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Roundtable Discussion

Telesurgery and Robotics

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TELEMEDICINE AND E-HEALTH faces many challenges and opportunities. Many of us in the various fields that support telemedicine and e-health have gained knowledge and experience through our endeavors. Oftentimes these are conveyed in peer-reviewed manuscripts which appear in this Journal. Other venues are various scientific meetings. Another tool that can be used to convey issues, opportunities, and innovation is to conduct roundtable discussions. This forum is an assemblage of subject matter experts for the purpose of an in-depth review of select topics. The group is led by a moderator, and the conversation is tape-recorded and transcribed.

This roundtable, the first in a new feature for Telemedicine and e-Health, *was focused on the concepts of telesurgery and robotics. During the past 5 ATA scientific meetings, telesurgery has been presented and discussed. The US Army's Telemedicine and Advanced Technology Research Center (TATRC) has a keen interest in telesurgery and has funded much of the research. The individuals who participated in this roundtable are thought leaders and represent many of the organizations involved in telesurgery and robotics.*

—Charles R. Doarn, M.B.A.
Editor-in-Chief

Charles R. Doarn (Moderator): Thanks, everyone, for participating in our discussion today. I'm Chuck Doarn at the University of Cincinnati. We do a fair amount of work with DoD and NASA in the area of telesurgery. One of my colleagues, Dr. Tim Broderick, who is an avid telesurgeon, couldn't be with us today. He sends his regards and has a lot of discussion points for our conference today.

Thomas Low: This is Tom Low from SRI International in Menlo Park where I'm Director of the Medical Systems and Robotics Program. SRI has been involved in telesurgery from the early '80s, with very early work funded by NIH and DARPA. I was part of the original team that developed the early systems behind the Intuitive da Vinci as well as the current system called the M-7.

Kevin Hufford: I'm Kevin Hufford, a research engineer at SRI, where I worked on developing the M-7 robot into a deployable system that could be set up in a short period of time and helped harden it for working in an extreme environment.

Blake Hannaford: This is Blake Hannaford at the University of Washington. We work on robotics applied to surgery and have developed a system we call the Raven, which is also a portable telesurgery system. We have also looked at the characterization of surgery in order to derive requirements for surgical robotics, such as network characterization, and how Internet properties affect performance of tele-

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surgery. Our surgeons here at The University of Washington work closely with us in the areas of surgical skill assessment, surgical training, and simulation.

Jacob Rosen: This is Jacob Rosen at the University of Washington. Together with my colleagues Blake Hannaford (Dept. of Electrical Engineering) and Mika Sinanan (Dept. of Surgery), we developed the Raven—a surgical robotics for telesurgery. The system was developed based on extensive experimental database that was in part used for objective assessment of surgical skills using the stochastic modeling approach as well as tissue damage. The system was subject to several teleoperation experiments including transatlantic teleportation (Seattle, WA–London, UK), as well as teleoperation in extreme environments (Simi Valley, CA and underwater in NASA's NEEMO 12 mission—Seattle, WA to Key Largo, FL).

Charles R. Doarn: I'm looking at this purely from a business perspective rather than a science, engineering, or even a medical perspective. Some topics for us today are the issues of latency, business models, quality of service, cost and potential future reimbursement, infrastructure to support such activity, bandwidth issues, and the general scope of telesurgery.

I started writing a manuscript with Tim Broderick, Gerry Moses, and others looking at telesurgery from a historical perspective. It has been said that telemedicine and telesurgery were, in fact, first used on Early Bird in 1964, one of the United States' first successful launches of a communications satellite. I have often heard Dr. Michael DeBakey say he allowed people in Geneva, Switzerland, to observe an open-heart surgery case he was doing at Methodist Hospital in Houston. Clearly, the concept of linking two remote sites via a telecommunication link can be portrayed as telemedicine or telesurgery. In essence, however, it is really just television.

This prompts the question, what is telesurgery? Panel members, what is your definition and concept of telesurgery?

Thomas Low: For anything to be considered telesurgery, one would actually have to do a manipulation, rather than simply observing or mentoring, which is a different sort of telemedicine.

Blake Hannaford: Certainly, that's an important difference. Of course, it's not enough to just provide manipulation. Surgery is a highly skilled manipulation and so the technology has to support that. It must allow the surgeon to do all the things done in a normal surgery, if not more. It has to give the surgeon confidence that the procedure is safe for the patient. This means paying a lot of attention to the quality of surgeon feedback, video quality, and latency.

Charles R. Doarn: Robotic surgery is really the foundation of interventional telemedicine. Some people in radiology and pathology might differ with our definition. The original intent of robotic surgery development—both with Computer Motion's, Zeus platform, and SRI's work to develop the da Vinci (Intuitive)—led us to believe that we could manipulate a device from a distant site, perhaps in the same room.

