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REVIEW ARTICLE

Toward versatile cooperative surgical robotics: a review and future challenges

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Abstract

Purpose Surgical robotics has developed throughout the past 30 years resulting in more than 5000 different approaches proposed for various surgical disciplines supporting different surgical task sequences and differing ways of human–machine cooperation or degrees of automation. However, this diversity of systems influences cost as well as usability and might hinder their widespread adoption. In combination with the current trend toward open and modular “plug and play” dynamic networks of medical devices and IT systems in the operating room, a modular human–robot system design with versatile access to cooperative functions with varying degrees of automation on demand is desirable. Therefore, standardized robotic device profiles describing essential functional characteristics of cooperative robotic systems are mandatory.
Methods Surgical robotics is analyzed from a human–machine interaction perspective to identify generic cooperative robotic device profiles, features and use cases. Therefore, cooperative aspects are introduced from a general point of view. Relevant communication channels used for human–machine interaction are then analyzed, referenced by surgical scenarios. Subsequently, proposed classifications of surgical task sequences and surgical robotic systems are analyzed with a focus on a modular design for cooperative robotics in surgery.
Results Considerations based on cooperative guidelines are given and features are identified and summarized in a classification scheme used to define distinct generic cooperative robotic device profiles. The latter can be the basis for a modular architecture of future surgical robot systems.
Conclusion Modular system design can be expanded toward functionalities or different degrees of autonomy, shared or manual control. The proposed device profiles of cooperative surgical robots could lay the foundation for integration into open and modular dynamic “plug and play” networks in the operating room to enhance versatility, benefit-to-cost ratio and, thereby, market spread of surgical robotics.

Keywords Surgical robotics · Synergistic systems · Shared control · Robotic manipulators · Human–machine interaction · Haptics

Introduction

The main objective of the introduction of computer and robotic technology into the operating room (OR) since its early days has been the aspiration to augment the surgeon’s abilities by technical means to improve the surgical outcome. A sound understanding of task characteristics, constraints and boundary conditions, on the one hand, and characteristics of both human and technical systems, on the other, are crucial for the allocation and distribution of specific tasks and task sequences between human and machine. This also applies to the design and integration of solutions for surgical robotics to provide versatile and cooperative systems adaptable to the requirements of each intraoperative scenario. The strengths of humans, for example, are the capability to work with complex stimuli and use qualitative information, even against high background noise levels. However, their dexterity is limited, and they are prone to fatigue and susceptible to radiation and infection. Furthermore, humans’ control abilities are limited regarding processing signals from multiple sensor information and accurately and effectively selecting responses. Consequently, task complexity increases with the degrees of freedom (DOF), and while 3-DOF tasks

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are already challenging to perform (e.g., riding a bike), the amount of practice to accomplish tasks with more DOF (e.g., riding a unicycle, 5-DOF) is comparably high. This becomes even more demanding if the input sensory information has to be derived and fused from multiple reference systems (e.g., displays) with nonlinear or varying dependencies. By contrast, machines exhibit an excellent geometric accuracy, can fuse information from multiple sensors and are untiring and immune to radiation and infection. However, they are difficult to instruct and limited in their ability to interpret complex information. [1–4]

A robot was used for the first time by Kwoh et al. [5] to perform a needle biopsy in neurosurgery in 1985. Since then, multiple robotic devices have been developed for further surgical specialties, such as orthopedics, otorhinolaryngology, ophthalmic surgery and laparoscopic surgery, to name just a few examples. However, the type and nature of robot-augmented capabilities and related technical realizations and the risks associated with the specific context of use across surgical domains vary immensely. Consequently, a multitude of robotic systems were developed which, apart from size, workspace, payloads and system dynamics, differ concerning their degree of automation [6, 7]. This spectrum ranges from adapted industrial robots [8] to small and more application-specific robots [9–12]. The degree of automation extends from automated "active" systems, such as the pioneering ROBODOC system [13, 14], through "semi-active" robotic systems positioning mechanical tool guides, up to hands-on "synergistic" devices providing so-called virtual fixtures by varying mechanical impedances of n-DOF kinematics [15–17]. Furthermore, there are handheld robotic tools controlling one or more DOFs of motion or providing a position-based actuation of the machining tool (e.g., burr or saw) [18, 19].

