Surg Endosc
DOI 10.1007/s00464-012-2656-y

Toward increased autonomy in the surgical OR: needs, requests, and expectations

Michael Kranzfelder · Christoph Staub · Adam Fiolka · Armin Schneider · Sonja Gillen · Dirk Wilhelm · Helmut Friess · Alois Knoll · Hubertus Feussner

Received: 3 June 2012 / Accepted: 10 October 2012

Abstract
Background The current trend in surgery toward further trauma reduction inevitably leads to increased technological complexity. It must be assumed that this situation will not stay under the sole control of surgeons; mechanical systems will assist them. Certain segments of the work flow will likely have to be taken over by a machine in an automatized or autonomous mode.
Methods In addition to the analysis of our own surgical practice, a literature search of the Medline database was performed to identify important aspects, methods, and technologies for increased operating room (OR) autonomy.
Results Robotic surgical systems can help to increase OR autonomy by camera control, application of intelligent instruments, and even accomplishment of automated surgical procedures. However, the important step from simple task execution to autonomous decision making is difficult to realize. Another important aspect is the adaption of the general technical OR environment. This includes adaptive OR setting and context-adaptive interfaces, automated tool arrangement, and optimal visualization. Finally, integration of peri- and intraoperative data consisting of electronic patient record, OR documentation and logistics, medical imaging, and patient surveillance data could increase autonomy.
Conclusions To gain autonomy in the OR, a variety of assistance systems and methodologies need to be incorporated that endorse the surgeon autonomously as a first step toward the vision of cognitive surgery. Thus, we require establishment of model-based surgery and integration of procedural tasks. Structured knowledge is therefore indispensable.

Keywords Minimally invasive surgery · Operating room · Robotic systems · Structured knowledge · Surgical autonomy

The operating room (OR) constitutes the key factor of value creation in surgery. However, the OR is also the most cost-intensive and complex unit of the surgical department. Accordingly, any effort is justified to make surgical performance more cost-effective and safer.

The current trend in surgery toward further trauma reduction and less invasive interventions (minimally invasive surgery [MIS], monoport surgery [MPS], and natural orifice transluminal endoscopic surgery [NOTES]) could potentially endanger the reaching of these two goals. Innovative surgical techniques inevitably lead to an increased use of complex technology. For smooth procedure enforcement, an increasing number of sophisticated instruments and systems must be applied. As a result of the higher functional range, the handling becomes increasingly more complex and time-consuming. In addition, the probability of severe

M. Kranzfelder (✉) · S. Gillen · D. Wilhelm · H. Friess · H. Feussner
Department of Surgery, Klinikum Rechts der Isar, Technische Universität München, 81675 München, Germany
e-mail: michael.kranzfelder@tum.de

H. Feussner
e-mail: hubertus.feussner@tum.de

M. Kranzfelder · A. Fiolka · A. Schneider · S. Gillen · D. Wilhelm · H. Feussner
Workgroup MITI (Minimally Invasive Interdisciplinary Therapeutical Intervention), Klinikum Rechts der Isar, Technische Universität München, 81675 München, Germany

C. Staub · A. Knoll
Department of Informatics, Robotics and Embedded Systems, Technische Universität München, 85748 Garching, Germany

Published online: 13 December 2012

failures is growing [1] because the control is challenging and greatly increases the workload of the surgeon. Before advanced MIS, MPS, or NOTES can be considered mature for routine clinical use, new strategies are required to make the surgical work flow simpler, to make human–machine communication easier and more intuitive, and to make the execution of surgical maneuvers faster. As a result, surgical workload and strain could be reduced, which diminishes the probability of failure. Simultaneously, OR time could be reduced, making surgery more cost-effective.

Several approaches are conceivable to reach these aims. One of them could be to make the overall technical environment in the OR more intelligent, enabling it to support the surgeon actively. If it is possible to develop a context-sensitive system with the ability to understand the actual part of the procedure based on comprehensive online data acquisition, analysis, and interpretation, it should also be possible to make it able to foresee the further course of the operation. If the accuracy of work flow prediction is sufficiently high—which depends, among other factors, on precise work flow modeling—specific tasks could be carried out autonomously by the system.

Autonomy has already become a topic in surgery as a result of the use of robots [2], but a more comprehensive discussion of autonomy in the surgical work flow is still lacking. Generally, the term *autonomy* in the field of surgery means that a defined surgical task is performed autonomously by a technical system—for example, by a robot. However, autonomy is more than a repetition of predefined movements; it involves perception of the environment and corresponding adaption of behavior if needed [2]. It is our aim here to identify potential applications of autonomy in ORs for advanced surgical techniques scaled to near-term, midterm, and future developments.