I know that Dr. Mehran Anvari and Professor Jacques Marescaux actually took that to a completely new level by taking the Zeus robot controls and moving them several thousand miles away. They were very successful in doing some of those kinds of activities. Do any of you have comments on this from your own unique perspectives?

Jacob Rosen: We should defer to the classical terminology of telemanipulation, namely, master and slave. The surgical console is the master and the surgical robot is the slave. As long as you have a master and slave separated by distance with a communication link (video and data) between them, then the definition of telesurgery is met.

Blake Hannaford: I would just add that the goal is to reproduce the capabilities of the human hand at a remote site. That's another way to look at it, sometimes with the added benefit of miniaturization. The ideal system would be something able to reproduce the human hand at small scales at a distance. Of course, the human hand is incredibly versatile and it can do many, many things. This suggests that telesurgery is a foundation for lots and lots of different types of procedures and interventions.

Another way to look at it is that, if the task involves manipulation, the best user interface is clearly the surgeon's hands. The surgeon's input from the hands and feedback to the hands could be connected to a little miniature reproduction of the hand, but it could also be connected to a steerable catheter, laser, or some kind of other interventional device. A key property of telesurgery is the user interface to and from the surgeon's hand. Obviously, this is a critical part to any kind of interventional telemedicine.

Charles R. Doarn: One of the issues we always struggle with in the realm of telemedicine is the ability to project expertise to a distant site, whether it's on the battlefield, Mount Everest, in space exploration, or underwater. The individual providing medical or surgical care should have a basic understanding or knowledge of that. In these environments, being able to project this expertise virtually or naturally has huge benefit. We've been able to demonstrate this a number of times over the last couple of years with our various experiments.

I guess the question that comes up is, "If one assumes you have a fairly robust robotic system, what about the communication infrastructure that needs to support it?" Oftentimes, people ask me, "Well, what if the Internet goes down or the computer stops working?" There are always questions of latency and reliability in the infrastructure itself. What kind of infrastructure do you think really needs to be in place to make this a reliable effort?

Blake Hannaford: The Internet is becoming more and more the fiber of our society. Like electricity, we are depending on it more and more for all kinds of things. A hundred years ago, it was just a given that electricity would go out now and then—you couldn't count on it. Today, it's a big problem if the electricity goes off when we don't have ways to back it up.

The Internet is turning communication into a utility that, more and more, we can count on. That doesn't mean we can just plug in and forget about reliability. But, at the same time, there's a whole industry that's working to bring it more and more into the direction we need. For each specific situation such as a battlefield, remote site, or a clinic in Alaska, there's going to be different ways to provide the safety and reliability guarantees that are obviously necessary.

In a remote clinic, for example, you can have somebody present who may not be fully capable of doing the procedure, but is fully trained to take over and stabilize the patient in the event of communication loss.

Jacob Rosen: Another aspect of system robustness is its redundancy. The Internet as a wired or wireless communication network is inherently redundant. However, redundancy is not built into the endpoints in telesurgery which are the computers that control the master and the slave. Redundancy of the endpoint and not just in the network itself will secure the communication links between the two endpoints such that if one of the computers at one of the endpoints will fail, another computer will maintain the communication link.

Kevin Hufford: When reliability is an issue, there are some simple things that we can do on the remote side. This may mean holding the current position until the connection's re-established. Or, if the robot understands something about the procedure being performed, it could be autonomously moved to a safer state. Yet, Blake is right; reliability is only going to increase.

Charles R. Doarn: Let's focus for a bit on telecommunication requirements for telemedicine versus telesurgery. Two large events have occurred in the last five or six years. One is Operation Lindbergh that Professor Marescaux did between New York and Strasbourg, France. The other is Dr. Anvari's work in Canada. In both of these events, the networks were fairly large and fairly robust. At both sites, however, there are always teams of medical and surgical personnel who can support the surgery. If the robot or communications fails, these teams can take over the surgical procedure.

As we go through the next period of time, telecommunication can only get better and more reliable than it already is. We are also at the stage where, eventually, these systems may have some intelligence, where they could perhaps carry on in a steady state some activities that you were doing until you re-establish the connection. One day, they could be smart enough to do the entire procedure. This is certainly something that Dr. Richard Satava has presented at many, many meetings since I've known him for almost seventeen years now. Clearly, the telecommunications needed to do telesurgery is far superior than it is for telemedicine. Telesurgery is just an opportunity for telemedicine to expand.

