Minimally Invasive Expeditionary Surgical Care Using Human-Inspired Robots

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Abstract – This technical report serves as an updated collection of subject matter experts on surgical care using human-inspired robotics for human exploration. It is a summary of the 'Blue Sky Meeting', organized by the Florida Institute for Human and Machine Cognition (IHMC), Pensacola, Florida, and held on October 2-3, 2018. It contains an executive summary, the final report, all of the presentation materials, and an updated reference list.

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Executive Summary

Planning for human exploration missions to the Moon, to Mars, and perhaps asteroids has included the consideration of advanced healthcare capabilities where the crewmembers would need to function independently of terrestrial-based controllers. Part of this consideration is what can be done to help the crewmembers deliver healthcare, including on orbit surgical care capability. When NASA presented its Space Technology Roadmaps in 2011, it included several areas where robotics could play a role in exploration space missions. Area 6, Section 2.3 (Human Health and Performance) of the Roadmap called for "…the development of medical assist robotics for laparoscopic surgery and a surgical suite with sterile, closed-loop fluid and ventilation systems for trauma and other surgeries." A report from the National Research Council in 2014 reiterated this need for surgical capability by calling for the development of "…highly capable diagnostic and treatment equipment, including surgical facilities designed for operation in-space and on the surface, would reduce the threats posed by injuries and illnesses." Consequently, there has been a continuing interest in surgical capabilities for exploration space flight including the use of robotics to help with the healthcare delivery.

It is reasonable to assume that there will be a human inspired, dexterous robot on an exploration spacecraft to assist with many kinds of tasks. Current concepts for an exploration space mission anticipate a small crew size, possibly four to six astronauts. Given the small crew size, we posed the question. "Can a human-inspired, dexterous robot serve as an effective medical and surgical assistant?" Florida Institute for Human and Machine Cognition (IHMC) organized a small discipline specific meeting 'Blue Sky Meeting' in Pensacola, Florida on October 2-3, 2018 The primary goal of this meeting was to explore the role of robotic involvement in surgery for exploration spaceflight. Twenty four subject matter experts from robotic surgical companies, surgeons who perform robotic procedures as a part of their clinical practice, academic surgical robotics developers, and a physician/astronaut who has spent time on the International Space Station (ISS) engaged in directed discussions stimulated by topical presentations.

This report captures the content of the eight presentations at the symposium and the lively discussion that was stimulated during and following each presentation. The impressions of all of the participants and recommendations for further investigation and advancement on the topic are presented at the end of the report along with a glossary of acronyms and terms. Supplemental materials in appendices include the agenda for the symposium, participant biosketches the slides from the eight presentations, and a bibliography of references related to the topic of this Blue Sky symposium. This report is intended to be a useful reference for everyone interested in the topic of the role of robotic assistance for healthcare delivery during exploration space missions and related topics.

This Blue Sky Meeting was supported by the Translational Research Institute for Space Health (as a part of Grant T0110) through NASA Cooperative Agreement NNX16AO69A. Meeting participants, identified in the agenda as rapporteurs, created the text for this report with input from the presenters. Dr. Karen (Sam) Miller and Dr. Timothy Broderick kindly provided editorial review. Mr. Charles Doarn served as the production editor for this NASA Technical Publication. The reference section was compiled by Mr. Charles Doarn, Dr. Mark Campbell, and Dr. George Pantalos. Many thanks to all for their efforts to see this report to its completion.

Formal 'Blue Sky Meeting' Report

Minimally Invasive Expeditionary Surgical Care Using Human-Inspired Robots

October 2nd & 3rd, 2018

Minimally Invasive Expeditionary Surgical Care Using Human-Inspired Robots

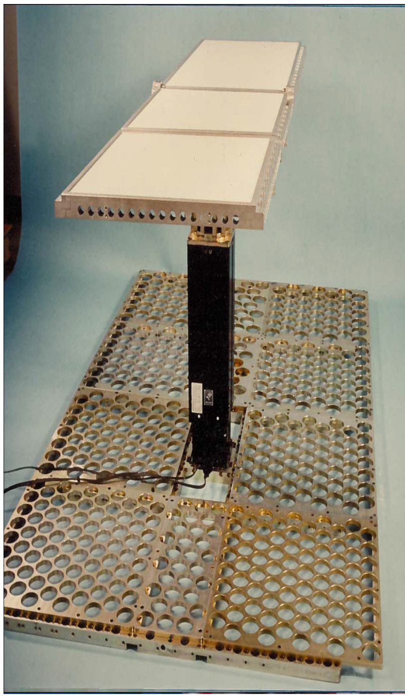
Blue Sky Meeting, October 2nd and 3rd, 2018

INTRODUCTION

Consider the following scenario in transit to Mars: "An astronaut develops abdominal pain associated with nausea, vomiting, and fever. A low-grade leukocytosis is identified on laboratory evaluation: probable diagnosis is appendicitis. Pain and mild tenderness localize to the right lower quadrant (RLQ). Abdominal ultrasound (US) imaging confirms an abnormal, dilated structure in the RLQ consistent with acute appendicitis. The astronaut is treated with antibiotics and intravenous hydration resulting in partial resolution of symptoms. Within a week, the astronaut develops a higher fever and increased RLQ pain. Repeat US imaging reveals a probable peri-appendiceal abscess. The crew medical officer (CMO) prepares the abdomen for abscess drainage as the assistant prepares the instruments and positions the US probe. With US imaging for guidance, the CMO inserts a percutaneous needle under local anesthesia. Needle aspiration reveals pus from the suspected abscess. Using the Seldinger technique, a guide wire is slid through the needle to the site of the abscess, then the needle is removed. Using a #11 blade scalpel, the CMO makes a small incision along the wire, then slides a multi-port drainage catheter over the wire to the location of the abscess. The wire is withdrawn and suction is applied to the catheter draining the abscess. Antibiotics and catheter suction are continued for a week. The drainage finally decreases and the catheter is removed. The small wound from the drainage catheter heals with daily change of the Band-Aid. There are no sequelae, and after a course of rehabilitation, the astronaut returns to normal duty for the duration of the mission."

There are several unique features of this scenario that may not be readily apparent. The CMO is not a surgeon, but has been trained pre-flight (with periodic in-flight refresher sessions) on advanced healthcare techniques including the minimally invasive surgical (MIS) placement of a drainage catheter. The medical/surgical assistant for the CMO (who manipulates the US imaging probe and assists with the drain placement) is not a human crew member, but an interactive, human-inspired dexterous robot. Both the CMO and the robot assistant use integrated augmented reality images of the patient's abdominal contents to evaluate and guide the anatomic placement and advancement of the needle and drain insertion. The #11 scalpel blade was part of the conventionally manifested medical supplies, but the handle for the scalpel blade was printed on demand for the procedure, matched to the human and robotic manipulator dexterity, using the space craft's multi-material 3-D printer. These unique abilities do not currently exist as described for space flight, but are reasonable to anticipate for exploration space missions within the next two decades and inspired the "Minimally Invasive Expeditionary Surgical Care using Human-Inspired Robots" theme for this Blue Sky Meeting.

Part of the design concept for "Space Station Freedom" in the 1980s designated an entire module as the Health Maintenance Facility (HMF) to provide comprehensive medical care. Surgeon/engineer Bruce Houtchens created a light-weight, deployable operating table for the HMF anticipating the need to surgically treat injury and disease on long-term space missions. In the 1990s, Mark Campbell, Roger Billica, and Smith Johnston evaluated instruments and techniques for laparoscopic surgery on laboratory animals in reduced gravity during parabolic flight. During the next decade, Andy Kirkpatrick and Tim Broderick considered other details of laparoscopic surgery in reduced gravity including the level of insufflation needed and the possible role of surgical robotic techniques in reduced gravity.



NASA presented its Space Technology Roadmaps in 2011 that included several areas where robotics could play a role in exploration space missions. Area 6, Section 2.3 (Human Health and Performance) of the Roadmap called for "the development of medical assist robotics for laparoscopic surgery and a surgical suite with sterile, closed-loop fluid and ventilation systems for trauma and other surgeries." This research and development work was projected to take place between 2015 and 2025. A report from the National Research Council in 2014 reiterated this need for surgical capability by calling for the development of "highly capable diagnostic and treatment equipment, including surgical facilities designed for operation in-space and on the surface, would reduce the threats posed by injuries and illnesses." In 2017, the Integrated Medical Model of the NASA Human Research Program included a list of 100 medical conditions that could be anticipated during space flight. Of those conditions, 27 would typically have surgery as a part of the treatment plan. Consequently, there has been a continuing interest in surgical capabilities for exploration space flight including the use of robotics to help with the healthcare delivery.

This Blue Sky Meeting was held on October 2-3, 2018 at the Florida Institute for Human and Machine Cognition (IHMC), Pensacola, Florida, with the goal of exploring the role of robotic involvement in surgery for exploration spaceflight. The 24 participants included individuals selected from robotic surgical companies, surgeons who perform robotic procedures as a part of their clinical practice, academic surgical robotics developers, and a physician/astronaut who has spent time on the International Space Station (ISS) to engage in directed discussions stimulated by topical presentations. Questions and issues included:

- The potential of surgical robotics tempered with the constraints of exploration space missions (volume, mass, power, time, risk, cost, and crew competence) and the scope of possible surgical procedures; and what capabilities for robotic assistance should be developed in the near-term?
- What technological barriers exist to creating the anticipated level of assistance?

- What hierarchies of human-machine interfaces and artificial intelligence are needed to integrate flight crew instructions, input from the crew medical officer, information from monitoring and diagnostic instruments, and situation assessment or guidance from mission control?
- What level of robot autonomy is desired to safely perform surgical tasks versus what limitations need to be imposed on the robot?
- What authorization procedures and failure safety protocols should guide the use of a robot assistant?
- How is crew training with the robot pre-flight and proficiency training with the robot in-flight accomplished, including creating job aids and guides for support of non-surgical personnel performing surgical procedures?
- Possibilities for assisting with preoperative preparations, anesthesia, and postoperative care and rehabilitation were also discussed.

By considering these and other questions, the goals of this Blue Sky Symposium were to describe the function and specific capabilities needed from a medical/surgical assistance robot, and to identify the technological and training achievements needed to implement this desired performance. This Blue Sky meeting was supported by the Translational Research Institute for Space Health (Grant T0110) through NASA Cooperative Agreement NNX16AO69A.

EXPERIENCE & QUALITFICATIONS OF STUDY TEAM

Study participants were carefully selected as thought leaders in robotic surgery, human spaceflight, and related fields. Participants included NASA scientists and technologists, former NASA executives, astronauts, and leaders from academia and industry. See Appendix-1 to see the biographies of the participants.

METHODOLOGY

Day 1 (Oct. 2nd) included introductory comments to provide overview and context; six presentations, each of which included Q&A and discussion; and an end-of-day consolidation discussion. Day 2 (Oct. 3rd) included introductory comments that synthesized Day 1 and provided context for Day 2; two presentations with Q&A and discussion, a meeting consolidation discussion, and final closing comments. See Appendix-2 to review the agenda.

The order of presentation was designed to introduce general topics and challenges, and then to explore specific issues in depth. The daily summary discussions were designed to synthesize information with emphasis on providing all participants with foundational knowledge now in hand, and specific questions being explored in order to provide greater direction for each of their areas of study. Presenters and participants were encouraged to use the event to discover potential synergies in their projects' processes and outcomes.

Day 1 (October 2nd, 2018)

Day 1, Session 1, Presentation #1: "Astronauts Perspective on Robotic Surgery" – Mike Barratt

NASA Astronaut Mike Barratt presented a crewmember and flight operations perspective on surgical capabilities for exploration space missions. He emphasized that when planning for such missions, there will need to be the continuous compromise between wanting to expand capabilities versus the limitations of the flight environment – What do you have to leave on the ground in order to gain a new capability in space? One reality of space operations that Mike emphasized is that particularly on exploration missions, crews need to be prepared to function independently from mission control not only due to communications latency due to great distances, but also due to periodic and unpredictable loss of communications with mission control. This questions consideration of surgical teleoperations, even on the Lunar surface. Due to the limitation in the size of the crew and the impact of injury or illness of one crew member could have on all of the crew members and the mission success, all crew members should be trained to the proficiency of a paramedic.

He emphasized keeping whatever surgical capabilities that may be developed and selected for exploration space missions to be simple with proven reliability as well as excellent proven performance rather that "cutting edge." There will not be a surgical suite on the spacecraft, so whatever equipment and instruments are used must be easily deployed from storage or reconfigured from other applications to support the identified treatment task. For critical situations, a battlefield mentality of 'do whatever needs to be done' will be executed. Risk analysis, such as calculated by the Integrated Medical Model, will help to identify the most likely situations to be encountered, but it is not possible to prepare for all situations.

The crew medical officer (CMO) will probably not be a surgeon and will have many responsibilities for all aspects of crew health "stuff management" including environmental control and life support systems, crew health monitoring, diet/nutrition, behavioral health, and countermeasures implementation. Prior to and during a mission, there will need to be ways to effectively and efficiently train and refresh training with in-flight drills that might include a surgical treatment scenario.

George Pantalos: What is the ideal background for a CMO?

> *Mike Barratt*: For a crew of six, one physician with training in acute/critical care, burn and wound care, smoke inhalation, simple abdominal surgery, etc., supported by one emergency medical technician (EMT).

Mike noted that a lot has already been learned about elements of surgical procedures in reduced gravity from the animal research that has been conducted on parabolic flight research missions, life-science oriented Space Shuttle missions and on the International Space Station (ISS). These elements include anesthesia, blood sampling, organ/tissue sampling, survival surgeries, surgical instrument use, and management of blood and body fluids. Mike also pointed out that many crew members (medical and non-medical) have performed IM injections, phlebotomy, IV placement, Foley and straight catheter placement, minor wound care (non-suture), eye foreign body removal, ultrasound imaging, and even simulated advanced cardiac life support (ACLS).

Andy Kirkpatrick: What are you using ultrasound (US) for?

> *Mike Barratt*: Supporting life sciences investigations such as measuring dimensions of the jugular veins, heart and femoral vasculature as well as abdominal and ocular imaging.

Tim Broderick: Are you using defined procedures to acquire US images?

> *Mike Barratt*: Yes.

Dwight Meglan: Butterfly Network, Inc., (Guilford, CT) has developed its neural net-based "iQ" US on-a-chip device that can connect to an iPhone to provide cardiac US capability along with other imaging.

Possible human surgical procedures that could be considered are wound repair, US-guided cyst/abscess drainage, and peripheral limb amputation. Given the possibility that robotic systems can fail, the role of the robot will be most useful as an assistant to the surgeon, rather than expect it to actively initiate and execute surgical tasks. The tasks assigned to the robot must be simple and well defined with alternative ways of accomplishing the task in the event of robot failure.

Despite the deep integration of robotics into human spaceflight activities and operational experience with robotic manipulator arms and other robotic systems on the Space Shuttle and ISS, systems will have to plan to fail safely and have a means of easy repair with the failure modes understood in advance. ISS Expedition 19 reported uncommanded robotic arm motion on multiple occasions, and just last night there was an arm power failure. On the Space Shuttle (STS)-133 mission, the remote manipulator system (RMS) froze with astronaut secured to the end of arm and, because the failure mode was not understood, the crew switched control to a different computer rather than reboot. Even when using a proven robot on a NASA Extreme Environment Mission Operations (NEEMO) study, the robot system failed, and the science objectives were lost.

Many useful insights have been gained, sometimes by pilots and engineers, on the ISS into performing small animal procedures on-board including euthanasia, surgical preparation and tasks and dissection in microgravity using experimental animals in the Microgravity Science Glovebox (MSG).

In summary, potential space craft surgical systems will be integrated into a holistic medical suite (not vice-versa) where robotic surgery will be one aspect of the medical capability. It must be as simple as possible, with proven reliability and validated field history oriented toward a reasonable set of likely, but manageable problems. The design process must include a criticality determination to define redundancy requirements and system failure modes must be understood and fail into safe operational modes. Mark Campbell prompted the discussants to define the starting point for enabling the evolving capability for space exploration medicine.

Discussion:

Mark Campbell: How are the weight limitations for ISS medical equipment and for crew training determined?

> *Mike Barratt*: If medical says it's needed, it goes. As a reference, the current load for medical care on the ISS is 60 to 80 pounds.
>
> *George Pantalos*: The Advanced Resistive Exercise Device (ARED) on ISS weighs over 1,000 lbs., as does the Combined Operational Load Bearing External Resistance Treadmill (COLBERT) because it's needed.
>
> *Mike Barratt*: The requirements for ARED have been reduced, so the weight has dropped. We have removed some capabilities and no longer require field medical training for the crew (we used to require 80 hours of training, but now about half of that). The current time allotted for pre-flight CMO training is 24 hours.

Tim Broderick: What about autonomous robotic medical care and decision support?

> *Mike Barratt*: We are definitely working on autonomy for robotics and increasing training of CMOs. We currently do medical drills inflight. Flights to Mars will consist of mostly training rather than science.

Dwight Meglan: Machine learning (ML) and artificial intelligence (AI) is big now, but much of it has not proven useful for medical systems.

> *Mike Barratt*: At any given time, there are two to three smart diagnostic systems that advise the crew on medical issues.
>
> *Dwight Meglan*: Might device companies be afraid the AI is real and will work?

Kris Lehnhardt: The ground likes control; how do we change that?

> *Mike Barratt*: The communications latency in exploration will impose a change in roles.

Tania Morimoto: What will medical training look like during Mars missions?

> *Mike Barratt*: Mostly simulations and drills, not reading. Currently we do ACLS drills, which keeps everyone current and oriented. It is essential during a mission to have periodic hands-on training with equipment to "maintain muscle and brain memory" – this will be particularly so for surgical procedures.

Alex Garbino: Where will development take place when ISS de-orbits?

> *Mike Barratt*: We want ISS to extend, but can use other commercial facilities (e.g., Bigelow Aerospace, LLC, North Las Vegas, NV). A lot of space medicine is based on relatively short duration Space Shuttle studies, not long duration ISS. We need more physiology and basic science studies in long duration missions.

