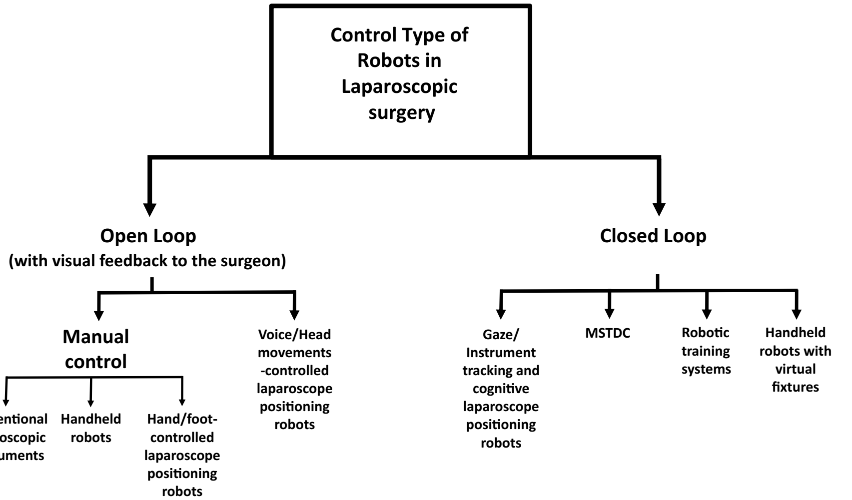

Figure 4. *Classification of robots in laparoscopic surgery according to control type.*

fixtures exhibit closed-loop control. Moreover, open loop systems may use monitoring systems to evaluate their performance by measuring parameters such as instrument's position and/or contact force in test platforms [21, 26, 33].

3. Generalized control block diagram of robots in laparoscopic surgeries

The color-coded generalized block diagram, shown in Fig. 5, demonstrates the general control scheme of robots used in laparoscopic surgeries following the subdivisions of the previous section.

It can be easily seen from the block diagram that in conventional manual laparoscopy, the surgeon directly controls conventional laparoscopic instruments. Handheld robots allow the surgeon to directly control the actuators using control interface on the robot's handle (button, joystick), enabling the robot to manipulate the articulated instrument's tip in an open loop manner [19, 20]. However, handheld robots with virtual fixtures provide closed loop control by limiting the instrument's motion into restricted pre-defined region/path [37]. In manually (hand/foot) controlled laparoscope positioning robots, direct commands are sent to the manipulator's actuators to position the laparoscope accordingly. While in the voice, head movements control, the actuators' controllers (c1, c2... cn) send the required control signals to the actuators. These control signals are modified according to the joints' angles feedback, i.e. closed loop motor control [45, 65]. However, there is no feedback that compares the actual end effector's position with the desired position, that is why the whole system is considered an open loop system,

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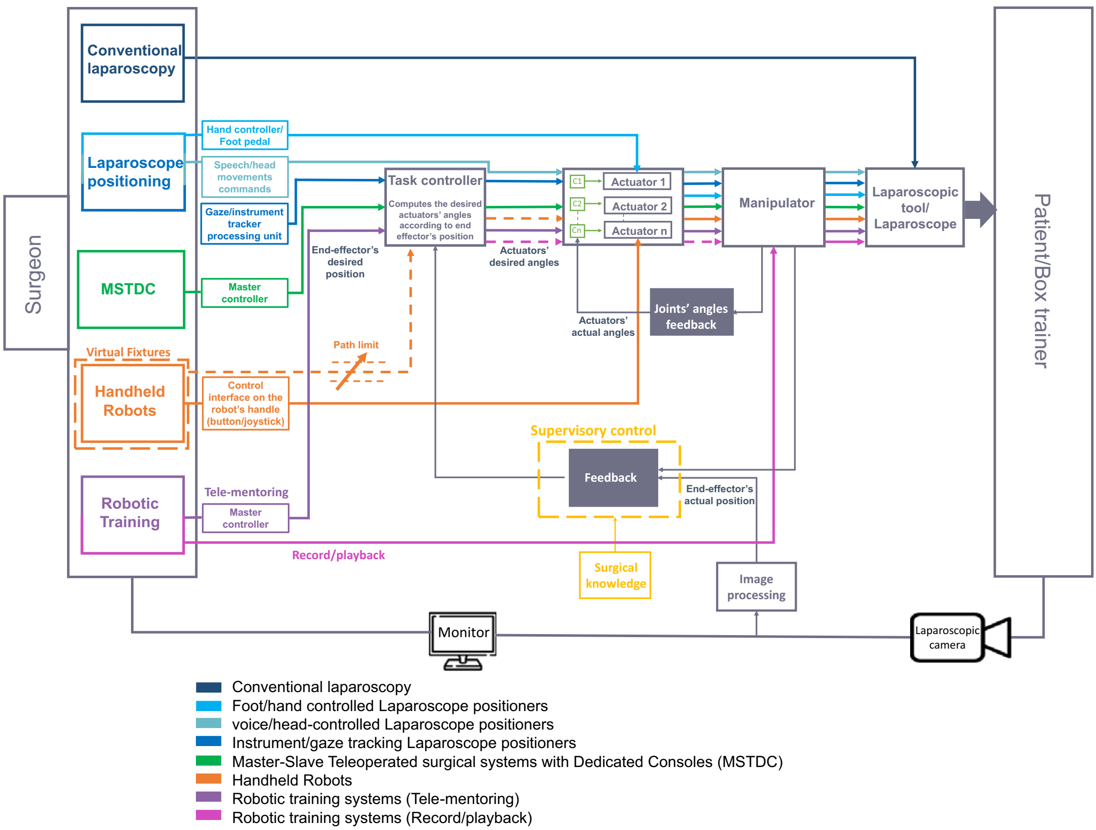

Figure 5. *Generalized block diagram of robotic systems in laparoscopic surgery.*

although the actuators exhibit closed-loop control. In the eye gaze/instrument tracking, the end effector's desired position is obtained from the image processing unit and is fed to the task controller, which in turn sends commands of the actuator's required angles to the actuators' controllers [5, 13, 181]. These commands are modified according to feedback of the actual end effector's position (in addition to the joints' angles feedback). Furthermore, supervisory control can be achieved by providing laparoscopic robots with preliminary surgical knowledge such as the sequence of procedures, instruments used in each stage, and the preferred laparoscope view at each one. The robotic arm can estimate the current stage using surgical knowledge and information of surgical environment and suggests the proper laparoscope view corresponding to the estimated surgical stage [182–184].