We worked on the HAPsMRT Program with UW and HaiVision and Aero Environment out in California last year. We actually used an unmanned airborne vehicle (UAV) that was far easier to use and with less latency than perhaps using a low Earth-orbit satellite or geostationary satellite, because you don't have that time delay. Did you guys at UW want to talk a little bit about some of that experience from a communication perspective?

Blake Hannaford: Time delay comes from different sources, and one of them is just the speed of light being an ultimate limit and communication satellites are 22,000 miles above the Earth, and so there's, fundamentally, about a quarter of a second speed of light delay to get up there and back down. Often, you have four of those links in a complete loop, so you may have up to a second of delay there. And so the other techniques like the airborne, unmanned aerial vehicle that carries a communication node—it can really eliminate that source of delay.

And we've been working pretty hard to really study where the delays are coming in practical implementations of this system, including using global Internet links, terrestrial Internet links. And an interesting finding that's coming up is that the Internet continues to get faster. The delays that we're measuring around different sites—to different sites in the planet, really—have dropped over the last few years, as you might expect.

But there's actually another very significant source of delay, which is the compression equipment that's used to compress the video and decompress the video at the other side. And that—those delays are now bigger than the Internet delays, even using very advanced, expensive custom video CODEC equipment, which is very nice, but often not designed to really minimize latency. We're starting to work with experts on video compression and multimedia networking to see if we can't figure out the absolute best way to minimize those delays.

Jacob Rosen: There are potentially three communication links between the master and the slave: Video is transmitted from the slave to the master, position commands are transmitted from the master to the slave, and force feedback (depending on the implementation) is reflected from the slave to the master. One of the major difficulties in teleoperation is that each one of these communication links is subject to a different time delay. In addition to the fact that the communication links are not synchronized, the time delay distribution of each channel may vary. One way in which the operator copes with the time delay variability is a strategy known as "move and wait": The operator will not move the master unless he or she will see the slave's end effector response to his or her previous position command. Examining the evolution of surgical robotics shows a transition between the two ends of the spectrum while moving from a fully autonomous system based on pre-planning utilizing pre-operative imaging of the anatomy in which the surgeon is completely out of the loop to a fully teleoperated system in which every movement of the robot is totally under the control of the surgeon, excluding motion scaling the tremor removal. One potential solution to overcome time delay is semi-autonomous operation. This mode of operation will put the surgeon at a high level of controlling the system (decision making). The surgeon will be able to mark the beginning and the end of the suture, and the robot will automatically stitch the tissue. The mode of operation can be extracted to other substeps of the surgical procedure and eliminate the need for a human control for every robotic movement.

Charles R. Doarn: In 1993, I was at a meeting in Montreal and this was the first time I met

Rick Satava, who was talking about telesurgery. This was before anybody had actually deployed a—or the FDA had approved the use of any kind of—robotic surgery. And I remember him talking about this, and there was another gentleman there who was from the Air Force, Dr. Al Elsayed, and he—we were—the three of us were talking about this and I kind of was the naysayer, being the non-clinician that I am, and I said, "If you are doing a surgery and you are in a particular body cavity and when you go to pull something and you cut something by mistake, you can certainly repair some things, obviously, like a blood vessel, for instance, if it's not too large." But the way in which the latency was played out at that time was that there was no way you could have a surgeon remotely do this task because the body would be reacting so rapidly that the robotic system couldn't compensate for it because of this latency.

And so, from what I've seen in the last fifteen years or so is that latency is still an issue, but I think we've been able to overcome some of that by design. And I think, Jacob, you make a very good point about autonomous functions. If you make a mistake, you have to consider not only the delayed response to repair it, but the body has moved ahead into a different state. But when we use the da Vinci, if you're in the middle of doing something and you take your head out of the—the workstation—the system stops and for good reason. If you design into the system some of those features, I think you add a lot of usability.

Kevin Hufford: I think there's also another benefit of autonomy that we noted in NEEMO 12. When we were doing the autonomous needle insertion, the robot was able to insert the needle perfectly along the needle axis, so there was no bending of the needle and no unwanted interaction with tissue. And that's something that would be more difficult to do in a telemanipulation case.

So, for us, seeing the sort of supervised autonomy in NEEMO 12 was very rewarding. It's not only just a compensation for latency: the robot can do some certain specified tasks better than the surgeon could remotely, even in a low-latency situation.

Charles R. Doarn: The other thing that always comes to mind when we talk about remote manipulation are the two robots—Spirit and Opportunity—that are on the surface of Mars. Now, realize that the communication delay between the surface of Mars and the Earth can be upwards of 22 to 28 minutes, one way. So, by sending commands to these robots, they then do exactly what they're commanded to do. As we go down this path of robotic surgery or systems that can do robotic telesurgery, they can be programmed to do certain things.

