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ROBOTIC SURGERY:
IN SAFE HANDS

ASME

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Future issues of *Dynamic Systems & Control Magazine* will include the following themes:

December 2015
Powertrain Control

March 2016
Biomimetic Systems

Robotic Surgery: In Safe Hands

The practice of surgery has been integral to human civilization, with ancient texts from Mesopotamia, Egypt, Greece, India and China highlighting various surgical procedures and tools. The Sushruta Samhita, from India, discusses surgical techniques from simple incisions and probing, to deeply invasive hernia surgery & caesarian sections. The Code of Hammurabi, dating back to 1754 BC, contains specific legislation regulating surgeons and medical compensation. Since then, the surgical experience for both patients and providers has been greatly enhanced by advances in technology (imaging, instruments), techniques (minimally-invasive) and chemistry (antibiotics, anaesthetics).

Arguably, the greatest advances ensued from infusion of "scientific rigor" into the "art of surgery" – by way of systematic record-keeping, characterization, analyses – and further accelerated by the automation/computer-integration in 21st century surgical systems. Various FDA-approved robotic surgical systems significantly enhance and extend the reach of surgeons (and even surgical teams). Arguably the two most critical surgical enablers are *enhancement of perception* and reliable *execution of the intent* via capable tools. Novel modalities (magnified Stereo-Views, Magnetic Resonance Imaging, Computed Tomography scans etc.) have dramatically extended the surgeon's visual perception. Mediating interfaces between surgeon and patient scale and remove tremors while enabling intuitive access to highly inaccessible surgical fields. Other efforts seek to address the loss of tactile sensing, limited field of view, network delays for teleoperation and enhancing training, skill acquisition and assessment.

This special issue presents a snapshot of the five articles discussing *cutting-edge* (bleeding-edge?) research addressing critical issues in Computer Integrated Surgical systems. The first article in this magazine by Nabil Simaan, Russell H. Taylor and Howie Choset highlights efforts with developing natural orifice trans-luminal endoscopic surgery (NOTES) systems by first developing *highly flexible manipulators* and in *enhancing the situational awareness via sensor-fusion*. The second article by Krovi/Corso/Hager groups at SUNY Buffalo/University of Michigan/Johns Hopkins University address the need for *quantitative skill assessment* and development of *data-driven computational-skill models* together with automation tools. The third article by Gregory Fischer exploits the excellent soft tissue imaging contrast within Magnetic Resonance Imaging (MRI) for *closing the loop in image guided surgery*. In the fourth article, Ma and Rosen demonstrate development of *autonomous peg transfer task* (part of the Fundamentals of Laparoscopic Surgery) involving pick-move-drop operations on RAVEN II surgical robot. The last article by Kazanzides and colleagues at Johns Hopkins University showcase *open-source, modular and interoperable software* architectures to match the advances in open-source research platforms (RAVEN II, DVRK: da Vinci Research Kit), laying the foundations of a plug-n-play ecosystem for surgical-robotics research.

We hope that you enjoy the articles in this feature section – I'm grateful to Nabil Simaan in helping identify the authors and to Suren Kumar for the logistics help.

In lieu of news items, this issue features a letter from Del Tesar, with inspiring comments on his vision of the future of mechanical technologies. If you have any ideas for future issues of this magazine, please contact the Editor, Peter Meckl **(meckl@purdue.edu)**.

Venkat Krovi, PhD
Guest Editor, *DSC Magazine*

UPCOMING CONFERENCES

THE 2015 DYNAMIC SYSTEMS AND CONTROL CONFERENCE
Columbus, OH Oct. 28-30, 2015
http://www.asmeconferences.org/DSCC2015/

THE 2016 AMERICAN CONTROL CONFERENCE
Boston, MA July 6-8, 2016
Draft manuscripts are due on Sept. 27, 2015
http://acc2016.a2c2.org/

SUMMARY OF THE NEXT WAVE OF TECHNOLOGY

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A new urgency is being recognized at the national level because of under-investment in the mechanical tech base in the U.S. This weakness limits the strength of other tech base sectors (computers, communications, medical, transportation, military, etc.). The urgent need is to create a balance of all supporting technologies required in electro-mechanical systems (trains, orthotics, aircraft, robot surgery, vehicles, etc.), especially those of high economic magnitude. This argument is presented in a paper entitled **Next Wave of Technology** by D. Tesar just submitted for publication to urge serious consideration of this under-investment by our federal agencies. The desired tech base is described in terms of ten major topics which will be summarized here to indicate its relevance to meeting the needs of mankind, to its potential to reinforce our national security, and to augment our consumer product competitive position.

1. OVERALL VISION: The goal is to open up the architecture of electro-mechanical systems, use standardized interfaces to permit plug-and-play of highly-certified components (especially intelligent actuators as computer chips are to electrical systems) produced in minimum sets for each application domain and provided by a competitive supply chain to continuously improve the performance/cost ratio of these components. The concept of long-duration design/evaluation/production of one-off systems would be a thing of the past enabling more rapid infusion of technology, repair on demand, and frequently the elimination of single-point failures and the prediction of performance failure without false alarms.

2. MACHINE SYSTEM INTELLIGENCE: All future machine systems will increasingly be highly nonlinear, reconfigurable to meet changing needs, and architecturally a mixture of serial/parallel control structures. This means that the influence of any one control input (an actuator) faces an ever-changeable physical plant. This complexity can now be addressed by using very low-cost/distributed sensors providing operational data (in a milli-sec., or less) to a criteria-based decision structure (set by humans) with a full evaluation of the system in 5 to 10 milli-sec. (effectively linearizing the system) because of superior computational resources available today. Given decision inputs as a result, the command/response must be managed by ever-improving actuators to adequately respond in the 5 to 10 milli-sec. time frame.

3. COMPUTATIONAL INTELLIGENCE: A computational revolution for decision making is now feasible because of our accelerating computer technology. This revolution will be based on the geometry of the decision process. If it is serial, as for a centralized company (top-down decisions), the criteria are set by leaders at the top of a decision pyramid. Flow control from the bottom is virtually impossible. By contrast, parallel structures (holding companies, universities, multiple government agencies) can accept and facilitate flow control from the bottom in layers with nominal control from the top. Then, decision criteria in the serial case are fewer and change less often. Those criteria in the parallel case are more numerous and change more frequently. The power of predictive analytics would set/rank these criteria based on archived operational data. Of course, mixed/parallel systems do exist and their sensed/archived data would be managed in both the serial and the parallel flow with selected criteria set at each level or intersection of the decision geometry.

4. SYSTEM LEVEL SENSORS: Fortunately, sensors for all components and systems are becoming very low cost (some averaging $1 in quantity). Body sensors will soon enable effective orthotics to assist the disabled. Freight trains will embed sensors to locate hot bearings, cracked wheels, unbalanced loads, etc. Vehicles will embed torque sensors to monitor wheel traction, etc. All this information on component and system performance goes in milli-seconds to inform the decision structure to compare actual and desired performance (against operator-set criteria). Further, the real performance data can then be archived to continuously update the criteria (say, efficiency, response time, lack of precision, temperature, etc.) using predictive analytics. In the past, control techniques were structured to make decisions based on the minimum of sensed data. This approach is no longer germane in today's computational world.

5. MARRIAGE OF MAN AND MACHINE: To meet human needs, we must integrate a parametric representation of the human with that of the responsive system. Each system will be represented by hundreds of performance maps (and envelopes) at two or more physical layers. Each intelligent actuator may require 40 maps to adequately represent its nonlinear nature. Given 10 actuators, that would represent 400 maps, which then, must be built into a reconfigurable decision structure at the system level (because the system may be reconfigured to meet the ever-changing needs of the human). Doing so structures the full decision process and enables highly refined data on the map surface to be retrieved and combined in terms of human-set criteria. Of course, performance maps also apply to the human. Hence, all human and system maps/envelopes become part of the decision process with far less uncertainty and far less response time (clearly, this is useful for operator training, as well). Note that autonomy only augments this process, removing from the human the burden of repetitive low-level decisions (as long realized in the case of a fighter pilot).

6. HUMAN OPERATOR VISUALIZATION: Given truly complex and critical decisions where human life is at stake (surgery, battlefield operations, orthotics, etc.), it becomes essential to provide visual guidance to the human operator so that decisions can be made more rapidly and more accurately. Most visual representations will be to difference an actual system performance envelope relative to an embedded criteria-based envelope (prioritized by the human). This difference must highlight desired sweet spots (say, for efficiency) or operation where danger is involved, etc. A useful difference map must contrast good and bad on the same map so that critical decisions can be made quickly, probably moving away from danger in favor of a good performance region). This command would be tracked visually on one or more supportive decision envelopes.

7. COMMAND/RESPONSE: The idea that all decisions can be predetermined exists far in the past. Today, our low-cost sensors can completely document how all parts of the system are functioning. This data can then inform all parts of the decision structure (autonomy, human, envelope-based criteria, etc.), and then instruct each actuator to respond to its coordinated command, all in 5 to 10 milli-sec, or less. For example, a car moving at 70 mph will cover the distance of 2 feet in 10 milli-sec., which may not be sufficiently quick to respond to special road surface conditions (i.e., loss of traction). The same may be true of surgery, response to battlefield threats, precision response to force disturbances in manufacturing, etc. The 10 milli-sec. decision window enables the linearization of highly complex, coupled, nonlinear systems, enabling strictly algebraic/geometric decisions without the use of cumbersome continua mathematics, which are easily incapacitated by any form of coupling, or nonlinearity in the system. It also means that pseudo inverses which are computational approximations no longer need to be relied on to make timely and accurate decisions.

8. OPEN ARCHITECTURE IN EMS: Computer technology became open in the 1980 decade where standardized and highly-certified computer chips enabled the construction, almost on demand, of unique and popular computer "boards". This, then, created a demand for higher performance at lower cost for all chips utilized in each board's domain of application. Eventually, the whole design process was inverted in favor of a minimum set of computer chips of ever-higher performance-to-cost for each application domain; i.e., the board designer had to design based on the chips readily available in the supply chain or specify a unique, but more expensive, chip for a special function. The Next Wave of Technology is built on this concept of a minimum set of classes of intelligent actuators (from 2 to 4 orders of magnitude better than the SoA) to operate electro-mechanical systems (EMS). The goal is to concentrate on five classes of actuator technology to create an equivalent of Moore's law for actuators. Special cases in each class will meet unique needs (torque density, stiffness, backdrivability, efficiency, shock resistance, etc.), as is now done for computer chips. Each class/case will become available in the supply chain certified to meet acceptable performance standards (i.e., certified in-depth). Each actuator will utilize standard interfaces to permit rapid integration in a targeted domain of application. Then, the system designer becomes an architect assembling the system on demand to respond to the widest possible set of downstream conditions by reconfiguration commands from the operator or from the embedded decision structure (say, the equivalent of autonomy).

9. ENHANCED AVAILABILITY: Durability is one ingredient of availability. Reliability is one measure of durability. Standards for effectiveness and a fixed schedule for component replacements are another means to manage unexpected failure and long down times. Here, this managed failure avoidance will be expanded to enhance the technical basis for almost complete availability, almost no false alarms, and reduced cost by eliminating extended outages. Each system will be composed of components with birth-certificate performance maps. Each component will use predictive analytics to update their actual maps and difference the updated maps against the functionally required maps to estimate remaining useful life (i.e., a modernized form of condition-based maintenance). Based on this predicted RUL, spares can be brought in for replacement before failure in a timely and cost-effective manner. Using this archived data, this degradation history can now be quantified to assist the component designer to improve the design (documented in terms of performance maps), move towards lower cost, and be more responsive to the customer (as part of the supply chain process). Given that the open architecture EMS will continue to become more complex (do more in multiple configurations), this expanded view of availability will become the norm and a necessity.

10. ACTUATOR INTELLIGENCE: Item 5 highlights the absolute importance of intelligent decision making within all future actuators (as it is now for all market-driven computer chips). Given a decision time span of 10 milli-seconds at the system level, it must be 1 milli-sec., or less, for the actuator because these systems are highly coupled in most systems (frequently in a force fight). Unfortunately, all actuators are highly nonlinear making their command/response approach largely untractable by that embodied in the concept of automatic control (usually good for simple linear systems of a few DOF). To make each actuator responsive to command, at least ten sensors (voltage, current, temperature, velocity, acceleration, torque, etc.) must generate data to accurately represent the actuator's real condition (in much less than a milli-sec.). This data, then, locates each performance measure on its respective embedded maps. Each such data point then enables algebraic decisions to be made as to how to respond to commands in the next time frame (say, 1 milli-sec.). These algebraic decisions are based on operator-set performance criteria to meet the system's operational demands in this allotted time span. This includes torque, acceleration, stiffness, backdriving, etc. It also includes condition-based maintenance and fault avoidance. Actuator operational software will be dedicated to each actuator class and evolve over time depending on the application domain. There may eventually be a concentration on forward (what is commanded) and inverse (depending on what actually occurred) decisions.

RECOMMENDED ACTIONS: The weakness in the mechanicals will require a national reawakening especially among the U.S. federal funding agencies. The following may build a wave of development based on a strong tech base community of interest.

1. Convene an industrial council of interested R&D vice presidents of our high-valued industries to advise multiple federal agencies on balancing all technologies, with emphasis on rebuilding the mechanical tech base.

2. Have the DOE revisit the critical role of the mechanicals in the energy sector (oil & gas, efficient vehicles, manufacturing, power plants, etc.).

3. Have DARPA commit to a revolution in intelligent and highly-certified actuators with emphasis on military systems, as it did for the computer chip in the 1970s.