Tim Broderick: What about changes in astronaut demographics with the addition of commercial space astronauts?

> *Mike Barratt*: The demographics of the NASA astronaut corps have also changed with changes in mission parameters.

Day 1, Session 1, Presentation #2: "Robotic General Surgery Clinical Experience and Implications for Future Surgical Care in Space" – Mark Campbell

Surgeon Mark Campbell reviewed the current state of clinical surgical robotics (SR) based on his clinical practice experience. He noted that rapid acceptance and expansion of SR in the U.S. has led to an exponential increase in the numbers of patients undergoing robot assisted procedures and of subspecialties utilizing SR, since U.S. Food and Drug Administration (FDA) approval in 2000 (i.e., ~1,000 in 2000, to ~400,000 in 2012, to greater than 1,000,000 per year currently).

Andy Kirkpatrick: Canadian clinical practice is still limited to robot assisted prostatectomy.

Mark Campbell: Canada has centralized robot assisted prostatectomies at SR centers.

While laparoscopy and SR are both preferred over open procedures, for some cases there is a preference for laparoscopy over robotic assistance. Most general surgeons still use laparoscopy, though the numbers are changing toward SR. Unfortunately, many facilities have already maximized utilization of their robots, diverting urgent and emergent cases to laparoscopic and open procedures and many residencies and bigger medical centers are still not embracing SR. Hospitals will need to buy more robots to improve patient access.

Based on the current experience with SR:

1) SR does not improve outcomes
2) SR does not increase complications
3) SR may reduce length of hospital stay
4) SR does not increase the conversion rate to open procedures
5) The key reason for SR is the subjective assessment by surgeons that it is easier than laparoscopic procedures.
6) Knot-tying with SR is easier than with minimally invasive techniques.
7) Current clinical SR systems are not acceptable with an exploration spacecraft – they are far too bulky with electricity needs too great for spaceflight.

SR benefits include improvement in surgical technique by increasing dexterity, precision, accuracy and reducing tremor. Haptic feedback in future systems will probably not be an enormous advancement as many are predicting because an experienced surgeon can reliably ascertain tissue tension using visual cues. The ongoing challenges of SR include the applicability to a few selected surgical procedures, the large amount of operator training time and the large amount of ancillary supplies and outside technical support required.

Mark was quick to point out that the surgical assistant (or first assistant as shown on page 8), whose role is to initially position surgical probes and change-out end effectors, is key to the success and efficiency of a SR procedure. Hence, any consideration of doing SR in space needs to design the system with the role of the first assistant in mind. SR systems can help minimize camera movement and use filtering to eliminate hand tremor. For an SR system to be successful in the future either in exploration space flight or ground-based surgery, the systems must be highly reliable with no maintenance required and designed to be easily repaired. He noted that electrocautery may cause radio frequency interference with spacecraft avionics, so there may need to be a laser cautery capability built-in.

He made clear that one may not need an MD to be the surgical assistant. An MD would need to be involved (even remotely) to provide guidance to do the procedure, but a well-trained surgical first assistant with remote surgical oversight would be able to act on the diagnosis and treatment as a surgical first assistance is technically trained but not cognitively trained. Mark also pointed out that wound infection from environmental contaminants is not as big a concern as may be expected.

Tim Broderick: With respect to the suturing studies performed with the SRI International (SRI) robot in the NASA KC-135 during parabolic flight at zero, lunar and Martian equivalent gravity, you did not think [the SRI Robot] was useful?

> *Mark Campbell*: We did not train on the SRI robot before the flight and could not really evaluate its capabilities for spaceflight.
>
> *Rob Ambrose*: Very often, human factors and training are not a high priority in these systems.
>
> *Thomas Low*: Having practice time on the ground would have helped improve the study results.
>
> *Dwight Meglan*: We have many simulator options now for training.

Mark Campbell: We only need a few hours on the simulator.

Tim Broderick: We don't have haptic feedback and have to remain aware of instruments positioned off the screen

Mark Campbell: In clinical practice, it's manageable.

Mark commented that telementoring will be very valuable for an exploration space mission so research on how to most effectively telementor a minimally trained surgical first assistant needs to be conducted recognizing that some personalities are easier to telementor than others. As a final observation, Mark suggested that "de-skilling" advanced medical equipment may make its operation more straightforward and increases the value of telementoring.

Jacob Rosen: What is the inconsistency in preference and why are some surgeons not amenable to robotics?

Mark Campbell: Mostly it has to do with experience and individual skills with technology enabled systems. Hand assisted laparoscopic colon resection is still much faster, and only requires same incision size as SR for removal of tissue. With current technology, you would never drain an abscess or perform a hemorrhoidectomy with SR.

Thomas Low: Limitations of da Vinci (e.g., positioning for access and exposure) and cost effectiveness prevent use in some procedures.

Tim Broderick: For some procedures, the surgeon is forced to move the robot around the operating room table to successfully perform the procedure.

Andy Kirkpatrick: 95% of cholecystectomies are performed laparoscopically due to the huge advantages over open cholecystectomies. Because there is no similar order of magnitude advantage for SR, Canadian centers could not get SR systems without government support.

Mark Campbell: With respect to laparoscopic cases, SR does not affect the rate of conversion to open procedures, and the complication rates are about the same.

Steven Hong: From the current data, in Canada laparoscopic surgeons who do hundreds of gynecological cancer procedures may not see much improvement with SR, though the average surgeon will have improvement with robot.

Rob Ambrose: This is relevant to exploration missions crewed with non-expert surgeon CMOs.

Alex Garbino: How does currency of technical skills come in to play?

Mark Campbell: It's not a problem; it's like riding a bike.

Kris Lehnhardt: With good robots, we may not want or need the CMO to control the procedure.

Shane Farritor: We need to define unmet needs, procedural challanges, and robotic advantages similar to what has been done for the da Vinci surgical system.

Tim Broderick: The da Vinci SR system's databases contain much data that could be analyzed to guide development of training and robotic system capabilities.

Robotic Surgery has a TRL (Technology Readiness Level) of 9 (full application), Surgery in Space has a TRL of 6 (prototype system functions in intended environment), but Surgical Robotics in Space has a TRL of only 1 (unproven concept without testing).

With a forward-looking perspective, Mark speculated that SR systems do not replace the need for a surgeon. SR enhances and enables the existing skills of the surgeon, but does not replace the need for those skills. Any surgical procedure can be done faster and easier with less training, and with less equipment without SR. Given current SR capabilities, SR in space flight is a complex liability. For the future of exploration spaceflight, the goal is to create at least partially autonomous, miniaturized SR that could perform surgical procedures with minimal human assistance. Autonomy is important as a latency of greater than 500 msec makes direct telerobotics non-feasible.

Discussion:

Mike Barratt: Do you recommend that you not have an MD on Mars missions?

> *Mark Campbell*: I'm changing my mind on the need of an MD; we need 6 months of specific training on a procedure to train an MD, but we train motivated techs to do most CMO procedures.

Matt Johnson: What about diagnosing medical issues?

> *Mark Campbell*: We'll need to have telementoring, with advice from ground, so there will be no need for the CMO to diagnose.

Thomas Low: How is the bioburden (due to lack of settling of bacteria in the absence of gravity) affected, do you need to avoid open procedures?

> *Mark Campbell*: Colony counts are more related to filtering than to gravity, little of the technology in the operating room actually reduces the wound infection rate.

> *Tim Broderick*: Data from other countries for procedures such as tubal ligations performed outside the operating room show that wound infection rates can be acceptable even when using clean, but non-sterile techniques.

> *Mark Campbell*: We may only need clean, but not sterile techniques and procedures.

> *Jacob Rosen*: Automation will change dynamics of surgery. Actual manipulation will be automated, but the decisions will be made by the surgeon.

Peter Pirolli: What are the challenges of telementoring in long duration spaceflight? How much can be carried on board?

> *Mark Campbell*: AI and resources for training can be carried out onboard, but every case is different, telementoring for procedures would be very helpful.

> *Dwight Meglan*: SR device companies are very interested in telementoring. Also, they are looking at part task automation and de-skilling to bring improved quality of care in rural and underserved regions.

> *Tim Broderick*: Surgical telementoring worked for NEEMO missions, but its application will be impacted by communication delays during exploration-class spaceflight.

> *Andy Kirkpatrick*: Mentoring is easier with non-surgeons performing procedures such as chest tube placement and US imaging. MDs also do not always make the best mentors. A

mentor won't always be needed, but a mentor can reduce the potential for catastrophic complications. Conversely, reliance on a mentor can hinder as much as help, particularly with communication delays.

Kris Lehnhardt: Placing a chest tube is a short procedure, and the potential communications delay would mean it's over before any advice could be provided or utilized.

Dwight Meglan: Long term planning for SR should focus on autonomous systems that catch issues and prevent mistakes.

Day 1, Session 2, Presentation #3: Roles for Humanoid Robots - Rob Ambrose

Dr. Rob Ambrose described the potential role of a humanoid robot to help lend an extra pair of hands and perform human-scale tasks – "Imagine extra hands that are autonomous and expert." In order to fully define the word "humanoid," (which literally means "having human form or characteristics") he explicitly described human characteristics beyond simply a "bipedal primate". This includes binocular vision (depth perception), hands and feet for grasping, enlargement of cerebral hemispheres, etc.

Rob described that to be human involves four main components: (1) perception, (2) intelligence, (3) manipulation, and (4) mobility. Perception and intelligence are characteristics of the human *mind*, and manipulation and mobility are characteristics of the human *body*.

Tania Morimoto: Do they have to be humanoid robots?

Rob Ambrose: Not necessarily, but it is the subject of this talk. We build a robot animal kingdom of designs. Some applications make sense for multipurpose humanoids.

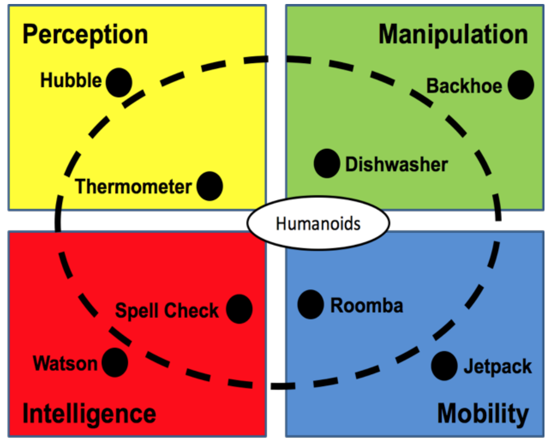
Current humanoid robots are relatively developed in terms of movement and manipulation, but are lacking in sensing and intelligence. When determining whether a humanoid form-factor is the correct choice for a given task, it is important to look at both mobility and manipulation. For certain environments, including narrow passageways, traversing over barriers, and climbing steps, human legs are often the best option. When considering manipulation tasks, it is critical to examine the scale, including the scale of movement, force, power, and resolution and solutions can mix humanoid and non-humanoid features. A collection of single purpose robots can perform different capabilities of humans (both greater and less than human capability). Single purpose robots can excel in limited, specific application but usually need humans to interact and tend them.

The manipulation scales and dexterity can vary by over six orders of magnitude in size, weight and power (SWaP), depending on whether the tasks are being performed with a large boom crane with a hook versus a small cell manipulation robot using a pipette, and humanoids are a good choice if the tasks are in the middle – at the human scale.

Combining mobility and manipulation requires a large degree of coordination, and the addition of a waist helps improve the coordination of upper and lower bodies. Bending at the waist enables the robot to have shorter arms for the same reach envelop. Humans are the only great apes with a waist (other apes that cannot rotate their torso separately from their hips/pelvis), and Robonaut, even when using a wheeled base, maintains a functional waist.

Overall, humanoids have the potential to help move objects or humans (e.g., for ground-based palliative care), perform medical scans, act as a therapist, perform bedside visits, or act as a surgical assistant or midwife.

To be Human vs Humanoid



Compiled Chart of Arm Scales

	movement	force	electrical	resolution	interface
crane	100 m	100,000 N	1,000,000 W	100 mm	hook
excavator					
human arm	1 m	100 N	100 W	1 mm	general
surgical arm					
cell manipulation	0.0001 m	0.001 N	1 W	0.001 mm	pipette

Discussion:

Tania Morimoto: What does the current interface for teleoperating the robots look like?

Rob Ambrose: Virtual reality head-mounted display plus gloves and full body tracking.

Kris Lehnhardt: Maybe the robot should change end effectors without involving a technician.

> *Thomas Low*: The Trauma Pod implemented voice actuated tool changes to support totally unattended patient care.

Rob Ambrose: Humanoids are good for human scale activities and mobility; autonomy and perception are catching up. We have capabilities with telepresence and soon we'll catch up in autonomy.

Dwight Meglan: We did not implement tool changes at Medtronic with our clean sheet design. Also, a significant amount of robot power is needed to manipulate the body wall, but very little is transmitted to end effectors.

> *Rob Ambrose*: Two-point contact is a different class of interaction than we typically employ.

Tim Broderick: Trauma surgery robotics could require much higher forces than general surgery.

> *Andrew Kirkpatrick*: [Surgical] residents often misplace ports, which can require increased forces to reach target areas.

Rob Ambrose: We will also need robotics capable of handling animals for experiments in space.

> *Mike Barratt:* We took a look at telesurgery for animal surgeries for ISS, but with humans available in ISS, it did not provide an advantage. The *cis*-Lunar Gateway may have different requirements during untended periods, and may present an opportunity to use different techniques of robotic interaction with animals.

Shane Farritor: You could put the robot inside the body and not worry about wall interactions.

Matt Johnson: Can you describe the benefits of force versus position control?

> *Rob Ambrose:* Force sensing and control are the key to safety when working around humans. In order to get Robonaut 2 approved for ISS, we constantly monitor three different force sensing loops.

Jacob Rosen: All the services to the surgeon can be automated. There's a spectrum of robotics decisions that need to be made.

George Pantalos: With Trauma Pod, what level of human interaction was needed to prepare the patient?

> *Thomas Low:* The medic put the patient in the pod, after that, the surgeon controlling the robot had the only direct interaction with the patient.

Dwight Meglan: ORIS uses a lightly modified commercial robot, snap on and off arms to enable multi-use/multi-task capabilities. Current surgical arm designs are based on safety concerns.

> *Rob Ambrose:* Arms need to have high strength to weight ratios, but may need to have a taxonomy of robots for specific tasks

Thomas Low: The surgeon needs to have good visualization for success [which also supports human-robotic interactions], but big bulky arms can block the view.

> *Dwight Meglan:* Cameras are dramatically cheaper than before, and now we can also use spectroscopy.

Tim Broderick: Medical robots that don't mimic human stereoscopic vision and bimanual manipulation could enable significant capabilities.

Day 1, Session 2, Presentation # 4: Dexterous Robotic Care-taking in the ISS and its Applications to Remote Surgical Care- Julia Badger

Dr. Julia Badger described how a dexterous robotic caretaker, such as Robonaut 2 (R2), developed through a NASA-General Motors collaboration has the potential to help with surgery in space. R2 has numerous characteristics that enable its dexterity and ability to interact safely with humans. For example, R2 is able to grasp, using its four-degrees of freedom (DOF) thumb and tactile system, and is scaled to successfully use human tools. R2 can also safely share human workspaces due to its series elastic control, joint level torque and force control using six-axis load (force & torque) tactile sensing. R2 uses torsional springs at the joints that have linear [spring constants] K to interact in environments with variable compliance (i.e., with humans). The modular joints contain the drive and feedback electronics and perform analog to digital conversion locally to minimize signal noise

Dwight Meglan: How much do the load cells cost?

> *Rob Ambrose:* R2 uses cost effective [micromachined electromechanical systems] (MEMS) sensors.
>
> *Thomas Low:* There are also newer sensor technologies under development.

Being "human-safe" is critical and must be a priority, especially when the robot is being used as an extra set of "helping hands." Several tests were performed with both collocated and remote teleoperation. Local operator control worked well enough to catch objects, but the latencies associated with remote operation when opening a soft goods panel required four operators and a high cognitive cost. The most current software has moved away from supervised control towards more autonomous control and an affordance template. The goal is to minimize the remote input from a human operator in order to verbally command the robot the same way in which one would command a human crew member. The main challenge of interest is to determine how R2 can be guided (not teleoperated) by a human, especially in dangerous, hard-to-access locations. The Gateway will have about 330 days per year of untended operation. Consequently, the role humanoid robots could play during the period without a human onboard is being examined. Such a robotic tender could potentially manage animal populations and a variety of experiments during these periods.

For ISS caretaking tasks, R2 uses seven-DOF legs with grippers for mobility and interfaces with handrails and the ISS wireless network. R2 has recently received upgraded controls and sensors prior to being returned to the ISS.

Tim Broderick: Does R2 you use LIDAR or structured light?

> *Julia Badger:* We could not find a small enough radiation hardened system, so R2 uses stereo vision.

R2 uses the opensource Robot Operating System (ROS) for software layers above safety critical controls and implements the TaskForce general purpose algorithm development environment. The current software only requires limited human teleoperation for high level (human level) interactions to direct R2 on task. The manipulation strategy centers around user affordance templates, frameworks that use models of objects encoded with afforded grasps and manipulations registered to the robot's frame of reference to enable tool use. This method works with both constrained and non-constrained tasks (softgoods bags, etc.), reducing the impact of communications latency and operator cognitive workload. R2 also now has voice recognition capabilities and can place affordance templates on verbally identified objects, which it can then grasp/manipulate. Using ultrasound guided venipuncture as a task, R2 demonstrated effective handling of medical tools.

Discussion

Andy Kirkpatrick: Was R2 able to actually place the central line?

> *Julia Badger:* It was able to use force control to manipulate the ultrasound probe and place the needle, but it is yet to be determined how much more of the procedure it could safely execute.

Rob Ambrose: The intubation tests went very well.

Tim Broderick: We need to re-consider and optimally design procedures to optimize ease and success of medical care provided by CMO and robotic systems during exploration missions.