I think the Trauma Pod project has some of those attributes to it—both SRI and UW can certainly talk a lot more about that than me. But I wanted to just go back real quick and talk about telesurgery as it was originally intended or as it was originally developed, based on the trauma surgery program that ended up being then developed into the da Vinci robot.

The next item is talking about the historical perspective, the recent advances, and the extreme environment challenges that we've worked on. And so there's certainly a long list of the things that we, as a team, have been working on. I know that the whole concept of taking commercially available systems and pushing them together oftentimes leads to new devices and new ways of doing things.

I know in Operation Lindbergh the proof of concept that was done was the most missed story of 2001, because of course, as we know, it had been done just a few days before September 11th and the tragedy of that day. But, again, this was one of those systems with a completely dedicated communications link.

And I recall, when we did some early telemedicine work in the late '80s and the early '90s, we again used commercially provided telecommunications, but it was dedicated. It wasn't a shared sort of service. When we did our Intuitive Surgical robotic activity from the University of Cincinnati to Sunnyvale in March of 2005, we used the open Internet and, of course, we repeated that at the American Telemedicine Association in April, through the one that was in Denver. But that used the open Internet and I'm not so sure that you'd want to do surgery on the open Internet, because—people getting into a system and perhaps making—making problems with that.

But from a standpoint of a wide-scale telesurgery application, do you think that the biggest challenge for us out there is the communications and the problems that are caused by it—latency and quality of service? Or do you think it's more of the design of the interface to replicate the surgeon's hands?

Jacob Rosen: I would just like to conclude the previous discussion regarding autonomous operation before we move to the new topic by saying that one may implement autonomous operation at two different levels. The first level of incorporating autonomous operation into the operating room is to automate the services to the surgical robot, and this is at the core of DARPA's Trauma Pod–Phase 1 program in which services such as tool changing and equipment dispensing were performed automatically and initiated by the surgeon's voice command. The second level, as I mentioned before, is to automate the surgical tasks. The difficulty with automating the surgical task is the fact that the anatomy is an unstructured environment. Bone and teeth as hard tissues can be considered structured environment once they are fixed and registered with respect to the robot. However, soft tissues are more difficult to fix. Moreover, their biomechanics is extremely complex, and therefore predicting their geometry based on the boundary condition and external loads is still an open research question. Surgical tasks such as intubations in which the anatomy guides the tool or even needle insertion preformed under real-time ultrasound guidance may be an immediate procedure to explore with semi-autonomous operation of surgical robotic systems.

Charles R. Doarn: I think the concept of simulation is very, very important. We here at the University of Cincinnati, obviously, like most medical schools, are beginning to integrate a wide variety of simulation into the curriculum and I think that's very important.

One of the things that we—actually, Tim Broderick—talked about at the ATA a few years ago was the whole concept of being able to do the driver's education concept with the da Vinci robot, where you could actually sit and do the procedure on a simulated patient, perhaps the night before, so that, when you get in to the operating room, you've already done the procedure on that very patient, just in a simulated environment. And, of course, that takes a tremendous amount of computing power and storage and so forth.

So I think those are very, very useful tools, as we come into this next phase, if you will, of advancing medical care.

So we talked a little bit about, just before that, Jacob, a little bit about whether we thought it was the communications infrastructure and the nuances that go with that or if it was really the systems that are going to be the show-stoppers or at least—not show-stoppers, but the stumbling blocks, if you will, to make this a more comprehensive business model.

Jacob Rosen: I believe that there is a consensus among clinicians and engineers that although surgical robotics is an exciting field, it is a very young field and we are individually and collectively involved in developing the first generation of these surgical robotics systems. Using a surgical robot, we removed the surgeon's hand from the surgical site and introduced a system with a unique set of end effectors. However, the surgeon's hand includes an array of sensors that is missing in the surgical robotics tools—sensors that can sense texture, temperature, force, pressure, blood pulse. The new generation of effectors (tools) for surgical robotics may include more sensing capabilities for conveying to the surgeon information regarding the state of the tissue.

Charles R. Doarn: Kevin, what do you folks think about it at SRI?

Kevin Hufford: The communications issues will likely become much less significant. Video encoding latency certainly is an issue that, if improved, will definitely help the usability of such a system. Mentally compensating for latency in a teleoperated situation is something that requires conscious effort, so minimizing the latency or possibly providing some latency compensation to assist the surgeon would help.

Addressing the simple manipulation issue has been a strong focus of the current technology. In fact, for laparoscopic procedures, the da

Vinci provides more dexterity than possible in conventional laparoscopic surgery and also provides three-dimensional imagery.