This plurality of surgical robots along with their narrow application fields influences cost and usability negatively and, consequently, prevents their widespread adoption. Therefore, a modular system design seems to be crucial regarding a versatile adaptation of workspaces, number of DOF, tools for the specific boundary conditions and needs for each specific application [10, 20, 21]. Furthermore, according to Spath et al., "flexible automation, rather than the highest degree of automation, is the aim" ([22], p. 594 (34.4.1)). Therefore, modularity should be extended toward different modes of shared or manual control and human–robot cooperation, depending on the requirements of different application scenarios. This also bears the current trend concerning integration into open and modular "plug and play" dynamic networks of medical devices and IT systems in the OR in mind [23]. So far only standard OR equipment (e.g., OR table, lights, foot switches, microscope) is integrated into the network. However, current efforts aim at integrating a reliable real-time network [24]. To enable a seamless integration based on the IEEE 11073, standardized device profiles are mandatory. These device profiles cover essential device characteristics and functionalities to support the risk management and usability engineering process of open integrated medical devices in the OR. In a three-step testing procedure, manufactures can then test their devices regarding conformity, interoperability and integration. In this way, manufacturers do not need to disclose sensitive information such as risk analysis and related confidential expertise or proprietary information [25, 26]. Against this background, distinct generic cooperative robotic device profiles (CRDP) are needed to open the door to enhanced versatility, benefit-to-cost ratio and, thereby, market spread of surgical robotics.

The aim of the first part of this paper is to provide a review. Therefore, cooperation from a general point of view is presented first, to infer recommendations for system design, before the different communication channels of human–machine systems available are described. Subsequently, different characterizations of the surgical task and task sequences are presented, and existing cooperative surgical robotic systems are classified. The second part then aims at discussing the different communication channels, the task at hand and the different subgroups of cooperative surgical robotic systems in the overall context of cooperation. Finally, available cooperative robotic systems and features are categorized and related to each other for a systematic description. This description can be the basis for interoperability and a seamless integration into an open and modular "plug and play" dynamic network of medical devices and IT systems in the OR.

General considerations of cooperation

Many species in natural systems exhibit cooperative behavior, both within and in between species—as exemplified by the comparison of horse riding with shared control modes in vehicle control—whose concepts can be transferred to human–automation interaction [27]. The main features of cooperation inferred are a dynamic choice of communication tools, adaptation to the competency of the partner and continuous mutual monitoring between the partners [8].

There is a rising demand in surgical robotics for an adequate human–machine system design as a variety of systems and cooperative approaches with varying levels of automation are proposed. It should be adaptable to the specific requirements and boundary conditions of each surgical use scenario and context of use which could be achieved by an adequate modular composition [10, 28–30]. Hence, the challenge is to map known concepts of cooperative behavior to related functional robotic modules and specific surgical task profiles to enable an enhanced human–machine system performance.

However, associated potential risks, such as overreliance, dependency on the system and retention of skills, should be considered and analyzed carefully [28, 29, 31, 32]. Abbink et al. [28] propose four guidelines for human–automation interaction: Firstly, the human operator should always remain in control, while smooth shifts in the authority allocation can be experienced or initiated. Secondly, continuous feedback should be available such that limitations of the automation and the functionalities are evident to the operator. Thirdly, there should be a continuous interaction with the automation, and finally, benefits from either increased performance or reduced workload should exist.

Communication channels

Humans process information in three stages: Firstly, the information is perceived and preprocessed by the human sensory system before, in a second stage, the operator utilizes this stimulus to select an appropriate response and, lastly, the associated response is executed. The adequate allocation of information to different communication channels is an essential aspect in cooperative system design, whereby avoidance of interference of information processing and efficient time-sharing between tasks (i.e., multitasking) is crucial. According to the multiple resource model by Wickens et al. [33], humans incorporate three information input channels: the visual, auditory and tactile channel, whereby the latter is part of the haptic sensory system. In addition, their code of processing can be either spatial or verbal. While sometimes differentiation is ambiguous, perceiving differences in orientation of surfaces is dominantly spatial, whereas verbal information processing is typically associated with the recognition of the meaning of words. Following the perception, the information is processed depending on the complexity and consistency of the task design and the training status of the user. Three levels of action regulation (skill-, rule- and knowledge-based) have to be considered regarding cognitive information processing and related error mechanisms [34, 35]. According to Wickens et al. [33], responses can be either manual (e.g., hand movement), spatial (e.g., nodding), vocal (e.g., sounds) or verbal (e.g., words). Depending on the channel to which information is allocated, different human resources are used for processing, which affects the interference of information and time-sharing. Regarding robotics in surgery, various input and output channels have been used in different surgical robotic systems. Some examples and considerations related to the different user interfaces are made in the following, based on the model proposed by Wickens et al.