Rob Ambrose: For robotic assistance, we need to find a collection of tasks that require a human scale arm to justify including one.

Tim Broderick: The patient is often not considered in the design. We need to include an imaging system that acquires and registers images rapidly enough to allow manipulation of moving and deformable tissues.

Andy Kirkpatrick: Percutaneous tasks will be an important capability to have.

Tim Broderick: We had previously proposed to develop a simple device that incorporated needle/catheter guides and an US probe to facilitate percutaneous access.

George Pantalos: What are the common features of the robots Rob showed?

Rob Ambrose: These force-control robots use series elastic actuators (SEAs). We have developed the tech dramatically over the past decades. Using SEAs improves safety, but some situations still would not be safe for interactions with humans. We need to understand the requirements before committing to a design (e.g., Do we really need four fingers?).

Tim Broderick: What is the ranges of forces R2 can generate?

Julia Badger: R2 is limited to 20lbs, but it could be made stronger. Static endurance is indefinite, but does not have much capability for speed or twitch.

Mike Barratt: Have you been to the user community and asked what they would like? The technology demonstration was fine, but no one asked ISS what they would like to have the robot do. R2 was being developed for some tasks that astronauts may not actually mind doing themselves.

Rob Ambrose: Most ISS tasks are unpopular crew tasks (unclogging filters, cleaning, checking fire extinguishers, etc.); R2 is general purpose so we can evaluate ways to address new mundane as well as dangerous tasks requests.

Thomas Low: We need to define the class of emergency that would require a surgical intervention, we can then design the right robot.

Kim Hambuchen: Some interventions are more common on the ground than in space missions

Tim Broderick: Trauma surgery uses procedures developed to keep a damaged ship afloat (damage control). Based upon SWaP limitations, we may want to develop a system that addresses the damage control model for space exploration first and then work toward non-trauma models later.

Day 1, Session 3, Presentation #5: What Makes a good Robotic Surgical Assistant? - Matt Johnson

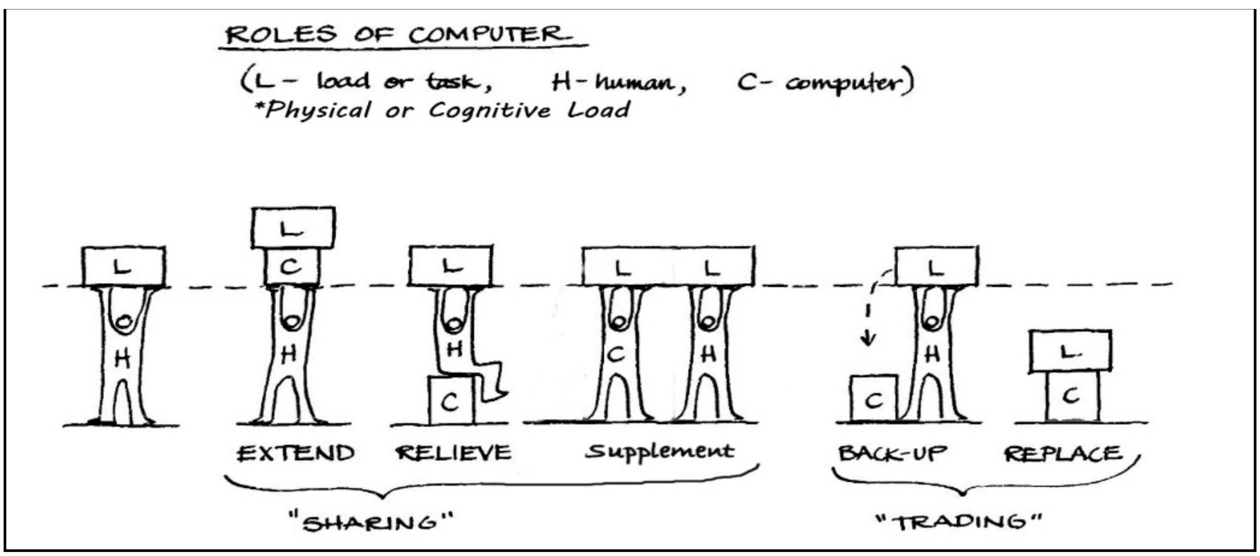
IHMC Research Scientist Dr. Matt Johnson reviewed SR advantages (shortened hospitalization & recovery, reduced pain & discomfort, minimal incisions, improved precision & tremor filtering, magnification, etc.) and disadvantages (loss of true depth perception, no tactile feedback, loss of natural eye-hand coordination). Because SR can augment both physical and cognitive capabilities for the surgeon, autonomy and AI can enable use cases ranging from control by a local surgeon, collaboration between a remote surgeon and local human assistants (perhaps under staffed or under trained) up to, potentially, performing SR with no local human staff. Adding autonomy and AI, however, requires greater sophistication in teaming and collaborative skills, and analysis of the tasks and the required skill levels to perform them. System architects need to design with respect to interdependence (coactive design) to move from teleoperations to autonomy. Interdependence, which differs from supervisory control, encompasses how the human and the system work together. In general, we need to design machines to work well with humans in the environment. For expeditionary robotic surgery, people will always be involved and surgical robots will need to work around the constraints of a medical suite, not the other way around.

> *Rob Ambrose*: It would require a major change [in the process to design the medical suite around the robot].
>
> *Mike Barratt*: Robotics will not replace the surgeon.

Expeditionary spaceflight imposes additional constraints on mass, power and volume and other requirements (anesthesia, drug delivery, contamination issues) beyond those of ground SR, which makes planning for interdependence more critical.

Dr. Johnson organized his presentation into three sections using the framework of interdependence: (1) The different roles of the Robotic Assistant and the da Vinci as an example, (2) The future roles an assistant can play by using Coactive Design to create effective teamwork, and (3) The crucial requirements for effective human-machine interaction.

1. Roles of assistants:



The function of a Robotic Assistant is multifaceted and can play various roles – not just an "extra hand." The term "assistant" is often too narrowly interpreted – commonly visualized as a "junior assistant" who can do some simple tasks. However, the Robotic Assistant can take many forms, as depicted in the figure above. The da Vinci SR systems, the most established and leading example of the surgical robotic assistant, fulfills many of the roles above:

- *extend* human capability (e.g., magnification of small structures)
- *relieve* the loads on the surgeon (by providing hand rest, ergonomic posture)
- *supplement* human limitations (by including a tremor filter to correct for resting tremors)
- *back up* the human during breaks (by disabling the manipulators when the surgeon is not looking at the surgical field)

There are no examples of "replacing" the human altogether in the physical surgical realm (da Vinci) – indeed; Mark Campbell was quoted from his presentation earlier:

> "Robotics will not replace the need for a surgeon".

2. Future roles – *Coactive Design* and *Teamwork*

Having a broader concept of what it means to assist the human reveals very interesting additional possibilities – that of Coactive Design, which allows for Interdependence: where the human and computer support each other, working as a team to achieve capabilities that could not be done independently.

Interdependence embodies the concept that for complex tasks, collaborative teamwork is required. For example, an individual can collect vital signs at a clinic, but to work in an operating room more sophisticated collaborative skills are needed. A parallel to this is in security, where a single security guard can manage a specific location, but for complex tasks, such as special operations teams, complex collaborative teamwork is necessary. This extends to machines, and has particularly high potential with better artificial intelligence. One particular example discussed was the use of remote-piloted vehicles (drones), which have a complex infrastructure of automated and human-controlled systems. These systems need to work together to minimize the cognitive load on the remote operators.

Coactive Design is the focus on this interdependence at the outset of the system design, so that the strengths and weaknesses of human and computer systems are accounted for and managed to maximize the system potential - interdependent teamwork.

Human Needs	**Issues**	**Robot Needs**
What is the robot doing?	Mutual Observability	What is the intent of the human?
What is the robot going to do next?	Mutual Predictability	What does the human need from me?
How can we get the robot to do what we need?	Mutual Directability	Can the human provide help?

3. The Crucial Requirements for Effective Human-machine Interaction

Dr. Johnson then highlighted the crucial requirements for interdependence: Observability, Predictability, Directability. These three factors are critical to ensure teamwork, as a system without these will break the trust of the human in the system, impeding the development of teamwork.

These relationships were illustrated with several examples. The first was the IHMC entry into the 2015 Defense Advanced Research Projects Agency (DARPA) Robotics Challenge (DRC), which required robot-human teams to work together to solve multiple challenges. Example tasks included driving a vehicle, operating an industrial valve, cutting a hole in a wall to access internal structures, walking over rubble, etc. The discussion focused on the latter tasks. Solutions for improving performance during telerobotic surgery, such as managing latency, force feedback, control mapping, etc., do not address additional actions that come with higher levels of automation. Without the key functions of Observability, Predictability and Directability, and thus trust and explainability, team cohesion is broken, and the notion of a robotic assistant falls apart. To force the DRC teams to consider these issues, the teams were provided high bandwidth, low latency communications until the robot entered the "building", where latency increased and bandwidth decreased. During this phase of the challenge the teams were also presented with a surprise task (unplug & replug a cable) to complete without dedicated time to preplan the action. The team utilized a first-person view video feed and 3D model (avatar) for visual control by a single operator. This supported full teleoperations during the driving task, which provided maximum available bandwidth with minimum latency. The robot, however, had inherent latency even when high bandwidth was available. When the robot reached the valve turning task inside the building, the latency rose to 20-30 sec and included communications dropouts. For this and other tasks in the building, the IHMC team developed affordance template analogs. To complete the valve task, the operator directed the robot to move the valve object. The robot then path planned to move the valve and executed the action. The drywall cutting task imposed unpredictable reaction forces to the robot while it used a rotary tool to cut a hole in the wall. The team added higher level autonomous behaviors but compensated for the impaired communications and ensured directability by providing a preview of the robot's planned arm motion to the operator, who could adjust the plan (e.g., depth of cut) before execution.

Thomas Low: Was there any local closed-loop control for variations?

> *Matt Johnson:* No, not for this competition. We also did not have great perception because the drywall cut created so much dust.

We spent a lot of effort on ensuring Observability, Predictability and Directability, which made the overall system resilient. Observability, for example, allowed the team to identify a bent joint based on actual sensor values that differed from the model. Error analysis of the DRC showed that most of the errors resulted from interdependent human and machine causes.

Dr. Johnson provided a second operational example, from his experience with the Aircrew Labor In-Cockpit Automation System (ALIAS) robotic copilot. The ALIAS robot consisted of a set of actuators that interfaced to human control inceptors in the cockpit that could "manually" fly the aircraft. The concept did not follow interdependence guidelines; it provided no Observability and Directability was limited to robot on or off, which made the system inflexible. In addition, the actuators were quite noisy. The system often performed "not human" actions that a real copilot would not, and the human pilot would automatically have a negative reaction and lose trust in the system. This *increased* task-loading and distraction to the pilot, who now not only has to fly the aircraft (or be ready to do so at any moment), but also has to supervise the robot. This critical aspect – that the human needs to trust the robot – is key. It also suggested that simpler more predictable robots would be more acceptable than a more complex robot that does not behave in a predictable way. From a task analysis view, the concept took the task of flying away from the pilots (pilots want to fly), but couldn't perform non-flying tasks that distract pilots (e.g., changing radio frequencies). Essentially, the human became the robot's co-pilot. Using a similar train of thought there is potential to turn surgeons into assistants when using surgical robot. Mundane tasks, such as repositioning arms in the operative field should be managed by the robot, while leaving the cognitively interesting tasks to the surgeon. Surgeons, like pilots, can analyze unanticipated events and use checklists, prior experience and intuition to work toward a solution; robots facing uncertainty would not know what to do.

Technical discussions on some factors that affect the above were latency (with 500ms as the upper limit), and that traditional force/tactile feedback are not critical. A further line of discussion focused on the fact that a robot assistant, and indeed any form of AI, would have to be extensively proven on Earth and demonstrated to be reliable before being flown – although space exploration is often considered cutting edge technology, it is not the place to field test unproven and completely new technologies that are not specific to spaceflight, and indeed can be tested and improved on Earth. Also discussed was that it is critical to define the work, roles and interdependencies in completing a task to then define the purpose of the robot. A "multiuse" robot will have a huge problem matrix; however, building hardware often takes longer than programming solutions. The programmed solutions build a toolset that can be used to solve unexpected problems. However, solutions often involve adaptability, which requires human intervention – scripts never work the same way twice, so the system has to recognize and stop/pause (either by human supervision or automated system). While latency can be partially countered with scripts (that have an adequately defined start/stop points), perception is also a limiting factor – categorizing the different environments (or tissues and structures such as ureters, blood vessels, etc.) – which is a particularly hard problem for robotics: "Registration" – how you deal with moving tissues, glare from light, etc.

The Cognitive Model reviewed was:

Data -> Information -> Knowledge -> Decision -> Action -> Execution -> Loop back.

As a counterpoint, the surgeons explained that during surgery, decisions are NOT stepwise, and are NOT black/white; one has to "be paranoid about what things are or are not" (anatomy), and carry uncertainty that may never be resolved.

Discussion

Tim Broderick: Where would you start? Team composition or team performance?

> *Matt Johnson:* You need to know who the user is and their level of competency, then dive into the work itself. You need to identify the interdependencies, complete a work analysis with the user in mind and then define the team member roles. You need to drive the design based on human and automation role options and think about a tree of options for flexible execution.
>
> *Tim Broderick:* Multi-use and multi-role will create a large number of options and may become intractable
>
> *Matt Johnson:* The analysis reveals the interdependence that is there in the system, whether you account for it or not.

Dwight Meglan: How do you address events that depart from your state machines?

> *Matt Johnson*: We adjusted parameters on the fly using affordances. We also had a scripting mechanism that could replay, but with human supervision, to retune on the fly. It's hard to address automation problems with automation. We need to use each other to complete tasks.

Shane Farritor: How did you account for the plug surprise task?

> *Matt Johnson:* We didn't have a script for that, but we did have primitive tool sets that we could apply to this task. The operator used his judgement to choose which tools to use. We challenged the operator to figure out how to manage surprises before the competition.
>
> *Tim Broderick*: Do they simulate surprises in the astronaut training?
>
> *Mike Barratt:* We do more simulation on expected errors, but it would be better to include simulations with more diverse errors.

Ken Ford: The DRC was ostensibly designed around the Fukushima nuclear power plant mishap. Japan has many robot developers and robots, but none of their existing robots could navigate human spaces. The robots needed to go up and down stairs, walk catwalks, and use human tools.

> *George Pantalos*: Was there a time constraint in the DRC?
>
> *Matt Johnson:* You had an hour to complete eight tasks. Driving was fast, getting out of the vehicle was slow. Wall cutting was a slow task, and you had to turn on and off the cutter before and after making the hole.

Peter Pirolli: How did the scripting work, was it real-time?

> *Matt Johnson*: We could run scripting ahead of the robot's actual motion, but the robot was compliant and loose, so error adds up quickly.

Dwight Meglan: Did you just use SLAM (Simultaneous Localization and Mapping) or rigid body dynamics?

> *Matt Johnson:* We didn't use any SLAM, just relative position and contact. We segmented task plans to know when to pause to allow for a remote intervention.
>
> *Dwight Meglan:* For SR, we need knowledge of the environment instead of just images. Pixels need to be mapped to specific anatomical structures using spectroscopy (e.g., this pixel is a on a ureter).
>
> *Matt Johnson:* We did not have any perception, which could have helped.

Rob Ambrose: Losing sight and registration can cause error. We can't currently interact with moving objects like a beating heart.

Peter Pirolli: A big component beyond skill is perception; you or the system has to identify when something is different or wrong.

> *Dwight Meglan*: We broke the process down as raw data, data processed into information, knowledge, perception, decision, and action. We worked on different solutions for each step

Mark Campbell: Each of those steps may be black and white, but you may have more uncertainty between steps. You have to know with a high level certainty before executing a step.

Andy Kirkpatrick: Also, you have to account for congenital differences.

Mark Campbell: Surgeons need to convert the SR procedure to an open one if they are uncertain.

Ken Ford: An AI system could be trained to have seen thousands of examples and recognize more variants, but that can cause classification errors from lack of understanding the examples in context.

Matt Johnson: My perception and cognition are always working parallel.

Shane Farritor: The last thing the surgeon will do is make the decision for open conversion.

Tim Broderick: AI may just provide the surgeon with a prompt suggesting conversion to an open procedure.

Mark Campbell: A surgeon's pride may prevent him from converting; a robot's won't.

Dwight Meglan: The sequencing provides opportunity to enhance the different components.

Matt Johnson: Maybe the skill set changes from hand-eye coordination to perception.

Kris Lehnhardt: At what stage can you train the robot like you trained the operator?

Matt Johnson: We're not tackling the problem the same way. We need to provide the robot training to identify unknowns.

Rob Ambrose: We found that people with spatial reasoning skills, as well as tai chi practitioners, make good operators.

Alex Garbino: There's a huge research gap in robotics that is just software development. When on EVA (extra-vehicular activity), you have many systems that need to be tracked as well as the task itself. This could benefit from intelligent software (decision support algorithms) with no SWaP penalty. It would be good to have a way to identify when the human needs to be brought into the loop.

Matt Johnson: As an instructor pilot, that was my job.

Alex Garbino: How does your ML translate to medical or surgical systems?

Mark Campbell: If you provide data that can support information processing, that would be helpful. For example, if the system could report to the surgeon: "You are taking more than ten minutes to identify the cystic duct, and you now have an 84% chance that you haven't identified it."