In MSTDCs, the ergonomic handles (master controller) controlled by the surgeon provide the desired instrument position that is mapped to the slave's workspace and sent to the task controller. The controller sends the required control effort to the slave's actuators' controllers which are modified according to feedback of the actual end effector's position (in addition to the joints' angles feedback) [101, 106]. Moreover, bi-lateral control can be achieved if haptic feedback signal is sent from the slave to the master control unit [185, 186].

For robotic training systems, the tele-mentoring mode operates in a similar manner to that of the MSTDC [163]. The record/play training mode allows the surgeon to directly move the manipulator while manipulating the laparoscopic instrument. The instrument's trajectory/video feedback/ manipulator's joints angles are recorded and stored then the task controller sends the required control effort to the actuators' controllers in the playback stage [160, 161].

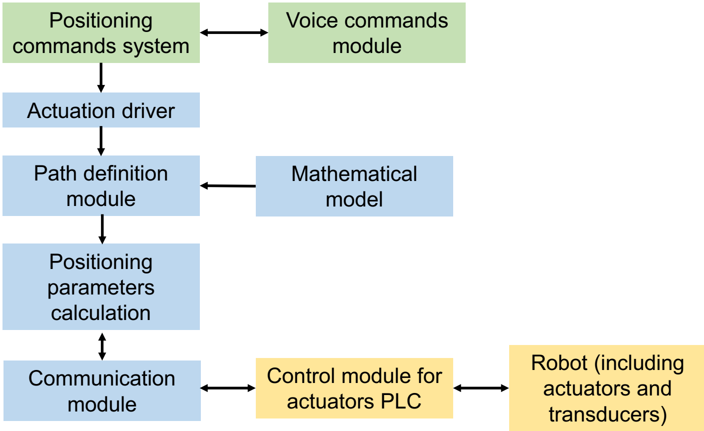

Figure 6. *Control block scheme of the actuation system for Paramis robot [45].*

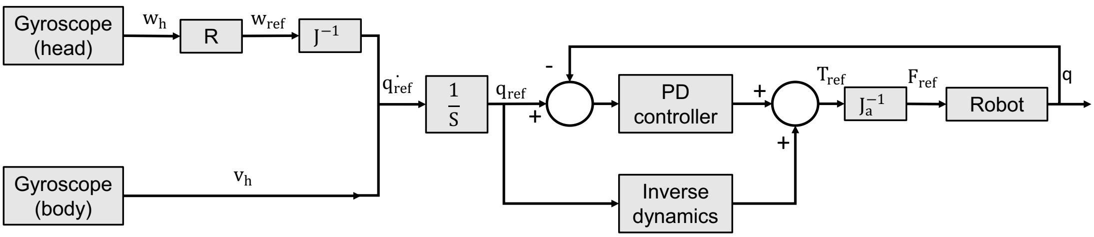

Figure 7. *Control block diagram of Emaro robot [65].*

Further to the generalized control block diagram of laparoscopic robots, the following subsection discusses more detailed control strategies of selected laparoscopic robots in previous studies.

3.1. Technical control strategies of laparoscopic robots in selected previous studies

Paramis voice-controlled laparoscope positioning robot is composed of three system levels [45]: user interface (shown in green in Fig. 6), PLC (shown in blue), and the robot (shown in yellow). In the user interface level, the surgeon interacts with the robotic system through vocal command inputs that are processed using the voice commands module and translated into a given command for the controller level. In the PLC level, the actuation driver performs the connection between the motion elements and software application. The mathematical model provides the kinematic model of the robot to the path definition module that uses it to calculate the position variation for each actuator for a given command. Then, motion parameters are calculated in the positioning parameters calculation module based on the manipulator's kinematics and its current position. The communication module ensures communication between the computer, PLC, and robot actuators based on CANOpen protocol. Finally, the robot level represents the mechanical structure and the actuators. The control module in the robot level calculates the position of the robot as a function of the parameters imposed by the voice commands and current position of each actuator obtained from position transducer.

The 4-DOF head movements-controlled robot Emaro [65] is controlled by first measuring the angular velocity (wh) and translational velocity (vh) using gyroscopes mounted on the surgeon's head and body, respectively, as shown in Fig. 7. The reference angular velocity (wref) of the robotic arm is obtained by multiplying the angular velocity by the matrix that indicates the angular position of each rotational joint of the robot (R). Then the angular velocity of each rotational joint is obtained using the Jacobian matrix. Velocity of the axis responsible for the zoom motion is defined as the anteroposterior direction of vh.

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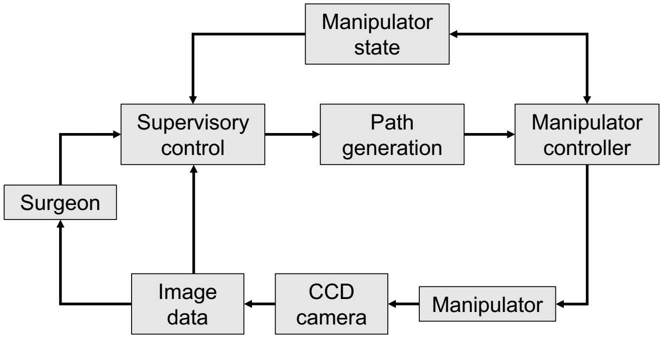

Figure 8. *Control and interface architecture of KaLAR robot [71].*

After obtaining velocities of all four joints of the robot, they are integrated to provide the reference position vector qref and the reference torque (Tref) is calculated using PD controller along with feed-forward compensation using inverse dynamics calculated from the reference position.

The control and interface architecture of the instrument tracking laparoscope holder KaLAR is presented in Fig. 8. The real-time surgical image is acquired from CCD camera and using the Meteor-II board from the Matrox Co. The image data is sent to the supervisory control system (that can distinguish the procedure in progress and recognize the optimal view corresponding to each procedure, after having preliminary knowledge of the surgical procedure loaded from the database) and to the surgeon/operator. This data is used to generate the desired path of the manipulator that is sent to the manipulator's controller [71, 94].

A recent work proposed and simulated the application of Model Predictive Control (MPC) with fuzzy approximation for active RCM constraint (caused by the incision point) on the industrial serial 7-DOF robot KUKA LWR + used as a laparoscopic robot [187]. The control objective is to make the robot follow a desired trajectory while controlling the position and orientation of the surgical tool simultaneously. First, 2D trajectory tracking and RCM constraint for the surgical tool are considered. Modeling the surgical tool as a virtual dynamic system with virtual velocity along the two axes and virtual angular velocity around its end and transferring the trajectory tracking and RCM constraint problem into the control problem of the virtual system. Then MPC is applied to design the controller of the virtual dynamic system. Second, the 3D workspace of the robot is simplified, by projecting it into xy-plane and xz-plane, respectively, so the 2D MPC solution can be used to solve these two 2D problems. By solving the angle and angular velocity of each joint of the robot using inverse kinematics [188], the robot can be controlled to get to the actual pose and realize the trajectory tracking and RCM constraint. Finally, the fuzzy approximation is introduced to compensate for the external disturbances introduced by the motion of organs during breathing. The control framework is shown in Fig. 9 [187].