The visual input channel is broadly used throughout surgical robotic applications, both verbally (displaying written information or warnings) and spatially (displaying navigation information). However, human sensorimotor control of precise spatial motion can be significantly impeded by incompatibilities in eye–hand coordination or the necessity for mental fusion or transformation of information from different (particularly interdependent) reference frames [33, 36]. The auditory channel is constrained due to verbal communication of the surgical team and noises related to devices and alarms, both verbally and spatially, respectively. As a result, visual and auditory channels are overloaded leaving haptic interfaces as a complementary channel for robotic surgery scenarios with potential benefits, especially related to spatial motion control [37]. As the majority of haptic interfaces address the kinesthetic and tactile receptors, considerations are expanded to both receptors [37–39]. Introduction of the haptic channel in robotic surgery is limited mainly to research prototypes, except for the formerly known ALF-X system which got its FDA clearance and was made commercially available in 2017 as the Senhance™ Surgical Robotic System by TransEnterix Surgical Inc. (Morrisville, NC 27560, USA) [40]. So far, the haptic channel is used mainly to mirror haptic feedback from the situs to the surgeon, which is lost due to the physical decoupling by, for example, telemanipulation. However, haptics can also be used to augment information, for example, related to spatial guidance, and, therefore, reduces the mental workload for manipulation [41], shifting the surgeons attention to higher level decisions. Realizations of this haptic guidance can be either mechanical tool guides [5, 36] or virtual fixtures generated by passive or active robotic arms or master manipulators [42, 43].

Following perception and information processing responses by the human can be either vocal, verbal, spatial or manual. Instances in which voice control has been used are, for example, the AESOP or VikY system, where simple commands are used to control an endoscope holder [44–46]. Spatial outputs are used, for instance, by FreeHand v.12 by ORPE d.o.o. (1000 Ljubljana, Slovenia), an endoscope holder which is controlled by nod movements [47] and an example of a manual output are the input devices for the da Vinci surgical systems (Intuitive Surgical Inc., Sunnyvale, CA 94086-5304, USA) [48].

Considering the input and output channels presented in the context of the cooperative behavior explained initially, haptic interfaces are very promising. They can provide haptic information and be used by the surgeon to make manual responses simultaneously without the need for mental transformations due to the same spatial reference system. Thus, an incongruity of reference coordinate systems of the perceptive information channel and the human hand coordinate system (manual response channel) is inherently avoided, which leads to decreased performance in eye–hand coordination [33, 36, 49]. Furthermore, haptic devices pose a suitable interface for arbitration between human intent and machine planning. Both actors can apply forces at the same interface and, therefore, negotiate to settle any dispute due to the bilateral character of the device (provide haptic information and serve as manual response channel simultaneously) [50]. Additionally, using the haptic channel enables shorter human reaction times compared to the auditory and visual channels, especially during constraint violation in telemanipulation tasks [51].

Classification of surgical tasks and task sequences

Knowledge about the task characteristics (e.g., DOF to be controlled, forces, accuracy, dynamics and criticality) is essential to evaluate particular assistance with respect to performance and ergonomics to assist the surgeon appropriately with a robotic device during intraoperative execution. Regarding minimally invasive surgery, Mack [52] classifies surgical procedures based on tissue processing into excisional (tissue removal), ablative (tissue destruction) and reconstructive (tissue joining) tasks. Thereby, fundamentals of navigation in surgery for any of these tasks constitute the localization of an anatomical target and the position of the instruments, definition of an admissible trajectory to reach the target and the relative placement of several components and their target [53]. Troccaz et al. [54] propose a classification dividing a surgical procedure into reaching a defined position, tracking and speed control along trajectories with varying application-specific geometric complexity and action execution. Action execution ranges from linear (e.g., drilling) and planar (e.g., sawing) through conical (e.g., laparoscopic surgery) to spatial actions (e.g., cavity preparation for prosthesis fit). Additionally, certain scenarios require the relative placement of 3D structures (i.e., in 3–6 DOF), avoidance of critical anatomical structures, application of a defined force and compensation of motion of anatomical structures [54]. Radermacher [36] suggested considering up to 9-DOF (pose, speed and/or forces) of control and six different types of application-specific geometric constraints: (1) entrance point and orientation of a drill; (2) entrance and target point connected by a linear trajectory; (3) orientation of a, for example, osteotomy plane/saw; (4) orientation and variable cutting depth depending on the backside contour; (5) milling along a defined surface contour with constant depth (pocket milling) and (6) 3D freeform surface milling for the classification of surgical instrument guidance in orthopedic surgery. Moreover, Vitiello et al. [55] emphasize that the tracking of optimal pathways with high precision is particularly a major task in surgical robotics in orthopedic surgery and neurosurgery.