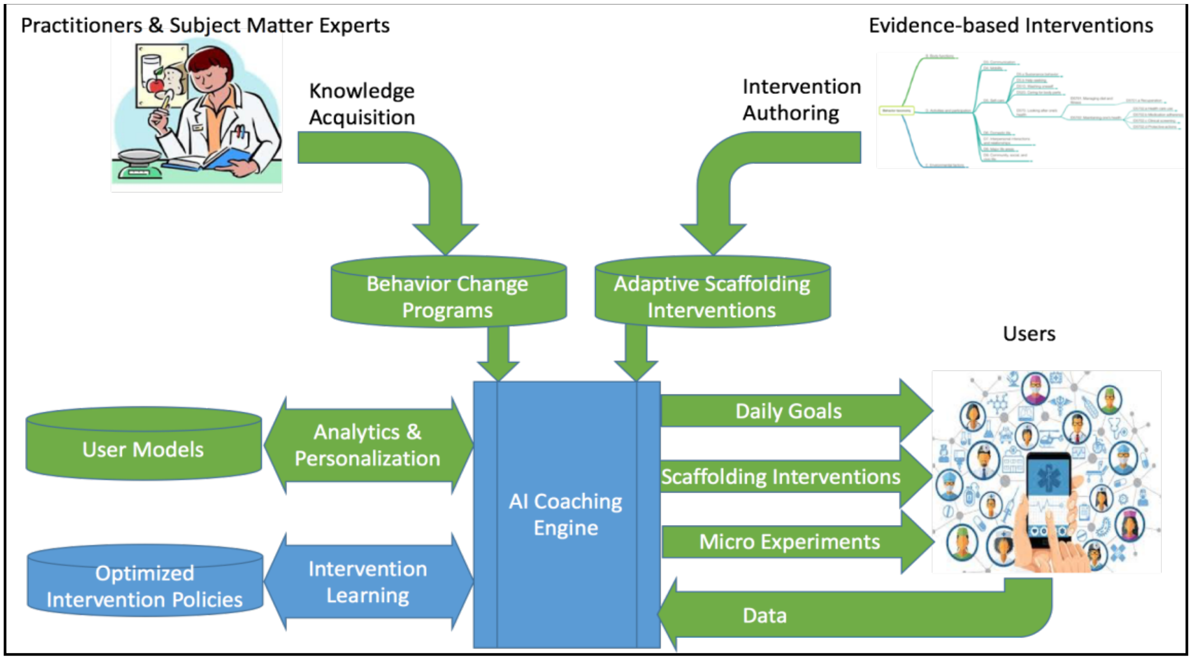
Day 1, Session 3, Presentation #6: Explainable AI in Health Systems - Peter Pirolli

IHMC Senior Research Scientist Dr. Peter Pirolli focused his discussion on the use of AI not to build and drive robots, but rather to build implementations that modify and drive human behavior. This is different from "classic behavior modification" theory, which tends to be monolithic, particularly as it comes to time scales. The AI-based approaches span a large time domain, considering dynamical psychosocial interventions at *multiple time scales* – hours, days, months.

The driving force behind behavior modification is that 70% of healthcare costs are due to modifiable behavior (e.g., diet, fitness, smoking). The main driver for implementation is the opportunity presented by combining machine learning/artificial intelligence (ML/AI) tools combined with The Internet of Things (IoT) and connected sensors provides an opportunity to exploit pervasive, ubiquitous sensing and monitoring. This combination allows data sets to be scaled such that effective interventions can be discriminated from background noise when used in the ecology of everyday life. Health management using ML/AI and IoT devices faces many of the same challenges as crew monitoring and health maintenance, and perhaps surgery, in space missions.

His initial case focused on the use of “Fittle+”, an app-based system that integrates predictive ML/AI models and coaching to create a scaffold to achieve goals using fine grained, frequent interventions that build healthy habits (eat slower, exercise, etc.). This includes evidence-based interventions for behavioral changes including setting daily goals and conducting micro-experiments with the user. The Fittle+ system includes an interactive avatar, analytics, and social network that can connect the user with other individuals who have similar goals. This provides an opportunity to improve computational neurocognitive models, such as ACT-R (Adaptive Control of Thought—Rational), a model initially developed by John Anderson in the 1970s), and apply them to personalized goal adjustment.

Dr. Pirolli explained a number of model-based tools that can help determine which rate/frequency and intensity of interventions work best to produce long term, persistent changes in behavior. These include instance-based learning, which can accurately track performance and adaptively adjust goal difficulty using a day-by-day, exercise-by-exercise predictions for each individual. Adding utility learning enables prediction of an individual’s memory of their self-generated plans to determine strength of habit formation and goal achievement potential. Providing reminders can improve memory and can be used to generate a computational cognitive model that provides a prediction of how much an individual can retain or learn. These approaches can be used to support skill acquisition for diagnosis, procedures, and pre- and post-operative care.



In order to leverage the decade or more of surgical robotics system experience to support expeditionary missions, designers will need to address the five challenges of engineering Human-AI systems, namely:

1. The *Autonomy Paradox* which relates to creation of new tasks and training requirements, and increases in the number of humans involved and their skill set requirements

Rob Ambrose: This differs from the sense-perceive-act loop used in robotics.

> *Peter Pirolli:* The associate-intervention-counterfactual approach has more mechanistic and deeper causal content.

The USN Littoral Combat Ship, for example, incorporated extensive automation in its systems, without increasing crew size. Rather than operating simple systems, however, the crew had to be trained for three times as long to learn to correctly monitor the automation of the onboard systems.

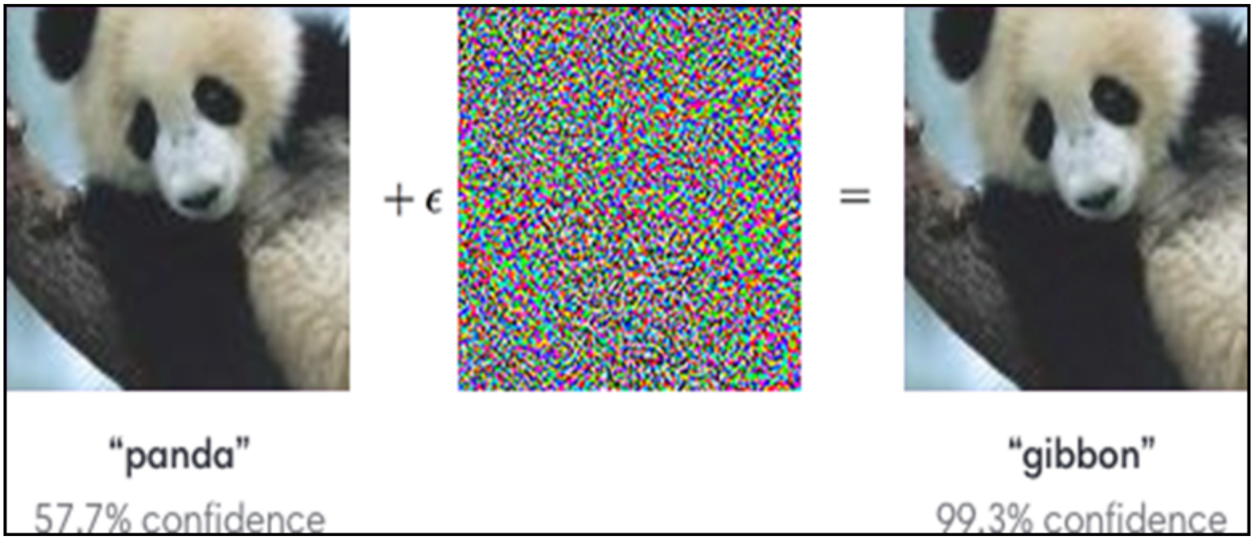
2. Causal Understanding is critical because associations and predictions are not necessarily cause-effect. AI systems still mostly work on *correlations*, not *causation models*; that is, they do not yet implement *counterfactual* reasoning (what would have happened if…).

3. Not all problems are *Suitable for ML.* Deep learning and neural nets works with well-defined tasks that have well-defined inputs, clear goals, feedback and outcomes without long chains of reasoning are best adapted to AI/ML approaches. Phenomena that change over time require an explanation of *what, how, why*, or with little tolerance for error and suboptimal solutions are not good targets for AI/ML tools. We need to do more intensive knowledge engineering, a labor-intensive endeavor, to generate enough data on habit formation and behavior to make them suitable for machine learning.

4. *Explainable AI* is necessary for understanding and improving AI. A traditional AI system that is given a learning set and becomes a "black box" with a trained output is not explainable, and thus fails in a very peculiar and hard to predict fashion. Deep learning algorithms can be confused into making categorical errors. An example system could correctly classify a picture of a panda bear

with 58% confidence, but adding a small amount of random noise caused it to erroneously classify the image as a gibbon with 99.3% confidence, although the images are indistinguishable to a cursory human glance, and remain obviously a panda bear.

Ken Ford: It's important to note that the noise does not have to be intentional.



The DARPA Explainable AI (XAI) program seeks to develop more transparent, AI solutions to make it easier for humans to understand why a specific algorithm did what it did. Current ML/AI techniques are less understandable than desired.

Ken Ford: It's not that performing better causes more opaqueness, rather the method is more opaque.

As an example, Dr. Pirolli discussed a simulated drone learning to drop a package at specific location (i.e., to a lost hiker). The system can learn to accurately select the descent and drop profile based on altitude and location, but it lacks explainability and sometimes fails in a non-random fashion.

5. Engineering *Interactive Task Learning* algorithms is still a challenge for AI. Whereas humans can learn new tasks rapidly – the medical school adage "See one, do one, teach one" was immediately mentioned by physicians on the panel– robots tend to have more difficulty in discriminating the goal from the procedure. Future systems must be able to adapt to a new situation by rapidly combining a set of different skills and techniques to develop a new, custom solution to a unique problem.

The generation and recording of a large data set of telementoring cases with significant constraint on the inputs and communications and amenable to digital processing would support development of supervised autonomy. Interdependent human-AI collaboration requires holistic systems level, human-centered research and development. However, significant progress is occurring in the typically difficult field of "One Shot" task learning.

Ken Ford: "One shot" learning is difficult, but in context of robotic surgery and simulation, it may be more tractable.

Kris Lehnhardt: We can automate suturing using similar examples.

AI-based optimization of health should be considered a part of a holistic medical suite integrated as part of a larger system that includes surgical support (and pre-/post-operative care), exercise, diet/nutrition, behavioral health, medical monitoring, prevention readiness, resilience, AI coaches, tutors and trainers.

Discussion:

Andy Kirkpatrick: A minimally competent individual or system has one way to do something, the expert might have 30 ways in the "bag of tricks" – something AI systems are far from reaching.

Dwight Meglan: We need to have accurate models in simulations. A couple of open source surgical simulations exist now (one from France is active and accurate).

Peter Pirolli: Are people logging telementoring data? At Xerox, learning often occurred during social interactions, so they started logging and tracking them.

> *Dwight Meglan*: Ethicon bought C-SATS company that builds an annotated database of telesurgery. Google's Verb Surgical mined and annotated all the surgical video available on Internet.
>
> *Thomas Low*: Annotation of the video with speech can add a great deal of information.
>
> *Dwight Meglan*: The telementoring would be a trusted colleague narrating the mentoring session.
>
> *Tim Broderick:* Where is the short-term opportunity?
>
> *Peter Pirolli:* Bringing large numbers of cases into the AI system so the system can provide interventions, training and coaching.
>
> *Tim Broderick:* What about natural language processing (NLP) for team interactions between humans and AI?
>
> *Dwight Meglan:* We tried to instrument operating rooms with cameras to document everything for building models, but we need to have support from the hospital system to enable the monitoring.
>
> *Andy Kirkpatrick*: Privacy issues exist, but the ethics can be addressed (e.g., by destroying the video after use).
>
> *Dwight Meglan:* Organizations and individuals both value the raw data as well as privacy.
>
> *Alex Garbino:* Crew resource management and cockpit voice recorders in aviation have been accepted, but in medicine privacy still trumps sharing of individuals' data.

Tim Broderick: The US Army funded development of a decision support system for the trauma bay ten years ago.

Andy Kirkpatrick: Every surgical robot has the capability to record data during cases, but the feature is not used.

Matt Johnson: Do you perform after action debriefs following surgeries?

> *Tim Broderick*: Yes, after trauma resuscitation.
>
> *Mark Campbell*: We are starting to, but it's not required.
>
> *Andy Kirkpatrick*: The World Health Organization has a checklist system for surgeons.

Erica Sutton: We have the System for Improving and Measuring Procedural Learning (SIMPL, Procedural Learning and Safety Collaborative, Boston, MA) debrief and prebrief mobile app. It was designed for education but is used for debriefs.

Jacob Rosen: We need an open system for development for surgical robotics systems (da Vinci is closed). Pilots won't get sued over recorded data, but doctors will be and are reluctant to release information.

Day 1 Consolidation Discussion: Surgical Capabilities Blue Sky

Kim Hambuchen:

- We have to consider the risk of latent communication without on-board expertise. It would be ideal to develop adjustable systems with multiple levels of autonomy that could be flexibly applied depending on the degree of latency.

Andrew Kirkpatrick:

- If we are talking about surgical care, a broad-based general surgeon would be key for a long-duration crew. For this solution, one major concern is the gap of time that would be present since that individual has done surgery. A skill refresher for the crew and surgeon on board would keep that gap minimized.

Mark Campbell:

- We need to keep in mind that "fault-free systems" that we have confidence in can and do still fail.
- The overview by Mike Barratt on operational requirements was eye opening and needs to be taken into consideration for this discussion.

Michael Barratt:

- One thing that has to be considered is what is the acceptable mortality rate for a long duration mission? What is acceptable personal and mission risk when considering performing a surgical intervention, and what is the reasonable risk of death and mission failure vs risk of mission failure if the procedure is not performed?

Matt Johnson:

- People assume, but they shouldn't, that autonomy and AI fill the gaps between what humans are capable of doing. We shouldn't assume this, as humans always fill the gaps.
- We should consider using AI as an observer of off-nominal behavior.

Julia Badger:

- Performance parameters must be met for space for any solution or system being used for long-duration missions.

Tim Broderick:

- Matt's idea of coactive design should be considered from the beginning of the development of a surgical system for long-duration missions.

Kris Lehnhardt:

- We need to define what the term "surgery" means? When we try to visualize surgery for spaceflight, we currently consider it to be similar to the OR and what we know about surgery on earth. We should think about it as interventional medicine. Defining "surgery" in this discussion will better define the decision and design process.

Shane Farritor:

- Crew should have training videos. Cost and weight would be minimal, and we should have the human entirely in the loop for all medical procedures.

Tania Morimoto:

- Extra hands are always needed in surgery. We could think about how robots and humans will interact when it comes to extra hands in a procedure.

Erica Sutton:

- The surgeon should be a trained human surgeon, or at least two crew members trained to deliver surgical care.

Alex Garbino:

- ISS has a short lifetime. Gateway will be limited with respect to manned spaceflight capabilities. We should use ISS or platforms through Bigelow, etc. for testing and assessing capabilities.

Kim Hambuchen:

- Has anyone considered internal robotic surgical implants?

Anil Raj:

- We should also think about defining what a "robot" is. Is it a large machine conducting the surgery, or could it be small and implantable?

Thomas Low:

- If we put surgeons on long-duration missions, we need to find a way to update their skills.

Matt Johnson:

- There will be difficulty when it comes to accumulating enough scenarios for knowledge capture for AI/machine learning, but we could get some willing volunteers to make those videos in traditional surgical scenarios.

Dwight Meglan:

- We should think about concentrating on humanoid robots, then build towards a surgical robot. There is an amazing amount of knowledge in the surgical robotic commercial area when it comes to surgeon training updates (e.g., Intuitive Surgical, Verb Surgical, etc.). We should come up with a mechanism to allow their engineers to provide information to NASA.
- A common simulation surgical platform that is truly open source could be provided not only for space, but also as a societal resource.

- As Matt mentioned, there is a risk of how we can get enough data to train AI, but perhaps we could collect enough videos of anomalies to start to build the database.

Rob Ambrose:

- Some injuries will not be treatable in space, so we should think about methods like deep sleep for evacuation. We should also remember that standard of care is going to be different in space (e.g., fluid resuscitation).

Alex Garbino:

- Solutions like hibernation could take a lot of other resources.

Jacob Rosen:

- There are many tasks in surgery that are repetitive that you could make autonomous.

Peter Pirolli:

- There are huge datasets on surgery and surgical anomalies already present, so how do we get that data and appropriate data/info for training AI?

Dawn Kernagis:

- Given limited space and resources on a long-duration mission, we should focus on development of multi-use tools and expanding their capabilities (e.g., ultrasound) or approaches for creating tools as needed in space (e.g., 3D printing).

Jonathan Clark:

- We should think about how to convert a surgical disease to a medical disease. Other areas of expeditionary medicine have limited tools and approaches for doing just this, and they have been successful. We should be learning from those solutions, too.

Alex Garbino:

- I agree with Dawn that multipurpose tools are more important than a specific solution. On this note, why do we even want to carry hardware when we can focus on bringing software or other ‘soft’ capabilities?

Andrew Kirkpatrick:

- We should use AI to predict risk (decision support).

Tania Morimoto:

- I like the idea of using multiple/smaller robots for specific cases. In this scenario, we could have a surgical robot ‘toolbox’.

Thomas Low:

- We should harness robotics with adaptable systems that can do more than one thing (like an iPhone).

Timothy Broderick:

- Crew will already have an autonomous system and user interface in the vehicle, so we should look at how we can integrate our biomedical robotic system and flight system.

Mike Barratt:

- We need to keep in mind the physiological impacts from the space environment and how that will impact surgical procedures.

Day 1 Summary Perspective: Kris Lehnhardt, Exploration Medical Capabilities (ExMC), NASA Human Research Program

We must recognize that we cannot be totally accurate in our predictions. Even if we were able to predict a medical incident, something else can occur that no one could have predicted and the crew will have to improvise. To this end, NASA developed the integrated medical model (IMM) risk assessment tool. It includes approximately one hundred conditions: either medical conditions that have occurred in spaceflight or that NASA believes have a high likelihood of occurrence in space based on ground risk. IMM gives a paradigm to evaluate risk on ISS, but other exploration conditions are not incorporated into this model. NASA is developing the Exploration Medical Condition (EMC) list to expand IMM and to arrive at a better risk prediction model for exploration. This list also includes ~100 conditions, but not the same ones as the original IMM, for spaceflight evaluated for parameters such as likelihood of occurrence, resource intensive conditions, and futility score (e.g., is it worth expending all resources for a futile resuscitation?) They are trying to further narrow the list to a more manageable subset to guide design medical support systems. Because mission impact is not a well-defined concept, it is not included in the EMC, and we use the Crew Health Index to estimate the how a medical event will affect astronauts' ability to achieve their mission objectives.