A cognitive control architecture is proposed in ref. [189] that integrates the appropriate surgical task determinism using supervisory controller, motion safety using velocity-constrained MPC, and adaptability to human task execution timings provided by action segmentation using multi-modal neural network. The system's overall block diagram is shown in Fig. 10. The employed robotic system consists of the daVinci surgical system (tele-operated by the surgeon) along with the SARAS robotic arm (autonomous). The surgeon tele-operates the daVinci system and the AI module processes the cartesian poses of both the daVinci system and the SARAS arm using knowledge of the training data. Implementing the neural network EdSkResNet to integrate multi-modal learning over the data available during robotic laparoscopic surgery, action segmentation is achieved. After the action segmentation module estimates the current action and the confidence level, the supervisory controller determines the next task to be performed by the robot (the next goal position and confidence level). Finally, the MPC receives the current goal and confidence level required to control the SARAS arm, where it is intended to maximize the performance and the safety of the arm incorporating both a collision

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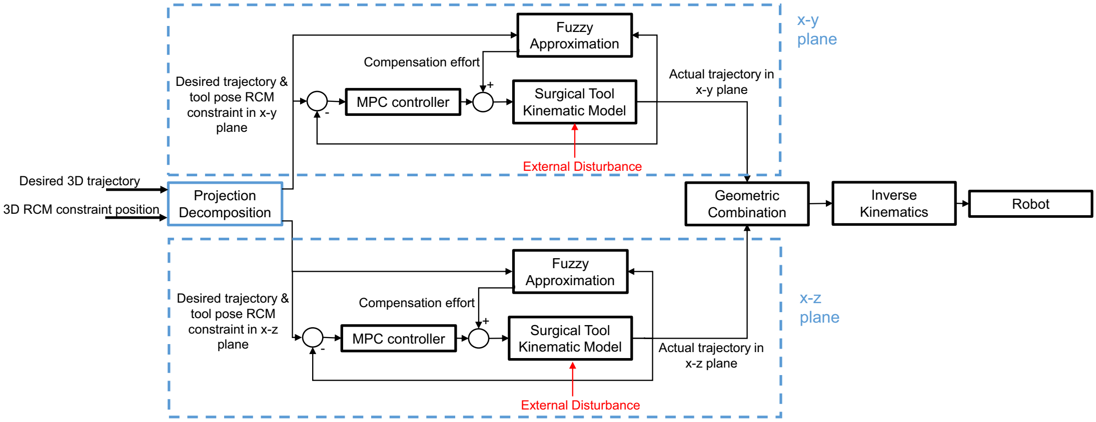

Figure 9. *Control framework of Model Predictive Control with fuzzy approximation for active RCM constraint [187].*

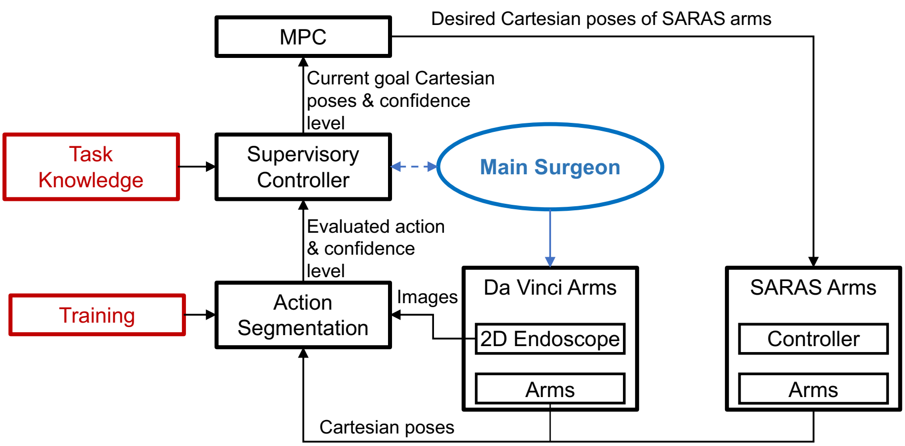

Figure 10. *Control framework of a multi-modal learning system to control surgical assistant robots via action segmentation [189].*

avoidance formulation and velocity modulation based on the uncertainty of the action segmentation module.

In ref. [190] a physical human-robot interaction (pHRI) control scheme of a haptic 9-DOF master manipulator used in laparoscopic robots is presented for enhancing the precision and comfort of operations. A sensor-less force control scheme based on torque pattern is proposed to estimate the complete dynamic information without explicit acceleration calculation. To further improve the performance of the proposed system, a compensator based on time-delay neural network (TDNN) is introduced. First, the inverse dynamics equations of the manipulator are derived, and a joint torque observer based on the generalized momentum is derived from the manipulator's dynamic model. To reduce the residual error between the output of the observer and the actual data, multilayer perception (MLP) networks have been used, but they are unable to compensate for the inertia moment calculation error which will impact the performance of the pHRI. Since the inertia moment can be obtained without explicit acceleration calculation by using the angular velocity information and its filtered value which is obtained using the current and previous velocity information, TDNN is used to add a delay operator to the MLP allowing the network to have a finite dynamic response to time series data. Finally, comparative experiments were

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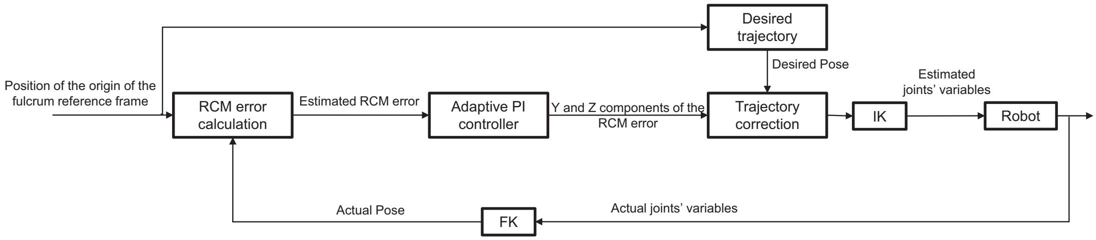

Figure 11. *Control framework based on RCM tracking [191].*

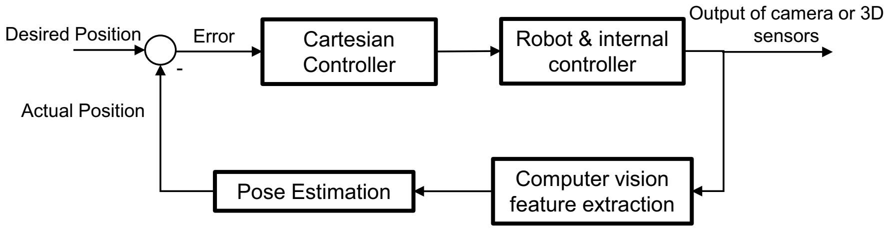

Figure 12. *Control framework using position based servoing [191].*

conducted by the simulation to verify that the proposed compensator can fit the nonlinear function of the system. The framework of the proposed pHRI control scheme is presented in ref. [190].