Materials and methods

The analysis was focused on three different areas: robotic surgical systems (camera control, intelligent instruments, automated surgical procedures), general technical environment (adaptive OR setting, context adaptive interfaces, tool arrangement, visualization), and peri- and intraoperative data integration (electronic patient records, OR documentation and logistics, medical imaging, patient surveillance). Advisements for an increased OR autonomy were scaled in near-term, midterm, and future developments, respectively.

Analysis is based on our own clinical experience in laparoscopic surgery and MPS as well as experimental work in NOTES [3, 4] including the use of a robot prototype.

The technical background was a highly integrated OR system (Sios; Siemens, Erlangen, Germany) with augmented sensory equipment, as described elsewhere [5]. For mechatronic support, the highly versatile single-port robotic system was used [6]. This system was mainly used in the surgical training mockup ELITE [7] and in animal experiments.

In addition to our own research [5], we performed a Medline, Cochrane, and Google Scholar database literature review with the medical subject headings OR autonomy, OR environment, OR setting, MIS, laparoscopy, laparoscopic visualization, instrument detection, medical imaging, and robotic surgical systems. We also examined corresponding links. We used no restriction to publication date, but we limited our search to published articles with full text available in the English language. The last search was carried out covering literature published through March 2012.

Results

In addition to our own clinical experience, detailed analysis of the literature revealed a comparatively broad range of potential applications of autonomy in the surgical OR. The main subject was robotic surgery, as expected.

Robotic surgery

Multiple classifications of robotic surgical systems can be found in the literature, mainly depending on the underlying robot specification. In the context of our study, the classification according to autonomous function by Wolf and Shoham [8] with four categories (passive robots, semiactive robots, active robots, and remote manipulators) seems to be most suitable. Remote manipulators (surgical extenders) are the most common surgical robots used today (e.g., Da Vinci robot; Intuitive Surgical, Sunnyvale, CA, USA).

The level of robot autonomy (adaption of robot behavior to new tasks by perception of the environment) can be defined by three parameters: complexity of the mission, environmental difficulty, and human independence, according to the ALFUS (autonomy levels for unmanned systems) model [9].

At this time, robotic surgical systems for MIS, MPS, and NOTES are mainly designed for the purpose of manual task execution rather than for autonomous decision making. Accordingly, the surgical workload is high and is even growing with the augmented functionalities of advanced systems. Partial autonomy could reduce the number of tasks that have to be performed by the surgeon.

Near-term developments

Camera control The use of mechanical camera holders [10, 11] in laparoscopic surgery allows the surgeon to perform the operation without the help of an assistant (solo surgery). Zooming behavior similar to those of a human camera assistant has already been achieved [12]. However, the manipulation of the mechanical arm that holds the telescope remains a crucial point, as joystick, foot panel, or voice-activated controls are not yet sufficiently intuitive and reliable. The surgeon has to take over an additional workload, which was formerly otherwise the task of an assistant. A real alternative would be the development of stand-alone solutions for camera guidance systems that enable the robot to follow the surgeon to the point of interest automatically or autonomously. Some attempts have already been made to achieve this goal. Most of them are based on the hypothesis that the position of the tip of the instrument in the dominant hand is a suitable indicator of the actual point of interest. If the position of the instrument tip can be defined precisely in three dimensions, the camera can then easily be focused as necessary. Several techniques have been elaborated to identify continuously and in real time the position of the tip of the instrument. Tracking may be done by pattern recognition [13], color identification [14], and optical [15] or electromagnetic instruments [16].

Neither has really gained broad clinical acceptance because these systems are in fact automatons and do not offer real autonomy. In 90 % of cases, camera adjustment according to the situational position of the instrument might be adequate and helpful, but in another 10 %, it would be better if the telescope did not change its position, although the instrument is withdrawn from the view. In other words, what is needed is not an automatic guidance system but an intelligent, cooperative system that is able to react in a situation adapted mode. Gaze-tracking technologies might be helpful to achieve this step of autonomy [17].

It is certainly not too optimistic to assume that contextual information from work flow recognition will be available in the future to derive optimal laparoscope guidance beyond of more or less position recognition. If the system works reliably, it could greatly reduce the surgeon's workload.