Day 2 (October 3rd, 2018)

INTRODUCTION

To open Day 2, Dr. George Pantalos described the experience of flying the Utah 100 artificial heart ("Art Heart"), in a NASA Getaway Special (GAS) canister payload to study how hemodynamic changes associated with microgravity affect cardiac diastolic function (the Hearts in Space experiment). The Art Heart was flown on the STS-95 Space Shuttle mission, which included two MDs (Drs. Mukai and Parazynski) along with Sen. John Glenn. The Art Heart had flown on STS-85, where data was lost due to a failure in the data logging system, and on STS-95 a capacitor failed during the experiment in the Art Heart electronics despite extensive ground testing pre-flight. While valuable data was acquired, Dr. Pantalos stressed that equipment failures will occur and spaceflight surgery will need plan for contingency solutions.

Day 2, Session 4, Presentation #7: With 30 Years of Robotic Assisted Surgery Now Behind Us, What Can We Imagine Lies Ahead? – Thomas Low

Thomas Low, Director, Medical Systems and Telerobotics, Robotic Systems, SRI International (Menlo Park, CA) gave the first presentation of Day 2. He began with an overview of SRI International, which resulted from the merger of the Stanford Research Institute and the Radio Corporation of America (RCA) Sarnoff Laboratories. As an independent not-for-profit research Institute, SRI International (SRI) focuses on 6.3-6.6 research and product development.[1] Past successful projects have included the computer mouse, the magnetic ink used on bank checks, Apple's Siri, medical ultrasound imaging and various robots (both humanoid and non-humanoid) and exosuits. Of particular relevance, U.S. Army Drs. Rick Satava and John Bowersox worked with Philip Green at SRI on the M4 robot for open surgical procedures. When integrated with the Massachusetts Institute of Technology (MIT) endowrist (providing additional end effector degrees of freedom (DOF)) and Jet Propulsion Laboratory (JPL) microsurgery robotics. This enabled M4 to perform robotic minimally invasive surgery (MIS) procedures. SRI licensed its technology to Intuitive Surgical, Inc. (ISI), as a start-up to develop the da Vinci series of surgical robots. SRI is currently working with Johnson and Johnson Ethicon Endo-surgery (advanced instrument design) and Google (machine learning) to develop the Verb Surgical system, the next generation endosurgical robot. For reference, he noted that it took 13 years for the U.S. Food and Drug Administration (FDA) to approve the da Vinci robot for clinical use.

Mr. Low reviewed the history of the development of surgical robotics, starting with the full suite of features available on the two-arm (each with 4 DOF plus manipulator grip) M4 robot. This system was intended for battlefield trauma care, included all haptic (force feedback) servos, stereo video and could be operated over 100 Km using a microwave data link. The system was licensed to ISI in 1995. ISI added a 2 DOF wrist and incorporated unique, patented coordinate transformations to preserve a consistent "intuitive" interface, improving the ergonomics, while

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[1] This is a Department of Defense (DOD) – unique designation where 6.1 is Basic Research, 6.2 is Applied Research, 6.3 is Advanced Technology Development, 6.4 is Demonstration and Validation, 6.5 is Engineering and Manufacturing Development, and 6.6 is Research, Development, Testing, and Engineering Support. SRI, however, continued to develop the M7 field deployable remote surgical robot (transportable in two-40lb Pelican cases) and demonstrated its capabilities during a NASA Extreme Environment Mission Operations (NEEMO) underwater habitat mission (NEEMO 9) with artificially induced communication latencies of up to two seconds to simulate Earth-moon time delays. In addition, SRI has developed a paradigm of remote human supervision of locally automated (a.k.a., autonomous) procedures including ultrasound guided intravenous cannulation.

maintaining the advantages, of existing laparoscopic tools. While this system could be operated over 100 Km using a microwave data link, ISI focused on a locally controlled robotic MIS design rather than one optimized for remote surgery.

In NEEMO 9, a surgeon located in Canada operated the system in an undersea habitat located off the coast of Florida. This proof of concept demonstration also explored the practical limits of communication latency in telerobotic surgery. In NEEMO 12, the surgeon demonstrated supervisory control of the modified system that included limited autonomous capabilities. Over a 1,500 km data link, a clinician used ultrasound imagery to identify the target vessel and plan the procedure, but then instructed to robot to execute the plan. In related NASA C-9 parabolic flight experiments, SRI also built a flight ready system that included improved visual and manual interfaces as well as acceleration compensation to accommodate for changing conditions that could be encountered during an exploration class mission (e.g., turbulence dampening as well as operating in microgravity, lunar gravity, and Martian gravity). SRI has also developed a four DOF microsurgery robot, which has two DOF at each wrist and can deliver 2N of force at the end-effectors with a bandwidth of 25Hz. Furthermore, SRI designed an approach for control of multiple heterogeneous robots from heterogeneous control interfaces and successfully demonstrated it at the IEEE International Conference on Robotics and Automation (ICRA) PlugFest 2009: Global Interoperability in Telerobotics and Telemedicine (Kobe, Japan).

Rob Ambrose: Motion of the aircraft makes robotics more difficult than when in microgravity.

> *Tim Broderick*: Motion compensation worked very well in the aircraft. It also worked well when the surgical robot was installed in a van during terrestrial driving tests.
>
> *Dwight Meglan*: da Vinci and Medtronic robots have active (5Hz) dynamic balancing to compensate for motion.
>
> *Tim Broderick*: Military surgeons participated in this flight campaign and assessed active motion compensation for potential use in performing subspecialty procedures during United States Air Force (USAF) USAF Critical Care Air Transport (CCAT) long haul medical evacuation.

In the DARPA Trauma Pod project, SRI increased the automation of support tasks for surgical robotics using separate robots with voice and gesture control as well as kinematic and machine vision collision avoidance systems to augment the da Vinci. Automated tasks include automated tool changes, waste disposal and fully tracked management of supplies. The support robot could, for example, complete a tool swap that took the scrub technician ~30 seconds in ~12 seconds.

Mark Campbell: In current practice, tool swaps can be completed in less than five seconds.

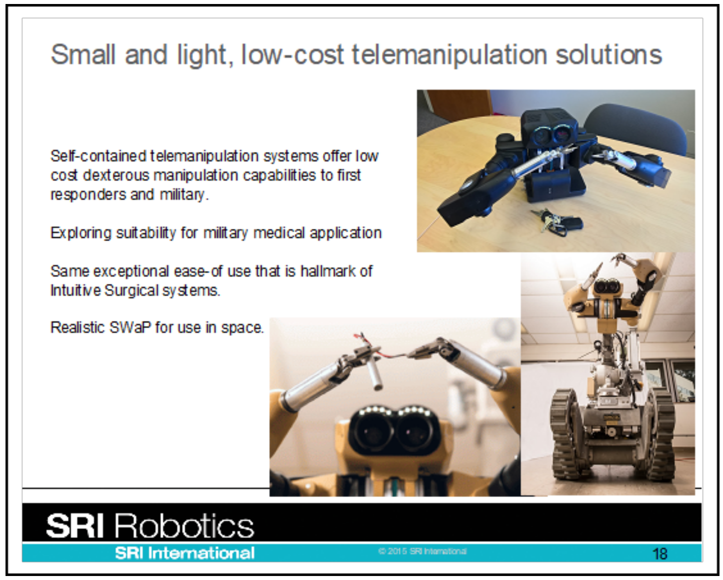
In 20-months SRI designed, developed and deployed the Robominer, a teleoperated humanoid torso mounted on a wheeled-base, designed to place explosives in copper mines under remote, wireless control.

> *Rob Ambrose*: The robot replaces the least skilled, newest hires, the ones they send in to do the most dangerous jobs.

SRI also has developed a self-contained dexterous manipulator package with seven DOF plus wrists, haptics for every axis and a stereo camera head with tilt and zoom (no panning) that has a size, weight and power (SWaP) footprint amenable to spaceflight. They are currently exploring applications for military medical and surgical robotics uses. When attached to the Taurus tracked robot, the package could augment bomb disposal activities. The aim is to create a low-cost, modular telemanipulation system with a goal of reducing the per unit cost down from about $250,000 to under $50,000.

Dwight Meglan: There is a startup in Boston developing a micro robot with two arms that can be inserted through a single port.

The next frontiers in robot-assisted surgery will likely incorporate machine learning (ML) or artificial intelligence (AI) elements and deep learning, leveraging big data techniques to improve future robotic surgical systems. A number of significant issues arise, however, with AI augmentation of surgical robotics, such as regulatory requirements, validation of reliability, and provability and explainability of the AI's function, intention and actions. Potential liability issues and user acceptance (both patient and surgeon) also will require resolution. Even with these recent advances, it will be a long time before AI enabled robots would take direct control of the instrument or manage the full surgical case. The key is to keep the surgeon in the loop and use proper design to enable the surgeon to work seamlessly with automated assistance and guidance.



While AI advances could identify critical anatomy, provide guidance in real-time and eventually overcome latency and bandwidth issues for distant remote surgery, enhanced visualization will aid in intraoperative differentiation of healthy and diseased tissue.

Tim Broderick: What about laser tissue welding?

> *Thomas Low*: Suturing is a difficult problem for telerobotic surgery, and there are potentially better ways to close tissues defects than suturing depending upon the application (such as robotic tissue welding of eye lacerations developed in a prior Army project).

Virtual reality (VR) has already made inroads into medical applications, and could potentially supplant the surgical robotics console using low latency, wide field of view, 3D high definition (HD) video, and high accuracy hand and head tracking. Low cost (~$400) consumer VR systems (e.g., Google, Facebook), the current standards, while adequate for first generation evaluations, do not currently meet requirements for clinical use. The visual quality and overall weight need improvement, which will come with non-medical market consumer demand. We can use newer commercial game controllers for inputs, but availability changes rapidly as the technology advances. VR taps into our mind's capability to create mental models of what we see with enhanced perception of space and size. These models exploit the mind's data fusion and movement coordination capabilities to help the surgeon to recognize and avoid damaging critical anatomic features. Visual range relates to the field of view of the camera, but immersive VR places high technical demands on image response to the wearer's head movement to avoid nausea. Non-medical consumer systems (VR tourism, meetings, social media) by well-resourced companies will drive the technology development, however, to the benefit of robotic surgery.

Rob Ambrose: We use VR trainers on ISS, but they will soon be out of date and need to be updated. Commercial VR systems currently available include integration with head and hand tracking and 3D visuals, which we had to develop ourselves previously. The video lag needs to be kept below a threshold of 3-4 msec.

Commercial development began with 360-deg video and 3D and has moved on to interactivity. Altering the prerecorded stereoscopic image in response to slight head movements will restore perceptual cues such as parallax and reduce nausea. The final step would be a true avatar inhabited by the user who will be able to experience and interact with a far-off place in real-time. A similar path exists for robot assisted surgery (RAS). VR training has made inroads and will likely extend to preoperative planning and procedure rehearsal. Students could explore recordings of expert surgeons performing procedures and, eventually, replace the RAS console and enhance rather than impair surgeon interaction with the patient and OR team.

Matt Johnson: VR can improve performance on manipulation tasks, but is not any faster for navigation tasks.

Dwight Meglan: Eye tracking is a major component necessary for improved VR; the Magic Leap headset includes eye tracking, for example.

Mike Barratt: For spaceflight, we want a small envelop, and don't need a 48in reach. We'll also need an enclosure to contain the system and surgical debris.

Dwight Meglan: da Vinci has capabilities for null space repositioning and rearrangement during procedures.

George Pantalos: You'll have both FDA and flight approval requirements. The military can defer the approval process, how about NASA?

> *Mike Barratt*: NASA has discretion to use without FDA approval.
>
> *Steven Hong*: The DoD can accelerate the process, but 95% of time requires military use requires FDA approval.
>
> *Tim Broderick*: DARPA helped the FDA set up a committee to address the need for faster approval for important national security applications. We have autonomy and path planning in other medical devices (e.g., radiosurgery, ventilators, LASIK).
>
> *Thomas Low*: The problem is in the black box machine learning (ML).
>
> *Tim Broderick*: The term "fuzzy logic" has caused difficulty with FDA approval of autonomous systems in the past such as oxygen regulation in ventilators.
>
> *Shane Farritor*: It's non-deterministic.

Thomas Low: The DARPA ALIAS program sought to reduce certification requirements by aiming to make a robot as good as a human pilot (not an autopilot).

> *Matt Johnson*: The ALIAS pilot, does not have human judgement, though.
>
> *Jacob Rosen*: In order to lower the bar for approval of new robot surgical devices, the software needs to be more transparent. The hardware seems to be easier to get approved.

Dwight Meglan: There's a fully autonomous hair transplant robot.

Thomas Low: Mathematical proofs of deterministic autopilots are feasible, but not for ML. We need to have probabilistic validation and approval.

Day 2, Session 4, Presentation #8: Challenges to Enabling Safe and Effective Robotic Telesurgery in Expeditionary Surgical Care – Steven Hong

For the final presentation of the workshop, U.S. Army Major Steven Hong, MD, began with a quotation by Neil de Grasse Tyson, "When the country is exercising its geopolitical interests, science piggybacks that - to great gain, I might add. And - that has been that case forever." Military needs for telerobotics for expeditionary medicine drove advances in the science and technology that led to commercial telesurgical robotics. Telerobotics specifically aligns with DoD goals to maintain military readiness and maintain global presence as well as provide enhanced capabilities and strategic operation advantages. Currently, the DoD has thirteen da Vinci Si and seven Xi systems installed in fourteen hospitals, the caseload and distribution of usage by a broadening range of specialties continues to increase. Each da Vinci system collects a significant volume of data from every case, which could be mined to identify and correct issues in robotic surgery. Intuitive Surgical, though, holds this data closely, limiting the ability to leverage current practice data to support future military needs. The Army battlefield of the future, however, is already here as evidenced by implementation of multi-domain battlefield concepts and constraints on medical resources. This includes limited freedom of movement for conventional vehicle platforms for emergency air and ground medical resupply and casualty evacuation.

Because of the wide dispersion of maneuver units and area of denial (due to chemical, biological, nuclear, radiological and explosive threats) and the six-dimensional threat environment (air, land, subterranean, maritime, space and cyber), air superiority cannot be assured. These environments have created a the "new normal" with manned assets in high risk areas that can force delayed evacuation and prolong field care. Unmanned systems could address these constraints with potential for improved speed, maneuverability, endurance, and operational footprint. As a result, Big Army Science and Technology has placed a high emphasis on surgical robotics for prolonged field care by issuing a Program Objective Memorandum (POM).

Of note, the battlefield of the future has many of the same constraints and requirements as expeditionary spaceflight, including limited or delayed options for evacuation to definitive care, although signal latency, bandwidth and gravitational variations are not as much of a problem.

Kris Lehnhardt: For patient data we are trying to provide the same information that we have on the ground.

Battlefield applications for man machine teaming need lightweight, durable, deployable robots with small logistical tail. Current systems (i.e., da Vinci) are not ideal, but improving with single port devices. The Army is currently testing the SRI Taurus Dexterous Telepresence Manipulation System modular medical robot T2 variant to evaluate the utility of VR for the surgeon interface. VR simulation with the da Vinci has demonstrated that a signal latency of 250 msec increases error rate and that procedures become tedious with a 750 msec delay. VR could provide a cost-effective (driven by commercial markets), portable solution with potential for low-bandwidth transmission, scalability, and minimal logistical tail. In addition, for remote deployment or locations where the user cannot hear or otherwise sense contextual information, VR and AR interfaces can enhance situation awareness (SA). The next step would use machine learning (ML) to develop and implement semi-autonomous robotic surgery protocols. While we want to have the robot perform repetitive tasks very well and reliably, the real challenge in AI is the execution of unplanned or unknown tasks. Using AI with reinforcement learning and domain adaptation in embedded AI modules could begin with surgeon led tasks followed by supervised actions and eventually, a hierarchical execution strategy where the surgeon issues "command tasks" to the AI-enabled robot rather than directly controlling it.

Tomas Low: No two patients are the same, so every case has unknowns.

There is a lot of correlation with "autonomous" vehicles, which will move from added semi-autonomy, followed by societal buy-in (trust) before full autonomy will be accepted operationally. The TraumaPod program ended before reaching societal buy-in for surgical robotics, but was already aiming for full autonomy. We can use Stanford University's Testbed for Rendezvous and Optical Navigation (TRON) program to bridge from DoD 6.2 to 6.5-6.6 technology levels while developing strategies for regulatory approvals.

The domain of microvascular procedures (e.g., repair of vessels <=8mm, which cannot be ligated without untoward effect) provides an ideal model for telesurgery. It is trauma relevant, requires skilled assistance, has limited anatomic variability with relative tissue stability and repositionability, and finite, discrete procedural elements. The required tasks are repetitive and can be executed with non-MIS robotic systems. Microsurgery currently requires two subspecialist surgeons, but we could replace one with a telerobotic assistant where the remaining specialist can jump in to take control, if needed.

Thomas Low: Telesurgery is difficult in the civilian world because medical licenses don't cross state lines.

When caring for local, non-US civilian patients when deployed, we can't send them stateside for definitive care, and we can't discharge them into the community with open wounds. Using microvascularized tissue flaps for wound coverage, however, can support safe discharge to the community after two-weeks, but the surgeries are exhausting for the surgeons. As a result, we have begun to re-think the process of vascular anastomoses; new technologies such as vascular coupling devices can reduce procedure time by ten times in comparison to conventional suturing.

Maj. Hong concluded by reviewing principals for expeditionary robotic surgical care: move the ball forward, define the scope, incorporate semi-autonomy with a team approach to enhance robotic-surgeon interactions, and engage the end-users early. Case in point with respect to end-user input, in an Army study using the Microsoft HoloLens for telementoring developers found that medics took the system off because they perceived that it was nagging them. For space surgical applications, there exists a continuum ranging from full autonomy, semi-autonomy, robotic assistance, robotic mentoring and no robotic systems. The entire range of systems have potential for specific space missions and applications.