4. Have NSF engineering restructure its program plans to rebalance their portfolio to create a proportional investment in the mechanicals to meet tech base requirements of our major economic product producers taking advice from the recommended industrial council so that young faculty would be able to seek balanced funding to support graduate students better oriented to real industrial needs. ■

INTELLIGENT SURGICAL ROBOTS WITH SITUATIONAL AWARENESS: FROM GOOD TO GREAT SURGEONS

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During the past thirty years, surgeons gradually converted open surgical procedures to minimally invasive laparoscopy and then to robot-assisted multi-port minimally invasive surgery (MIS). This conversion from open to MIS surgical technique has been driven by the aim of decreasing patient trauma, wound site infection, risk of incisional hernia, and post-operative recovery time and scarring.

Surgeons use multiple incisions (typically three to six incisions) to access the anatomy during multi-port MIS. By using insufflation of the surgical site (e.g. the abdomen) the operational field is enlarged to facilitate visualization and operation of multiple tools. Typically, three tools are used (right and left arms for manipulation/ablation and a third arm for visualization). Other access ports may be used for organ retraction and auxiliary tasks of suction or delivery of tools such as blood vessel clips. For instance, the da-Vinci Si system **(Figure 1)** uses a quadruple-armed tele-manipulator allowing the operation of additional tools and collaboration among two surgeons. The dexterous tools of the da-Vinci slave robot are matched via a telemanipulation interface to the mechanical architecture of the wrists of the master user interface. A high level telemanipulation computer relays commands from the master user interface to the slave arms thus allowing motion replication of surgeon's hand movements with tremor filtering and motion scaling.

Robotic systems such as in **Figure 1** have successfully

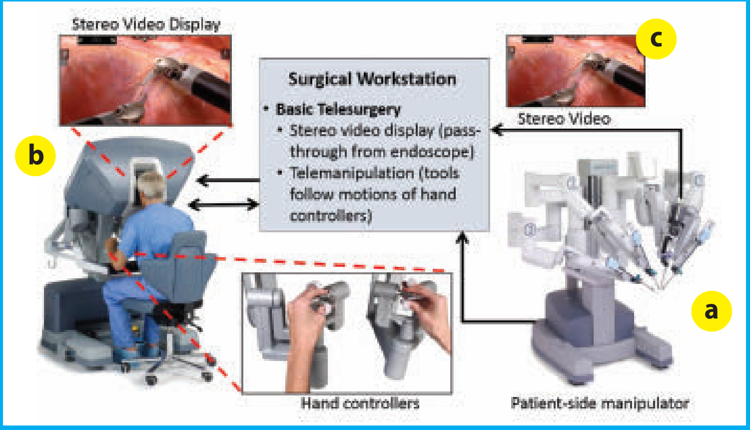


FIGURE 1 The da-Vinci Si system: (a) the patient side manipulator, (b) the surgeon master interface, (c) the correspondence between dexterous tool wrists and the master interface.

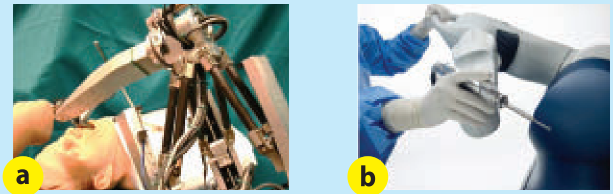


FIGURE 2 Examples of cooperative robots: (a) The JHU REMS robot for head & Neck microsurgery [4], (b) the Mako Rio® for orthopedic surgery.

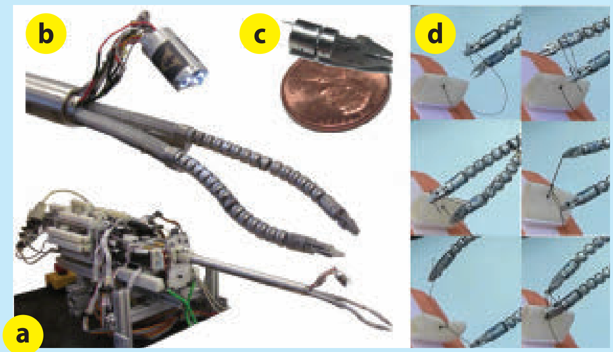


FIGURE 3 (a) The IREP single port access system, (b) the stereo- vision head with two seven degrees of freedom arms, (c) the distal wrist and gripper, (d) example of tying a double-throw knot.

enabled many surgical procedures using the multi-port MIS approach. However, with the aim of further reducing trauma to the patient, the last decade has seen significant growth in works investigating MIS in confined spaces, single port access (SPA) and natural orifice trans-luminal endoscopic surgery (NOTES). These new surgical paradigms present surgeons with unprecedented challenges that require a new approach to robotic assistance. This paper discusses these challenges and puts forth the concepts of *intelligent surgical robots* and *complementary situational awareness* (CSA) as means for achieving new surgical systems with unprecedented capabilities in terms of safety, ease of operation, and exact execution of pre-operative surgical plans. Within the context of this paper, intelligent surgical robots are robots capable of sensing and regulating their interaction with the environment in order to assist the surgeon in achieving safe surgical intervention and to facilitate CSA. Situational awareness is defined in accordance with [1] by the three stages of *sensory acquisition*, *sensory comprehension*, and *projection* (projecting the interpretation of sensed data to decide on a future action). A robotic system with CSA assists the user not only in manipulation, but also in forming the situational awareness regarding the task at hand by using perception resources beyond the capabilities of the user.

In the following sections, we show that the emerging surgical paradigms such as NOTES require new robot designs and human-robot interaction framework that go beyond the use of robots and computer assistance to allow manipulation augmentation. We will show that, while the two approaches of haptics and sensory immersion through virtual reality help surgeons overcome the sensory acquisition step, they do not help surgeons with obtaining full situational awareness. We will put forth the concept of CSA as a natural progression beyond these two approaches thereby allowing robots to help surgeons in interpreting the surgical scene and in projecting the perceived intraoperative sensory data to allow exact safe operation and the execution of pre-operative surgical plans.

FROM MANUAL TO ROBOT AND COMPUTER-ASSISTED MIS

The early drivers for robot surgical assistance stemmed from the desire to improve patient outcomes by achieving two goals: 1) offering patients the benefits while sparing surgeons the difficulties of laparoscopic MIS, 2) improving the accuracy of surgical execution of pre-operative surgical plans to ensure optimal outcomes. These two goals have driven most of the medical robotics research in the past three decades and resulted in several robotic systems reviewed in [2] and more recently in [3].

The concept of robotics for *manipulation augmentation* was introduced to overcome the challenges of manual laparoscopy. This radical move decreased the learning curve of surgeons who no longer had to contend with the reverse manipulation mapping typical of manual laparoscopy. Compared to laparoscopy robots provided increased dexterity, allowed the manipulation of multiple arms, improved precision and steadiness and lowered the physiological performance requirements of surgeons.

To improve surgical plan execution accuracy, computer assisted surgery was introduced in order to provide *perception augmentation* through intraoperative imaging and guidance. By using image registration a pre-operative surgical plan is matched to the intraoperative surgical reality. While image registration proved feasible for rigid anatomy (e.g. Orthopedics), it has been elusive in general surgery due to organ flexibility, deformation and gravitational shift and/or swelling.

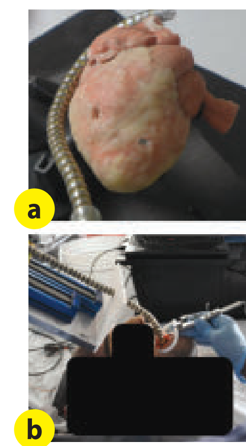


FIGURE 4 The HARP robot: (a) steering around a heart, (b) performing trans-oral access into the airways.

The advantages of telemanipulation robot assistance came at the cost of removing the surgical tool from the surgeon's hand, thus, resulting in limited sensory perception and situational awareness. Surgeons cannot feel the tool interaction with the anatomy and current commercial systems still do not provide force feedback. Surgeons are also challenged with interpreting and relating the surgical scene with pre-operative imaging.

Haptic feedback, augmented reality and assistive manipulation have been proposed to alleviate the loss of sensory presence and situational awareness. Haptic feedback aims at restoring sensory presence through force feedback or by sensory substitution (e.g. substituting force with sound feedback). Augmented reality partially restores situational awareness via image overlay allowing the surgeon to superimpose an intraoperative image or visual cues to anatomical structures on the image display of the telemanipulation master console.

Assistive manipulation uses control laws to help surgeons achieve critical surgical tasks. These control laws include active constraints and virtual fixtures. Active constraints enforce safety barriers preventing the surgical tool from venturing into sensitive anatomy. Virtual fixtures generalize this concept to facilitate tracing of a target geometry such as an ablation path or an anatomical surface (for an up-to-date review see [5]). Assistive manipulation can be applied during cooperative manipulation or telemanipulation. During cooperative manipulation, the robot and surgeon hold the tool and admittance control allows the surgeon to move the tool while benefiting from tremor filtering and enforcement of assistive manipulation laws. Examples of coopera-

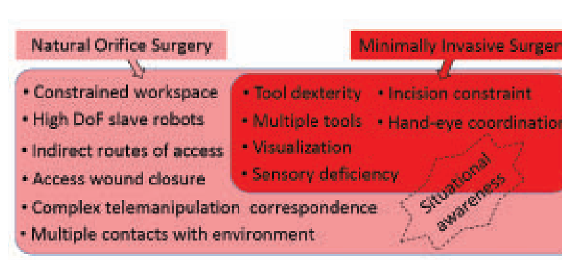


FIGURE 5 The challenges of MIS and NOTES.

tive manipulation robots are the REMS robot and the Mako Rio® shown in **Figure 2.**

By and large, the frameworks of assistive manipulation, augmented reality, and haptics have historically evolved with multiport MIS in mind as an application domain. Intraoperative information seamlessly gathered by the surgeon's hand (e.g. stiffness/constraint cues) during open surgery is not used. Also, existing frameworks for assistive manipulation typically assume single and known contact between the end effector and the environment. The newly emerging surgical paradigms violate these assumptions and therefore require a new approach.

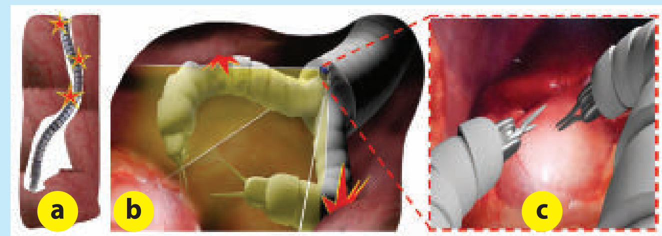


FIGURE 6 Example of perception limitations affecting situational awareness of the user: (a) invisible multiple contacts, (b) contacts outside field of view, (c) the field of view visible to the surgeon.

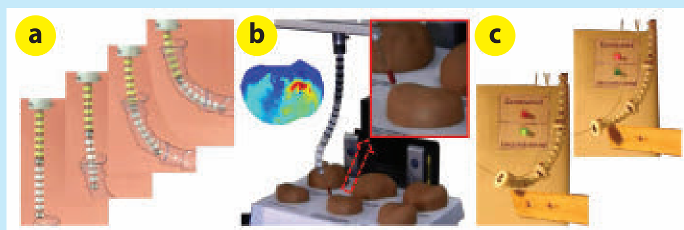


FIGURE 7 Continuum robots with intrinsic sensing capabilities demonstrating (a) active compliance to facilitate insertion [12], (b) palpation [13], (c) contact detection and localization [11].

NEW SURGICAL PARADIGMS AND CHALLENGES

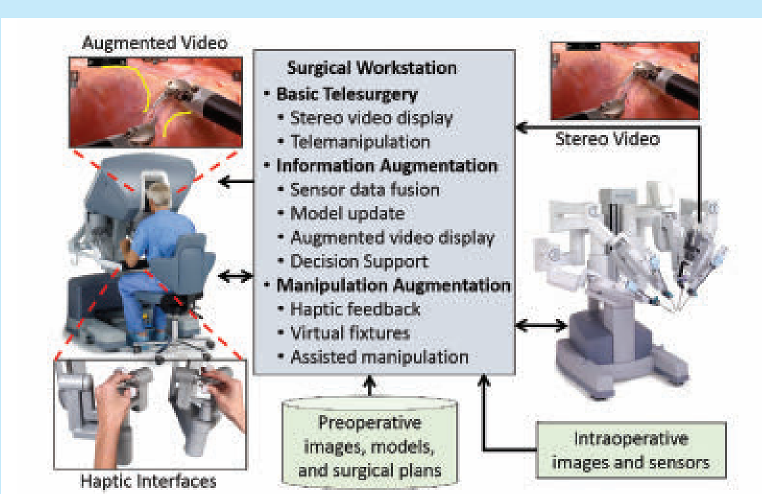
Multi-port MIS requires several small incisions that generally heal well, but can also be associated with pain, scarring and potential wound infection and/or hematoma. To ameliorate surgical outcomes, SPA and NOTES have been proposed to reduce or eliminate the number of surgical access incisions. During an SPA procedure a single access port is placed in the abdomen to provide surgical access to the necessary tools. **Figure 3** shows an example of the insertable robot effectors platform (IREP) [6] developed to operate on the abdomen through a single ø15 mm port. During NOTES procedures natural orifices are used to access internal anatomy. Examples of NOTES access routes include transurethral, trans-nasal, trans-oral, trans-esophgeal, trans-gastric, trans-anal, and trans-vaginal surgeries. **Figure 4** shows an example of the highly articulated robotic platform (HARP) designed to provide deep access into the anatomy and recently used for trans-oral surgery [7]. Much of the understanding we gained regarding the limitations of traditional manipulation paradigms has been through experience in using these two systems.