Midterm developments

Intelligent instruments Instrument configuration: Laparoscopic instruments have to be inserted into the abdominal cavity in a straight configuration; otherwise, they would not fit into the respective trocar. Within the abdomen, they have to be bent or brought into an angled shape to come into action. Up to now, the surgeon has initiated these actions manually. It should be feasible to develop intelligent instruments that are able to modify the shape or configuration of the end effectors autonomously, as required in the actual phase or step of the operation. During insertion through the trocar, the effector should remain in closed position. As soon as the abdominal cavity is reached, it should then open automatically [18].

If the instrument has to be withdrawn, or in cases of a risk situation leading to conversion to open surgery, special patterns should be initiated that close the effector immediately and ready it to be pulled out at once.

Avoidance of collision: If the position of the end effector in relation to the environmental anatomy were known, autonomous actions to avoid collision damage are conceivable [19]. This could be achieved by application of optical distance measurements (e.g., microcameras with structured light or time-of-flight technology). As soon as the distance between any part of the end effector and the adjacent anatomical structures became too small, the end effector should either stop the respective action or identify an alternative trajectory.

Motion compensation: Dynamic changes of the abdominal surgical site are common during surgery. Respiration-induced organ shift is only one example. If continuous intraoperative range measurement could be implemented, a robotic system should be easily able to compensate for these motions by keeping the distance between the end effectors stable, modifying the depth of insertion accordingly.

Future developments

Procedural autonomy Some steps of a surgical operation are either tedious and time-consuming because they consist of numerous, frequently repeated actions such as dissection, or are difficult to execute because of difficult kinematics like knot tying. Automating these tasks would greatly reduce surgical fatigue and shorten the total operation time.

Dissection and hemostasis: Tissue dissection and hemostasis are essential tasks in surgery. Up to now, the surgeon performs these interventions manually, either directly or by using a surgical extender (master–slave system). In the future, it should be conceivable that some standardized surgical steps, e.g., the dissection of the gallbladder from the liver, could be performed autonomously by mechatronic support systems [20]. This is certainly not a trivial challenge because many preconditions have to be met, such as reliable recognition of different tissue layers and identification and adequate sealing and dissection of blood vessels. However, these problems could be overcome. The surgeon's role could be limited to defining the line of resection on the screen and the depth of the incision and then to supervising the action.

Suturing: Intracorporal knotting remains a challenging task in MIS, even more so in NOTES, which is aggravated by the limited degree of freedom and constricted 2-D vision [21]. The surgeon has to perform very complex movements with both hands to perform a secure and reliable knot. Robotic (master–slave) systems may partly overcome some of these drawbacks, as they provide additional degrees of freedom allowing the needle to be grabbed and handled more easily [20]. Given that suturing occurs frequently during interventions, several research groups have worked to automate this task, e.g., by proposing an approach based on human–machine skill transfer, capable of learning arbitrary human skills and automatically executing the adapted tasks in new environments [22] or cooperatively executing the suturing task [23]. The system automatically identifies the completion of a manual subtask (e.g., piercing the tissue) and then seamlessly performs the next subtask (e.g., tightening the knot). Improving the execution speed of automated tasks is also subject of current research [24].

General technical environment

Autonomy of robotic function is an important issue, but in modern, high-tech ORs, many more devices and systems are required to provide functionality. Independent of whether or not a robot is used, a high-level OR has to have quite a few technical features, like a perfect visualization chain, illumination, patient positioning, gas insufflation, and electrosurgery devices. The following aspects were identified as further potential applications of autonomy in advanced surgical techniques.

Near-term developments

Adaptive OR setting An automatic adaption of the OR setting in accordance with both the planned procedure and the assigned surgeon would be most valuable to increase OR ergonomics and economics [25]. This includes peripheral settings such as the optimal height and tilt of the OR table, optimal positioning of monitors and screens, and optimal illumination. The object is an automatic presetting of the OR environment comparable to that found in the automobile industry, where each driver receives his or her own individual settings when entering the car.

Most remarkably, some stand-alone solutions have already been developed, like the "Dr. Dongle" of Bowa (Gomaringen, Germany). If a personalized dongle is inserted into the USB port of the electrosurgical unit, the device's parameters are adjusted according to individual surgeons' personal preferences [26].

Context-adapted interfaces The control of the vast range of different functionalities within the (MIS) OR makes the structures of commands voluminous and confusing. Therefore, a context-adapted interface that only presents the essential commands as required in a specific situation would be highly valuable. At least two methods are conceivable.