Discussion:

Ken Ford: We need to be careful with the use of the terms "autonomy" and "automation", which have specific standard meanings in the AI and robotic communities.

Matt Johnson: Keep in mind that solving one design problem does not necessarily solve other ones.

Andy Kirkpatrick: Do good macrovascular surgeons make good microvascular surgeons (and vice versa)?

Steven Hong: Our goal is to distribute TRON to multiple centers and for use in multiple specialties, but we can use other interventions for larger vessel repairs.

> *Thomas Low*: Such as hemostatic agents, balloons, and other methods.

Dwight Meglan: How do you deal with sterility? Do you just bag the end effectors?

> *Steven Hong*: Yes. It will use standard da Vinci tools for an achievable first step.

Mike Barratt: We won't be doing standard microvascular procedures on Mars. The coupler concept, however, would be useable. Transport from orbit is high-g with a final impact deceleration, so we can't rely on fragile repairs.

Thomas Low: What are the bandwidth limitations in space communications?

> *Mike Barratt*: Orbital satellites can be used to improve bandwidth.
>
> *Julia Badger*: We are planning for only eight hours per week of high bandwidth when the Gateway is untended (50 weeks/year), with latencies that vary by hundreds of msec.
>
> *Thomas Low*: We could use 3D point cloud representations of the operative field to reduce bandwidth requirements.
>
> *Rob Ambrose:* You can then paint an image on the point cloud and use multi-camera fusion for control of variable viewpoints to move within the transmitted image space, rather than send high bandwidth real-time video.
>
> *Dwight Meglan*: We are using technology from automobiles for visual fusion and viewing from alternate viewpoints without sending additional data.

Tim Broderick: We previously considered internal body cavity cameras with laser detection and ranging (LIDAR) to improve internal SA.

Day 2 Consolidation Discussion:

What was the one thing (or things) you heard over the past day and a half that was (were) most intriguing and most promising to advance the initiative of surgical capabilities in space?

Steven Hong:

- Realizing the different constraints associated with spaceflight, we should identify the similarities across space and DoD expeditionary operations.
- For the presentation on human robot interaction, we have always imagined the surgeon controlling the robot, but thinking about the robot acting as a mentor for a non-surgeon is a different and potentially valuable way of thinking about this approach. We need to distinguish between surgeon directed vs. robot-guided aid.

Mike Barratt:

- Application of just-in-time training, integrated consultation with latency, anatomy identification that a physical system can assist with, seems very real and possible if we really do define mission parameters.
- We should embrace what the holistic risk picture looks like, and how it defines the decision process.
- There are a number of fantastic space analogs that keeping coming up, and we should think about using those analogs as a test bed for future capabilities.
- Autonomous surgery is in its infancy and needs to be integrated into NASA's holistic risk program. Analog testing of robotic surgical systems, like occurred on NEEMO expeditions 7, 9, and 12, is a viable way to evaluate candidate technologies. Analog environments, including the ISS, should be considered as an enabling test bed for surgical robotic systems.
- We can be trained on any procedure, but it may take 6 weeks to reach proficiency. A robot may be able to learn something quicker.

Andrew Kirkpatrick:

- A general surgeon is still going to be needed for the short term, but I look forward to learning more about the possibilities enabled by more complex human-machine surgical teaming possibilities.
- Previous studies have shown that zero-g doesn't have a huge impact on performance in activities.
- The TRON and second generation TraumaPod developments are addressing critical human needs for terrestrial and space medicine (e.g., acute mass casualty bleeding control).

Julia Badger:

- We should focus on making surgery less complex. Given the human-robotic teaming possibilities we have discussed, we should also think about how to make a procedure simpler and more dependent on multi-use tools.
- Robot assisted surgery for space is still far away.

Matt Johnson:

- It will be critical to think about the different roles that the human and robot systems might play. Engineering and cognitive science are inherently interdependent. To assess these roles, we need to think through medical operations from simple to complex and how those roles could shift dynamically.

Erica Sutton:

- I still think a trained surgeon will be a critical crew member, or at the very least, two non-medical crew members who have undergone extensive training.
- Robotic assisted surgical systems could help a less trained provider perform procedures proficiently, and could expand to more complex procedures with telementoring support.

Dwight Meglan:

- Recent developments in human machine teaming have been very promising (e.g., the DARPA robotics challenge). Part-task automation of specific functions today will help push the technology forward.
- We could train more on 3D models/manikins to evaluate telerobotic simulation as well as evaluate effects of control latency, which has only been done up to 500 msec. Using simulators can improve skills even without automation.

Anil Raj:

- I liked the previously mentioned ideas of converting surgical problems to medical problems, and using existing or multi-use assets on the spacecraft.
- Human-Machine teaming with respect to assistance by a human surgeon is also something we should consider; i.e. limiting surgical intervention by converting to medical management, using automation to assist less-skilled practitioners perform as skilled experts and using decision support assistance to augment crew autonomy.

Mark Campbell:

- It is important that we can communicate between the surgery and AI/robotics communities. It was apparent that each community has a distinct language they use that does not crossover well. Understanding what the other team is talking about will be critical as we design solutions.
- We need true synergy between AI/robotics and medical/surgical teams management.

Jonathan Clark:

- In the aviation world, we use synthetic vision to assist with operations and improve understanding. Perhaps we could consider bringing in additional sensing through effectors to assist with visualization.
- We need an assistant that can do multiple tasks, besides just surgery (e.g., one that can complete repairs in a damaged or smoke filled compartment).

Jacob Rosen:

- To increase delivery of care, we will need to change the current paradigm. Some practitioners will become obsolete. We will need to have a multidisciplinary approach, and the human element will always be the best decision maker (better than any algorithm).

- Matt's presentation on coactive design brought fresh ideas. The time constant in this field is 10-15 years, but we need to look at something relatively near term.
- NASA needs to be very clear about the engineering/decision process and requirements. We are in a new era of information revolution which is having a profound effect on medicine, from molecular to cell, to tissue, to organism, and to organizations.
- We should consider a robotic system for glove box experiments which are currently done by humans.

Dawn Kernagis:

- We should always place an emphasis on the end user and human centered design by keeping the crew in the discussion loop and decision process given the relatively short time window to assess and set design requirements.
- Rob Ambrose had mentioned a pod or suite with small embedded sensors/cameras– I like that idea.
- Matt's presentation on coactive design, and the emphasis on incorporating it and AI from the start, is something we need to take into consideration.
- We should look at operational medicine and DoD overlap for field solutions, as Jon mentioned.

Kris Lehnhardt:

- We should define "autonomous". When ExMC thinks about autonomy, they are thinking Earth independence. There are different meanings for autonomy which depend on context and user perspective, and we need to be clear what autonomy means. Earth independence is what NASA considers autonomy. NASA heavily exploits different analog environments.
- NASA missions being considered include partial gravity lunar or Martian surface operations as well as microgravity on a deep space transit or at the Gateway outpost.
- Mass constraints are going to be significant for a long-duration or Mars mission. Pre-deploying supplies to Mars is going to be difficult. Probably not on Gateway, but once a presence on the lunar surface is sustained, we will have the ability to pre-deploy supplies, which could give us the ability to conduct this type of testing and development on the moon surface.
- One option is to consider using an existing mission need on the ISS as a test bed for robotics instead of humans, such as need for manually configuring flow cytometer or some other diagnostic procedure. The melding of human and technology is going to be critically important.

  Mark Campbell: We should think about using the term "Earth-independent" vs. "autonomous."

Shane Farritor:

- The AI question is open ended and will require development. I have no idea what the robots for spaceflight will look like 10-15 years from now, but AI will be valuable to enable minimally trained crew to perform complex tasks.

Tania Morimoto:

- Defining the problem will be critical. Specific problems need to be narrowed down for specific solutions. We need to design for human input to automation systems.

Kim Hambuchen:

- We should think beyond our current concept of surgical robotics as the technology is so dynamic and evolving. Intelligent automation assistance is "low hanging fruit", but software verification & validation is crucial.
- Smart processes injected into the da Vinci doesn't make it a robot, but rather a surgeon's tool (teleoperated manipulator). We should think outside the da Vinci and manipulator box. For future spaceflight assistive surgery, there may be new ways of thinking.

Thomas Low:

- Thinking about AI and intelligent assistance is going to be key – rather than placing the AI between the surgeon and the patient, the human should fall between the AI and the patient to correct AI errors and act as the final check and balance.
- We should consider how to give the crew real-time guidance for their situation at hand despite communications delay, and exploit decision support capabilities. Continuous update of system status is essential.

Peter Pirolli:

- It might be feasible to design an AI product that can coach or mentor, and give it more context using data from other sensors.
- We should think about how to augment the person with VR or visualization techniques since novices won't see the anatomical landscape like an expert would. We should think about how to provide additional information that would allow them to look at things like an expert. We can train people for standard procedures, but have to be able to provide help for non-standard events.
- It seems like it would be difficult for an expert to transfer skills in a zero-g scenario. How can we build an AI coach to deal with the situation as it will be in zero-g? The crew know the environment (microgravity) but don't have the special skills (surgery), so that should be the focus. If you pair AI with humans in games, you can identify new skills and techniques.

Mark Campbell: The three-year Lewis and Clark expedition only had one death (appendix).

Thomas Low: Is electrocautery possible in flight?

Mike Barratt: It would need to be vetted and verified

Thomas Low: Would microgravity itself make things more difficult?

Andy Kirkpatrick: Organization is affected, but it doesn't increase effort much.

Mike Barratt: We can train astronauts to do tasks fairly quickly, which may be also true for AI. How you adapt for a two-week flight is different than for months long missions.

Peter Pirolli: The training should occur in space.

Mike Barratt: Yes, we need to have simulator capabilities on spacecraft; we already have a robotic arm and a Soyuz trainer on ISS.

Tim Broderick: I agree that the surgical expert or crew medical officer needs to have zero-g skills in addition to surgical skills to effectively handle scenarios. We could consider allowing an AI robotic system to develop microgravity/biomedical skills for our "robotic toolkit" in the Gateway or lunar outposts when uninhabited, and then translate these skills into novel ways of solving surgical care and biomedical research problems in microgravity. We have noticed that some people are more skilled in microgravity than others.

Michael Barratt:

- The crew do learn basic techniques, and sometimes zero g can work against or with them.
- How you adapt acutely is very different compared to long duration exposure. Yes, it helps with acute tasks but not long duration skills.
- They have a robotics trainer on ISS and a simulator. We could use these tools to do test runs and assess proficiency.

Timothy Broderick:

- Coactive design in crew training keeps coming up, we need to get a team together from both the manned and robotic space communities (surgery and robotics as well as astronaut and robotics). Our greatest capabilities and mission successes will come from man and machine, not man or machine.
- Deployed sensing and imaging in a surgical suite are good ideas.
- Station keeping that includes biomedical research with a self-assembling robot or system would be a good idea to test out on Gateway. Medical devices have to be ultra-reliable for it to be of value in austere environments. We can expect suboptimal performance in the development process- it's only natural. Suborbital flight opportunities may be a viable analog testbed.
- Finally, we also need to connect to funding sponsors with an interest in advancing the field.

Rob Ambrose:

- We should think about modularity. Yes, robots will fail, but "surgery" on robots should be easy. Perhaps a robot that can take itself apart, or repair itself, or even swap out parts. This concept could be especially critical for exploration missions.
- Robotically conducted animal surgery during untended periods on Gateway outpost may be a viable use for surgical robotics.

Ken Ford:

- Each space environment is unique, LEO, cis lunar, lunar surface, and Mars surface, hence, robotic human interactions will be unique to each. Astronauts need to be involved early in the robotic human interaction process.
- Cognitive orthotics are a valuable option. Gateway mission is ideal as it could be robotic tended, as the majority of the time there won't be humans, and robots could fill a vital need.
- The lunar surface would be sensible first application and testing.
- We should exploit interdependence and facilitate teaming between human and robotic devices. It often gets swept under the rug that this can't happen after the fact – we should be thinking about coactive design from the start.
- Crew should be involved in preparing the training process from the start, perhaps even in a leadership role.

James Hury:

- Robots have always been associated with either mundane or dangerous tasks. It will be good to thinking about the robot augmenting the human with futuristic sensing or other capabilities.
- The focus should be on routine (mundane) tasks and on serious emergency asks.

Extended Discussion

George Pantalos: Lessons from reliability studies is that sooner or later things break or work less than optimally. Humans can adapt to suboptimal performance and we will need to design for suboptimal degradation into training for humans and AI.

> *Thomas Low:* The human in the loop has the ability to compensate, AI could do the same, but also must be able to clearly communicate its state with the humans before the system fails.

George Pantalos: From a funder's point of view, what are the feasible concepts?

> *Jon Clark:* We should give feedback to J. D. Polk, NASA's Chief Health and Medical Officer.
>
> *Dwight Meglan:* I would like to see a zero-g surgery simulator with correct physics. We have no simulation for surface tension clumping of blood. We need to make a computational simulation, validate it in parabolic and then move to ISS testing.
>
> *Tim Broderick*: We did simulator work in 1990s that could be leveraged.
>
> *Mark Campbell*: Parabolic flight is also fairly artificial because of its limitations.
>
> *George Pantalos*: But it could be used for development before spaceflight.

Tim Broderick: Are there any pending solicitations coming out?

> *Kris Lehnhardt*: HRP has focus on ExMC technology development and demonstration for high TRL ground systems that are low TRL for space. Developing new systems doesn't match NASA's goals for the next couple of years. TRISH may be better sponsor for this development level.
>
> *Thomas Low*: Can you use smaller aircraft instead of the C-9?
>
> *Andy Kirkpatrick*: The Falcon jet can give you 20 parabolas.
>
> *George Pantalos*: Suborbital flights can give you four minutes of zero-g. BlueOrigin is already flying science payloads, and human investigators may start flying next year.
>
> *Thomas Low*: Is it cheaper?

Jon Clark: Is the R2 on ISS now?

> *Rob Ambrose*: No, but may be headed back up in about one year.
>
> *Jon: Clark*: Crew time is the most valuable thing on ISS, can you off load tasks with R2 like chest compressions?
>
> *Rob Ambrose*: The robot could be the student with the ground-based surgeon demonstrating the task. It makes sense in LEO, but not with longer delays. The Gateway is not designed for full-time manned ops. Is there a role for animal research in Gateway?

Jacob Rosen: We demonstrated that ISS glovebox robot surgery with rodents was possible even with added time delays, but it was not further developed.

Rob Ambrose: People will only be at Gateway for two weeks/year.

Mike Barratt: We don't have the operations defined for Gateway yet, but we may be looking at longer term manned missions.

Julia Badger: The Japanese are developing automated rodent laboratory. ECLSS will be maintained in the Gateway at some less than normal levels when untended

Day 2 Summary Perspective: Johnathan Clark

Given that the guidance from NASA's Chief Health and Medical Officer, Dr. J.D. Polk, was to consider prime drivers for all human spaceflight are *Mass, Power, Volume, Time, Money, Risk, and Crew Competency*, a practical approach for robotics on space missions, including minimal invasive surgery, should be to offload crew time (doing routine or mundane tasks) or reduce risk (procedures where robotic assistance) to complement or augment the crew (extra set of intelligent hands). Upcoming deep space NASA missions include the Deep Space Gateway, a small (ISS module size) habitat at a Lagrange Point occasionally occupied by human crew, which would be an ideal opportunity for robotic tended systems. One very promising opportunity would be a robotic surgical system that could perform tissue sampling. It is very likely that a surgeon would not be a skill set for deep space mission crew complement. In addition, the communication latency issue of tens of minutes would allow a robotic surgical testbed in a non-mission critical task (biosample acquisition), evaluation of micro/partial gravity constraints to surgical procedures, and evaluation of failure modes of a robotic surgical system.

Recommendations

1) Because of the communications latency during exploration missions and periodic loss of communications, crews need to be prepared to execute healthcare procedures autonomously (independent of Earth involvement), but they should still take advantage of guidance from mission control (including diagnosis and treatment plan) when possible.
2) Equipment, instruments and supplies to be used for surgery during a space mission should be selected based on proven capability and reliability during Earth-based evaluation and clinical experience.
3) A human-inspired, dexterous robot might have the right combination of functional characteristics to be useful for assisting a human surgeon.
4) A robotic assistant in surgery and other healthcare procedures should be able to perform simple tasks on verbal command from the surgeon or crew medical officer also described as an "expert and autonomous set of responsive, helping hands."
5) A robot participating in a surgical procedure or other healthcare procedure may experience a failure mode. That failure mode must be to a "fail safe" condition that does not put the crewmembers at risk. The failure mode must have an alternate mode of operation, be easily identified, and corrected.
6) During an exploration mission, periodic hands-on training for the surgeon and surgical team (including the robot) is needed to maintain "brain and muscle memory" of the tasks to be performed during a procedure.
7) A well-trained and experienced surgical assistant may be capable of performing the needed surgical task with the assistance of a dexterous robot, but input from a surgeon will still be needed to confirm the diagnosis and develop a treatment plan.
8) The functional presence of the robot cannot obscure the vision of the human surgeon.
9) There is a persistent need to have better communications between the astronaut and robot developer communities to create robots that will provide the maximum task performance with minimum interference or involvement of the astronaut.
10) Development of interdependent teamwork between the surgeon and assisting robot is needed.
11) The use of artificial intelligence to guide a surgeon and a robot during a surgical procedure is a very complex consideration. The greatest value of AI may be to provide guidance for nominal procedures and suggestions when outlier situations are encountered.
12) Obtaining reliable proprioceptive alignment is key for laparoscopic surgeons to minimize mistakes. Therefore, the use of shared virtual reality, augmented reality, and other methods to augment visual interaction between the surgeon, patient and assisting robot may improve surgeon/robot interaction and task performance.
13) In order to adhere to the tenets for space flight equipment and supplies supporting a task (minimize volume, mass, power, time, risk, cost, and maximize crew competence), conduct a thorough review of items anticipated to be on an exploration space mission to identify the potential for repurposing or adapting to support medical/surgical procedures.