Figure 5 illustrates the encumbered difficulty of NOTES/SPA compared to multi-port MIS. In addition to the challenges of MIS, NOTES adds the complexity of operating in constrained workspace and traversing anatomical passageways. Unlike multi-port MIS where contact with the anatomy occurs only at the dexterous wrists on rigid shaft tools, in NOTES contact occurs along the length of the robot as it is inserted in anatomical passageways, **Figure 6-(a)**. Also, in procedures such as trans-gastric abdominal surgery there is the significant challenge of obtaining wound closure within the gastric wall after completing the procedure. And compared to MIS where generally there is a correspondence between the motion range and shape of the wristed surgical tools and the surgeon's hand (e.g. **Figure 1**), in NOTES the robots must have many degrees of freedom and arms and this correspondence become significantly more complex to learn. Finally, while situational awareness is limited in MIS, the limitation is exacerbated in NOTES due to the further limited perception of robot shape and its interaction with the anatomy. **Figure 6-(b)** illustrates the risks of operating in confined space subject to the limited perception of the endoscope: collisions between the robot and the anatomy can occur outside the perception range of the surgeon.

DESIGN, CONTROL AND SENSING FOR ENABLING CSA

When designing systems for NOTES/SPA, the prerequisites of safe deployment into the anatomical passageways, distal dexterity and collaborative multi-arm workspace must be satisfied. Depending on the mechanical embodiment of the robot, there are four ways of achieving deep access into the anatomy. The first approach tasks the surgeon with steering the front end of the robot using camera visualization and uses the robot controller to execute a follow-the-leader task. Such design requires a very large number of actuators to control the shape of the robot and can lead to slow deployment. The second approach implements passive compliance with a steerable end tip. Once the robot reaches the site the robot structure can be actively locked. The Transport® endoscopic access system by USGI Medical Inc. is an example of such an approach. The third approach is by steering the robot tip while allowing the back end of the robot to alternate motions of locking and relaxation of the robot backbone in order to match the anatomical passageway during insertion. The HARP robot in **Figure 4** uses this approach. Finally, the fourth approach requires the robot to use its sensing capabilities to actively comply with the constraint forces of the anatomy while tasking the surgeon with advancing the robot. **Figure 7-(a)** shows an example of this approach; which has also been reported in [8] to facilitate rapid trans-nasal access into the upper airway.

The second design prerequisite is distal dexterity



DA-VINCI COMPONENT IMAGES ©INTUITIVE SURGICAL

FIGURE 8 From basic telemanipulation to advanced computer-aided surgery via manipulation and information augmentation.

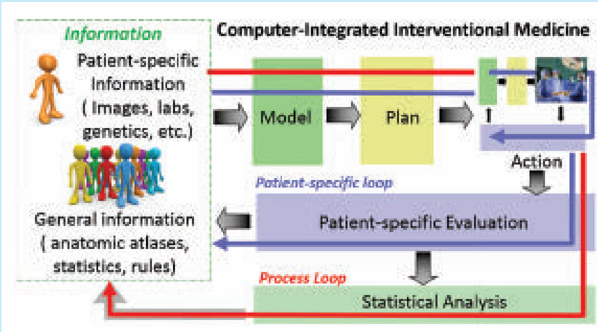


FIGURE 9 Computer-Integrated Interventional Medicine will exploit technology and information for modeling, planning, surgical execution, and evaluation to help physicians to treat each patient in an optimal manner (blue loops). Further, information about each intervention can be saved, compared to outcomes, and used to improve treatment processes for future patients (red loop).

with a dual-arm dexterous workspace. To effectively achieve dual-arm tasks, the robot arms must be able to oppose each other as human arms can. This challenging task is called triangulation of tools. This calls for designs enabling multiple dexterous arms to operate with almost parallel shafts. For instance the IREP, shown in **Figure 3**, has been designed with the ability to control the distance between its two snake-like arms in order to facilitate dexterous dual-arm operations such as knot tying. Other example of NOTES systems have been reviewed in [3].

Even if the design prerequisites of NOTES are satisfied, the success and safe use of these systems hinges on implementing advanced sensory and control capabilities to overcome the challenges in **Figure 5**. As initially proposed in [9], smart surgical tools can facilitate manipulation augmentation. In our work, we propose that intelligent surgical slaves are a critical component for enabling CSA. For example, intelligent robots with sensing capabilities can act as both surgical intervention and diagnostic tools much in the same way the surgeon's hand manipulates anatomy and helps in identifying stiff nodules invisible to the naked eye. These robots can act as *perception augmentation* tools by deploying sensory modalities that extend the human perception (e.g. ultrasound, optical coherence tomography, or confocal microscopy). As an example, the continuum robot shown in **Figure 7-(b)** is able to estimate forces and moments acting on its tip and it has been shown in [10] to enable palpation and building a stiffness map of a model prostate. To discern invisible contacts (as in **Figure 6**) [11] proposed kinematics-based models for detecting and localizing the contact. **Figure 7-(c)** shows a continuum robot demonstrating contact detection.

Finally, one of the key benefits of intelligent surgical slaves is their ability to offload cognitively burdensome tasks. To achieve this, the low level controllers of these robots must support force and motion regulation. For example, hybrid force/motion control can be used to facilitate controlled ablation along a path while maintaining a fixed contact force between the ablation probe and the anatomy. Our team is also working on other advanced capabilities of these robots including exploration of an unknown flexible environment with the aim of localizing and mapping the environment shape and stiffness and using this information for registration to a pre-operative model.

TOWARDS COMPLIMENTARY SITUATIONAL AWARENESS

Figure 8 shows our envisioned tele-robotic system with advanced features of computer-aided surgery, taking advantage of the fact that telesurgery systems essentially place a computer between the surgeon and the patient. In addition to basic telesurgery capabilities such as high quality stereo video, distal dexterity, motion scaling, and tremor filtering, these *Complementary Situational Awareness* (CSA) systems have the capability to combine sensing, imaging, and model information to provide the surgeon with significantly enhanced information and decision support, using augmented reality visualization, haptic feedback, and other means. These systems can also assist the surgeon in manipulating tissue through the use of virtual fixtures and other assistive methods. Further, haptic, imaging, and other intraoperative sensing during the procedure can update and refine the computers of the patient and surgical situation.

In the future, we expect that CSA systems will increasingly be embedded within a larger framework of Computer-Integrated Interventional Medicine **(Figure 9)**, in which patient-specific information such as images, lab results, and genomics are combined with general knowledge to model and diagnose the patients' condition and to develop an optimized treatment plan. All of this information will be available to a CSA system to help the physician carry out the treatment plan and assess the results. This closed-loop process (blue loops) will occur over multiple time scales, from an entire patient treatment cycle down to every second in the operating room or interventional suite. Further the CSA system will function as a flight data recorder enabling the creation of a much more complete record of what happened in the operating room. All this information can then be related to observed outcomes and statistical methods can be used to improve treatment processes for future patients (red loop). ■

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SURGICAL PERFORMANCE ASSESSMENT

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Skilled performance of manipulation tasks, especially in conjunction with innovative tools "to extend the reach of humans" has been instrumental to human progress. Numerous learning traditions have evolved over millennia to help characterize human sensorimotor skill for performing complex manipulation tasks while simultaneously developing the modeling techniques to capture skill acquisition and retention. For example, the careful assessment, nurturing and refinement of sensorimotor task performance has proven equally pertinent to the skilled operation of machinery as well as mellifluous musical performance. Yet, there are major gaps in our understanding of the human-operator interactions with tools in complex environments.

FIGURE 2 Evolution of surgery starting from open surgery to current minimally invasive teleoperated surgical systems.

In this article, we focus specifically on human skill understanding in the context of surgical assessment and training which has enormous and immediate application potential to enhance healthcare delivery. Surgical procedural performance involves interplay of a highly dynamic system of inter-coupled perceptual, sensory, and cognitive components. Traditional surgeries produced limited quantifiable data and, as a consequence, the skill acquisition and assessment was reliant on the philosophy of 'See one, Do one, Teach one'.

Computer-Integrated Surgery (CIS) systems are a quintessential part of modern surgical workflow owing to developments in miniaturization, sensors and computation. The tremendous proliferation of such devices ensues from their enhanced benefits: (i) reduced recovery time for patients; (ii) augmentation of sensorimotor and cognitive capabilities of operating surgeon; and (iii) potential cost-savings for healthcare-systems. However, these devices constitute additional 'intervening' layers between the operating surgeon and the patient resulting in loss of physical feedback pathways and potentially compromising the performance. Very similar research and development issues arose during the emergence of teleoperator- and haptic-systems [1] leading up to the development of insightful R&D roadmaps. There is significant value in building upon these roadmaps to characterize the extent of the attenuation and to study the role of design and control in enhancing overall system-level performance.

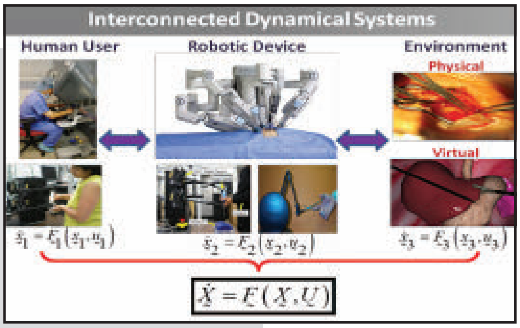

FIGURE 1 Interrelationships between structural sources and empirical spatiotemporal measurements.

It must be noted that the overall surgical task performance is dependent on bi-directional interaction between the neuromuscular system and its dynamic environment (human-machine interface + task dynamics) as shown in **Figure 1**. Given the vast spatio-temporal data from CIS systems, there is tremendous interest in generating atomic level indicators of skill acquisition. Researchers have pursued both 'constituent-element-based compositional modeling' as well as 'data-driven system-dynamics identification' perspectives, both of which we will discuss later.

The rest of the article is organized as follows. We begin with a basic historical perspective on surgical skill assessment both from clinical and research points of view. The *Skill Metrics* section outlines the important properties of a skill metric which in independent of the type of surgery, device, interface and surgical environments. As newer robotic devices are being introduced in Operating Room (OR), more surgical tasks are being automated; the interface between patient and surgeon is continuously evolving. Hence, an abstract treatment of skill is essential to develop quantitative metrics which can be applied to a variety of surgical tasks, devices and environment. The *Quantititative Performance Assessment* section describes recent research that uses a variety of sensor data such as video and kinematics, and their combinations. And last, we outline some of the open research issues with the current skill evaluation techniques.

HISTORICAL PERSPECTIVE

In 1904, Dr. William Halsted created the first residency program in United States, applying the 'See one, Do one, Teach one'[2] paradigm in which novitiate clinicians learn to perform procedures by observing experienced surgeons. The challenges to creation of successful surgical training regimen arise both from the complexity of cognitive- and sensorimotor skill-sets to be trained as well as the mission critical setting (literally life-and-death). Medical education relied on subjective or at best semi-quantitative metrics like Likert-scale proctored by experts, in order to assess the graduation requirements or skill of a surgeon. In select disciplines, such as general surgery and obstetrics, an Objective Structured Assessment of Technical Skills (OSATS) has been developed as an assessment tool – surgical task performance is rated by anonymous experts using task-specific checklists and a global-rating scale of performance with demonstrated inter-rater reliability and validity.

The requirement of an experienced surgeon during training and evaluation (in this apprenticeship- based model) places enormous constraints on the number of operation/trials by a trainee. Over the years, training of skills such as suturing, that are common across multiple procedures, has slowly led to transitioning from an apprenticeship-based to criterion-based models. Over the past decade, the ACGME (Accreditation Council for Graduate Medical Education) has espoused development of a cost-efficient proficiency-based advancement to bypass the limitations in the current apprenticeship-based system. Numerous objective methods for assessing technical skills are being considered for use in many surgical training programs today. OSATS as well as Objective Structured Clinical Examination (OSCE) emphasize the quantitative assessment processes without relying on expert evaluators using appropriate hardware (measurement device) such as Imperial College Surgical Assessment Device (ICSAD) and Advanced Dundee Endoscopic Psychomotor Trainer (ADEPT). But in the vast majority of other sub-specialties, such as pediatric nephrology, ACGME merely requires logging of performed procedures.

The next phase of research in surgical skill evaluation was enabled by the use of simulation methodologies and quantitative skills-assessment tools using the data collected during simulation. Such surgical simulators are relatively cheaper for hospital to operate and maintain and enabled novice surgeons to practice and sharpen specific skills. Computer-assisted surgical simulators (virtual-, physical- or augmented-reality) provide significant opportunities to sharpen the skills via developing different what-if scenarios and repeated/systematic training. Such systems exploit the quantitative recording and user-feedback capabilities of computer-based instrumentation (video and sensors). These simulators give various aggregate measures such as time to completion, path length etc. to rate surgical skill. An imperfect and incomplete understanding of the underlying relationships, coupled with insufficient computational support has led to an assessment regimen focused on easy-to-measure, quantitative but simplistic spatially- and temporally-aggregated measures. However, the use of such aggregated metrics (without repeatability, stability and potentially validity) to steer entire training regimen may lead to undesirable and unforeseen consequences.

The growth of computer integration in minimally-invasive-surgery (MIS) especially in the form of Robotic minimally invasive surgery (rMIS) now offers a unique set of opportunities to comprehensively address this situation. Arguably, the growth in MIS (and especially rMIS) has allowed a sheltering of the erstwhile fundamental challenge of "Nothing can come between a surgeon and his/her scalpel". A range of physical variables can now be transparently monitored via instrumented tool-usage in both simulated and real-life scenarios.

While the collection of quantitative raw physical measurements is growing (in this era of Big Data), the oversimplification inherent in using aggregated measures often results in loss of desirable user-specific discriminative characteristics. Key challenges to assessment and accreditation of surgeons in such a scenario include (1) creating appropriate clinically relevant scenarios and settings and (2) developing uniform, repeatable, stable, verifiable performance metrics; at manageable financial levels for ever increasing cohorts of trainees.