A recent study discussed perception, control, and manipulation of robotic laparoscopic tools with emphasis given to the pivot trajectories and RCM constrained motion planning [191] using the 7-DOF KUKA manipulator and the 3-fingered Barrett hand gripper attached to it for grasping purposes. The robotic arm is controlled to be able to detect, grasp, and manipulate a laparoscopic surgical tool. To achieve this goal, the robot should be capable of visually detecting the scene and the laparoscopic tools then calculating the relative position and orientation of the center of mass of each tool, calculating the contact points on the tool, on which the fingers of the gripper will be placed to make a firm grasp, calculating the path from the tool's table to the surgical site table, and finally calculating the required trajectory to be executed when the tool is inserted into the trocar. Several control system schemes were studied: RCM tracking, visual servoing, and firm grasping algorithm and force control. In the RCM tracking method, the RCM error is calculated and used as a feedback signal in a control system that makes sure that the laparoscopic tool is always aligned with the fulcrum point and satisfies the RCM constraint. Determining the line of the long axis of the laparoscopic tool and the position and orientation of the fulcrum reference frame, the alignment error is calculated as the distance of the line from the fulcrum point. Using the calculated RCM error and the estimated position of the origin of the fulcrum reference frame, an adaptive motion control system is implemented to correct the trajectory and to avoid RCM misalignment. The RCM tracking control system is shown in Fig. 11 [191]. Two visual servoing control system schemes were implemented: position-based servoing and image-based servoing. In the position-based servoing, depth information is extracted from motion, stereo vision, or 3D sensors, from which the desired position is calculated and used as the reference input in the closed-loop control system shown in Fig. 12. In the image-based servoing, the robot is directly controlled using features extracted from the images and positions on the image plane. The robot is driven so that the video frame is changed from an initial view to a final desired view. The image-based visual servoing closed loop control is shown in Fig. 13. Where the image controller is a PD controller that outputs commands to control the robot in task space (and the internal robot controller drives each joint to the desired angle). The computer vision feature extraction calculates the vector from the detected tool's center of mass to the center of image frame which is used to calculate the error for the controller. The firm grasping algorithm and force control combine position measurements with force measurements to ensure that the gripper firmly grasps the

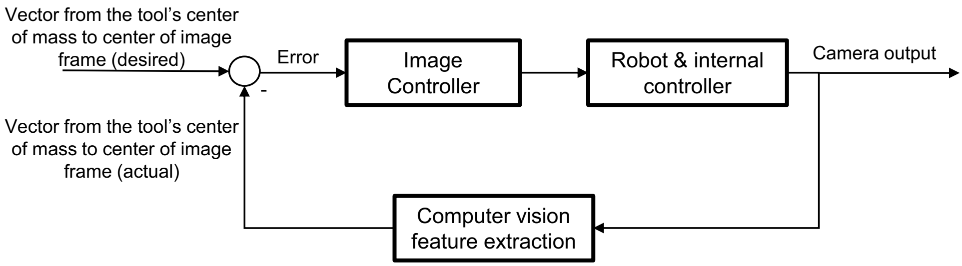

Figure 13. *Control framework using image based servoing [191].*

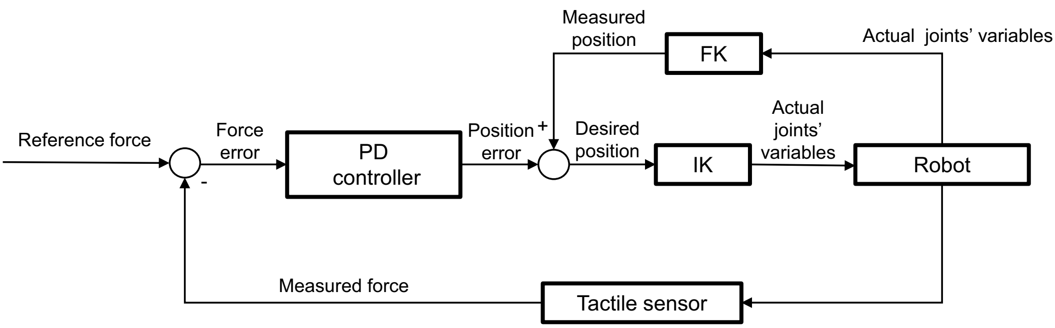

Figure 14. *Firm grasping algorithm and force control block diagram [191].*

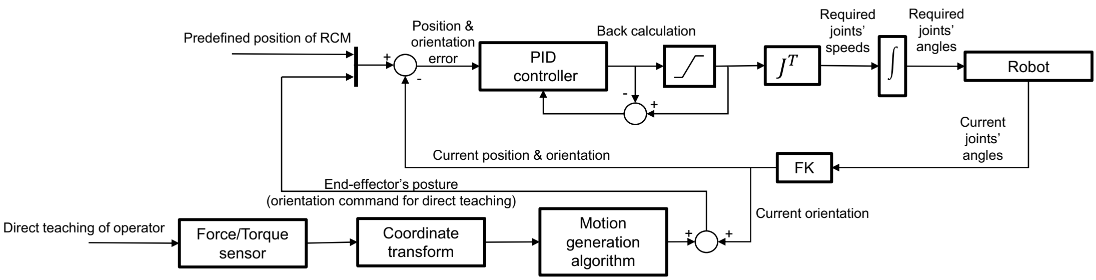

Figure 15. *Block diagram of RCM control and direct teaching with motion generation algorithm [192].*

surgical tool. The position of the finger of the Barrett hand is known using the forward kinematics and the forces are measured using tactile sensors. According to the block diagram shown in Fig. 14, the force error calculated using a reference force and the measured force produces a position error via the first PD controller. This position error is added to the current measured position and will make the gripper's finger move closer to (if the error is positive) or away (if the error is negative) from the tool. This loop is repeated until satisfactory contact is reached, and the desired force is exerted on the tool.