Classification of robotic systems

More than 5000 devices have been developed in the field of computer-assisted surgery throughout the evolution of surgical robotics [56], and different classification schemes for surgical robotics have been proposed. According to Cinquin et al. [36, 57], there are active and semi-active systems: Active systems perform some subtasks autonomously being supervised by the surgeon, whereas semi-active systems physically constrain the actions of a surgeon to correspond to a predefined strategy. The most typical implementation of the latter is the positioning of a tool guide which is subsequently fixed to direct a tool operated by the surgeon and, thus, reducing the number of DOF that the surgeon has to control simultaneously [36, 57]. Troccaz et al. [15] proposed adding so-called synergistic systems to this classification scheme, providing a simultaneously shared control of the surgical tool which is cooperatively held by the robot and the surgeon in a hands-on fashion. Davies [58] proposed extending this classification scheme with master–slave telemanipulators. In contrast to the latter three classes (active, semi-active and synergistic), the positioning and motion of the end effector or tool are not primarily controlled on the basis of a preoperatively planned (preprogrammed) geometry. The surgeon interactively controls the (remote) slave kinematic (robotic) system which follows the movement of a master device, such as a joystick or master manipulator. Optionally, transformations between the master input and slave output motion (amplitude/speed transmission ratio, superposition of movement, spatial transformation or tremor filters) could be applied/implemented. Therefore, telemanipulator systems also provide cooperative control by modifying information from sensors (e.g., tremor compensation, beating heart motion superposition) or could augment planning data in specific sequences of the surgical task (e.g., definition of working areas or trajectories allowed). Later, additional cooperative devices allocating some DOF to a handheld robotic system manually operated by the surgeon were proposed [18, 59, 60]. Even though synergistic systems were initially introduced by Troccaz et al. [15] solely as hands-on robotic devices, recent developments suggest adding two further subgroups because of their cooperative characteristics, namely *handheld* and *telemanipulated*, resulting in the following classification scheme:

- Semi-active
- Synergistic
    - Handheld
    - Hands-on
    - Telemanipulated
- Active

The following overview focuses on synergistic robotics and the associated subgroups due to their considerable cooperative properties. Similar classification subgroups have also been proposed by Dario et al. [6, 61] and Rodriguez y Baena and Davies [6, 61]. Major past developments, latest developments and advanced research prototypes and projects of synergistic robotic systems are presented hereafter and summarized in Table 1 to further consolidate this view. Thereby, cooperative features are differentiated between the two key roles of robotic systems in medicine [62]:

- To optimize and extend human surgical skill by, for example, tremor compensation, scaling of movements/forces and online compensation of, for example, beating heart or patient motion, which can be seen as a planning-independent (PI) modulation of signals and
- to provide a link between preoperative planning and execution of a surgery where actions are modulated to correspond to a presurgical plan (patient-specific planning-based: PSPB).

Handheld Synergistic Robotics

Handheld synergistic surgical robots are manipulated and held by the surgeon without a stationary mechanical reference, supporting him/her based on either a predefined plan or an increase in his/her dexterity by, for example, tremor compensation [6]. One example is the NAVIO system (Smith and Nephew, London, UK), which is equipped with a retractable burr to ensure the removal of only bone tissue planned previously [18], hence, providing a PSPB cooperation. Another example is the Micron, which is a manually guided tremor-compensating handheld instrument designed for vitroretinal microsurgery [63] or the Intelligent Tool Drive (ITD). Their purpose is milling predefined cavities in orthopedics while compensating for the movements of surgeon and patient [64].

Hands-on synergistic robotics

Hands-on synergistic systems are based on a dominantly stationary *n*-DOF kinematic mechanism manually operated by the surgeon, while providing mechanical constraints (varying mechanical impedance) according to a preoperative plan [61]. While these systems are able to magnify forces, constrain motion or filter tremor, motion transformation is unfeasible due to the rigid connection between the surgeon's hand and the tool [6]. Furthermore, the active motion is based on the manual motion of the tool by the surgeon. Therefore, hands-on systems do not provide an efficient control of milling parameters based on systematic path control as it can be provided, for example, by an automatic computer numerical control (CNC) or active robotic milling process. A comprehensive summary of hands-on synergistic surgical robotics is presented in Table 1. Their field of application has been limited so far to orthopedics, neurosurgery, cardiac surgery and eye surgery. The Passive Arm with Dynamic Constraints (PADyC) is based on a freewheel mechanism that constraints the position and speed of motion of the manually operated tool by the surgeon. However, PADyC cannot move on its own due to the mechanical design [42]. The MAKO system (Stryker Corporation, Kalamazoo, MI, USA) is commercially available and is used for partial and total knee and total hip replacement, which is similar to the original concept of the ACROBOT system [16]. Based on preoperative planning, the surgeon is haptically constrained to the volume planned. Additionally, the burr is turned off in case it is moved out of the preplanned area [43].