I think Jacob is right that there is room for improvement in the richness of information fed back to the surgeon. With these platforms, we have the ability to present different imaging modalities to the surgeon—as demonstrated for TraumaPod and during NEEMO 12. With emphasis on making interaction with such systems as seamless as possible, this capability can become a powerful tool without overwhelming the surgeon or preventing him from being focused on the surgical task.

The more we can move away from the surgeon's need to adapt to the system and move forward having the system adapt to the surgeon's need, the lower the threshold entry will be, allowing for more widespread adoption of this technology.

Charles R. Doarn: So we think about telecommunications as really the network or the roadway, if you will, of getting advanced healthcare into these remote environments, whether it be just strictly telemedicine or actually being able to operate on someone at a distant site in a disaster response, for instance, or, say, in the middle of Montana where a surgeon can't make it or you can't get to the surgeon for quite some time, but the systems can be deployed.

What do you think are the challenges for us to get to that point where this could be—I realize that there's only one commercial product in the market right now, at least in the United States, that being Intuitive Surgical's da Vinci system—both the classic or the new S device. What do you think it's going to take for this to become more widespread and, more importantly, more cost-effective for wider distribution?

Jacob Rosen: Typically, you'll see two surgeons standing next to an operating table. So two surgeons would have four hands and four eyes. So if you truly want to replicate it with a robotic system, you need four—at least four arms and at least two cameras to look at the surgical side from different perspectives.

From the surgical console, what we have done with surgical robotics is we changed the scene, because we put only one surgeon in control and all the rest are just floating around assisting him or her. There is a concept where we can develop multiple surgical consoles where two surgeons can work collaboratively, as they are used to—sharing some arms or even manipulating some arms individually.

So in deploying things in a complete vacuum where you don't have any medical expertise around, the only way to do it is to incorporate into the remote side some intelligence so it can overcome time delays where you cannot really control it in a one-on-one fashion and you also—you also want to deploy enough manipulation capability so it can emulate two surgeons working on one—on one patient.

Charles R. Doarn: I think that, if we were to go to a venture capitalist and say to them, "We have a robust robotic system that is smaller than the current systems, very easy to use and can be connected just by plugging it into your WiFi or the wall—wired or unwired"—what do you think would be the kinds of issues that they might have as an investor into seeing this completely deployed as a useful tool in the practice of medicine?

Kevin Hufford: I'm reminded of the offhanded comments made by passersby peering into the windows of the TraumaPod lab in our building. Comments like "Would you volunteer for that?" "No way!" "That looks eerie," and other similar statements remind me that there is still a challenge ahead for vast adoption of telesurgical technology. Those of us in the research community have to continue to demonstrate—as we have begun to do with the M7, Raven, and TraumaPod, along with others who have performed live operations—the capabilities that such a system provides which outweigh the difficulties of a remote surgeon compensating for latency and other communications issues. Of course, this must come at no expense to the safety of the patient.

If there is little or no medical help around, such a system is clearly invaluable, but an onsite surgical team can provide a very high standard of care. The safety of a telesurgical system as well as the perception of that safety, could prove to be a large factor in determining how widely these systems are used.

Charles R. Doarn: Well, I know that in disaster response telemedicine has been a vitally important tool, as was demonstrated in the Spacebridge to Armenia—Operation Strong Angel—which was a demonstration project, in the sense that it was—there wasn't a real disaster. But, certainly, one of the things that we learned from our UAV activity in Simi Valley was that you could deploy a relatively inexpensive communications tool, meaning this unmanned airborne vehicle, in an environment such as post-Katrina, where you could have a telecommunications link.

So if you have a robust telecommunication system that can link to remote sites or a surgeon in a surgical team with a surgical robot, I believe that you can do quite a lot of surgical intervention.

I think the challenge that lies before us is that the infrastructure, the cost, the quality of service, and the latency still remain significant—they're not necessarily huge barriers to overcome, but they still remain challenging for us to take telesurgery to the next level and that's a more wider distribution. Sometimes people ask, "Why would I want to have a robot do the procedure when there's a surgeon standing right there that can do the same thing?" And I don't think it's a matter of "because, it's the same thing with having the da Vinci in the operating room." Someone is always going to ask the question, "Well, it's great you have a robot, but what real value is it?"

And it's not necessarily measured in the cost or the fact that you're a university and you have this new technology. It's more in the opportunity costs and the changing dynamics of healthcare where you have to look for value. If you can do a robotic surgery remotely and the patient doesn't have as many incisions, takes fewer drugs after the procedure, loses less blood, and has less pain, then these are the measures of success.

But when you start to be able to manipulate systems from a distant site, now you can begin to affect a greater population. And then you tie in the whole idea of teaching and curriculum development, where you now can teach people remotely how to do a procedure, whether it would be using an animate or inanimate model.