A control strategy for RCM and direct teaching is proposed in ref. [192] that enables the surgical robot to mimic the movements of a nurse's wrist. The assistant robot has an end-effector attached to a 6-joint cooperative robot that holds the laparoscope. To maintain a non-mechanical remote center, force/torque applied by the surgeon is measured using a force/torque sensor attached between the robot and the end-effector and is then converted into a control command. Control objective is to maintain a solid remote center even while the end-effector's posture is operated with direct teaching. The control block diagram of the system is shown in Fig. 15. The position control inputs are the predefined remote center position and the end-effector's posture. Where the end-effector's posture is calculated from values generated by the force/torque sensor due to direct teaching through a motion generation algorithm based

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on impedance control [192]. The position control is designed by differential kinematics with PID control and back calculation.

Moreover, modeling and control of a laparoscopic parallel manipulator with three limbs having identical prismatic-universal-universal (3-PUU) architecture are discussed in a recent study [193, 194]. The manipulator has 3 DOFs corresponding to rotation about x-axis (E_x), y-axis (E_y), and translation along the z-axis (P_z). To avoid the computational complexity of solving the manipulator's kinematics in real-time application, two feed-forward artificial neural networks (ANNs) are used as forward and inverse kinematics estimators [194, 195]. The dynamic model of the 3-PUU manipulator is built using MATLAB Simscape environment, and several control schemes are investigated. Starting with motor control, PID and PID plus feed-forward using the model's inverse dynamics control schemes were studied. Simulation results were compared to the PID and adaptive fuzzy logic control schemes implemented in a previous study by Khalifa et al. [168]. Figure 16 depicts the comparison and shows that the PID plus feed-forward control scheme provides the best motor performance between the other control schemes [193, 194]. Compared to the adaptive fuzzy logic controller [168], the PID plus feed-forward control provided better motor performance with 78.26% less maximum tracking error, in addition to being easier to implement online than the adaptive fuzzy logic controller. Closed-loop trajectory control based on Cartesian space feedback of the manipulators' position and orientation and inverse kinematics ANN is then studied. Figure 17 shows the complete schematic control block diagram of the 3-PUU manipulator with closed-loop trajectory control. In this control system [193, 194], the position and orientation error is fed-back to the inverse kinematics ANN which acts as a controller. The ANN's output represents the error in the prismatic displacements d_1, d_2, and d_3 resulting from any change in the manipulator's actual model. This error is then added to the desired prismatic displacement to compensate for the actual position and orientation error. The closed-loop control scheme can enhance the system's performance, eliminating the error resulting from any change in the manipulator's actual model due to manufacturing or assembly defects. Simulation results of a defected manipulator model show that the closed-loop control scheme improves the manipulator's trajectory tracking capability compared to motor control, reducing the z-axis position error by 89.23% and the orientation error by 86.76% and 82.83% about x-axis and y-axis directions, respectively [193, 194].

Figures 18 and 19 provide classifications of the discussed control systems according to their control objective and control input (Fig. 18) and type of controller used (Fig. 19).

4. Clinical/Training applications of robotics in laparoscopic surgeries

Several experimental and clinical trials of laparoscope positioning robots have been performed, showing common results such as stable and accurate laparoscope movements, steady and less smudgy images, feasibility, safety, and no additional complications compared to conventional laparoscopy as shown in

Table VIII Detailed studies were conducted to gather this information. One study included 105 procedures of 21 different types that were performed by 43 consultant surgeons between 2013 and 2016 using Freehand robotic camera assistant. Overall surgeons' satisfaction was 4.29 out of 5 for setup, 4.12 for ergonomics, 4.39 for usability, and 4.34 for the overall experience and detailed statistical data for each procedure is presented in ref. [196]. In addition, several experiments were carried out to compare different laparoscope holders [15, 197–200]. Reported experimental/clinical trials of different MSTDCs (Table IX) show common results such as feasibility and safety, enhanced ergonomic posture of the surgeon, and enhanced surgical dexterity. In a recent study in Klaipeda University Hospital, 100 procedures were observed using Senhance robotic platform in general and colorectal surgery, gynecology, and urology. All surgeons felt confident with the system, reporting its feasibility and safety in different types of procedures [201]. From 2019 to 2020, 40 extraperitoneal radical prostatectomies were performed using Senhance, where it is reported that considerable surgical proficiency is gained after 30 cases and the learning curve is shorter for surgeons with previous laparoscopic experience. Detailed patient data and experimental results are provided in ref. [202]. Moreover, randomized controlled trials that compared