Telemanipulated synergistic robotics

In the case of so-called master–slave telemanipulator systems, the surgeon, seated at the master console, is operating a slave robot or manipulator by remote control [61]. Areas of application so far have been eye surgery, laparoscopic surgery, heart surgery and neurosurgery. As can be seen in Table 1, the predominant features associated are tremor compensation and motion scaling/transformation. The da Vinci (Intuitive Surgical, Sunnyvale, CA, USA) offers tremor compensation and motion scaling to the surgeon while relieving him/her of complex motion transformations and incompatibilities in hand–eye coordination common in conventional laparoscopic surgery (e.g., fulcrum effect) [48]. However, one of the major drawbacks has been the so far missing haptic feedback in almost all currently commercially available systems except for the Senhance™ Surgical Robotic System by TransEnterix Surgical Inc. (Morrisville, NC 27560, USA). Comparetti et al. [65] demonstrated the cooperative potential of telemanipulated synergistic devices for neurosurgery enabling different control modes (autonomous, hands-on and telemanipulated) depending on the surgical task and the surgeon's preference [65]. Additionally, virtual fixtures are implemented to prevent movement into delicate parts of the brain and target motion on the slave side during telemanipulation is compensated to enable the surgeon to operate in a stable reference environment [65].

Considering cooperative robotic solutions for surgery, it can be seen that there are different classes of system which inherently by design offer certain types of cooperative functions. Furthermore, first approaches have been made to increase the versatility of automation for a specific area of application. However, device profiles have to be further defined to allocate functions to particular devices and ensure interoperability to enable a modular and versatile operability also between devices and allow for an adjustable configuration based on the use scenario and context of use.

Table 1 Classification of synergistic robotic systems and associated cooperative features

Classification	Name	Field of use	Cooperative features		Description	References
			Planning-independent	Patient-specific planning-based		
Handheld synergistic devices	ITD (intelligent tool drive)	Orthopedics	Compensates for involuntary movements of the patient and surgeon	Automated milling of pre-planned cavities	Handheld device that mills predefined cavities while compensating for movements of the surgeon and patient	[64]
	Micron	Eye surgery	Tremor compensation, avoiding transverse movement at the point of entry	Automated subtasks (pointing, scanning, depth control, avoidance of blood vessels)	Handheld pencil-shaped device that compensates for the tremor of the surgeon and offers some automated subtasks	[63]
	NAVIO	Orthopedics		Position-dependent exposure of burr	Handheld by surgeon, but retraction of the burr if planned boundaries are exceeded	[18]
Hands-on synergistic devices	ACROBOT	Orthopedics		Virtual fixtures (haptic)	Robot end effector which is guided by a surgeon and provides haptic feedback dependent on the boundaries planned	[16]
	Eye-robot (formerly steady-hand)	Eye surgery	Tremor compensation, force scaling	Virtual fixtures (haptic)	Guided by a surgeon and provides haptic feedback dependent on the boundaries planned	[17]
	Neurobot	Neurosurgery (endoscope)		Virtual fixtures (haptic)	Hands-on robot for endoscope, which is guided by a surgeon and provides virtual fixtures, and additionally, channels for surgical instruments are provided	[66]
	MYNUTIA	Eye surgery	Tremor compensation, eye rotation prevention, prolonged tool immobilization		Hands-on robot that compensates for tremor and prevents unintended eye rotation, while offering prolonged tool immobilization	[67]

Table 1 (continued)

Classification	Name	Field of use	Cooperative features		Description	References
			Planning-independent	Patient-specific planning-based		
	Passive arm with dynamic constraints (PADyC)	Cardiac surgery		Virtual fixtures (haptic)	Constrains motion within a predefined region with a special freewheel mechanism to prevent the active motion of the robot	[42]
	MAKO	Orthopedics		Virtual fixtures (haptic)	Robot end effector guided by the surgeon and provides haptic feedback dependent on the boundaries planned, position-dependent tool performance control similar to navigated control of Strauss et al. [68]	[43]
	ROSA™	Neurosurgery/orthopedics	Compensation for patient movement	Virtual fixtures (haptic)	Positioning of a tool guide and compensation for patient movement during intervention	[69]
Telemanipulated synergistic devices	ACTIVE project	Neurosurgery	Autonomous and hands-on modes, motion compensation (robot)	Virtual fixtures (haptic)	Two KUKA LBR iiwa robots and an integrated neurosurgery platform for cooperative human–machine surgery	[65]
	ARTEMIS framework	Eye surgery (laser ablation)		Virtual fixtures (haptic)	Remote-controlled system for laser ablation incorporating haptic virtual fixtures	[70]
	da Vinci	Laparoscopic surgery	Tremor compensation, motion scaling		Remote-controlled system with several robotic arms for instruments or an endoscope for laparoscopic surgery	[48]
	EndoBot	Laparoscopic surgery	Surgeon controls some axes, while robot controls others, autonomous suturing		Remote-controlled system for laparoscopic surgery	[71]
	IBIS	Laparoscopic surgery	Tremor compensation, compliance control		Pneumatic, remote-controlled system for laparoscopic surgery	[72]