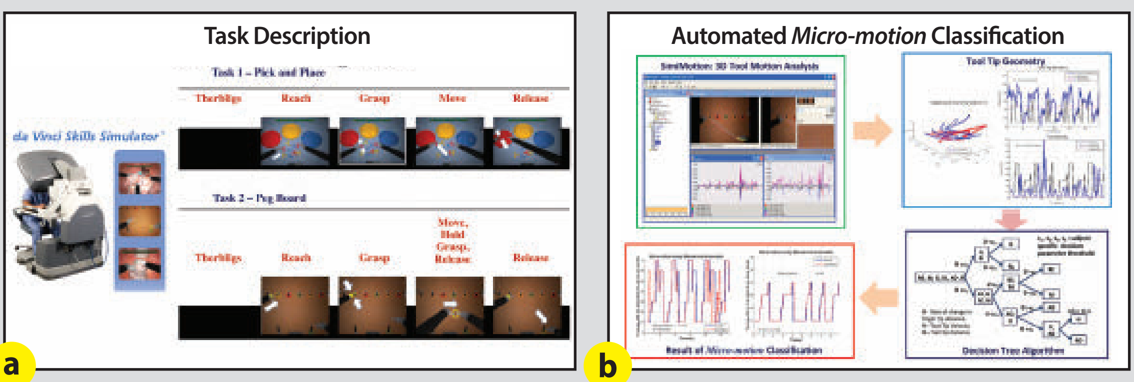

FIGURE 3 (a) Stereo-vision feeds acquired from daVinci Skills simulator; (b) The 3-stage process of extraction of the continuous motion trajectories from stereo; projection via a decision-tree; to facilitate easy comparison of ensuing Finite-State-Machine (FSM) signatures.

SKILL METRICS: DESIRED FEATURES AND CHALLENGES

Skill acquisition is fundamental to human experience enabling us to learn from the experience of people who have already mastered a task. Our education curriculum inherently involves various forms of testing skill acquisition in order to locate and correct various skill specific deficiencies. Entire traditions such as playing instruments, singing rely on the pedagogical approach of having an expert with "trained-ear" to find mistakes. Specific to surgical training, a variety of cognitive and sensorimotor skills must be learned in order to perform a variety of surgical interventions.

Critical impediments to unified skill representation and estimation arise due to the variety of: (i) surgical procedures, (ii) surgical devices; and (iii) anatomical complexity. **Figure 2** depicts the evolution of surgery: from open-to minimally-invasive (MIS) and further to robotic minimally-invasive-surgery (rMIS) which has redefined the surgeon-patient relationship in terms of available sensory feedback.

Given this dynamic relationship, it becomes imperative to consider abstracted/generalized treatment of skill assessment. Over the ages, several guidelines on the design of skill metrics have emerged (with clear implications to surgical education and accreditation)

- **Repeatability and stability (under controlled environments):** The skill metric should converge to a predictable set (law of large numbers) under repeated execution of the same task within an environment.
- **Gradated Feedback Mechanism:** Fundamentally skill evaluation needs to pinpoint the areas of improvement. Hence, in addition to a binary answer (Yes/No), the metrics need to provide a gradated scale. This enables the skill metric to be useful not just an accreditation mechanism but also improve specific skill deficiencies of trainees.
- **Real-time:** Feedback to a trainee/intermediary needs to be provided in (as close to) real-time conditions to enable course corrections.
- **Surgical Outcomes:** The skill levels either binary, discrete or continuous afford a comparison between the skill levels. However, another key characteristic is the need for correlation of skill-levels to actual surgical outcomes.

The aforementioned properties of skill metrics are quite broad, eventually there are some tasks that must be designed to evaluate the skill indicators of a trainee. As food for thought, we note that often analogies are made to liken surgical-task performance to another complex learned cognitive and sensorimotor behavior: automotive-driving.

As in surgery, driving capability can be assessed at a variety of spatial/temporal/hierarchical scales. For example: are we trying to assess a driver's ability to stay in middle of road (local short space-time scale task)? (ii) Or is the ability to get from City A to B under all types of road, traffic and weather (global spatial- and temporal-scale task)? Or are we trying to assess the ability to reject distraction e.g. cell-phones (cognitive vs spatiotemporal) during task performance? Despite these multi-scale issues, various road-transportation authorities have instituted a driving-test to assess performance. Often the test involves 'controlled performance of experiments' e.g. parallel parking test, three-point-turn test, which are scored by a driving examiner. While the manual assessment process is slowly making room for computerized diagnostic- and assessment-programs, this process is by no means complete. However, it may provide a useful roadmap of challenges and considerations for research and development of computer-aided/computer-enhanced surgical assessment.

QUANTITITATIVE PERFORMANCE ASSESSMENT

Many of the quantitative skill metrics currently available use acquired physical-measurement data from real surgeries as well as simulators. We will further elaborate on the type of data used to generate these metrics.

Aggregated Metrics

Contemporary surgical simulators use spatially- and temporally-aggregated measures such as MScore used in Intuitive Surgical's Skills Simulator . The MScore provides a binary (Yes/No) qualification answer and a continuous score to evaluate a trainee on various elementary tasks such as camera targeting, peg board manipulation tasks. Mscore and other similar scores integrate a variety of acquired sensory-data such as tool-drop, master-manipulator range, instrument collisions etc. Yet the MScore's ability – as a normalized weighted combination of multiple physical measurements (time-to-task-completion (TTC)), distance traveled) – to adequately capture subtle task-performance variations to form the discriminative basis between individuals and/or classes remains unclear. Other limitations including uncharacterized reliability, stability and repeatability of the employed metrics, hinder progress towards the final stages of validity.

Micro-Motion Studies

Robotic Minimally Invasive Surgery, and the engendered computer-integration, offers unique opportunities for quantitative computer-based surgical-performance evaluation. In our work[4], we examine an alternate method of manipulative skill evaluation using micro-motion studies, having deep roots in performance evaluation in manufacturing industries . The well-established micro-motion studies' methodology, originated in twentieth century, emphasizes on: (1) a top-down segmentation of a primary task into basic motion elements ('Therbligs'); (2) recording of elements and key subtask performance in process-charts; and (3) obtaining metrics of performance for skill evaluation. Any of the performance metrics of macro-motions—from motion economy, tool motion measurements to handed-symmetry—can now be extended over the micro-motion temporal segments.

Apart from considering representative manipulation exercises from da Vinci surgical (SKILLS) simulator, real surgical videos were also analyzed with a list of predefined 'Therbligs' in order to validate the clinical relevance of this method. This affords relatively controlled and standardized test-scenarios for surgeons with varied experience-levels. The resulting performance metrics over each sub-procedure enabled intra- and inter-user comparative studies.

Language Of Surgery

Colleagues in the Computational Interaction and Robotics Lab (CIRL) [3,5] have studied skill assessment[6] and gesture detection in both training and live patient surgical motions focusing on minimally invasive surgeries (such as robotic hysterectomy, functional endoscopic sinus surgeries (FESS), and septoplasty). Their idea is based on the fact that humans performing dexterous tasks follow a sequence of identifiable recurring motions (motifs) with some variability. To extract the surgical motifs, they designed a new technique that first translates the raw motion data into a domain that highlights the similarities and suppresses many factors of variability and then build a dictionary of important motifs (weighted statically based on their appearance in a particular surgery). The transformation function can be applied to streaming data, does not require manual processing, and is invariant to rigid transformation, cropping, and sampling frequency.

They also designed a similarity function that can measure the similarity between two motion trajectories by comparing them against a dictionary of motifs. They report accuracies about 80 to 90% for different surgical tasks. Besides learning surgical skill by demonstration of expert trajectories, they built a robotic planning system to generate an optimal expert trajectory based on a cost function and anatomical constraints for FESS. They showed that the optimal trajectory is more similar to the ones demonstrated by experts than novices, an indication that experts are probably optimizing their motions against the constraints of the environment.

Video Based Semantic Understanding

The skill evaluation metrics as discussed in the previous sub-sections need a variety of sensory data that limits the application to very specific robotic devices. The lure of using monocular/stereo data for assessment and training is due to the wide-spread availability and quintessential requirement of such modality for tele-operation. Such systems fundamentally rely solely on the surgeon-in-the-loop to ensure safe operation amidst a host of real-world uncertainties and complexities, e.g. the finite life and slack in the cables of the passive-robotic surgical instruments lead to tool-positioning inaccuracies, requiring surgeons to compensate for this error.

However, rich information content in video stream can also be used to automatedly assess surgeries. Specifically, in Kumar et.al [7] they leverage real-time video-based understanding for improved situational awareness and context-based decision support in robotic surgeries. Efforts at video understanding of real and virtual surgeries is pursued with a 2-fold objective: (i) Better understanding of skill of operator and (ii) Have a cascaded framework which can be useful from multiple perspectives – surgical guidance, safety, tracking and skill assessment. Though this preliminary study is restrictive (considers only two tools and two attributes), it can be easily extended to multiple tools and attributes.

OPEN CHALLENGES

Ultimately any automated skill assessment algorithm needs to rate and classify surgeon for which the algorithms need ground truth data. Jun et. al [4] classified surgeons into 3 different categories of expert, novices and intermediate which were pre-classified based on their experience. However this approach did not give any continuous scores. Ahmidi et al [6] used scores generated from human experts such as OSATS which were then classified as expert, novices or intermediates based on the resulting score. However both these works did not provide any sort of continuous/discrete measure of skill.

To our knowledge, published validity studies to benchmark against clinician-skill levels do not exist – although many ipso-facto studies are underway. Nonetheless, many surgical residency programs/hospital administrations are proposing to use such measures on training simulators to help pre-qualify trainees prior to actual wet-lab usage. As the Intuitive Surgical White-Paper notes "universally-accepted and validated" metrics are key to deployment of a staged and calibrated robotic-surgery training curriculum.

The field is replete with numerous open-problems that remain to be tackled. A series of workshops [ICRA2013 https://sites.google.com/site/ieeerassurgrobstandards/], [IROS2014 https://sites.google.com/site/ieeerasmedicalrobotics/] organized by the authors have sought to highlight the critical gaps in both fundamental research and technology development efforts especially as pertains to benchmarking performance of human users; training and accreditation; safety and risk-assessment. A few of them are listed below in no particular order:

- Benchmarked data with standardized metrics for better algorithm development: Surgical robotics hardware is prohibitively expensive to acquire, operate and maintain. To enable better algorithm development, the community needs to ensure open-source standardized information acquisition across various devices.
- Relating metrics to surgical outcomes and using these metrics for certification: Human anatomy shows wide variations and any skill metric should be related to surgical outcomes. The consensus in the community suggests "universally-accepted and validated" metrics are key to deployment of a staged and calibrated robotic-surgery training curriculum.
- Specific feedback such as "Your motion is not efficient while suturing" instead of "Sorry, you need to practice that motion again": Thin slices skill assessment is necessary to have person and operation specific skill assessment and feedback. This would allow one to focus on a particular area of concern such as manipulation, coordination etc.
- Presenting feedback to surgeon to improve safety based on skill: Can we provide real-time guidelines during occlusions or instructions to help doctor get his tools in view?

DISCUSSION

Success in understanding manifestation of human skill within the context of surgical tele-operated systems will have implications for a much broader arena of sensorimotor skill assessment and training, in particular ones assisted by robotic systems. Improved understanding of human manipulatory skills would be critical to designing a broad range of interactive robotic-manipulation systems, from telesurgical systems to various teleoperated vehicles and more generally to human user control of complex machinery.

From a broader scientific perspective, it will give us insights into organization of neuro-musculoskeletal interactions within the brain, including applications involving improvements of sensorimotor performance. The ability to couple quantitative, validated and stable metrics for surgical performance would lead to improvements in assessment and subsequently, training methods. Cognitive assessment can now be extended to also include sensorimotor assessment, with capacity to monitor and track skill across time. They would help usher in the next generation of virtual procedural simulators with significant impact on patient safety by providing a ready means to learn, maintain and improve surgical procedural skills. Specifically for the teleoperated surgical systems, skill understanding will also provide a quantitative method for surgical education assessment. ■

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ENABLING CLOSED-LOOP SURGERY IN MRI

In the field of automation and control, we often interact with rigid, known objects in a well-defined environment. This is especially true in most manufacturing settings where a continuous stream of consistent products passes down an assembly line with fixtures to hold them in a given pose or vision systems to identify part location. This scenario lends itself well to robotics and automation for reliably performing the required task. However, now think about your body... For starters, everyone is different, so the location and shapes of organs and other structures vary from person to person. Now add on top of that the fact that most internal structures are very compliant. Further, these soft structures do not maintain a consistent shape and can deform due to a patient's orientation, interactions with surgical instruments, or swelling causing a change in volume of an organ as it is being operated on. For example in a surgery where the goal is to remove a cancerous tumor, success of the procedure hinges on how precisely a surgeon identifies the tumor boundaries and ensures removal in its entirety while preventing unnecessary collateral damage. To ensure successful removal of cancerous tissue, often excess tissue is removed (aka increased resection margins) which may improve the odds of eliminating the cancer, but possibly at the additional cost of further complications and invasiveness of the procedure. Ideally one would like to track the structures in real-time and use this information to guide the procedure – this is what we refer to as Image-Guided Surgery (IGS). Further improving on this, we can incorporate electro-mechanical assistant devices to ensure that the surgical plan is performed as intended through Robot-Assisted Surgery (RAS).