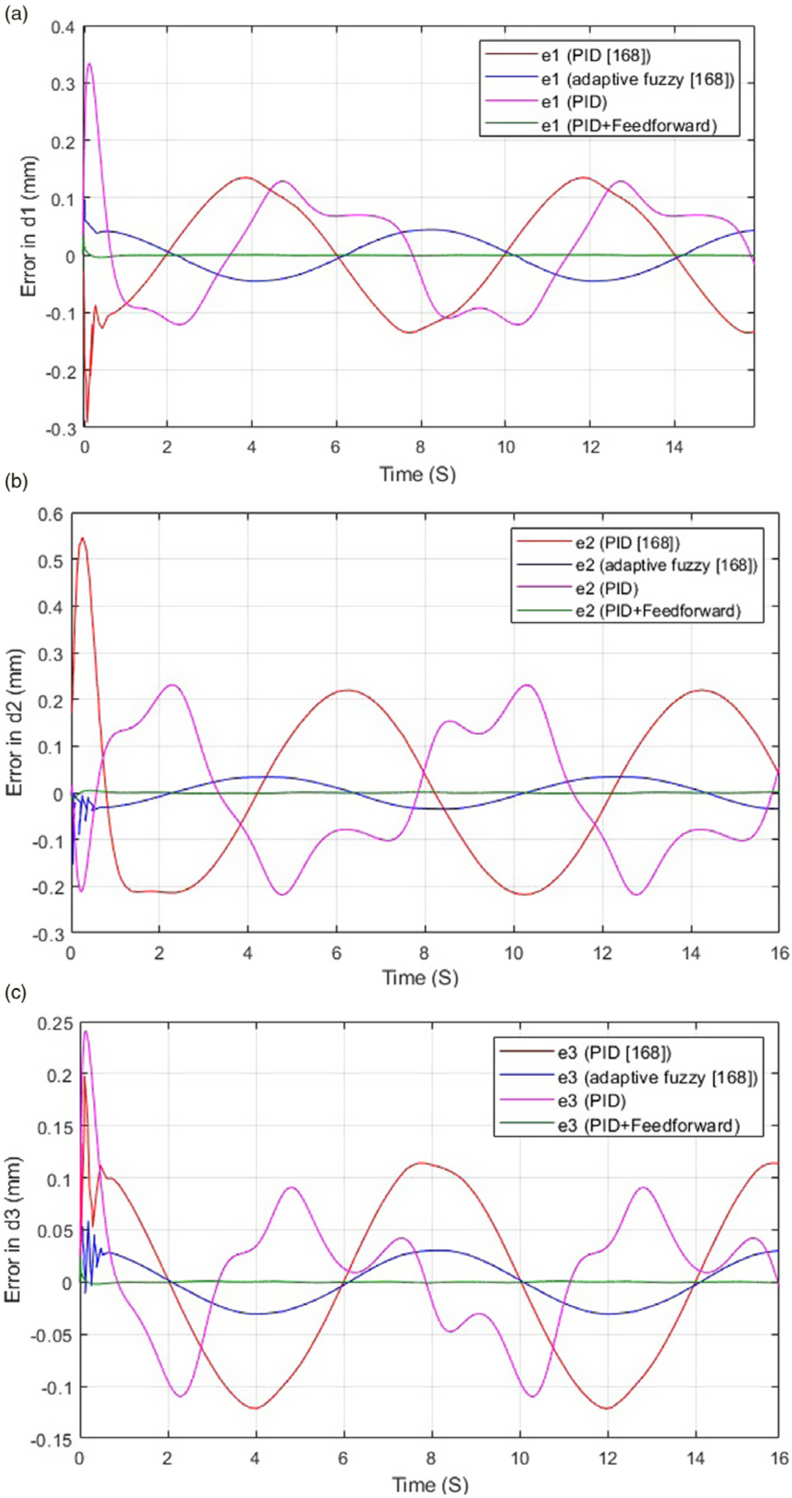

Figure 16. *Comparison between the error in motors' sine response using different control schemes for the 3-PUU laparoscopic manipulator [193, 194]. (A) Error in d1 (B) Error in d2 (C) Error in d3.*

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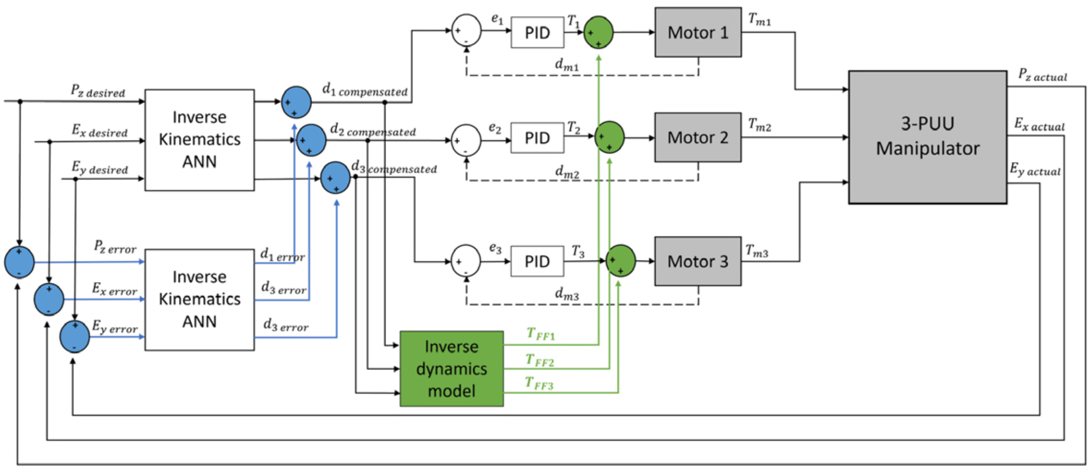

Figure 17. *Schematic of the 3-PUU manipulator with closed-loop trajectory control [193, 194].*

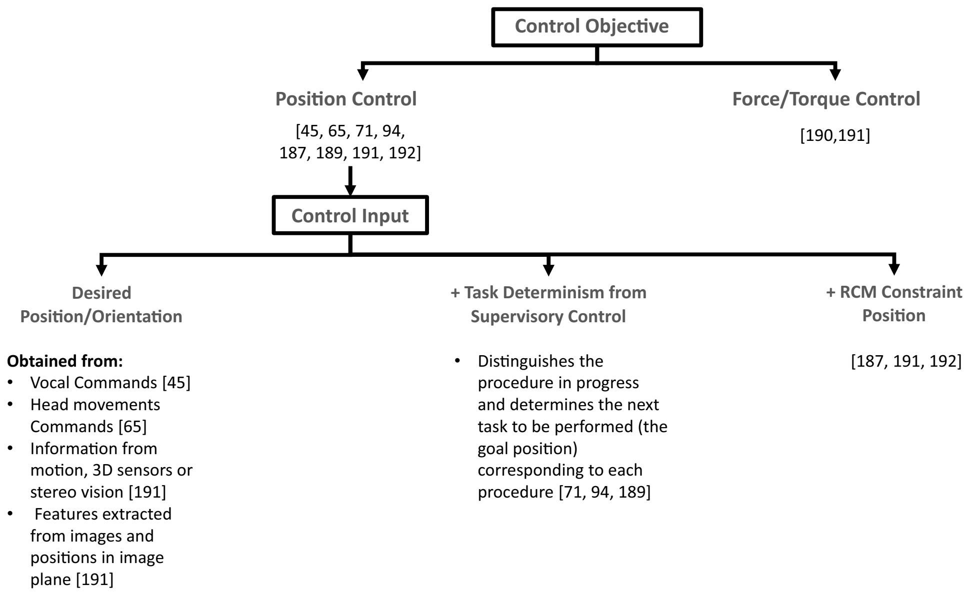

Figure 18. *Classification of control objectives and control inputs of the discussed control systems.*

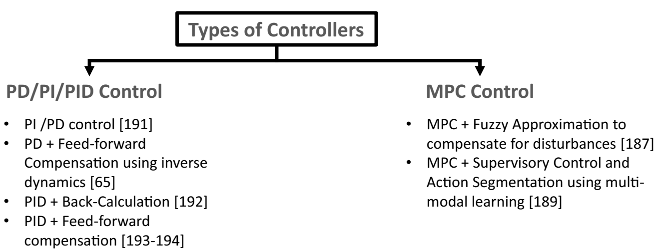

Figure 19. *Classification of types of controllers used in the discussed control systems.*

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Table VIII. *Summary of experimentation results of laparoscope positioning robots.*