Table 1 (continued)

Classification	Name	Field of use	Cooperative features		Description	References
			Planning-independent	Patient-specific planning-based		
	M7	Laparoscopic surgery	Tremor compensation, compensation for movement of the master console		Remote-controlled system for laparoscopic surgery	[73]
	MiroSurge	Laparoscopic surgery	Tremor compensation, motion scaling		Remote-controlled system for laparoscopic surgery	[74]
	PRECEYES (formerly EYE-Rhas)	Eye surgery	Tremor compensation, motion scaling, force scaling		Remote-controlled system for eye surgery with high precision	[75]
	RAMS	Eye surgery	Compensates for pitch and yaw orientation while operator controls *x*-, *y*-, *z*- and roll motions, tremor compensation, motion scaling		Remote-controlled system for eye surgery with shared control mode where surgeon controls *x*-, *y*-, *z*- and roll motions, while robot controls pitch and yaw	[76]
	Robin heart	Heart surgery	Tremor compensation, motion scaling, force scaling, movement sets in semiautomatic mode		Remote-controlled system for heart surgery which offers movement sets in semiautomatic mode	[77]
	Senhance™ surgical robotic system (formerly ALF-X)	Laparoscopic surgery	Tremor compensation, motion scaling		First commercially available remote-controlled system for laparoscopic surgery with force feedback	[78]
	Surgenius	Laparoscopic surgery	Tremor compensation, motion scaling		Remote-controlled robot for laparoscopic surgery	[79]
	SurgiBot	Single-port surgery	Motion scaling		Remote-controlled single-port system for endoscope and two instruments	[80]
	SYMBIS (formerly NeuroArm)	Neurosurgery	Tremor compensation, motion scaling, force scaling	Prerecord automated motion	MRI-compatible remote-controlled system for neurosurgery	[81]
	ZEUS (ruled out by da Vinci)	Laparoscopic surgery	Tremor compensation, motion scaling		Remote-controlled system for laparoscopic surgery	[82]

Toward versatile cooperative surgical robotics

The aim of this section is to combine the different considerations regarding cooperation, communication channels, surgical tasks and the defined synergistic subgroups (handheld, hands-on, telemanipulated). The resulting generic CRDPs could be used for a systematic description and potential optimization of characteristic cooperative features of existing robotic systems and induce future ways of cooperation in surgery. The four guidelines, mentioned in the section on general considerations, regarding cooperation by Abbink et al. [28] are used as a basic structure.

Firstly, the human operator should always remain in control, while smooth shifts in the authority allocation can be experienced or initiated [28]. Apart from simple technical means, such as emergency or deadman switches in case of supervisory control, a more versatile interface is needed to initiate a shift in control authority for cooperative system design approaches. While manual, spatial, vocal or verbal responses are implementable for such an interface, diverging intentions of human and machine could arise in the case of any inaccuracies or uncertainties which cannot be registered by the technical system due to limited sensor means. A bilateral communication interface is needed to be able to settle any dispute and allow for arbitration between conflicting intentions. Therefore, haptic interfaces are promising and should be further disseminated, as they can serve as a haptic input channel and a manual output channel in one reference system with comparably short perceptive latencies. Therefore, they fulfill the requirements for a successful negotiation between the intentions of human and machine [36, 49–51]. However, acting forces should not be too high to ensure that the human operator remains in final control and is always able to oppose the system. Studies found that a force of 9N is sufficient to generate the illusion of an immovable surface, while about 2N is perceived as a solid surface [83]. Furthermore, O'Malley and Goldfarb [84] found that perception of information conveyed reaches a limit at 3–4N, which is far below average human capabilities [85].

Secondly, continuous feedback should be available to support situation awareness, i.e., the human operator understands the automation system fully and intuitively and is not confused by any automation-induced incidents [28]. Therefore, visual, auditory or haptic input channels can be used; however, attention must be paid in case of allocation of information to either one of the channels such that situational awareness is supported and mental burdens (e.g., for hand–eye coordination) are minimized. Considering the latter, the mental effort necessary to perform a transformation between the reference system of a visual display and the hand of the surgeon varies depending on the rotation axes and the rotation degree and, hence, can decrease performance [33, 36, 49]. In the case of haptic interfaces, these mental transformations are inherently avoided due to the presentation of information in the human hand reference system. Additionally, as visual and auditory channels are overloaded [37], the integration of haptic interfaces as information display can relieve the remaining channels and support time-sharing between tasks (i.e., multitasking) [33]. However, in the case of hands-on or telemanipulated synergistic devices, attention has to be paid when allocating information to a haptic interface. Simple superposition of haptic feedback from position and force sensors of the surgical robot and auxiliary haptic guidance information based on preoperative planning data (PSPB modulation), illustrated in Fig. 1, makes it impossible for the surgeon to infer the