IMAGE-GUIDED SURGICAL INTERVENTIONS

The fields of IGS and RAS in their present form have existed for approximately three decades, but the concept of stereotaxis in surgical guidance dates back over a century, with the Horsely-Clark stereotactic mechanical alignment frame to align needles for neurological interventions in 1908. The field of IGS has grown significantly in recent years, with such systems becoming more widely accepted by medical professionals because they enable more information available at the surgical site while performing a procedure. A typical procedure requires a clinician to review preoperative medical images, formulate a plan, mentally register the plan to the patient, and then perform the intervention - often without any imaging updates. Typical IGS systems integrate: imaging, spatial tracking, registration, and visualization. However, often the 3D patient information is a previously acquired preoperative CT or MRI registered to the patient during the procedure and the information used to guide the procedure is essentially “stale” by the time it is being used. There is a tremendous need for integrating interactive, real-time, intra-operative imaging into the surgical navigation environment.

Although direct visualization or endoscopic cameras let us see inside the body, they only provide surface information and not inside of structures. Therefore, various medical imaging modalities and methods of presenting information in a timely manner, in an appropriate location, and assisting with interventions have been active areas of research. X-ray fluoroscopy provides inexpensive, convenient imaging but is typically limited to imaging bony structures or vasculature with the introduction of a contrast agent. Computed Tomography (CT) uses x-rays to generate high-resolution, cross-sectional images of the body. However, both of these approaches have poor soft tissue contrast and subject the patient and physician to ionizing radiation if used intraopereatively. Ultrasound is a very convenient and portable imaging system readily available in an operating room (OR), however it often has poor image quality and suffers from artifacts such as shadowing of tissue beyond a rigid structure or a needle that is being inserted under image guidance, for example.

Magnetic resonance imaging (MRI) is an excellent medical imaging modality for detecting and characterizing diseases due to its outstanding soft tissue contrast that allows for accurate delineation of pathologic and surrounding normal structures. Thus, MRI has an unmatched potential for guiding, monitoring and controlling therapy. In needle biopsies, the high sensitivity of MRI in detecting lesions allows excellent visualization of the pathology, and the high tissue contrast helps to avoid critical structures in the puncture route. Advances in magnet design and magnetic resonance (MR) system technology coupled with fast pulse sequences have contributed to the increasing interest in interventional MRI (iMRI).

INCORPORATING ROBOTIC ASSISTANTS

Computer Integrated Surgery (CIS) requires integration of information and action. The IGS systems provide information to the surgeon in a timely manner as the procedure is being performed. The next level of integration is to couple robotic action with that information to physically assist with the procedure. The field of medical robotics was born in the late 1980's and has seen tremendous growth over the years [Taylor 2003]. Often these systems fall into one of two categories, of which there is some cross-over: tele-operated minimally invasive surgical instruments and image-guided semi-autonomous robotic systems. The former acts much like a remote-controlled robotic manipulator, while the latter uses medical images to guide an intervention – often a needle-based percutaneous procedure.

CLOSING THE LOOP WITH MRI

Magnetic resonance imaging is an ideal interventional guidance modality: it can provide real-time high-resolution 3D images or 2D images at arbitrary orientations, and is able to monitor therapeutic agents, surgical tools, tissue biomechanical properties, and physiological function. With continuously improving MRI image quality and acquisition speed, it is now possible to perform interventions under real-time MR image guidance. However, MR brings unique challenges to the implementation of interventional guidance systems, and the benefits can not be readily harnessed for interventional procedures due to difficulties associated with the use of high-field (>=1.5T) MRI and conventional mechatronics approaches.

WHY IS IT SO HARD?

The ability to create and deploy a device capable of operating within the scanner bore is still frustrated by the high strength magnetic fields, and extreme sensitivity to electromagnetic interference (EMI). MRI poses formidable engineering challenges with limited access to the patient and a strong magnetic field that prevents the use of many conventional materials and electronics as shown in **Figure 1**. For example, the primary actuator in just about all traditional robotic systems is the DC motor – by its design such a device is just about the worst possible type of device to use in an MRI scanner. An MRI machine contains a strong magnetic field aligned with the scanner's axis (a typical 3 Tesla scanner is about 500 times the earth's magnetic field strength) and time-varying magnetic gradients used for localization. A motor typically comprises a steel can (ferromagnetic posing a projectile risk as well as inducing imaging distortion), permanent magnets (distorting the magnetic field as well as a safety risk), and coils of wires (which can induce eddy current that distort imaging as well as induce heating). Further, an MRI scanner incorporates a highly sensitive antenna that is used to pick up the resonant radio frequency signals of the excited Hydrogen atoms in the body – any electronics in the vicinity of the scanner that emit electrical noise may be picked up by the scanner's receiver and significantly degrade the quality of the images obtained.

With all of the benefits of MRI-guided interventions, there is a clear advantage to using MRI. But, due to these challenges the use of robotic assistants in a scalable, clinically viable fashion has really just started to take off. There are a number of technical aspects and concerns to consider when putting an interventional magnet into operation. The most pertinent ones are: configuration and field strength of the magnet (which necessitates a compromise between access to the patient and signal-to-noise), safety and compatibility of the devices and instruments that will be used in or near the magnetic field, spatial accuracy of imaging for localization and targeting, optimal use of the imaging hardware and software (the dynamic range of gradients, limitation and availability of pulse sequences, radiofrequency coils) and level of integration with guidance methods for accomplishing the procedure.

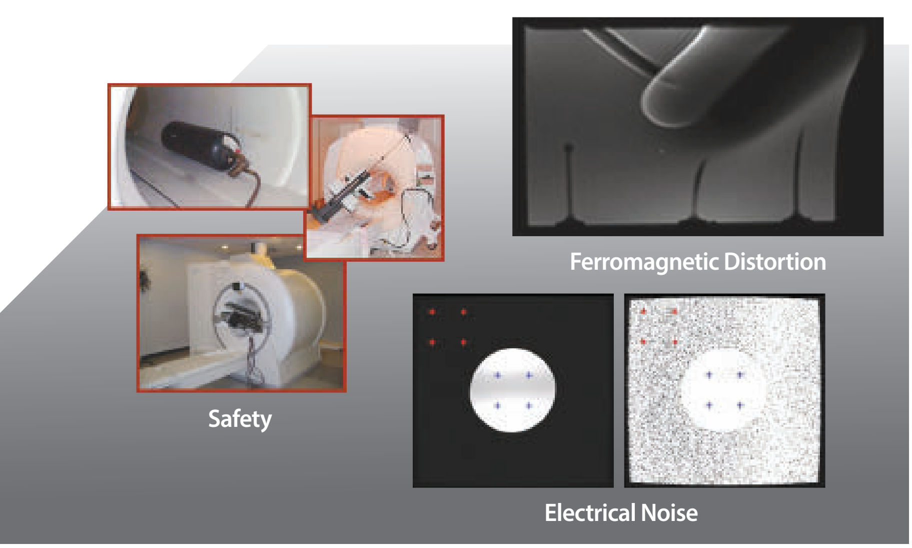


FIGURE 1 Examples of some of the difficulties encountered with robotics introduced into the MRI environment including safety issue due to projectiles, distortion of the magnetic fields, and introducing electrical noise that degrades image quality.

MRI-COMPATIBLE SURGICAL ROBOTS

Robotic assistance has been investigated for guiding instrument placement in MRI, beginning with neurosurgery and later percutaneous interventions with some examples shown in **Figure 2**. One of the first MRI-compatible robotic devices dates back to 1995 by Masamune et al. for stereotactic neurosurgery [Masamune 1995]. DiMaio et al. reported on the use of a robot suspended from a specialized open interventional MRI scanner for MR-guided prostate interventions [DiMaio 2007]. Krieger et al. developed a remotely actuated manipulator for access to prostate tissue under MR guidance in a closed bore diagnostic scanner [Krieger 2005]. Innomotion developed and commercialized a pneumatic robot aimed at performing percutaneous interventions inside the bore of a high field scanner [Melzer 2008]. Fischer et al. also attempted to develop a pneumatically actuated robotic assistant aimed at prostate biopsy and brachytherapy inside the bore of the scanner, with the goal of minimizing interference with the scanner [Fischer 2008]. Attempts at improving the accuracy of served pneumatic devices were attempted in [Wang 2010] and [Yang 2011]. Stoianovici et al. further attempted to improve upon the accuracy problems of pneumatic actuation by developing a robotic assistant for MR image-guided percutaneous prostate interventions based upon novel pneumatic stepping motors [Stoianovici 2007]. Although most systems to date are focused on image-guided percutaneous interventions within the bore of the scanner, Sutherland et al. have developed a dexterous robot for performing neurosurgery beside the bore of the scanner [Sutherland 2008].

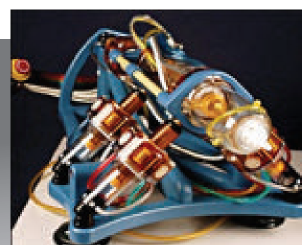
ENABLING TECHNOLOGIES FOR MRI-GUIDED INTERVENTIONAL SYSTEMS

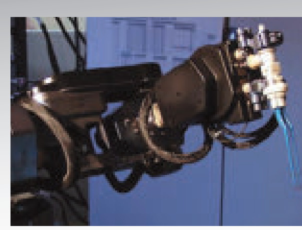
In order for a system to compatible with the MRI environment, it should: be safe in the MRI environment, preserve the image quality, and be able to operate unaffected by the scanner's electric and magnetic fields. The latest 2013 American Society for Testing and Materials (ASTM) made a detailed classification for the MRI-compatibility of devices environment [ASTM 2013]. The generally accepted classifications are: *MRI-Safe*: An item that poses no known hazards resulting from exposure to any MRI environment; *MRI-Conditional*: An item with demonstrated safety in the MRI environment within defined conditions; and *MRI-Unsafe*: An item which poses unacceptable risks to the patient, medical staff, or other persons within the MRI environment. Ferromagnetic materials must be avoided entirely because they cause image artifacts and distortion due to field inhomogeneities, and they pose a dangerous projectile risk. Non-ferromagnetic metals such as aluminum, brass, titanium, high-strength plastic, and composite materials are typically permissible with appropriate design considerations. However, the use of any conductive materials in the vicinity of the scanner's isocenter must be limited because of the potential for induced eddy currents to locally deform the magnetic field homogeneity. Electrical systems must be properly shielded and filtered, designed to limit noise emission. Care must also be taken to avoid resonance and heating.

Actuation Technologies: As previously noted, traditional DC motors are contraindicated for use in MRI. Although in some circumstances they may be able to be shielded and kept a distance away from the scanner, they are non-ideal and not able to be used within the confines of an MRI scanner's bore. Therefore, the most common approaches taken to actuating a robot designed to be compatible with the MRI environment are: pneumatics (either servo-controlled or more recently with air powered stepper motors), hydraulics (often using water or saline), cable-driven (with remote actuation units), and ceramic piezoelectric actuators (resonant ultrasonic motors and non-resonant low frequency variants). However, it should be kept in mind that often even with these inherently compatible technologies, often commercially available solutions are not practical. For example, most pneumatic cylinders still use steel enclosures, most fittings contain ferrous components, and drive or control electronics often are not configured to minimize the induced electrical noise. Some recent innovations or advancements in the field include pneumatic stepping motors, high precision servo control of pneumatic cylinders, cable-driven actuators, and piezoelectric actuation.

Sensing Technologies: Closed loop control requires multiple levels of feedback. At the joint level, we need a way to detect the position of each linear or rotary joint. This is often done using potentiometers or encoder. In MRI, these technologies can be used with special design considerations. As long as potentiometer housing are nonferrous, then the trick lies on effectively filtering the electrical signals. Optical encoders have proven to be successful for position sensing inside the scanner bore during imaging when coupled with differential line drivers (to eliminate false counts and increase signal robustness), filtering appropriate electrical lines, and thoroughly shielding cables to minimize EMI. Fiberoptic sensing has also been investigated, with available devices available now for absolute and incremental position sensing without direct electrical connections.

Haptics and Teleoperation: Although robotics provides a way to operate within the bore of an MRI scanner, a side effect is the loss of tactile feedback for the clinician. This is valuable information in many cases, and thus we strive to return haptic feedback for teleoperated approaches. Haptic feedback requires estimating or measuring the integration forces of the instrument (e.g. a needle in an image-guided biopsy or therapy delivery case), and therefore it is necessary to incorporate force sensing. An example is described by Su et al., that describes a robotic device for teleoperated needle insertion,





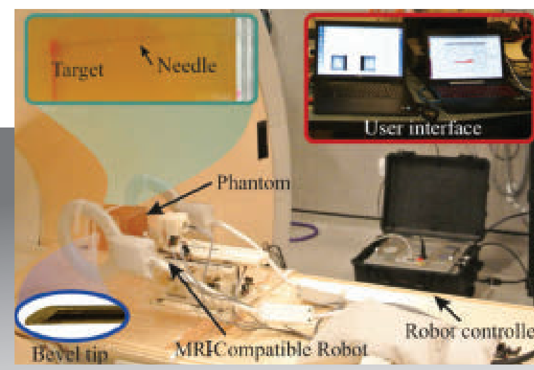


FIGURE 2 Samples of various MRI-compatible robotic approaches: Clockwise from left: A dexterous neurosurgical robot [Sutherland 2008], A percutaneous needle insertion robot [Stoianovici 2007],and an autonomous image-guided needle steering system [Patel 2015].

where the slave robot detects needle insertion forces and the teleoperation master reflects those forces back to the user [Su 2013]. Similar to potentiometers, traditional strain gauge based load cells may be able to be used if filtered, shielded, and of non-ferrous construction. However, fiberoptic sensors enable high accuracy sensing without imposing such constraints. There are a multitude of approaches that have been investigated for one degree of freedom (DOF) and multi-DOF force/torque sensing. Intensity based approaches measure differences in light intensity returning off a reflective object in the sensor; the problem with many of these approaches is the lack of robustness to various environmental factors (such as flexing of the fiber cables or ambient light). An alternative approach is essentially a fiber optic strain gauge. One technique, known as Fabry-Perot Interferometry (FPI), is based on measuring a change in interference patterns of light passing through a small cavity at the end of an optical fiber. Another technique is the Fiber Bragg Grating (FBG) approach which results in a wavelength shift of light based on the amount of strain in the fiber. Each approach has its strengths and weaknesses with regard to complexity, cost, size, and accuracy.