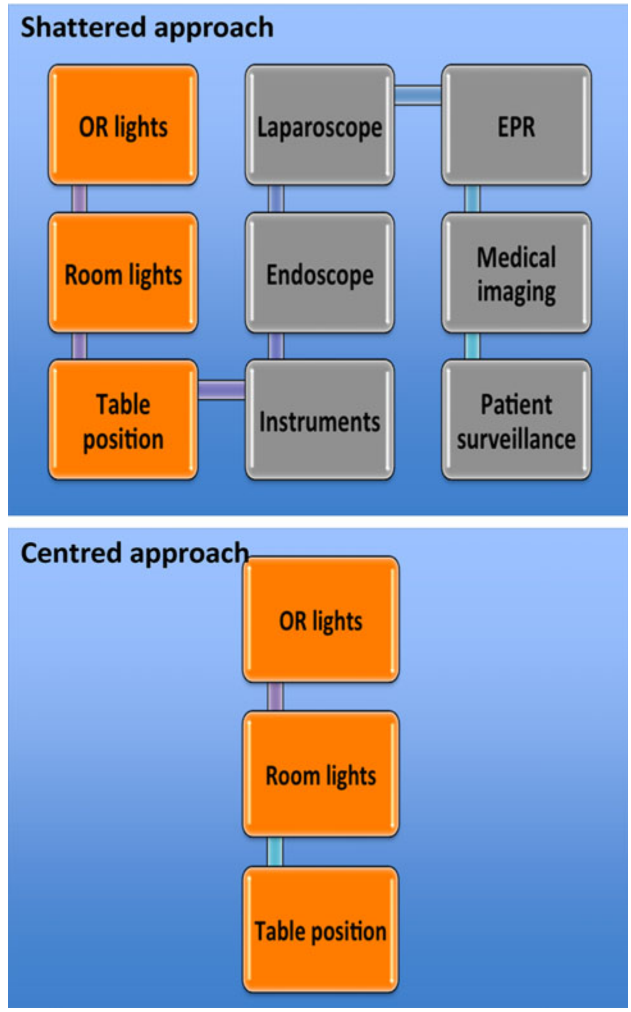

Fig. 1 Context-adapted interface: shattered and centered approach for display of different functionalities

With the shattered approach, different functionalities are ordered in a circle on a monitor display. Depending on the current operational step, only the relevant command buttons are highlighted and can be activated. Command buttons not in use remain visible in the periphery but are inactivate. In contrast, with the centered approach, only the relevant functionalities are displayed in the center of the monitor. All other functionalities are not displayed (Fig. 1).

Midterm developments

Preoperative tool arrangement and intelligent instrument delivery Because of the limited number of access ports, MIS requires multiple changes of surgical instruments to provide the surgeon with the full functionality necessary to complete the operation. Analysis of usage statistics for various deployed surgical instruments by Miller et al. using a fuzzy inference system revealed four main functions that generate a rating value of each instrument concerning its usefulness for the procedure. Thus, an efficient method of arranging tools was possible that performed better than simply placing the tools in a random configuration [27].

Following this approach, the current challenge is to accurately recognize the current phase of the intervention and to automatically supply the most suitable instrument for the next predicted step. For this task, dedicated devices can be used to manage and identify surgical tools and to deliver them in an automated and time-saving manner. The individual instruments are marked with bar codes or RFIDs that guarantee proper selection [5]. Simultaneously, their usage times can be recorded.

Future developments

Visualization Horizon alignment: A crucial point in MIS visualization, especially in NOTES interventions, are the provision of a stable horizon in video images, provided by flexible endoscopes. We developed an approach for automated image orientation that employs a microelectromechanical system inertial sensor, which is placed on the distal tip of an endoscope. Thus, the rotation angle can be estimated by measuring the impact of gravity on each of the three orthogonal axes [28]. Image alignment has proven to facilitate especially NOTES interventions, as orientation within the abdominal cavity is easier if a stable horizon is automatically provided.