Name	Laparoscopic procedures reported for clinical evaluation	Experimentation results
AESOP [43, 48, 50, 219–223]	• Cholecystectomy • Hernia repair • Colectomy • Nephrectomy • Adrenalectomy • Thoracoscopy • Pelvic laparoscopic procedures	• Slightly longer operation time due to the additional setup time • No significant difference in postoperative complications • steadier, less smudging, and inadvertent movements of the laparoscope
VIKY [224–229]	• Cholecystectomy • Hernia repair • Colectomy • Gynaecological surgery • Prostatectomy	• Slightly longer operation time due to unfamiliarity • No significant difference in setup, breakdown times • No postoperative complications were reported. • Feasible and safe • Can also be used as a uterine manipulator
PARAMIS [44, 230]	No reported clinical evaluation on human subjects. • Cholecystectomy on human torso trainer • Cholecystectomy on porcine model	• Smooth, precise, stable view of the internal surgical field • Fast response and great manipulation capability • Rapid returning to key positions • Simple and fast introduction of new commands or modification of the existing ones
EndoAssist [15, 59, 231–233]	• Urological procedures: ◦ Nephrectomy ◦ Pyeloplasty ◦ Radical Prostatectomy ◦ Radical Cyst prostatectomy • Cholecystectomy • Colectomy	• Steady image • optimum task performance • No significant difference in complication rates and operation time compared to human assistant • No intraoperative complications
Freehand [61, 63, 196, 234, 235]	• Extraperitoneal radical prostatectomy (EERPE) • Cholecystectomy • Appendicectomy	• Stable and steady image • Accurate and fast scope control without compromising the outcome of the procedure • Wide range of movements • Reduced average procedure time • Reduced personnel cost • More space for surgeon • Minimal user discomfort

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Table VIII. *Continued.*

Name	Laparoscopic procedures reported for clinical evaluation	Experimentation results
Emaro [64, 65, 236]	• Inguinal hernia repair • Sacral colpopexy (LSC)	• TEP inguinal hernia repair with Emaro was reported to be more feasible and safer than with previous endoscope holders • No significant change in the median operative time • No significant change in complications • The surgeon may have required assistance for some parts in the procedure
KaLAR [182, 184]	No reported clinical evaluation on human subjects. • Cholecystectomy in porcine model	• Reduced surgical time and number of vocal commands

robot-assisted abdominopelvic surgery with laparoscopy, open surgery, or both were conducted. Data were gathered from 50 studies including 4894 patients, where 39 studies reported the incidence of complications requiring further surgical interventions, and 4 of which (10%) showed fewer complications with robot-assisted surgery [203]. Although the majority of studies showed no difference in intraoperative complications, conversion rates, and long-term outcomes, surgeons reported that robotic-assisted surgeries provided an ergonomic advantage [204]. Furthermore, experimental trials of handheld devices were carried out in box trainers to evaluate their performance and effect on ergonomics [21, 27, 28]. Only RobotDex showed no improvement in technical performance, and Kymerax's handle was described as non-ergonomic (Table I). Reported experimental evaluation of robotic training systems show better performance and enhanced accuracy compared to conventional training as shown in Table VI.

5. Discussion

Several robotic applications have been adopted to reduce the challenges opposed by laparoscopic surgeries. Laparoscope positioning robots are found to provide the surgeon with a steadier and less foggy view, eliminating the unintended moves resulting from the human assistant's hand tremor. The voice control method offers a simple way of communication. However, voice recognition for each operator and vocal commands must be set before the operation. Head movements control is more intuitive, but the operator might find it more difficult to focus on his/her head movements while pressing the foot pedal. Both voice-controlled Viky, and infrared headset controlled Freehand endoscope positioners are considered leading robots in this category in terms of accuracy, applicability, and weight. They are also still commercially available and FDA approved. Attempts have been made to develop more intuitive solutions, where cognitive laparoscope positioners with preliminary knowledge are emerging to provide real autonomous behavior.

MSTDCs have already been used in millions of laparoscopic surgeries, mostly under the name da Vinci. However, other systems might end this monopoly because of their lower cost and desirable features like haptic feedback and intuitive endoscope control. Nevertheless, handheld robotic devices that integrate both the master and the slave in one handheld device provide a much cheaper and smaller solution. They combine both benefits of conventional and tele-operated laparoscopic surgeries, enhancing surgical dexterity using ergonomic handles with wrist joints at the instrument's tip and increasing the number

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Table IX. Summary of experimentation results of MSTDCs.

Name	Reported Preclinical and clinical trials	Reported Results and conclusions
Senhance	• Preclinical studies in porcine models [237] • Gynaecology [201, 210, 238–241] • General / Abdominal surgery [201, 242–249]: ◦ Hernia repair ◦ Anti-reflux ◦ Cholecystectomy ◦ Colorectal procedures • Urology [201, 202]	• Feasibility and safety • Reduced operating times along the learning curve • No (or low %) intraoperative complications • Patients with high ASA score and right sided colon surgery may experience major post-operative complications • Enhanced ergonomic posture of the surgeon • Cost reduction due to reusable instruments
REVO-I	• Preclinical studies on porcine models [213–215, 250] • Urology [251] • General /Abdominal surgery [252, 253]: ◦ Cholecystectomy ◦ Pancreatectomy	• Technically feasible and safe • No needed conversions to open/laparoscopic surgery • No major complications • Surgeon and patient satisfaction with the performance • Vision quality requires improvements • More energy devices need to be developed
Versius	• Preclinical studies on human cadaver and porcine models [254, 255] • General/Abdominal surgery [256]: ◦ Cholecystectomy ◦ Appendectomy • Gynaecology [256, 257]	• Feasibility and safety • No device related or intra-operative complications • Major post-operative complications may occur (ureterovaginal fistula) [257] • No prolonged hospitalization
Micro hand S	• General/Abdominal surgery [137–139, 258, 259]: ◦ Robotic CME ◦ Right colectomy ◦ Gastric perforation repair ◦ Appendectomy ◦ Cholecystectomy ◦ Hemicolectomy ◦ Sleeve gastrectomy	• Feasibility and safety • No needed conversions to open/laparoscopic surgery • No major complications • Enhanced dexterity • Natural hand-eye movements

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Table IX. *Continued.*

Name	Reported Preclinical and clinical trials	Reported Results and conclusions
Da Vinci SP	• Preclinical studies on cadaver models [260–262] • Urology [141, 263, 264] • General surgery [142, 265]: ◦ Thyroidectomy ◦ Transoral surgery • Gynaecology [143]	• Feasibility and safety • No intra-operative complications • No conversions to open or laparoscopic surgery • Acceptable operative time and blood loss
SPORT	• Preclinical studies on human cadavers and porcine models [146]	• Feasibility • Enhanced dexterity • Ergonomic platform