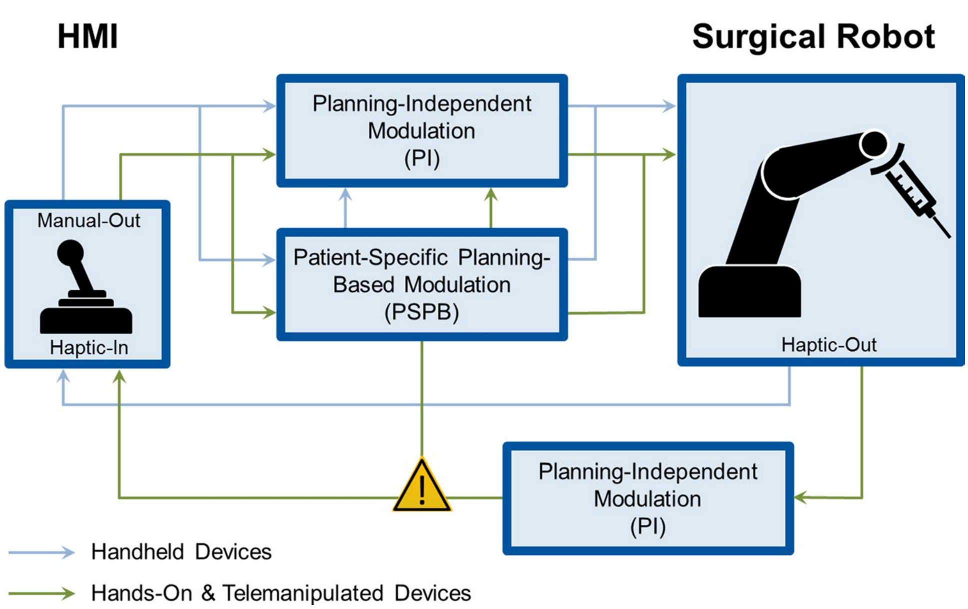

Fig. 1 Scope of information processing of manual output and haptic input for handheld, hands-on and telemanipulated synergistic surgical robots

origin of the force. Furthermore, in the case that the forces measured by the sensors of the surgical robot counteract the virtually generated guidance forces (PSPB modulation) they can partly or fully cancel each other out. As a result, the surgeon would, in the worst case, not perceive any haptic feedback even though forces are applied on the remote environment [86, 87]. In summary, feedback information should be divided between the several channels to support time-sharing, while considering advantages and limitations of each channel during the allocation process and, hence, support situation awareness.

Thirdly, there should be a continuous interaction with the automation [28], which can be realized in either one of the communication channels or distributed between channels to support information processing and time-sharing as previously mentioned. However, the capabilities of manual interaction are also dependent on the characteristics of the robotic devices. There are generally two key roles of robotic systems in medicine mentioned in section 0 [62]: To extend human surgical skill and provide a link between preoperative planning and the execution of a surgery. As can be seen in Fig. 1, handheld devices can fulfill both roles; however, there is no interaction between the surgeon and the automation following the PSPB modulation and, therefore, no possibility for the surgeon to intervene except retraction of the whole robotic system from the situs. Additionally, haptic information is distorted by the dynamics of the whole device and modulations (e.g., force scaling) are not possible due to the direct haptic feedback. By contrast, hands-on and telemanipulated devices can interact with the surgeon by, for example, virtual fixtures (PSPB) and, therefore, the surgeon can intervene in case any conflicts arise. Furthermore, haptic information from the surgical robot can also be modulated (e.g., scaled or filtered). However, as previously mentioned, caution must be taken when it comes to the superposition of haptic (sensor) feedback and guidance information. In case the third guideline of Abbink et al. [28] considered in this paragraph is not met, particularly dangers, such as overreliance, dependency on the system and retention of skills, have to be investigated [28, 29, 31, 32].

Fourthly, benefits from either increased performance or reduced workload should exist [28], which is where abstraction of the surgical task is important. Effects on the workload and performance characteristics (effectiveness, efficiency) should be known in conjunction with a standardized classification of tasks to find appropriate modular modes of cooperation for each intraoperative scenario. A standardized selection of suitable modular modes could be proposed to the surgeon based on the specific requirements and standard operating procedures defined for an intervention. Therefore, a classification scheme of standardized cooperative features is required as a basis for the technical development of generic CRDPs, which, in turn, will support a modular architecture of related robotic devices and user interfaces [24, 25].

A classification scheme of cooperative features based on the surgical task sequences presented in section 0 and existing synergistic robotic systems (Table 1) is given in Table 2.