Indication of forbidden zones: A limit in MIS is the ability of the surgeon to accurately visualize the target organ. A promising new technology to overcome this limitation is augmented reality visualization that allows the fusion of three-dimensional medical images (e.g., CT or MRI scans) with live camera images in real time [29]. Thus, a virtual transparency of the patient is provided that increases the surgeon's intraoperative vision. Hidden organs or vessels can be shown, for example, thus helping the surgeon prevent injuries. Current limitations are mainly dynamic tracking of organ motion (e.g., by respiration) or organ deformation (e.g., due to pneumoperitoneum). A possible solution could be the use of 3-D intraoperative imaging (e.g., MRI scan) [30]. However, implementation in MIS is technically challenging and cost intensive. For increased OR autonomy, methods of augmented reality visualization need to be developed that allow an automatic adjustment of the augmented reality image toward the surgeon's region of interest, e.g., by combination with instrument tracking technologies. The visual indication of forbidden regions belongs to the general concept of virtual fixtures, originally defined by Rosenberg et al. [31]. In addition to a visual or auditory feedback, researchers are currently investigating the feasibility of haptic virtual fixtures. Haptic constraints capitalize on the accuracy of robotic systems, enhancing the operation speed and reducing mental stress while permitting the user to retain ultimate control over the system [31]. The fixture can be implemented to take on an active or passive role. A passive fixture simply scales the user's input force to drive the operator back to a desired path, while active guidance generates forces to actively guide the operator along a predetermined path, e.g., during knot tying or cutting.

Selective 3-D visualization: Currently, a new generation of 3-D hardware is being offered by leading industrial companies because it has been demonstrated that surgical performance (speed of manipulation, motion economy) can be improved if the third dimension is provided [16, 26]. However, 3-D viewing remains cumbersome and leads to fatigue. High-definition 2-D viewing is therefore widely favored by most laparoscopic surgeons.

Selective 3-D viewing would probably be the best compromise. A 3-D display is only provided in a surgical situation when it is most helpful, such as while suturing, but normal 2-D vision is the standard for the rest of the operation to avoid unnecessary strain.

Switching from 2-D to 3-D and back again whenever appropriate should be induced autonomously by a cognitive system able to analyze the actual work flow and resulting tasks.

Perioperative data integration

Comprehensive online data acquisition, analysis, and interpretation are the basis for the development of context-sensitive systems [5]. If the accuracy of work flow prediction is sufficiently high—which depends, among other factors, on precise work flow modeling—specific tasks could be carried out autonomously. Therefore, integration of perioperative data is an inherent part.

Near-term developments

Electronic patient records Easy intraoperative access to electronic patient records seems basic but is not provided in most ORs. However, automatic prioritization of documents would be mostly helpful if only relevant documents could be shown (e.g., laboratory values, endoscopy report) related to the current procedure. Ideally, electronic patient records should not be controlled manually or by voice or gesture control, as already realized [32], but present the required data automatically depending on the actual part of the intervention. The benefit lies in the reduced effort required to retrieve patient data as well as in an easier intraoperative consultation of patient records in case of potential uncertainties. Generally, such systems provide the OR team with greater flexibility and may reduce operating time.

Midterm developments

Medical imaging Medical imaging methods such as x-ray, CT, or MRI tomography play a decisive role in planning and performing surgical interventions. However, a crucial point herein is the consistent integration into the master console and the correct mapping to the patient's anatomy. [33]. Common input devices such as keyboard, mouse, touch screens, and foot switches show significant limitations, especially in terms of work flow disruption and sterility issues.

Up to now, gesture recognition interfaces [34] or voice recognition systems [35, 36] are most often used for intraoperative display of medical images. Prior annotated gestures or spoken commands of the surgeon are used to control, e.g., a medical image viewer.

However, for an increased OR autonomy, we need to go one step further. The system should be able to present the appropriate medical images according to the actual step of the procedure autonomously, without circumstantial gesture or voice input. Of course, this requires that the system recognize the actual part of the operation automatically and that the corresponding images to each operational sequence are deposited and retrievable.

OR documentation and logistics Nowadays, surgeons typically document the operative report after the operation by using dictation services or by writing by hand. However, dictated or manually written reports are frequently incomplete or delayed [37]. Electronic templates could potentially improve this process, enhancing timeliness and comprehensiveness of operative documentation. Because each part of a standardized operation follows a defined surgical sequence, it can be automatically added to the operative report if recognized by the system.

Future developments

Patient surveillance Anesthesia information management systems entering ORs worldwide have the potential to measure and improve perioperative quality of care [38]. By continuous automated information delivery of data such as vital signs or depth of anesthesia, surgeons may achieve an improved situational awareness of the overall procedure and the state of the individual patient in various stages of the intervention. However, in most ORs, anesthesiological data are not routinely presented to the surgical team, although integration of these data into laparoscopic monitors is technically easy and would facilitate surgical autonomy. Furthermore, valuable feedback could be given, as the surgeon in MIS, for example, often realizes a reduced depth of anesthesia earlier than the anesthetist by an increase in abdominal pressure. If these integrated perioperative data were combined with decision support and alerting algorithms, the OR team could achieve a higher documentation reliability of the patients' intraoperative status and also initiate supporting or salvage mechanisms in case of potentially threatening situations.