I was going to just touch on the use of these—Polycom versus HaiVision. And I'm not so concerned about those two particular companies but the whole idea of using a CODEC. What is the experience that both of your companies have had using these different kinds of codecs as far as the quality of the actual video image? How do you see those improving?

Thomas Low: The industry is obviously—in terms of videoconferencing—focusing more on bandwidth reduction and quality of image than they are on low latency. The requirement of low latency is something that's unique in our application. And it is something that HaiVision has put some emphasis on, but with the MPEG-4 standards, you're pretty much stuck with—what is it Kevin—90 milliseconds?

Kevin Hufford: With MPEG-2, the encoding delay can get down to 90 milliseconds, but with MPEG-4 Level 10 (h. 264) the encoding time is 120–180 millisecond range.

Thomas Low: So that's sort of a fundamental bifurcation, if you will, in terms of how it has been looking. Whether or not ultimately it will be worth the bandwidth to have a low-latency solution is yet to be seen.

Charles R. Doarn: Jacob, how about you? What do you think?

Jacob Rosen: Broadband capabilities are similar to computational power. As the infrastructure and hardware improve a non-compressed, high-definition video constantly running between two endpoints on the network will be the standard, and therefore in some respect we will be limited by the speed of light. Even today there are demonstrations of communications using non-compressed, high-definition video capabilities between major nodes on the Internet, for example, between Washington state and California. Bounded by the speed of light, there will always be delays in the communication between two remote sites. In surgery a delay of 250 milliseconds (quarter of a second) is still perceived as an acceptable delay that will not significantly reduce the surgical performance. The problem as I mentioned before is that the delays of the various communication channels are non-synchronized and constantly changing. In one of our teleoperation experiments with Raven we deliberately lowered the sampling rate to cope with a given delay distribution in favor of better performance overall.

Charles R. Doarn: The experience that we had with the Polycom versus the HaiVision when we did the da Vinci test between the University of Cincinnati and Sunnyvale—we knew, when we put the HaiVision in, it was a much better quality, but I would state that the CODECs that are out there today—and Tom, you made this comment very well a moment ago—are those codecs predominantly made for videoconferencing? And do the videoconferencing companies predominantly make systems for videoconferencing, not telemedicine necessarily, and certainly not for surgery.

I know that TATRC had released an SBIR last year for a number of companies to look at the next version of the CODEC. But I'm just wondering whether we're going to need, from a telesurgery perspective, something completely different or if we can piggyback on current developments for the traditional videoconference world.

Thomas Low: Well, even in videoconferencing, latency is an issue. It's just not such a critical one and not such a limiting one. But, as Jacob said earlier, as the bandwidth becomes more and more predominant, I see the need for compression and, with it, the inevitable latency becoming less and less. So it may be that CODECs eventually become things that are sort of unnecessary when it comes to telesurgery and that we essentially just use the broadband.

Charles R. Doarn: When we talk about latency and the possibility of it maybe going away with, obviously, a lot of bandwidth, what about the whole concept of automation? Does that require a significant—significantly more bandwidth to remotely control something, or can you space it out and just take some more time?

Thomas Low: Well, there are two elements that contribute to the latency. There's the actual compression and decompression time, which is predominant when you're communicating over a relatively short distance.

As soon as you start talking about significant distances—now, I'm talking about satellite bouncing or communications to the moon and beyond—then the predominant contributor to latency becomes the actual time of flight of a signal. And that is, obviously, unavoidable.

And as those become predominant, it doesn't matter how much bandwidth you have, you're going to be forced to move into a mode in which greater amounts of autonomy are provided on the remote side, so that more complex procedures can be performed without the operator's continual intervention. And it's really not about the need for the bandwidth as much as it's about the ability of a system, remotely, to be able to react immediately to changes in the environment through local sensing. With a human in the loop remotely, such reaction would be impossible.

Charles R. Doarn: Good comment. Jacob, want to follow up on that comment at all?

Jacob Rosen: Surgical robotics is still a young field. Early adaptors in the surgical community purchased FDA-approved surgical robotic systems and explored their capabilities by developing new procedures and perfecting existing ones. However, the unfulfilled expectation of the surgical community members is that surgical robotic will not just replace their manual tools but will allow them to use capabilities that are beyond the state of the art: to teleoperate; to see through organs and navigate the surgical tools based on this information; to reduce the cognitive load and remove the limitation of the human hand dexterity by semi-autonomous operation; to put the surgeon in a decision-making position by incorporating an intelligent layer into the robot; to increase the flow of the operation by automating the services to the surgical robot (tools and supplies); to foster collaboration in surgery in which two surgeons control multiple arms where one of them might be a trainee or an assistant. Some of these capabilities were already demonstrated; others are still open research questions that are currently pursued by active research in the academia.