Acronyms and Glossary

ACLS – advanced cardiac life support

ACT-R – Adaptive Control of Thought—Rational

AI – artificial intelligence

ALIAS – aircrew labor in-cockpit automation system

AR – augmented reality

ARED – Advanced Resistive Exercise Device

CCAT – Critical Care Air Transport (US Air Force)

CMO – Crew Medical Officer

COLBERT – Combined Operational Load Bearing External Resistive Treadmill

DARPA – Defense Advanced Research Projects Agency

DRC – DARPA Robotic Challenge

da Vinci – a robotic surgical system made by the American company Intuitive Surgical. Approved by the Food and Drug Administration in 2000, it is designed to facilitate complex surgery using a minimally invasive approach, and is controlled by a surgeon from a console.

DoD – Department of Defense

DOF – degrees of freedom

ECLSS – environmental control and life support system

EMC – exploration medical condition

EMM – exploration medical model

EMT – emergency medical technician

EVA – extravehicular activity

ExMC– Exploration Medical Capabilities

FDA – U.S. Food and Drug Administration

GAS – Getaway Special

Gateway – The Lunar Orbital Platform-Gateway is an American-led international proposed project headed by NASA to create a lunar-orbit space station

HD – High definition

HMF – Health Maintenance Facility

ICRA – International Conference on Robotics and Automation

IEEE – Originally the Institute of Electrical and Electronic Engineers founded in 1912, IEEE is now the largest professional organization in the world for the advancement of technology.

IHMC – Institute for Human and Machine Cognition

IMM – integrated medical model

IoT – Internet of Things

ISI – Intuitive Surgical, Inc.

ISS – International Space Station

JPL – Jet Propulsion Laboratory

Lagrange points- Regions in space where the gravitational forces of a two body system, like the Sun and the Earth, are relatively balanced. These can be used by spacecraft to reduce fuel consumption needed to remain near those locations.

LIDAR – laser detection and ranging

MIS – minimally invasive surgery

ML – machine learning

msec – millisecond

MSGB – micro-gravity science glovebox

NASA – National Aeronautics and Space Administration

NEEMO – NASA Extreme Environment Mission Operations

NLP – natural language processing

POM – Program Objective Memorandum

R2 – Robonaut 2, dexterous robot now in development

RAS – robot assisted surgery

RCA – Radio Corporation of America

RLQ – right lower quadrant (human anatomy)

RMS – remote manipulator system

SA – situation awareness

Seldinger technique – a medical procedure to obtain safe access to blood vessels and other hollow organs.

SEA – series elastic actuators

Sequelae – the aftereffect of a procedure, disease, or injury

SIMPL – system for improving and measuring procedural learning

SLAM – simultaneous localization and mapping

SR – surgical robotics

SRI – SRI International is an American nonprofit scientific research institute and organization headquartered in Menlo Park, California.

STS – space transportation system

SWaP – size, weight and power

TRL – technology readiness level

TRON – Testbed for Rendezvous and Optical Navigation

US – ultrasound

USAF – United States Air Force

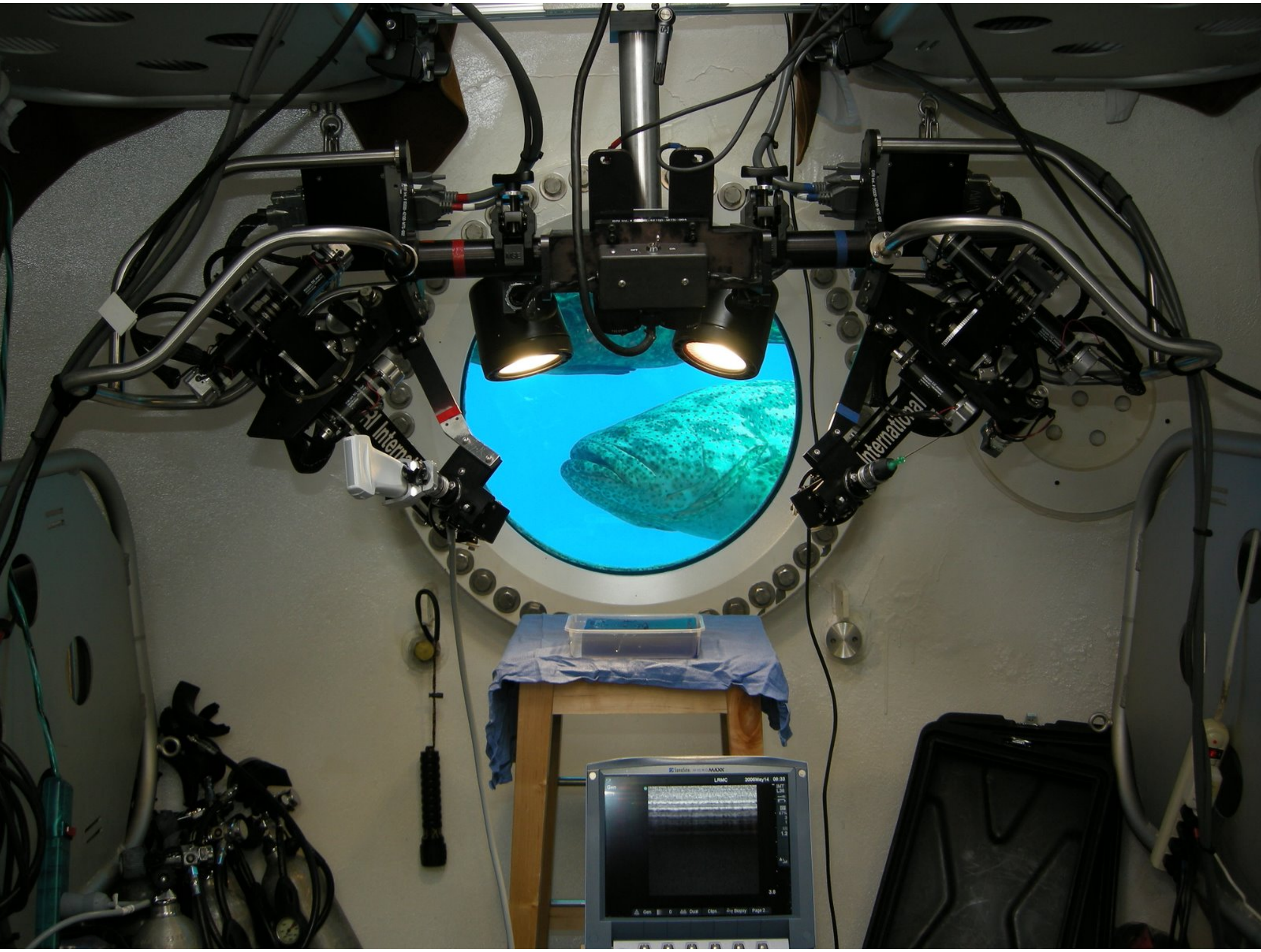
VR – virtual reality

XAI – DARPD Explainable AI

3D – three dimensional

Appendix 1 – Agenda

Blue Sky Agenda



Minimally Invasive Expeditionary Surgical Care using Human-Inspired Robots

October 2nd, and October 3rd, 2018

Monday, October 1, 2018

5:50	Meet in the Courtyard Marriott Lobby - Shaner
6:00	No-Host Dinner: Union Public House – 309 South Reus Street

Tuesday, October 2, 2018

7:50	Meet in the Courtyard Marriott Lobby – Shaner
8:00 – 8:30	Hot Breakfast - IHMC
8:30 – 8:45	Introductory Comments - Ken Ford, George Pantalos, and Tim Broderick
8:45 – 9:15	Presentation: "Astronaut's Perspective on Robotic Surgery" – Mike Barratt
9:15 – 9:30	Discussion
9:30 – 10:00	Presentation: "Robotic General Surgery Clinical Experience and Implications for Future Surgical Care in Space" – Mark Campbell
10:00 – 10:30	Discussion
10:30 – 10:45	Break
10:45 – 11:15	Presentation: "Roles for Humanoid Robots" – Rob Ambrose
11:15 – 11:45	Discussion
11:45 – 12:15	Presentation: "Dexterous Robotic Care-taking on the ISS and its Applications to Remote Surgical Care?" – Julia Badger
12:15 - 12:45	Discussion
12:45 – 1:30	Lunch
1:30 – 2:00	Presentation: "What Makes a Good Robotic Surgical Assistant" – Matt Johnson
2:00 – 2:30	Discussion
2:30 – 2:45	Break
2:45 – 3:15	Presentation: "Explainable AI in Health Systems" – Peter Pirolli
3:15 – 3:45	Discussion

3:45 – 4:00	Break
4:00 – 4:40	Wrap-up and Consolidation Discussion
4:40 – 5:00	Closing Comments – Ken Ford, George Pantalos, and Tim Broderick
5:00	Social – IHMC

Wednesday, October 3rd, 2018

7:50	Meet in hotel lobby for transportation to IHMC – Shaner
8:00 – 8:30	Hot Breakfast
8:30 – 8:40	Introductory Comments – Ken Ford, George Pantalos, and Tim Broderick
8:40 – 9:10	Presentation: "With 30 Years of Robotic Assisted Surgery Now Behind Us, What Can We Imagine Lies Ahead?" – Thomas Low
9:10 – 9:40	Discussion
9:40 – 9:50	Break
9:50 – 10:20	Presentation: "Challenges to Enabling Safe and Effective Robotic Telesurgery in Expeditionary Surgical Care" – Steven Hong
10:20 – 10:50	Discussion
10:50 – 11:00	Break
11:00 – 11:50	Day 2 Wrap-Up and Meeting Consolidation Discussion
11:50 – 12:00	Closing Comments – Ken Ford, George Pantalos, and Tim Broderick
12:00	Lunch

Blue Sky Participants

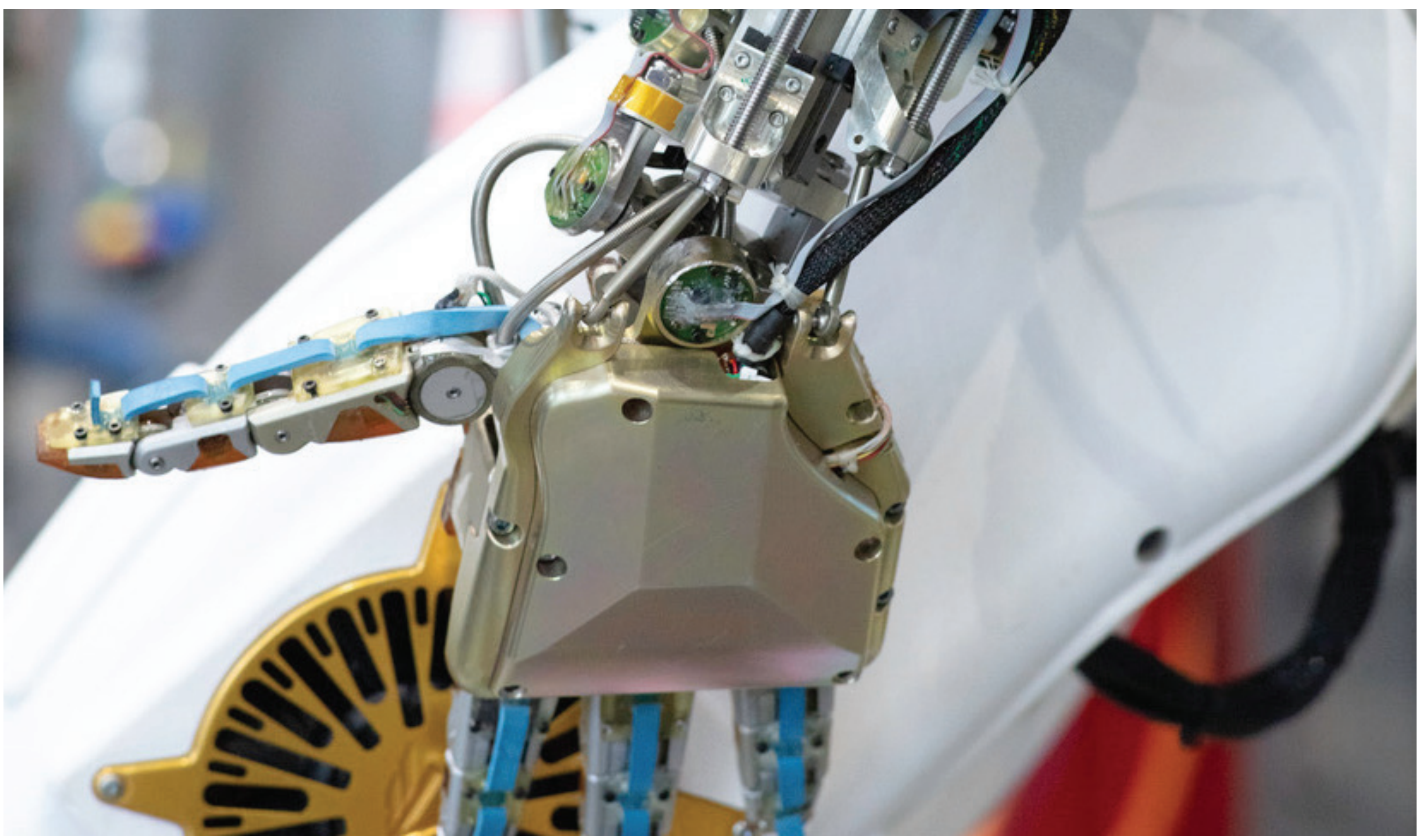
@Rob Ambrose
@Julia Badger
@Mike Barratt
*Dave Blakely
*Tim Broderick
@Mark Campbell
†Jonathan Clark
*Shane Farritor
†Ken Ford
†Alex Garbino
#Kate Gunning
*Kim Hambuchen
@Steven Hong
#James Hury
@Matt Johnson
†Dawn Kernagis
*Andrew Kirkpatrick
*Kris Lehnhardt
@Thomas Low
*Dwight Meglan
†Tania Morimoto
†George Pantalos
@Peter Pirolli
†Anil Raj
*Jacob Rosen
*Erica Sutton

†Rapporteur *Discussant @Presenter #Observer

Appendix 2 – Bio Book

ROBERT AMBROSE

Robert Ambrose serves as the Division Chief of the Software, Robotics and Simulation Division at NASA's Johnson Space Center in Houston, Texas. He is responsible for flight spacecraft software, space robotics and system simulations for human spaceflight missions. Ambrose co-chairs NASA's Robotics and Autonomous Systems roadmap team, and is the robotics lead for NASA's human spaceflight architecture studies. Ambrose is the NASA's POC for the National Robotics Initiative (NRI). He received his B.S. and M.S. degrees from Washington University in St. Louis. Ambrose received his Ph.D. from the University of Texas at Austin in Mechanical Engineering.

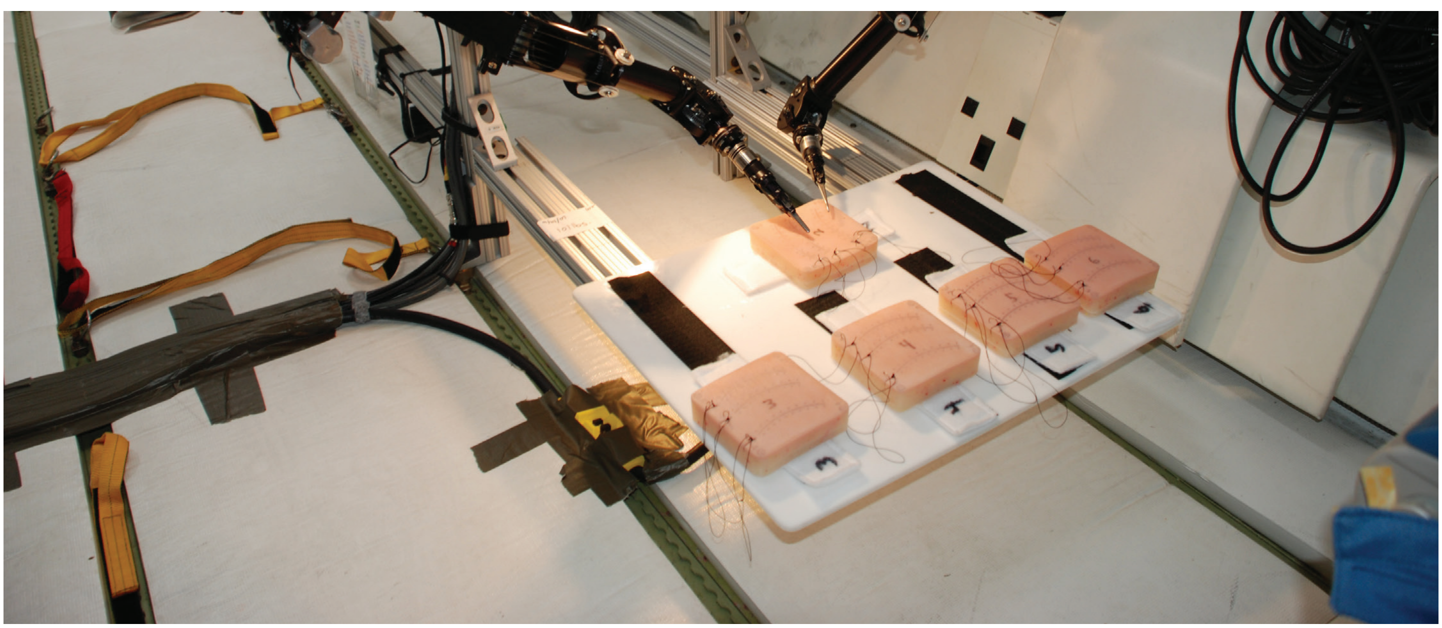


JULIA BADGER

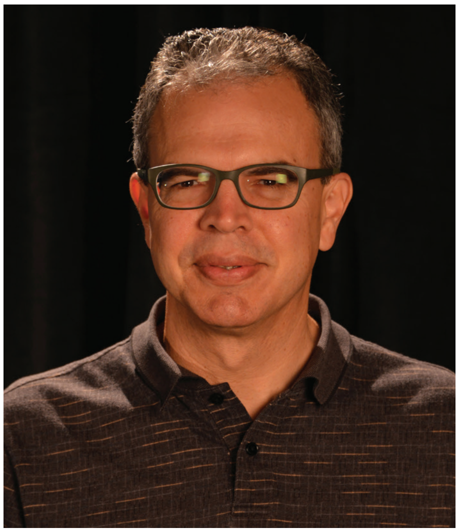
Julia Badger is the Project Manager for the Robotics and Intelligence for Human Spacecraft Team at NASA-Johnson Space Center (JSC) in Houston, TX. This team includes the Robonaut dexterous humanoid robot for caretaking human spacecraft as well as the Modular Autonomous System Technology (MAST) framework for Autonomous Spacecraft Management for human spacecraft. She also serves at the Gateway Systems Engineering and Integration lead for both Autonomy and Intravehicular Robotics. Badger is the JSC representative to the NASA Autonomous Systems Capability Leadership Team and an adjunct professor at Rice University. Badger is responsible for the research and development of humanoid robotic capabilities, both on the Earth and on the International Space Station, that include dexterous manipulation, robotic autonomy, and human-robot interfaces. She is shaping the architecture for smart human spacecraft of the future, from smart sensors to ubiquitous actions to robotic caretaking. She has previously worked at developing autonomous control and planning algorithms for the various robotics projects in the Robotics Systems Technology Branch, including the Space Exploration Vehicle and Robonaut 2. Badger was recently the principle investigator for an effort to create an integrated formal methods tool for requirements engineers, using her expertise to increase formal analysis capabilities in the earliest stages of design. Badger has a B.S. in Mechanical Engineering from Purdue University (2003), a M.S. in Mechanical Engineering from the California Institute of Technology (2005), and a Ph.D. in Mechanical Engineering with a minor in Planetary Science from the California Institute of Technology (2009). Her thesis centered on creating formal methods solutions for hybrid systems, particularly in the field of robotics. Badger has published more than 20 peer-reviewed papers in the fields of robotics, formal methods, simulations, and control. She has been awarded a NASA Group Achievement Award for the Robonaut 2 Mobility System (2014), the NASA Johnson Space Center Software of the Year award for the Robonaut Mobility Control and Safety System in 2015, a NASA Space Technology Mission Directorate Early Career Award (2015), and a JSC Director's Commendation Award for MAST (2018).