Cost analysis Although at the beginning the expanding use of new technologies will most likely increase the financial burden on the health care system, benefits such as an increased patient security, reduced surgeon workload, and innovation for the medical engineering industry should also be taken into account when evaluating cost-effectiveness. Robot-assisted laparoscopic surgery, for example, has been shown to be cost-effective if performed in high-volume centers. One can assume that technical devices, when utilized to their maximum potential and with market-driven competition, can become affordable in the future [39]. Furthermore, even if achieved only partially, future developments for increased OR autonomy would surely be valuable and challenging for both the research and medical industries.

Discussion

It is common experience that in technical systems, the degree of automation runs parallel with its complexity. Certain tasks have to be carried out autonomously by the system; otherwise, control would be impossible. In everyday life, numerous examples can easily be found, like the airbag in a car that is initiated in a completely autonomous mode within milliseconds in case of an accident. Human reaction would be far too slow. This life-saving feature, however, could only be implemented into serial production as soon as it was sufficiently sensitive, specific, and reliable. It had to be provided that any accident is identified reliably but that negative activation is avoided. As a result of advanced sensor technology and advanced filtering algorithms, this is feasible today, and it has greatly improved safety.

Although automation in biological systems is always far more complex than in a technical environment, we should nevertheless also consider it in certain fields of surgery. Of course, it cannot be a topic in everyday open surgery, but the more engineered modern surgical techniques like MPS or NOTES become, the more could automation and autonomy become applicable, relevant, and even necessary. In particular, autonomy will become essential as soon as mechatronic support systems (robots) are used. For smooth surgical procedure enforcement in MIS, MPS, and NOTES, the application of an increased number of technical instruments is essential. However, as a result of their higher functional range, the handling is becoming more and

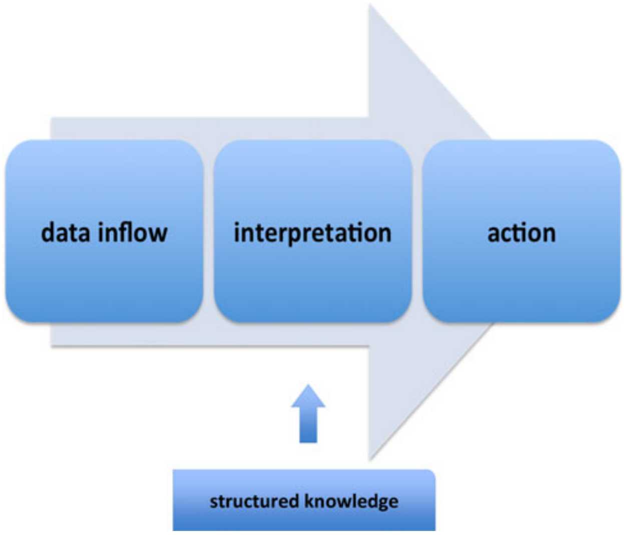

Fig. 2 Development of cognitive surgery. Precondition is a comprehensive data inflow, which is interpreted according to the actual step of the procedure (context awareness), then is transformed into action. Without the input of structured knowledge, contextual data interpretation is impossible

more complex. It can be foreseen that this degree of mechanization and specialization will not be controllable for the surgeon without adequate assistance systems.

The complexity of this topic must not be underestimated. Many, if not most, surgeons and even engineers are skeptical and doubt whether this high level of situational awareness could ever be reached; such skepticism is warranted in cases of even modest system autonomy. Some might even claim that current knowledge and technology are still far too limited to accomplish this task at all, and cost-effectiveness calculations, e.g., for robotic surgery, are poor [40]. Because any wrong decision could lead to catastrophe, the highest safety levels have to be achieved according to comprehensive data acquisition as well as reliable information analysis and interpretation. However, even only partly applied, autonomy would be helpful in improving surgical procedures, making it a challenging but valuable task for research and development. In this context, surgeons have to do some homework: they must have the structural knowledge and experience necessary to create sophisticated models of the surgical procedure; they have to develop highly standardized procedures; and they have to exactly quantify the influence of additional patient-related factors onto the surgical work flow (Fig. 2).