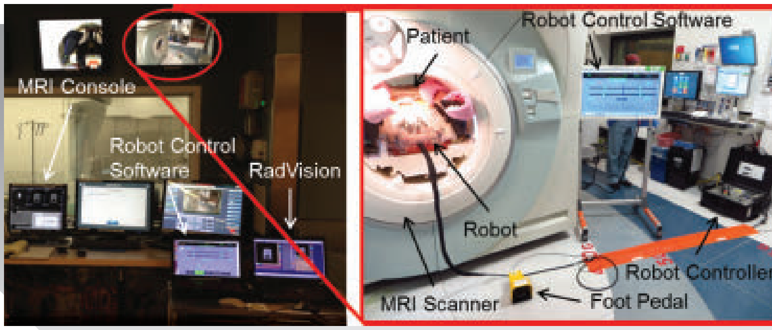


FIGURE 3 An example of a clinical configuration for MR image-guided prostate cancer biopsy using the robot described in [Eslami 2015].

Localization and registration: Not only does the robot need to have proprioceptive feedback, but typically it is required to also have external localization of the robot. Often fiducials are placed on the robot and used to determine the 6-DOF pose of the robot with respect to the MR imaging system, thus enabling targeting of features identified in the MRI images and calculating the corresponding inverse kinematics to move the robot. Various localization approaches have been implemented, including identifying discrete points on the robot as well as localization based on cross-sectional images of various unique patterns. These fiducials are often passive tubes or spheres filled with MR contrast agent, but improvements in imaging may be made with passive self-resonant tracking coils or active tracking coils that directly interface with the MRI scanner. These tracking coils may be integrated into the robot base, its end effector, or in some cases a needle, cannula, or catheter itself.

System Architecture: Various teams have taken different approaches to integrating these technologies into their robotic devices and the corresponding control systems. Often the system design was based upon the requirements of the surgical procedure being addressed. For example, many systems use sensing and actuation technologies that are safe for use in MRI, but are not overly concerned with EMI because the system is designed to iterate between sessions of MR imaging and robotic manipulation rather than manipulation during live imaging. Another design consideration is whether to place the control system (such as the valve controller or motor driver units) inside the scanner room or in the adjacent console room.

Putting a controller outside the MRI scanner's room eases some design considerations, but comes with complicating issues. For pneumatics, this requires long air hoses which significantly reduces bandwidth and control performance. For electrical control of piezoelectric motors, this requires running wires into the scanner room which can act as antennas (bringing in unwanted EMI), or require custom patch panels to route signal in and out of the scanner room (which is practical for a permanently installed system, but less so for a portable compact robotic assistant). The use of well-shielded, low-noise control systems that reside in the MRI scanner room and communicate to an external control system via fiber optics allows for ultra-portable devices that require no modifications or special requirements of the MRI suite.

CLINICAL SYSTEMS

MRI is a highly effective soft tissue imaging system, and the ability to utilize this procedure in-vivo coupled with precision computer controlled motion will prove to be an invaluable asset in the future development of minimally invasive surgery. With all of these challenges, there have been some amazing advances of late. Several systems have successfully performed clinical trials such as those described in [Krieger 2005], [DiMaio 2007], [Stoianovici 2007], [Sutherland 2008], and [Eslami 2015]. One such example of an ongoing clinical trial for MR image-guided prostate biopsy is shown in **Figure 3**. New systems on the horizon promise for further integration of real-time imaging with semi-autonomous robotic control of curved needle paths as instruments are delivered to targets in the body such as those described in [Su 2013] and [Patel 2015]. ■

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AUTONOMOUS OPERATION IN SURGICAL ROBOTICS

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When a surgical robotic system is introduced to the surgical scene two human-machine interfaces are established and define its primary operation: (1) the surgeon-robot interface (S-R) and (2) the patient-robot interface (R-P). Each has a unique set of requirements that dictates its design capabilities and functions. **Figure 1** maps several commercial systems, research systems and systems during commercialization process that were classified based on these interfaces [1].

The S-R interface is defined by a wide spectrum of control levels provided to the surgeon over the surgical robotic system. Assuming that a certain level of control is required to complete a task, it can be distributed between the human operator and the robotic system at different ratios which in turn defines the level of automation allocated for the task. This level of automation is bounded by two extreme operational modes. The right hand side of the horizontal axis in **Figure 1** describes a mode in which the surgical robotic system is fully autonomous [2-5]. The left hand side of the horizontal axis in **Figure 1** describes a mode of operation in which any movement of the surgical robotic system is in direct response to a real time position/orientation command input provided by the surgeon. The system architecture used to enable this approach is teleoperation, utilizing a master/slave configuration. The master is defined as the surgical console and the slave serves as the surgical robot itself interacting with the patient's tissue through the surgical tools. [6-8].

The robot-patient (R-P) interface determines the level of invasiveness (vertical axis in

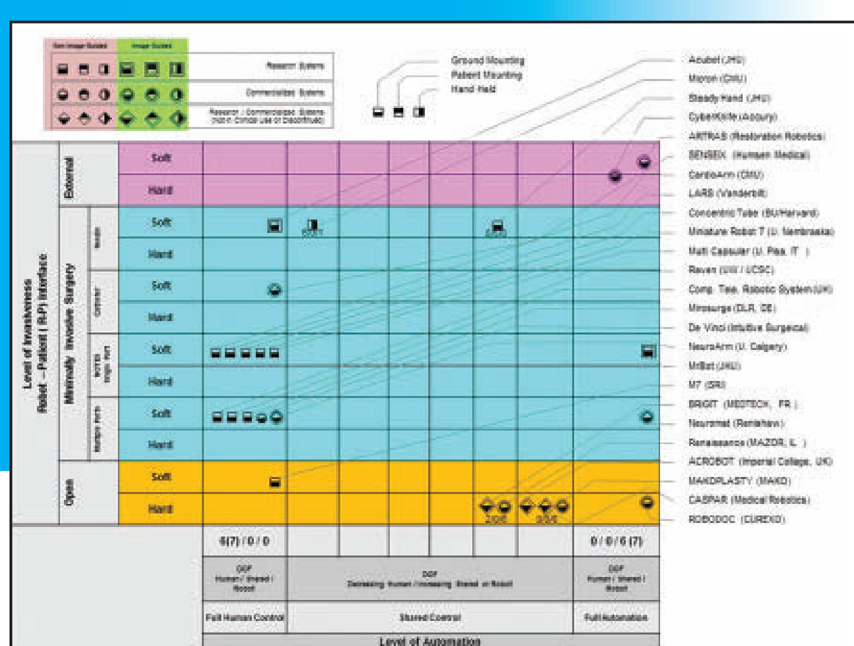
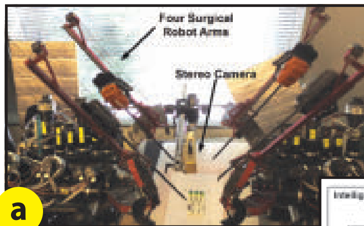


FIGURE 1: Classification of surgical robotic systems based on a Surgeon-Robot (S-R) interface (horizontal axis) defining the level of automation and a Robot-Patient (R-P) interface dictating the level of invasiveness.

Figure 1). The level of invasiveness spectrum spans across a range of surgical approaches including (1) the invasive open-procedure approach, which requires a large incision to expose the targeted anatomy, (2) variations of minimally invasive surgical (MIS) approaches with a gradual reduction of invasiveness, such as multiple tools inserted through ports, natural orifice transluminal endoscopic surgery (NOTES), catheters [9-11] and needles [12,13] and (3) a noninvasive approach in which energy (radiation) is provided by an external source to a localized space to provide a localized therapy [14]. As the level of invasiveness decreases, the level of manipulation also decreases and, as a result, the surgeon has fewer degrees of freedom to mechanically manipulate the tissues. The surgical robotics field as a whole progresses towards the reduction of invasiveness limiting the trauma at the periphery of the surgical site and increase of semi-autonomous operation while positioning the surgeon as a decision maker rather than as an operator.



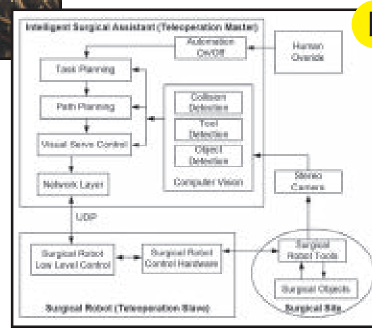


FIGURE 2 System Architecture (a) Raven II surgical robot (b) block diagram of the control system software.

The reported study is focused on developing an algorithm for automation based on stereo computer vision and dynamic registration in a surgical robotic context. The performance of the algorithm was further tested experimentally utilizing the block transfer task which corresponds to tissue manipulation as defined by Fundamentals of Laparoscopic Surgery (FLS) [15]. The surgical task was performed autonomously by a surgical robot (Raven II) and then compared with the performance of a human teleoperating the same surgical robotic system.

METHODS

System Architecture

Raven II (UCLA/UW/Applied Dexterity Inc.) was used as the surgical robotic system for experimentally evaluating the performance of surgical task both in an autonomous mode and in a teleoperation mode [16]. A compact commercial stereo Point Grey Bumblebee2 camera (BB2-03S2C-38) was positioned 0.23m to 0.3m above the surgical site pointing down. This position and orientation allow to encapsulate all the surgical tools into the field of view while eliminating potential collision between the camera and the four surgical robotic arms (**Figure 2a**). The camera has image update rate of 48 FPS at full resolution of 640x480. A custom support for the camera in OpenCV was developed enabling the use of OpenCV as the primary tool for real time image processing. The stereo vision was used for surgical tool detection, surgical tool visual servoing and surgical environment perception.

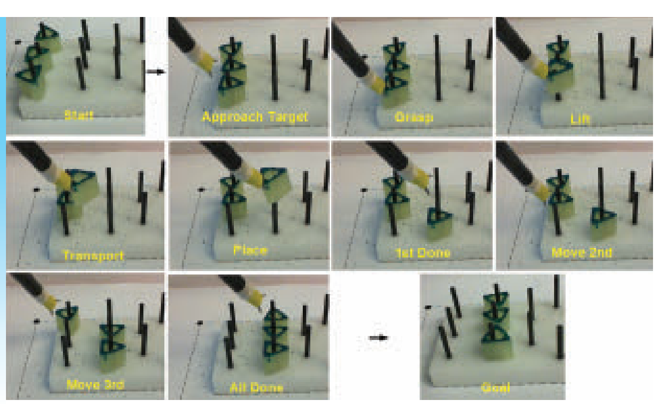


FIGURE 3 FLS peg task of using one tool to transfer three objects.

Given the master/slave architecture of the system a block diagram of the software architecture (**Figure 2b**) depicts the corresponding two components. The slave components software consists of the robot low-level real time servo control software, in a teleoperation mode the surgeon generates the position and orientation command signals using the master. In particular the reference command information sent from master to slave consists of the incremental Cartesian positions, the absolute orientation transformation matrix, and the absolute tool joint angles. However in an autonomous mode the operator is replaced with an intelligent agent generating autonomously the same inputs to the surgical robotic system. The autonomous intelligent software component substituting the operator includes the following modules: (1) computer vision module, (2) task and path planning module, (3) visual servo module, (4) network module and human interface module. A UDP layer is used for the data communication between the two software components. Both manual and automatic switching are included in the software between the teleoperation mode and the autonomous mode.

Task Definition and Decomposition

The FLS are a set of tasks that are used widely and primarily as part of a curriculum for surgeon training in MIS and performance assessment tools. In addition the FLS tasks provide a standard platform for comparing performance of manual operation as well as various teleoperated surgical robot systems. The FLS block transfer is a task that simulates tissue manipulation. It may be also defined as a "pick and place" task in which a set of blocks mounted on pegs are picked with one MIS surgical tool, transferred to the other tools and placed on a new set of pegs one at a time.

The FLS task was further decomposed into subtasks and potential failure modes were identified. The FLS block transfer subtasks are (**Figure 3**): (1) Starting configuration - Three triangle objects are placed in three left pins; (2) Move tool from the initial position to the location of the block; (3) Pick a block from the left pin and place it in the right pin, and then repeat until all three left blocks are transferred to three right pins (4) Move tool back to the initial position. The failure modes are (1) Grasping Failure: failing to grasp the block or dropping the block during the grasping process (2) Transport Failure: dropping the block during the transportation between the pegs (3) Place Failure: Failing to place the block on the peg (4) Collision Failure: Collision or an application of a large force by the tool on the peg board that causes it to move.

Computer Vision

Surgical Tool Detection

A high precision but low rate computer vision based method was developed to detect the position / orientation of the surgical tools in the camera frame and enhance the high rate but lower precision forward kinematics approach which is compromised due to the compliance of the cables incorporated into the mechanical system as well as the limited information regarding the exact position and orientations of the robotic arms' bases.