Charles R. Doarn: Okay. Let's see. When we've talked about—well, I guess, I'm thinking of a few things, and then we're probably going to need to wrap up here in a few minutes—because I know each of you has some other things that you need to get to. We're going to be doing a series of experiments on the DC-9 this coming Fall and in the past we've done stuff on NEEMO 9 and NEEMO 12, with both robots. When I say "both robots," meaning the RAVEN, University of Washington, and, of course, the SRI M-7.

When we look at putting telesurgery in extreme environments, from the standpoint of a technology demonstration or evaluation, what do you see as the biggest challenge, aside from the financial aspects of it? What do you see as the most technically challenging activity of getting things deployed in these environments and actually doing this work?

Jacob Rosen: I believe that the core capabilities of performing telesurgery were already demonstrated. As scientists, our role is to describe these efforts using a quantitative methodology. We are interested for example in quantifying by how much the performance of the operator (surgeon) is degraded as a function of the latency in teleoperation. Once we have conducted several teleportation experiments, we better understand the nature of the time delay distribution and we can emulate realistic scenarios in a well-controlled lab environment using a standard platform such as the fundamental laparoscopic skill (FLS) set. However, every field experiment creates a new set of technological and scientific challenges that enable scientific discoveries.

Thomas Low: Both the M-7 and the Raven are very sophisticated instruments. And it certainly was a challenge in NEEMO 9 for SRI to re-engineer that system to a point where the layman could deploy it. And that would be robust enough to withstand the rigors of deployment into that kind of environment.

The DC-9 is going to be sort of a similar situation. The master controller that SRI developed many years ago is an area where I think significant advances can be made before telemanipulation or telesurgery is widespread—an area where the costs and accessibility of such systems need to improve. And that's one of the areas where we are planning on focusing some effort in coming months—and this is something that I think UW has already done, to some degree—making the master controller a more accessible piece of hardware than the remote side, the slave system.

There is still room for improvement in terms of the robustness of our systems. I know we breathe a sigh of relief when we get through one of these extreme environment missions with our robots still perfectly functioning and there obviously needs to be more engineering effort put forward before these systems can really see widespread practical application.

Jacob, would you agree with that?

Jacob Rosen: Compared to typical systems that are developed for lab experiments, I think that both systems (M7 and Raven) are built according to an industrial standard. We benefit from it significantly as we try to deploy them in extreme environments. Moreover, as we build more mature versions of these systems, we better understand the difficulty of laymen operating them. Standardizing the communication protocols between the master and the slave, as Tom mentioned, is a key step toward modular solutions. Relying on a common standard may allow us to use any master with any slave.

Thomas Low: And I guess it probably would make sense to just briefly discuss the work that is ongoing to develop such protocols. Blake and I have been in communication and have developed a draft protocol to allow eventual interoperation of SRI's and UW's robots. This will, we hope, eventually permit anyone who's interested in developing robotic instruments to share that interface standard.

Jacob Rosen: Even Intuitive Surgical when they start selling the da Vinci surgical robot which was already a FDA-approved system, they had a technician onsite every time the system would run. The surgical robotic systems are definitely getting more robust, and one of the ways to explore their limits is to keep deploying them into extreme environments in which they will be installed and set up by personnel with limited training.

Charles R. Doarn: One of the biggest challenges is building the systems and making them robust and connecting them. From the user perspective, the biggest challenge is usage. If it is just used in the OR and not for telesurgery, where it takes a huge effort to turn it on or a huge effort to deploy it, then it may not get a lot of use.

And I know Dr. Ron Merrell made this comment to me many, many years ago. He was talking about how surgeons sew—how they suture, how they suture a wound, for instance, or do an anastomosis—in that, when Singer developed his sewing machine, the way the sewing machine works is nowhere near what you do when you use your hands.

So the concept of surgery—manipulating what your hands do—we're still stuck in the—I don't mean 20th century mindset, because we've been doing surgery like this for many, many centuries. But perhaps the next generation of robotic systems that can be manipulated from a distant site will be completely different.

Thomas Low: Oh, I agree completely, Chuck. And, again, this is one of the basic tenets of our future work in Trauma Pod as well as our own internally funded work. We are exploring techniques which emphasize and take advantage of the capabilities of a robot, especially those that are better than what a surgeon does. We no longer want to mimic a one-to-one the way things are done conventionally, but to exploit areas in which the robot can excel.