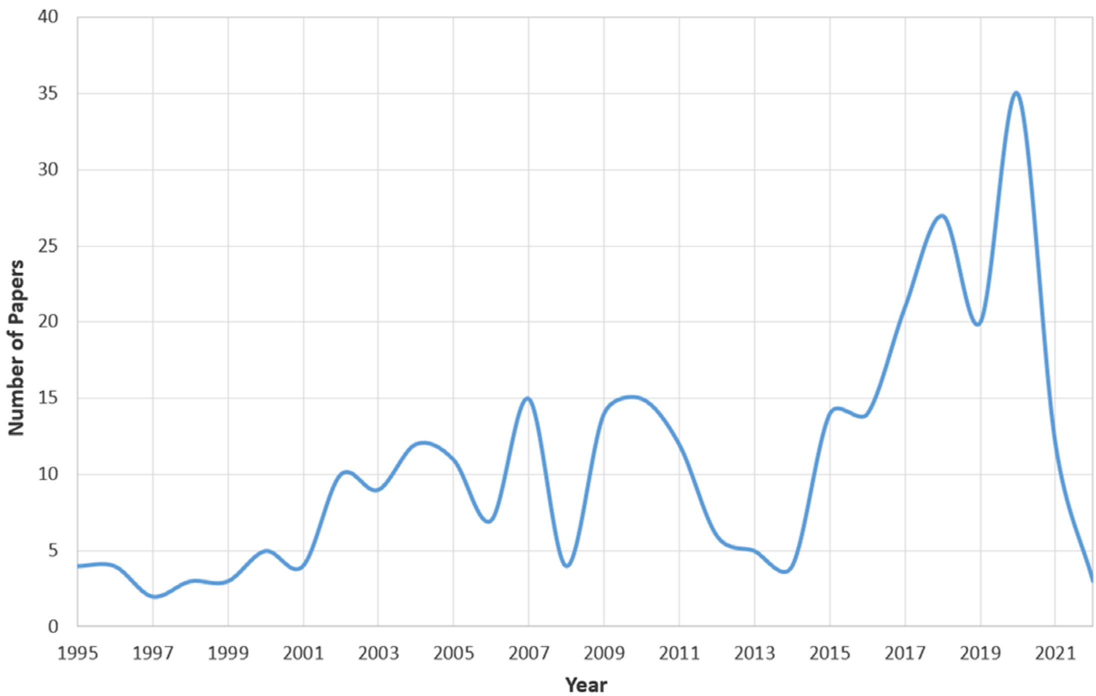

Figure 20. *Distribution of references included in this literature review over a timeline from 1995 to 2022.*

of DOFs, without losing the advantages of reduced setup time and haptic feedback of conventional laparoscopy.

Finally, robotic training systems provide an intelligent alternative to the hand-over-hand conventional training and assessment of surgical trainees.

The number of references gathered to conduct this literature review and their distribution over a timeline from 1995 to 2022 is presented in Figure 20. While Fig. 21 shows reference distribution based on the type of application.

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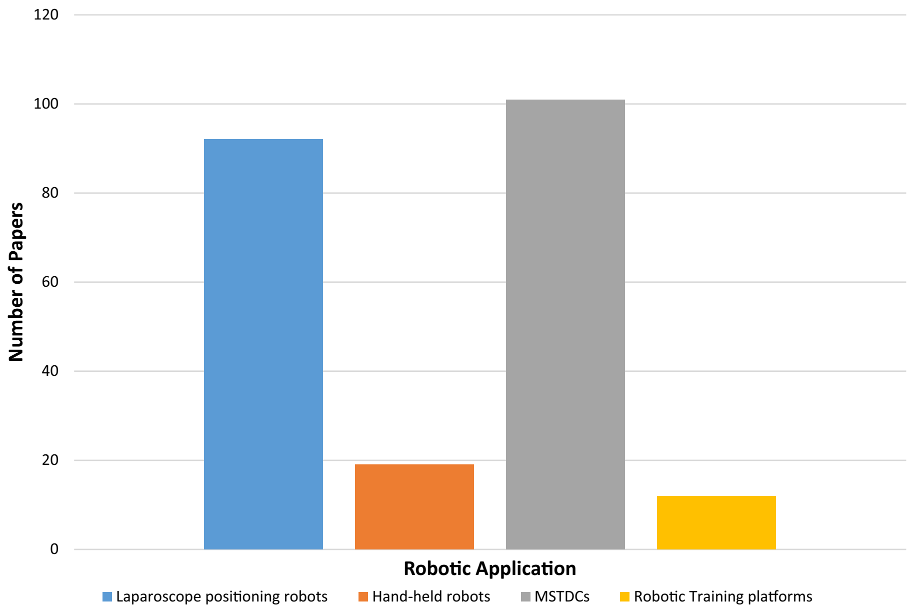

Figure 21. *Distribution of references included in this literature review based on the type of application.*

6. Conclusion

This paper has reviewed different robotic technologies implemented to overcome the challenges of laparoscopic surgeries. Existing papers classified robotic systems according to their application only, or focused on a single category as laparoscope positioners, tele-operated master–slave systems, or handheld devices. All of the proposed systems have proved to be beneficial in laparoscopic surgeries, and some of them offer real autonomy. The major benefit this paper has over existing papers is that it classifies the proposed systems into main categories according to their application and provides further classifications of the systems based on their configuration, DOFs, and control scheme, in addition to presenting a generalized block diagram. This approach can provide researchers/students with a starting point for the state of art in their research fields. Where the different classifications' criteria along with the generalized control block diagram provide summary and comparisons of the existing laparoscopic robots, paving the way for future research and selecting the best robotic technique to be used in a certain laparoscopic surgery.

Future directions of surgical robots in laparoscopic surgeries will include a higher level of automation. It is anticipated that robots with the ability to make real-time surgical decisions and execute desired tasks - under the surgeon's supervision- will be used in the operating rooms in the future [10, 205], with the aid of DL and providing robots with preliminary knowledge of the surgical procedures. Repetitive, time consuming, and tedious tasks, like instruments maneuvering, and suturing tasks will be autonomously performed by robots. According to Asensus Surgical CEO [206], the next phase is cognitive robots, "building a digital twin for the surgeon" using ML and recorded data from successful surgeries that will be deployed more to systematic surgical tasks than those that rely heavily on experience and skill. Moreover, future work will also include hardware modifications. Snake-like continuum robots represent an active field of research and development that might replace conventional rigid-link robots.

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Competing interests. The authors declare none.

Ethical considerations. No ethical issue with this paper.

Authors' contributions. Iham F. Zidane and Yasmin Khattab conducted the review and wrote the first draft; Iham F. Zidane, Yasmin Khattab, Sohair Rezeka, and Mohamed El-Habrouk revised the manuscript; and Iham F. Zidane, Sohair Rezeka, and Mohamed El-Habrouk provided advice and supervision.

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