Acknowledgments Supported in part by DFG project "Single-Port-Technologie für gastroenterologische und viszeralchirurgische endoskopische Interventionen" (FOR 1321).

Disclosures Dr. med. Kranzfelder, Dipl. Inf. Staub, Dipl. Ing. Fiolka, Dr. Ing. Schneider, PD Dr. med. Gillen, Dr. med. Wilhelm, Prof. Dr. med. Friess, Prof. Dr. Ing. Knoll and Prof. Dr. med. Feussner have no conflicts of interest or financial ties to disclose.

References

1. Herron DM, Marohn M (2008) A consensus document on robotic surgery. Surg Endosc 22:313–325
2. Moustris GP, Hiridis SC, Deliparaschos KM, Konstantinidis KM (2011) Evolution of autonomous and semi-autonomous robotic surgical systems: a review of the literature. Int J Med Robot 7:375–392
3. Gopel T, Hartl F, Schneider A, Buss M, Feussner H (2011) Automation of a suturing device for minimally invasive surgery. Surg Endosc 25:2100–2104
4. Kahler G, Bulian D, Collet P, Eickhoff A, Feussner H, Fritscher-Ravens A, Fuchs K, Hochberger J, Kratt T, Meier PN, Meining A, Schafer H, Wilhelm D (2011) Endoscopic surgery through natural orifices (NOTES) in Germany: status report, 2010. Z Gastroenterol 49:543–549
5. Kranzfelder M, Schneider A, Gillen S, Feussner H (2011) New technologies for information retrieval to achieve situational awareness and higher patient safety in the surgical operating room: the MRI institutional approach and review of the literature. Surg Endosc 25:696–705
6. Can S, Fiolka A, Mayer H, Knoll A, Schneider A, Wilhelm D, Meining A, Feussner H (2008) The mechatronic support system "HVSPS" and the way to NOTES. Minim Invasive Ther Allied Technol 17:341–345
7. Gillen S, Wilhelm D, Meining A, Fiolka A, Doundoulakis E, Schneider A, von Delius S, Friess H, Feussner H (2009) The "ELITE" model: construct validation of a new training system for natural orifice transluminal endoscopic surgery (NOTES). Endoscopy 41:395–399
8. Wolf A, Shoham M (2009) Medical automation and robotics. Springer, Berlin
9. Huang HM (2006) The autonomy levels for unmanned systems (ALFUS) framework: interim results. Presented at: Performance Metrics for Intelligent Systems (PerMIS) Workshop, Gaithersburg, MD
10. Jaspers JE, Breedveld P, Herder JL, Grimbergen CA (2004) Camera and instrument holders and their clinical value in minimally invasive surgery. Surg Laparosc Endosc Percutan Tech 14:145–152
11. Kristin J, Geiger R, Knapp FB, Schipper J, Klenzner T (2011) Use of a mechatronic robotic camera holding system in head and neck surgery. HNO 59:575–581
12. Nishikawa A, Nakagoe H, Taniguchi K, Yamada Y, Sekimoto M, Takiguchi S, Monden M, Miyazaki F (2008) How does the camera assistant decide the zooming ratio of laparoscopic images? Analysis and implementation. Med Image Comput Comput Assist Interv 11:611–618
13. Groeger M, Arbter K, Hirzinger G (2011) Motion tracking for minimally invasive robotic surgery. Institute of Robotics and Mechatronics, German Aerospace Center, Cologne
14. Omote K, Feussner H, Ungeheuer A, Arbter K, Wei GQ, Siewert JR, Hirzinger G (1999) Self-guided robotic camera control for laparoscopic surgery compared with human camera control. Am J Surg 177:321–324
15. Kranzfelder M, Schneider A, Blahusch G, Schaaf H, Feussner H (2009) Feasibility of opto-electronic surgical instrument identification. Minim Invasive Ther Allied Technol 18:253–258
16. Beller S, Eulenstein S, Lange T, Hunerbein M, Schlag PM (2009) Upgrade of an optical navigation system with a permanent