Discussion and conclusion

In summary, a variety of communication channels have been used in surgical robotic applications. The communication channels can be used in conjunction with the classification of cooperative features presented (Table 2) for a systematic description of a particular cooperative robotic system. In particular, the haptic information channel should be further disseminated as it poses many advantages. Furthermore, different classes of synergistic robotic systems exist: handheld, hands-on and telemanipulated devices. Each of the classes mentioned can inherently offer only certain types of the cooperative features presented (Table 3). Handheld devices can support the surgeon during the intraoperative execution of a predefined plan or enhance his/her dexterity, but haptic arbitration of different intentions of human and machine is not feasible. Hands-on devices offer a haptic channel for arbitration, but struggle to incorporate motion scaling due to the rigid connection between surgeon and tool. Telemanipulated systems offer the widest spectrum of cooperative functions by incorporating planning-independent modulations inclusive of motion transformations and PSPB modulations, with the possibility of arbitration between human and machine. While the physical decoupling of the surgeon and the tool has so far led to the loss of the haptic input channel, telemanipulation systems can be extended to include haptic feedback: This cannot only be used to mirror haptic feedback from the situs, but also to augment information or provide spatial guidance and, therefore, reduce the mental workload of the surgeon, enabling him/her to shift his/her attention to higher level decisions. Additionally, this physical decoupling provides the versatility to control different configurations of a modular surgical robotic slave system with varying DOF and workspaces, or various systems for different task areas (e.g., rough and fine positioning). Thus, versatility is provided, and the principle of inherent safety by application-specific kinematics is preserved [20, 66] and the same familiar interface is offered, simultaneously increasing safety, ergonomics and versatility. Additionally, modularly designed application-specific robots can reduce the number of slave robots needed for a wide variety of clinical applications. Furthermore, as a “flexible automation, rather

Table 2 Classification of Cooperative Features

Scope of cooperation	Cooperative features	Subcategories
Patient-specific planning-based guidance	Find pose (point and orientation)	Define pose
		Positioning
		Degrees of freedom
		Absolute/relative
		Action execution (e.g., drilling)
	Follow trajectory	Define trajectory
		Tracking variable (e.g., position, speed)
		Degrees of freedom
		Absolute/relative
		Action execution (e.g., sawing)
	Volumetric constraints	Define volume
		Constraint enforcement (e.g., avoidance of volume, guidance within volume)
		Absolute/relative
		Action execution (e.g., cavity preparation)
Planning-independent features	Compensation of motion	
	Tremor reduction	
	Motion scaling/transformation	
	Force scaling	
	Application of defined force	
	Planning independent movement sets	
	Compliance control (to prevent excessive loads on tissues)	
	…	

than the highest degree of automation, is the aim" ([22], p. 594 (34.4.1)), modularity should be expanded to different modular functions to support the surgeon in specifiable DOF depending on the requirements of different application-specific scenarios. Hence, in contrast to different distinct classes of surgical robotic solutions, a versatile and modular combination of related functionalities with different levels of shared or autonomous (and optional remote) control of (optional tele-) robotic systems [65] will be one main requirement. Thereby, versatility, benefit-to-cost ratio and market spread of surgical robotics can be enhanced. In combination with an open communication standard in the operating theater, where recent developments aim at integrating a reliable real-time network [24], utilized surgical robots and user interfaces could even be independent of the manufacturer and make cross-vendor interoperability applicable. The CRDPs and their associated cooperative features presented in this paper could lay the foundation for integration of cooperative robots into open and modular dynamic "plug and play" networks in the OR.

Table 3 Degree of fulfillment of cooperative features by cooperative robotic device profiles (✓: feasible; (✓): limited realizable, ×: unfeasible) supported by references to existing systems

	Scope of cooperation									
	Patient-specific planning-based guidance		Planning-independent features							
Cooperative robotic device profiles (CRDPs)	Arbitrative	Supervisory (by human or machine)	Compensation of motion	Tremor reduction	Motion scaling/transformation	Force scaling	Application of defined Force	Planning independent movement sets	Compliance control (to prevent excessive loads on tissues)	…
Handheld	×	✓ [63, 64]	✓ [63, 64]	✓ [63]	(✓)	×	×	✓	✓	…
Hands-on	✓ [16, 17, 42, 43, 66, 69]	✓ [18]	✓ [67, 69]	✓ [17, 67]	×	✓ [17]	✓	✓	✓	…
Telemanipulated	✓ [65, 70]	✓ [65, 81]	✓ [65, 73]	✓ [48, 72–79, 81, 82]	✓ [48, 71, 74–82]	✓ [75, 77, 81]	✓	✓ [71, 77]	✓ [72]	…

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors. This article does not contain patient data.

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