Markers detected by the computer vision were placed on several locations on the shaft of the tools away from the tip in a known location that is not occluded by the potential tool tip tissue interaction. Forward kinemics which is limited to the last two DOF was then used to estimate the tool tip position and orientation. **Figure 4** depicts the Point A and B that were detected in 3D by the computer vision system which led to the

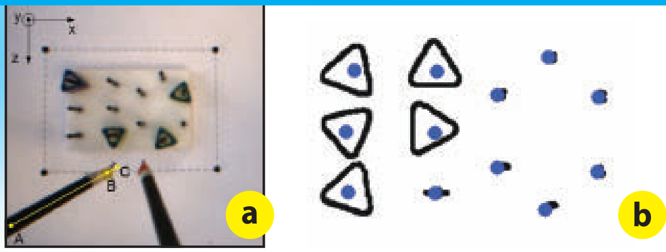


FIGURE 4 Computer Vision Tool and object detection: (a) Locations of markers (Points A, B) on the surgical tool as acquired by the stereo camera for predicting the location of the tool tip (Point C); (b) Top view computer vision detection of the set of pegs tips (dots) and the triangular shaped block.

estimation of point C marking the tool tip.

Object Detection

Each triangular block is placed on a peg with a random rotation angle and with a non-coincided axis with respect to the peg. A dynamic real time algorithm was developed to detect the location and orientations of the blocks and the pegs–necessary information for the path planning. A dynamics real time algorithm is required to deal with potential changes in the environment. In the current experimental setup the environment may change due to collision between the tool and the blocks or the peg board. However in a clinical setting the surgical site is constantly subject to change due to tissue manipulations, dissections, and suturing.

Tool-Environment Collision Detection

Given the lack of force sensor incorporated into the tools substantial tool/environment collision can be detected by a significant translation or deformation of the environment or the tools. In the context of the experimental setup substantial collision is defined by a movement of the pegboard. Such a collision triggered the dynamic registration and facilitated uninterrupted completion of the task autonomously. Furthermore, collision that led to pegboard displacement was also used to quantify as an error for performance evaluation. In a clinical setting fiducial markers or key anatomical structures pointed by laser dots may be used for detecting a significant change on the operational field.

Automation Algorithms

Visual Servo Control of the Surgical Robot

A hybrid Cartesian based visual servo approach was developed to mediate the requirement to update the control loop at a rate of 1 KHz for stable operation and the visual performance rate of maximum 48FPS and visual image processing rate of 25 Hz.

The Raven II robot (slave) is controlled with its low level joint controllers at a 1 KHz rate. The visual servo running at a rate of 25 Hz was incorporated into the automation algorithms controlling the master to provide delta Cartesian position commands (X,Y,Z), which are calculated as the difference between the desired position based on the planned trajectory and the actual position and orientation of the tip as acquired by the stereo camera. The proportional gains of the visual servo controller were selected experimentally to achieve fast and stable response. The visual servo control error at steady state along each axis is within 0.4 mm as measured in 3D camera frame.

Task Planning and State Machine

In order to automate the task, the FLS block transfer subtasks were decomposed into nine states defined in **Table I** and formed a state machine repeating state 1 to 8 three times for transferring the three blocks and terminating the process in state 9. An internal verification mechanism was used to check the completion of each state prior to every switch to the following state. An internal error correction mechanism was incorporated to correct for potential failures within each state and potentially moving to a different state to recover from the potential error. If the failure is not recoverable, such as object is dropped out of camera view, then the state machine will continue to next subtask cycle to transfer the other remaining objects.

Path Planning

Generic path is predefined offline for each state. However the actual 3D path points are dynamically generated to accommodate changes in the operational environment as detected by vision system, such that the path is adjusted in real time. The speed limits were set to 10 mm/s for high precision manipulation and to 30 mm/s for low precision translation.

Experimental Protocol

The block transfer task was completed 20 times (60 block transfers in each mode) in the following modes (1) Autonomous operation (2) Teleoperation by a human subject. Robotic arm kinematics, tool tip trajectory, task completion time, peg board marker motion trajectories and videos from the stereo camera and webcam in teleoperation were all recorded and collected for off line analysis.

RESULTS

Performance Comparison–Summary

Table II summaries the performance difference between the two modes of operation in terms of goal completion success rate, performance measures and safety measure.

Task Goal Achievement

The success rate for block grasping task is 100% in both modes. Although a grasping force sensor is not incorporated into the current design of the tool, the accurate tool tracking and object detection makes the grasping a success in the autonomous mode of operation. During the block transportation the block grasping success rate is again 100% in both modes.

For transporting grasped objects from one location to another location without dropping the blocks, the success rate is 100%. The slight decrease in the success rate of the block placement of 96.7% is accounted for in 4 cases out of 60 in which the blocks didn't fully drop to the base of the peg as a result of small misalignment between the center hole of the block and the peg. The success rate of the human teleoperation mode is as previously 100%.

Task Completion Time

For autonomous operation, the completion time is identical for all the repetitions (25 s). It takes a human operator about two times longer to complete the task (49 ± 5.7) with a standard deviation of about 5% in a teleoperation mode.

Surgical Tool Tip Trajectory

The surgical tool tip trajectory is used to analyze the efficiency of the motion. Given a specific task, a shorter trajectory is also perceived as a more effective trajectory with a lower potential for collisions. The average tool tip trajectory length in the autonomous mode is about 60% shorter

Subtask Level	Subtask Description
1	Find Object, Obstacles and Destination Locations
2	Fast Move Tool to Object Area
3	Precisely Move Tool Tip to Grasping Location
4	Grasp Object with Tool
5	Precisely Lift Object with Tool
6	Fast Move Tool with Object to Destination Location
7	Precisely Align Object to Peg Pin Upper Location
8	Open Grasper to Let Object Drop on Peg Pin
9	Return to Start Position and Task End

TABLE I Decomposed Subtasks for Autonomous FLS Peg Task.

Categories	Criteria	Autonomous Operation	Human Teleoperation
Goal Completion	Grasping Success (%)	100	100
	Transporting Success (%)	100	100
	Placing Success (%)	96.7	100
Performance Measure	Task Time (s)	25 (± 0)	49 (± 5.7)
	Tool Tip Trajectory Length (mm)	460.45 (± 4.43)	778.04 (± 82.61)
Safety Measure	Peg Board Motion (mm)	6.03 (± 2.75)	78.13 (± 21.18)

TABLE II Data of autonomous operation and human teleoperation.

than the tool tip trajectory during the human teleoperation mode as depicted in **Figure 5**. As indicated graphically the trajectories of the autonomous mode tend to be straight with smooth transitions between the individual segments. However the trajectories of the tip during the human teleoperation mode are composed of arches which are typically longer than the other mode. The arch like trajectories aim to clear the block from the array of pegs in an attempt to avoid potential collisions which in turn leads to longer trajectories and completion time.

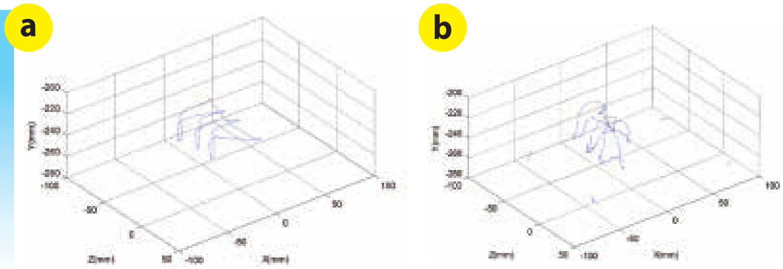


FIGURE 5 **Tool tip trajectory in 3-D space (a) Autonomous Operation The trajectory of four peg board markers has little movement due to dedicated tool-object interaction (b) Human Teleoperation The trajectory of four peg board markers shows large movement due to tool collision.**

Tool-Object Interaction / Environment Collision

The motion of the peg board is a result of force generated as the tool or the object interact with the pegs. The peg board motion is measured to evaluate the tool/environment interaction and defined as the sum of the trajectories of the four markers of the pegboard. Smaller peg board motion means fewer tool environment collisions and a smaller interaction force that may potentially damage the patient's tissue. The pegboard trajectory as a result of collision with the tool during teleoperation mode was more than 12 times longer than the autonomous mode, meaning that during the autonomous operation the collision between the tool and the environment is significantly lower than during the other mode. The trajectories of the markers are depicted in **Figure 5** as well surrounding the trajectory of the tool tip.

CONCLUSION AND FUTURE WORKS

As part of the reported research effort a fully autonomous algorithm was developed for a block transfer of the FLS simulating surgical tissue manipulation in a surgical robotic MIS setting. The algorithm for the autonomous operation is composed of stereo vision based surgical tool detection, surgical tool visual servo control, pegboard environment detection and object detection. The FLS peg transfer task is decomposed into a state machine for task planning and path planning.

The autonomous FLS task is implemented successfully and tested experimentally with the Raven II surgical robot system. The data indicate that the autonomous operational mode has better overall performance and limited tool-environment interaction compared with the human teleoperation mode. In addition the proposed computer vision based automation approach doesn't need the typical precise calibration of the robot arms since the autonomous agent software functions as an intelligent teleoperation master that is independent of the low level robot control system and can potentially be applied to different surgical robot systems.

Since the FLS peg transfer task includes the basic surgical skills and subtasks that are common in other surgical tasks it is likely that the proposed approach can be applied to the rest of the FLS tasks as well as to other surgical procedures' subtasks. One should note that the goal of autonomous mode is not to replace the surgeon but to remove the surgeon from his or her role as an executer of every single motion of the robotic system to the position of a decision maker. A potential expansion of the reported research is the use of trajectories learned from expert surgeon (learn by demonstration) as a substitution for artificially generated trajectories and speed patterns. Furthermore, surgeon's intention may also be extracted from a database [17-19] that may lead to seamless switching between the human operator and the autonomous system [20-21] and in that sense it may allow the autonomous algorithm to cope with more complex surgical environments. ■

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MODULAR INTEROPERABILITY IN SURGICAL ROBOTICS SOFTWARE

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Computers have been used to assist medical diagnosis and treatment for decades; early examples include computer-assisted tomography (CAT or CT) and stereotactic neuro-surgery. While computers can only provide information to guide a surgeon, the introduction of robotics enables computers to physically act on the patient, either directly or by providing mechanical assistance to the surgeon. For example, in stereotactic neurosurgery, the location of a suspected tumor is identified in a three dimensional (3D) CT scan of a patient's brain. Initially, passive stereotactic frames were used to position a guide for a biopsy needle based on the 3D coordinates of the suspected tumor. In 1985, a robot was used to position the needle guide [1], representing the first reported clinical use of a robot. In the early 1990s, robots were introduced for invasive surgical procedures, such as transurethral resection of the prostate (TURP) [2] and total hip replacement (THR) surgery [3]; in both of these cases, the robot autonomously performed part of the surgical procedure.

Today, the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) is the most widely used surgical robot, with 3,266 installations according to the company's 2014 Annual Report. The da Vinci is used for minimally-invasive surgery, especially in urologic and gynecologic applications, but is currently limited to teleoperated control, where the surgeon sits at a master console and controls instruments inserted into the patient's body through small incisions, called ports. Stereo visualization is provided by a stereo endoscope (also robotically controlled) inserted through one of the ports.

Recently, some common research platforms have emerged. The da Vinci Research Kit (dVRK) [4] is a research system based on the mechanical components of the first-generation da Vinci Surgical System. Another common platform is provided by the Raven II surgical robot (Applied Dexterity, Inc., Seattle, WA) [5], which is functionally similar to the da Vinci Patient Side Manipulator (PSM).

The focus of this article is on modular interoperability of the software that is used for these types of systems. This is important for several reasons. First, surgical robots are not just robots, but rather integrated systems that typically incorporate other sources of information. This includes static information, such as preoperative images or models, and real-time information such as mono or stereo computer vision, ultrasound, optical coherence tomography (OCT), fluoroscopy (x-ray), tissue properties, external forces, and user (surgeon) input. There is no single software package that can provide all these capabilities and few, if any, researchers have expertise in all of them. Thus, it is necessary to have modular interfaces to enable interoperability between the different software packages that incorporate the state-of-the-art knowledge and capabilities in each area. Second, even within robotics, there is a need for interoperability between systems. For example, the da Vinci Console (stereo display and master manipulators) could be used to teleoperate other robots, including the Raven II.

SYSTEM AND SOFTWARE ARCHITECTURES

Surgical robots typically adopt the hierarchical multi-rate control architecture that is found in general robotics. This architecture is depicted in **Figure 2** and each layer is further discussed in Section 3. The Hardware and Low-Level Control (LLC) layers are similar to those in general robotics, possibly with additional safety mechanisms. The unique characteristics of surgical robots become more evident at the High Level Control (HLC) and Application layers. The HLC may interface to external sensing, such as force sensing or real-time imaging, to implement closed-loop behaviors based on these sensors. The Application layer implements the surgical workflow and user interface and may include interfaces to other sub-systems, such as a database of patient information and possibly other medical devices.

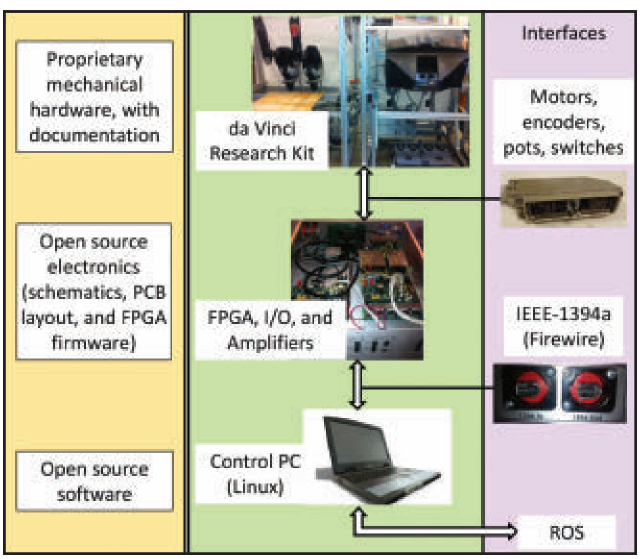

FIGURE 1 Overview of telerobotic research platform: Mechanical hardware provided by da Vinci Surgical System, electronics by open-source IEEE-1394 FPGA board coupled with Quad Linear Amplifier (QLA), and software by open-source cisst/SAW package with ROS interfaces.