One example is the ability to compensate for vehicle motion. If you have a device like this mounted into an evacuation vehicle or perhaps in an aircraft, evacuating soldiers, it may be possible to compensate for unexpected accelerations of the vehicle from a rough road or from air turbulence. This would be of great value.

Charles R. Doarn: Every once in a while, when I give a presentation about advancing medical care or robotics or whatever it might be, I always use this picture—and you may have seen it before. It's from the Rand Corporation and it shows this older gentleman standing in front of a very large bank of what looks like monitoring devices—you know, straight out of a mission control for NASA—and there's a big steering wheel. And the thing at the bottom says, "This is a home computer. Everyone will have one in the future." And this was in 1955.

And when computers first started coming out in a PC format back in the early '80s, there were a lot of people that thought that this would never be of value and no one would ever really use them and they still needed the big IBM computers for data manipulation, and yet today we all carry these cell phones and iPods and all that with memory and all these capabilities.

And so it's clear to me that the way we develop surgical tools will continue to evolve and that the ability to link them at distant sites, regardless of where we are—one could assume that, if you had a disaster, for instance, and you wanted to deploy a robotic, a surgical robotic system, to this disaster zone, that would have to be ready and packaged and ready to deploy at a moment's notice and I'm not sure we're quite there yet. But it can't be this huge da Vinci robot.

It can't be these big—I mean, I've seen both the RAVEN and the M-7—they take a little bit to put together. But once they are together, they're fairly easy to use, although I don't know what it would be like to actually do surgery on a human from a distant site with such a system, but that's clearly something on the horizon that we need to focus on.

Thomas Low: And it may be that before we perform surgeries, there may be other manipulations or diagnostic procedures that are done that are perhaps not considered surgical, but that also have great value when performed at a distance. For example, an ultrasound examination, a noninvasive procedure, or manipulation of endoscopes or things of that nature.

Charles R. Doarn: Right. A lot of the technologies coming out of home healthcare and telemedicine really lend well to changing these paradigms. I think it was *Wired* magazine that showed the M-7 being carried into someone's house. I'm not sure, but I got that picture, I guess, from Tim. But it clearly illustrates that perhaps one day you could do surgery at home. I'm not so sure that's the case, but with all the technology that's coming out and the way in which technology continues to evolve, there's no doubt in my mind that this is not that far off in the future.

Well, what I thought I would do in closing is have everyone make a summary statement, if you would.

So, Tom, would you want to make some closing comments?

Thomas Low: There are only a few key players in this emerging area. And I think that what makes a lot of sense is for us to continue to work closely together in a collaborative mode. The funding is somewhat limited and we need to be approaching this in a strategic manner where we develop a road map, if you will—that we collectively pursue as opposed to each pursuing our individual interests. I think that's the way that we are going to make the most progress and use the limited funding that is available in this field most productively.

Jacob Rosen: One source of inspiration is Dr. Richard Satava's approach to surgical robotics in which he refers to a surgical robot as an information system with arms and an imaging system as an information system with eyes. The patient may be also referred to as an information system. Following this view, we should divorce ourselves from the mechanized view of the surgical robot and treat it as an information system. This approach may help us to shape the next generation of surgical robotics. Developing an intelligent layer will put the surgeon in the decision-making position. It will also assist in synthesizing the different modalities and allow the system to perform semi-autonomous steps of the operation.

Charles R. Doarn: In closing, I'd like to thank everyone for participating. We look forward to further discussion. The future is very bright in this area of the integration of telemedicine, telecommunications, surgical care, and robotics. I believe that these are very useful tools, not only from a research perspective and, of course, we've done a of lot of really cool demonstrations. But I think it's more that these tasks that we've done are necessary steps to get us to the next level, not only from an education perspective, educating us as researchers, but also providing a platform to develop new education tools. So to become a surgeon doesn't take seven to fifteen years. Even today in the *New York Times*, there's an article about a shortage of cardiothoracic surgeons, that the average surgeon, by the time they are out practicing, they're 35 years old and have $200,000 or more in debt. Certainly robotics and simulation systems can help—we hope—help alleviate some of that.

I think telerobotic surgery is a natural extension of the surgeon's hands and is a very useful tool, as has been shown in numerous examples. And I think that this leads then to a paradigm shift in the way in which we practice surgery and the way we teach—always coming back to that concept of education.

I think telesurgery is no longer a novelty. It's not ready for prime time, of course, but it's certainly a very interesting field. It has a huge potential and has many applications and I think the barriers that we discussed earlier—and those barriers and characteristics are similar for telemedicine—also are impacting telesurgery. But, as I've watched over the last fifteen to twenty years, these barriers continue to ebb away and, I think that they'll ebb away faster now because the computer systems are far better than they were fifteen years ago—telecommunications gets better almost on a daily basis.