electromagnetic position control: a first step towards “navigated control” for liver surgery. J Hepatobiliary Pancreat Surg 16:165–170
17. Rantanen V, Vanhala T, Tuisku O, Niemenlehto PH, Verho J, Surakka V, Juhola M, Lekkala J (2011) A wearable, wireless gaze tracker with integrated selection command source for human–computer interaction. IEEE Trans Inf Technol Biomed 15: 795–801
18. Houston K, Sieber A, Eder C, Tonet O, Menciassi A, Dario P (2007) Novel haptic tool and input device for real time bilateral biomanipulation addressing endoscopic surgery. Conf Proc IEEE Eng Med Biol Soc 2007:198–201
19. Chiang MH, Lin HT, Hou CL (2011) Development of a stereo vision measurement system for a 3D three-axial pneumatic parallel mechanism robot arm. Sensors (Basel) 11:2257–2281
20. Hubens G, Coveliers H, Balliu L, Ruppert M, Vaneerdeweg W (2003) A performance study comparing manual and robotically assisted laparoscopic surgery using the Da Vinci system. Surg Endosc 17:1595–1599
21. Kenngott HG, Muller-Stich BP, Reiter MA, Rassweiler J, Gutt CN (2008) Robotic suturing: technique and benefit in advanced laparoscopic surgery. Minim Invasive Ther Allied Technol 17:160–167
22. Mayer H (2008) Human–machine skill transfer in robot assisted, minimally invasive surgery. PhD thesis, Technische Universität München, München
23. Padoy N, Hager GD (2011) Human–machine collaborative surgery using learned models. In: Proceedings of IEEE International Conference on Robotics and Automation (ICRA), Shanghai, China, pp 5285–5292
24. Chandra V, Nehra D, Parent R, Woo R, Reyes R, Hernandez-Boussard T, Dutta S (2010) A comparison of laparoscopic and robotic assisted suturing performance by experts and novices. Surgery 147:830–839
25. Supe AN, Kulkarni GV, Supe PA (2010) Ergonomics in laparoscopic surgery. J Minim Access Surg 6:31–36
26. Bowa Medical (2012) http://www.bowa-medical.com
27. Miller DJ, Nelson CA, Oleynikov D, Jones DD (2008) Preoperative ordering of minimally invasive surgical tools: a fuzzy inference system approach. Artif Intell Med 43:35–45
28. Holler K, Schneider A, Jahn J, Gutierrez J, Wittenberg T, Feussner H, Hornegger J (2010) Spatial orientation in translumenal surgery. Minim Invasive Ther Allied Technol 19:262–273
29. Nakamoto M, Ukimura O, Faber K, Gill IS (2012) Current progress on augmented reality visualization in endoscopic surgery. Curr Opin Urol 22:121–126
30. Nicolau S, Soler L, Mutter D, Marescaux J (2011) Augmented reality in laparoscopic surgical oncology. Surg Oncol 20:189–201
31. Rosenberg LB (1993) Virtual fixtures: perceptual tools for telerobotic manipulation. Presented at: Virtual Reality Annual International Symposium IEEE, Seattle, WA, pp 76–82
32. Dressler CR, Fischer M, Burgert O, Strauss G (2012) Evaluation of a context sensitive system for intra-operative usage of the electronic patient record. Laryngorhinootologie 91:368–374
33. Ebert LC, Hatch G, Ampanozi G, Thali MJ, Ross S (2012) You can’t touch this: touch-free navigation through radiological images. Surg Innov 19:301–307
34. Wachs JP, Stern HI, Edan Y, Gillam M, Handler J, Feied C, Smith M (2008) A gesture-based tool for sterile browsing of radiology images. J Am Med Inform Assoc 15:321–323
35. Nathan CO, Chakradeo V, Malhotra K, D’Agostino H, Patwardhan R (2006) The voice-controlled robotic assist scope holder AESOP for the endoscopic approach to the sella. Skull Base 16:123–131
36. El-Shallaly GE, Mohammed B, Muhtaseb MS, Hamouda AH, Nassar AH (2005) Voice recognition interfaces (VRI) optimize the utilization of theatre staff and time during laparoscopic cholecystectomy. Minim Invasive Ther Allied Technol 14:369–371
37. Hoffer DN, Finelli A, Chow R, Liu J, Truong T, Lane K, Punnen S, Knox JJ, Legere L, Kurban G, Gallie B, Jewett MA (2012) Structured electronic operative reporting: comparison with dictation in kidney cancer surgery. Int J Med Inform 81:182–191
38. Chau A, Ehrenfeld JM (2011) Using real-time clinical decision support to improve performance on perioperative quality and process measures. Anesthesiol Clin 29:57–69
39. Liberman D, Trinh QD, Jeldres C, Zorn KC (2012) Is robotic surgery cost-effective: yes. Curr Opin Urol 22:61–65
40. Lotan Y (2012) Is robotic surgery cost-effective: no. Curr Opin Urol 22:66–69