From a wider perspective, the surgical robot is often just one component in a larger medical system. **Figure 3** depicts one representative system design that incorporates a telesurgical robot and an ultrasound scanner. In this figure, the Left Master Robot controls Slave Robot 2, which holds an ultrasound (US) probe, and the Right Master Robot controls Slave Robot 1, which holds the surgical instrument (not shown). In a conventional telesurgical setup, the Cartesian position of each Master Robot provides the desired Cartesian position of the corresponding Slave Robot (after transformations from the master to slave coordinate systems). The conventional setup also includes a stereo Camera that provides video images that are displayed on the stereo Diplay Hardware. The new capabilities are due to the addition of the US probe. The system acquires the US images and a Feature Detection module looks for a specified target inside the organ. If the target is found, it is presented as an augmented reality overlay (e.g., a cross-hair marker) in the stereo display and is used to provide haptic guidance to the surgeon via the Right Master Robot. For example, the High-Level Controller can apply a small force on the Right Master Robot to guide the instrument held by Slave Robot 1 to the target. Alternatively, if the target is a critical structure that the surgeon should avoid, the system can impose a safety barrier to prevent accidental damage. In either case, it is necessary for the target to be transformed to the camera and robot coordinate systems. The transformation to camera coordinates is enabled by the Tool Tracking module, which detects the US probe in the stereo images. This module uses the measured position of Slave Robot 2, which is subject to kinematic and non-kinematic errors, but improves the accuracy by directly detecting the tool in the stereo images. Finally, the target position is transformed from camera coordinates to robot coordinates using a known (calibrated) transformation matrix.

One key point in **Figure 3** is that while hierarchical multi-rate control may be suitable for the master and slave robots, there is also a requirement to handle the video and ultrasound images. These image channels have their own timing requirements; for example, the video will typically run at about 30 frames per second, whereas the US is likely to run at a different rate. Furthermore, execution of these channels is distinct from the periodic execution of the robot's low-level and high-level controllers. But, it is also necessary to share data between the channels and the robot controller, as illustrated in **Figure 3**.

The above example motivates the discussion of a software architecture to enable its implementation. In robotics (as in other domains), the original functional programming model gave way to object-oriented programming (OOP), and has more recently transitioned to component-based software engineering (CBSE). In OOP, each module in the system is an object that is an instance of a class. The class methods define the capabilities of that module. For example, the low-level controller (LLC) could contain methods to query the current joint position and to move the robot to a new joint position. The high-level controller would directly invoke the LLC methods; for example, the current Cartesian position is obtained by querying the joint position and then applying forward kinematics. The OOP approach represents a tight coupling, where objects directly invoke methods of other objects. It is more challenging to implement when multiple computations occur in parallel at different rates, as in **Figure 3**, because data transfer between parallel execution threads requires proper use of synchronization primitives such as mutexes and semaphores.

In CBSE, the various modules in **Figure 3** become separate components and interact via message passing. This results in a loose coupling between the components. Essentially, CBSE is similar to the electrical engineering domain, in that software components are the equivalent of integrated circuits, and systems are built by "wiring" software components much like integrated circuits are wired together on circuit boards. Some CBSE implementations require each component to be in a separate process, whereas others enable multiple components to exist in a single, multi-threaded process. The latter is advantageous for hard real-time systems because communication between components can be done more efficiently, especially when the framework provides efficient, thread-safe mechanisms, as in Orocos [6] and *cisst* [7]. In

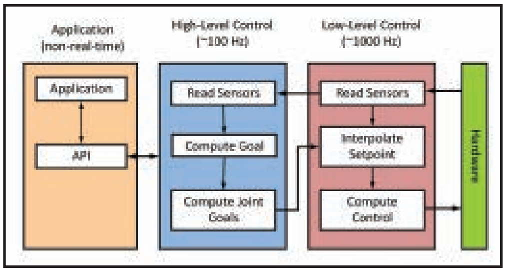

FIGURE 2
Layers of Canonical Robot Control Architecture.

contrast, the Robot Operating System (ROS) [8] requires each component (node) to be a separate process, although there is support for multi-threading via nodelets.

SYSTEM LAYERS AND INTERFACES

The following sections describe the layers shown in **Figures 2** and **3**, focusing on the interfaces to each layer. Although the real-time data channel could be considered part of the high-level control, it is sufficiently distinct from traditional high-level robot control to warrant its own subsection. For interfaces, the Robot Operating System (ROS) [8] provides a common middleware and standardized message types for robots and other devices and has been widely adopted by robotics researchers. The current version of ROS is not designed for real-time processing, however, and thus it is more suitable for the higher-level layers. For the lower-level layers, it is common to use a separate framework, such as OROCOS [6] or cisst [7], often with bridges to ROS. Because ROS is best supported on Ubuntu Linux, it is also common to use other standard protocols, such as OpenIGTLink [9], to interface to software on other platforms.

Physical (Hardware) Layer

The physical layer consists of mechatronics hardware, such as motors, encoders, potentiometers, and associated electronics. Traditionally, the electronics has consisted of input/output (I/O) devices, such as analog-to-digital (A/D) or digital-to-analog (D/A) converters, and power amplifiers to drive the motors. Recently, there has been a trend toward intelligent drive electronics, which combine the functions of the physical and low-level control layers.

Many systems employ custom interfaces to the physical layer, though some standard interfaces have emerged. One common standard is CANOpen (www.can-cia.org), originally developed for the Controller Area Network (CAN) bus, but now available for other physical network layers, including Ethernet. Another option is EtherCAT (www.ethercat.org), which uses a standard Ethernet port on the master device (e.g., PC) and custom hardware on the slave devices. Slave devices can be daisy-chained to form a common bus topology, and all slave nodes can receive data and respond via a single Ethernet frame.

For the dVRK shown in **Figure 1**, the physical layer consists of the mechanical components of the da Vinci and the custom electronics provided by the FPGA and QLA boards. The interface to the physical layer is via IEEE-1394a (FireWire), which is well suited for real-time control due to its high bandwidth, low latency, and support for daisy-chaining, broadcast, and peer-to-peer transfers. This interface was selected to achieve a *centralized computation and distributed I/O* architecture [10], where all control computations are performed on a familiar development environment (Linux PC). The FPGA implements the FireWire link layer so that packet data can be sent to, and received from, the I/O hardware with minimal latency. An Ethernet-to-FireWire bridge has recently been prototyped for the dVRK [11] to take advantage of the wider availability of Ethernet.

Low-Level Control (LLC) Layer

The low-level control layer is often referred to as the servo control layer. Typically, it consists of a simple control algorithm, such as proportional-integral-derivative (PID) control, periodically executing at a high rate (e.g., 1 kHz), to control the individual axes of the robot. The typical low-level control flowchart is to read the robot internal sensor feedback, such as joint encoder positions, compute the error between the desired and measured positions and/or velocities, apply the control law, and then output the desired motor voltage or current. Thus, this layer requires a reliable operating environment, preferably with real-time performance. For this reason, it is often implemented on special-purpose hardware, such as an off-the-shelf (commercial) controller board, or on a PC using a framework that supports real-time processing.

The LLC interface is an obvious candidate for standardization because most robots contain similar low-level controllers. In particular, a standard low-level control inter-

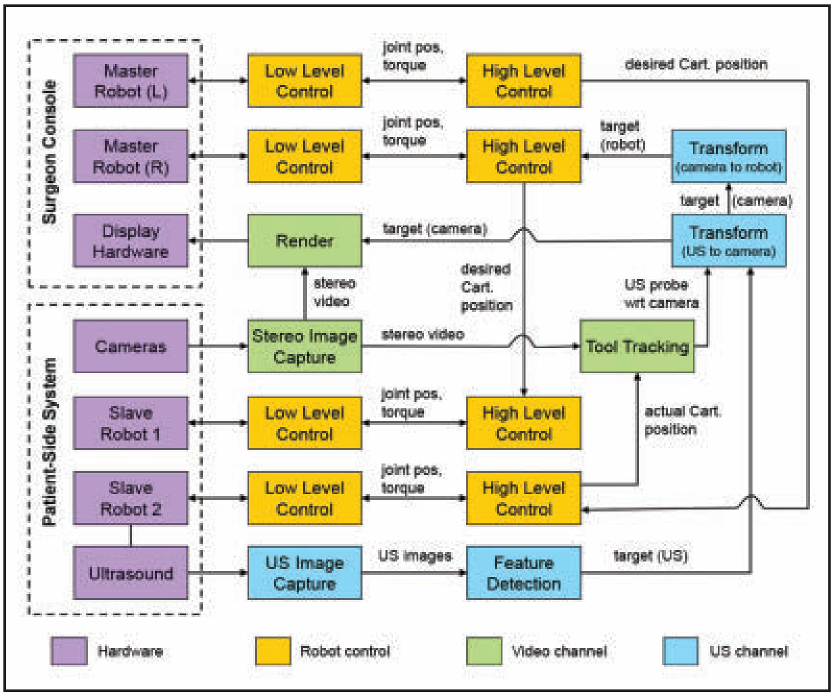

FIGURE 3 **Illustrative system architecture with telesurgical robot (two masters and two slaves), stereo video cameras and display hardware, and ultrasound (US) scanner. US probe is held by Slave Robot 2 and Feature Detection module looks for target. Tool Tracking module estimates position of US probe from stereo camera images, using Slave Robot 2 position to initialize image localization. Result of Tool Tracking is used to transform detected target to camera coordinates, which enables augmented reality overlay within Render module. Target is also transformed to Right Master Robot coordinates (using previously measured transformation) and provides haptic guidance to surgeon to position instrument held by Slave Robot 1 at target.**

face would include commands to enable/disable motor power, home (initialize) the robot, get the current joint positions, and move the joints to a specified position. The other advantage to standardizing at this interface is that it typically forms the bridge between the hard real-time and soft real-time parts of the system. This enables plug-and-play interoperability between systems with very different low-level control and physical layers.

High-Level Control (HLC) Layer

While the LLC provides joint-level control, the HLC provides more sophisticated motion capabilities. One example is Cartesian-level control, where the pose (position and orientation) of the robot end-effector can be measured and controlled in Cartesian coordinates. This requires knowledge of the robot's kinematics. This layer often also integrates feedback from other sensors external to the robot system, such as vision and force, that can be used for visual servoing or force control, respectively. Many surgical robot systems require a human (surgeon) in the loop, and so the high-level control may include assistive control behaviors, such as virtual fixtures.

For the HLC interface, it is straightforward to standardize some basic capabilities, such as Cartesian position control, and to allow system-specific extensions for other capabilities such as sensor-based control modes. This is also the level where ROS interfaces are most common, since the major advantage offered by ROS is the ability to integrate with other high-level software modules.

Data Channel Layer

Data channels are common in surgical robot systems due to the integration with real-time imaging such as video and ultrasound. A data channel consists of a source (e.g., a camera), several filters that process the data, and one or more sinks (e.g., a rendering device). There are two common implementation strategies: (1) a pipeline, where a separate thread or thread pool is used for each filter, and (2) a stream, where a single thread or thread pool is used to sequentially execute each filter. The advantage of the pipeline is that it can provide higher throughput, since processing of new data can begin immediately. The advantage of the stream is that it provides lower latency because there is no need for synchronization primitives between the execution of different filters.

The choice of a pipeline or stream depends on the application requirements and leads to the choice of implementation framework. For human-in-the-loop systems, which are common in surgery, minimizing latency (delay) may be critical, since added delay can affect surgical performance. For this reason, the *cisstStereoVision* (SVL) library (part of the cisst package) supports the stream processing paradigm. In SVL, each filter is a separate component, but the components can exist in a single executable and share memory buffers to reduce overhead. Synchronization primitives are not required because SVL sequentially executes each filter.

If low latency is not required, the pipeline is an attractive option because it enables the use of ROS nodes as filters (ROS provides a large collection of useful image processing components). In ROS, each node is a separate executable, so by default it contains its own thread (or thread pool) and a network of these nodes forms a pipeline.

Application Layer

The application layer primarily consists of the application logic (e.g., surgical workflow) and the user interface. There are many different packages that can be used to implement the application layer. If the application is primarily a graphical user interface, one could adopt a framework such as Qt (www.qt.io). Alternatively, if the application requires the display and manipulation of preoperative and/or intraoperative medical images, the application layer could be implemented in an extensible, open source framework such as 3D Slicer (www.slicer.org). In this case, it would be convenient to use Slicer's built-in OpenIGTLink interfaces. The rviz package provided by ROS is also an attractive option. It is based on the OGRE graphics rendering engine and has plugins to support Qt widgets, images, and other data types. Finally, some researchers choose Matlab/Simulink (The MathWorks, Inc., Natick, MA) as their development platform.

CONCLUSIONS

This article presented an overview of surgical robot systems, with the recognition that these systems are not just robots, but integrated systems that include robots, databases, and real-time sensors such as video and other medical imaging devices. Common research platforms, such as the da Vinci Research Kit (dVRK) and Raven II, have recently become available. This has underscored the need for modular software interoperability, so that researchers can share software modules and more easily integrate other robots and devices. Standardization and interoperability are most applicable at the higher software layers, and can benefit from the availability of widely-adopted middleware such as ROS. Other interface protocols, such as OpenIGTLink, can be useful due to their wide support within the medical imaging and image-guided intervention domains. ■

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