MICHAEL R. BARRATT

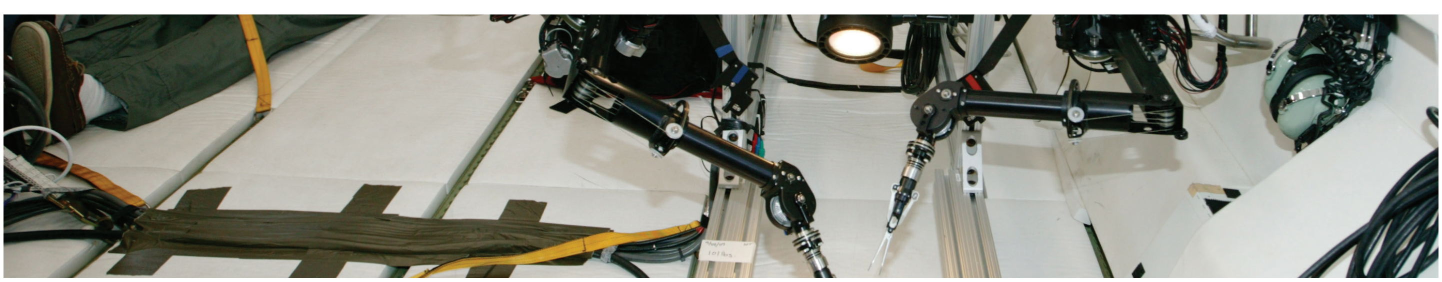
Michael R. Barratt serves in the International Space Station Operations and Integration branches to handle medical issues and onorbit support. He was selected by NASA in 2000. Barratt received his B.S. in Zoology from the University of Washington and his M.D. from Northwestern University. He also received Master's degree in Aerospace Medicine from Wright State University. He is board certified in Internal and Aerospace Medicine, he has participated in two spaceflights. In 2009, Barratt served as Flight Engineer for Expedition 19/20. This marked the transition from three to six permanent International Space Station crew members. During this time, he performed two spacewalks. He also flew on STS-133, which delivered the Permanent Multipurpose Module and fourth Express Logistics Carrier. Barratt received the Hubertus Strughold Award for Contributions to Space Medicine Research, 2011; Joseph P. Kerwin award for Advancements in Space Medicine, Aerospace Medical Association, 2010; W. Randolph Lovelace Award (1998), Society of NASA Flight Surgeons; Melbourne W. Boynton Award (1995), American Astronautical Society; USAF Flight Surgeons Julian Ward Award (1992); Wright State University Outstanding Graduate Student, Aerospace Medicine (1991); Alpha Omega Alpha Medical Honor Society, Northwestern University Medical School, Chicago, IL (1988); and Phi Beta Kappa, University of Washington, Seattle, WA (1981).



DAVE BLAKELY



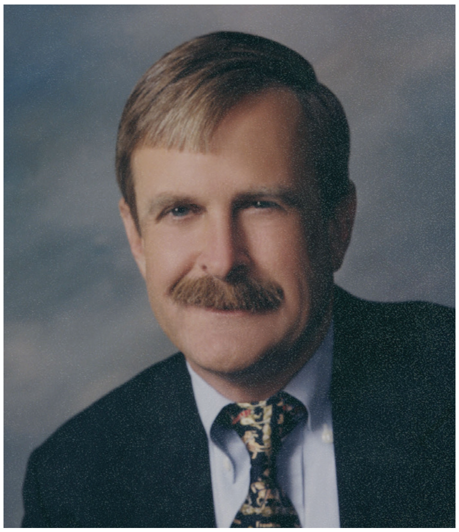
Dave Blakely is a visiting Research Scientist at the Florida Institute for Human & Machine Cognition (IHMC). He is also an innovation consultant who helps his clients to explore links between emerging technologies, business opportunities and customer needs. Blakely's project work involves helping companies to build innovative teams who can deliver breakthrough products and services to the market. He also helps organizations foster a culture of innovation to maintain market leadership. Blakely helps global companies understand how attributes of Silicon Valley culture can transcend political borders and organizational charts. Of particular value for many of these clients is Blakely's knowledge of emerging technology from Silicon Valley startups. He also advises executives at a number of different technology companies, serves on advisory boards for business and academia, conducts innovation workshops, and speaks frequently to academic and business groups. Blakely is proud to serve on the UC Berkeley Engineering Advisory Board, helping his alma mater to adjust the engineering curriculum to the needs of a rapidly changing global economy. He is also a faculty advisor to Singularity University, a new academic institution that understands and facilitates development of exponentially advancing technology to address broad challenges to humanity. Blakely received a B.S. in Engineering Physics (Class of 1982) with honors and an M.S. in Mechanical Engineering with a controls specialization (Class of 1983) with honors, both from the University of California at Berkeley. Blakely's experience comes from 25 enjoyable years spent at IDEO, most recently as Director of Technology Strategy. In this role he built and managed strategic business relationships with several of IDEO's technology-focused clients such as Cisco, Johns Hopkins and Qualcomm. In his earlier years at IDEO Blakely built and led a successful business unit of IDEO called "Smart Products" which focused exclusively on electromechanical systems with embedded controls. He and his 35-person team provided the market with full-service design and development of embedded systems by assembling an interdisciplinary staff of human-factors experts, interaction designers, and electrical, mechanical and firmware engineers. Working with his team, Blakely helped visualize the future of computing for Microsoft, created streaming media players for Philips, and created a new category of appliances for Whirlpool. Blakely holds six patents.



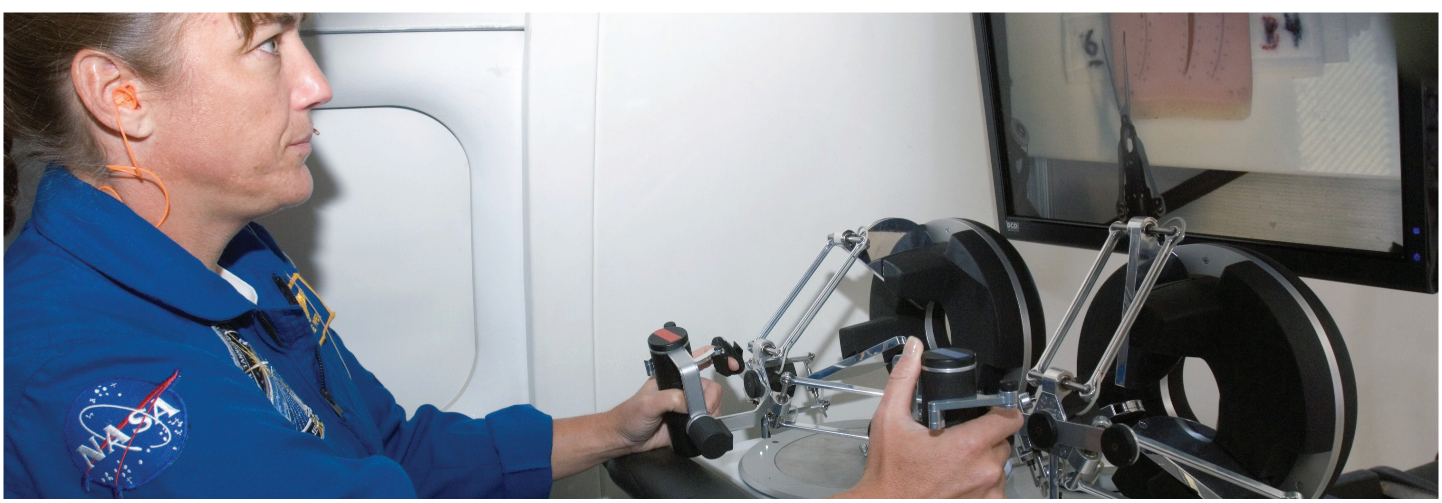
TIM BRODERICK

Timothy J. Broderick currently serves as Chief Scientist, Wright State Research Institute and Associate Dean for Research Affairs, Wright State University Boonshoft School of Medicine. Broderick is a surgeon and biomedical engineer focused on the development of high impact biomedical technologies. Applicable to needs of the Department of Defense and NASA, his research aims to revolutionize health and human performance in extreme environments. Broderick received a B.S. in Computer Science and Chemistry from Xavier University and an M.D. from the University of Cincinnati. He trained in general surgery at Virginia Commonwealth University. He is board certified and licensed in general surgery. Prior to coming to Wright State University, he served as a Program Manager at the Defense Advanced Research Projects Agency (DARPA). He previously served as Senior Scientist at the US Army Medical Research and Materiel Command Telemedicine and Advanced Technology Research Center, Consulting Surgeon on Telemedicine and Robotics within the NASA Medical Informatics and Technology Applications Consortium, and Smart Medical Systems Advisor within the National Space Biomedical Research Institute External Advisory Committee. As a peer-reviewed investigator and consultant, Broderick contributed to the development of multiple medical informatics, simulation and robotic systems. He has extensively published and presented his research on distributed robotic surgery and medical care in extreme environments. Broderick is a member of numerous professional societies. He is a Fellow of the American College of Surgeons and Associate Fellow of the Aerospace Medical Association. He has flown on the NASA parabolic laboratory and dived in the NASA Extreme Environment Mission Operations (NEEMO) program. Within NEEMO, Broderick served as NEEMO 7 Visiting Scientist and Back-up Mission Specialist 3, NEEMO 9 Crew Medical Officer and Mission Specialist 3, and NEEMO 12 Principal Scientist and Mission Specialist 3. His operational training and experience prompted recognition as a Professional Association of Diving Instructors Divemaster, NOAA Aquanaut (long duration undersea saturation diver) and Honorary NASA Flight Surgeon. Broderick has successfully developed and used enabling medical technologies in extreme environments and humanitarian missions around the world.

MARK CAMPBELL



Mark Campbell is a board-certified general surgeon and a Fellow of the American College of Surgery and the Texas Surgical Society. He currently is in general surgery private practice in Paris, Texas where he has performed over 1,400 robotic surgical procedures. He has been a member of the Space Medicine Branch and The Aerospace Medical Association (AsMA) since 1989 and was elected as an AsMA Fellow in 2009. Campbell has been a private pilot since 1984 and received his Air Force Flight Surgery wings in 1994. He was a NASA Flight Surgeon from 1994 to1995 and was deployed to Star City, Russia to support the Shuttle-Mir program. He has authored or co-authored 38 published papers concerning surgical care during space flight and surgical techniques in weightlessness. Fourteen of these articles were published in *Aviation Space and Environmental Medicine*. He was the author for the surgical section of "Medical Guidelines for Air Travel" published by AsMA and is the author of a chapter on "Surgical Care in Space" in the textbook, "Principles of Clinical Medicine for Space Flight." Campbell was on the *Aviation Space and Environmental Medicine* journal advisory board from 2006-2009 and currently edits the journal section "Aerospace Medicine History". He was the President of the Space Medicine Association in 2007-2008 and has been on the AsMA Council, the AsMA Executive Committee and the Space Medicine Association Executive Committee since 2007. He was the chairman of the AsMA Commercial Space Flight Working Group, which produced a position paper on "Medical Issues for Suborbital Commercial Space Flight Crewmembers". Campbell was on the FAA Commercial Space Transportation Advisory Committee from 2010-1015. In 2014 he received the AsMA Joe Kerwin Award for achievements in the field of space medicine.

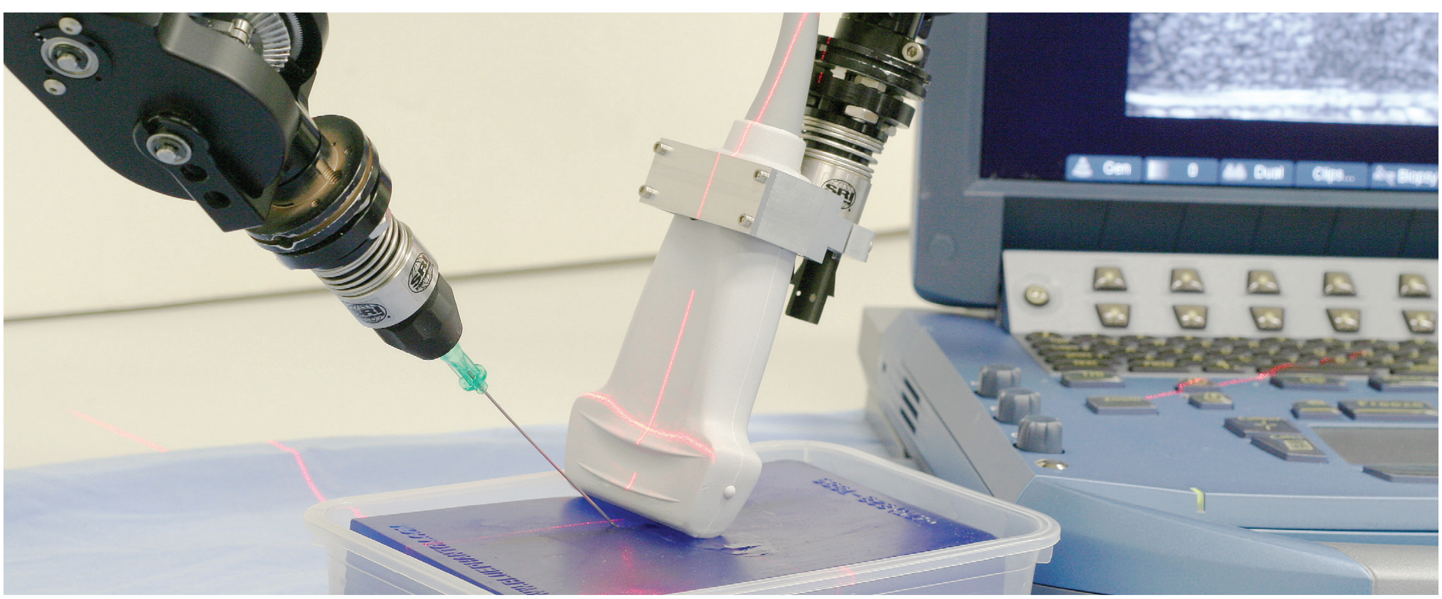


JONATHAN B. CLARK

Jonathan B. Clark is a Senior Research Scientist at the Florida Institute of Human & Machine Cognition (IHMC) and an Associate Professor of Neurology and Space Medicine at Baylor College of Medicine (BCM) and teaches operational space medicine at BCM's Center for Space Medicine (CSM). He is also the Space Medicine Advisor for the National Space Biomedical Research Institute (NSBRI). Clark is a Clinical Assistant Professor at the University of Texas Medical Branch in Galveston where he teaches at the Aerospace Medicine Residency. He received a B.S. from Texas A&M University, an M.D. from the Uniformed Services University of the Health Sciences, and is board certified in Neurology and Aerospace Medicine. Clark is a Fellow of the Aerospace Medical Association. He was a Member of the NASA Spacecraft Survival Integrated Investigation Team from 2004 to 2007 and a Member of the NASA Constellation Program EVA Systems Standing Review Board from 2007 to 2010. Clark worked at NASA from 1997 to 2005 and was a Space Shuttle Crew Surgeon on six shuttle missions and was Chief of the Medical Operations Branch. He devoted 26 years to active service with the U.S. Navy, during which he headed the Spatial Orientation Systems Department at the Naval Aerospace Medical Research Laboratory in Pensacola; the Aeromedical Department at the Marine Aviation Weapons and Tactics Squadron One in Yuma, Arizona; and the Neurology Division and Hyperbaric Medicine at the Naval Aerospace Medical Institute. He was a DOD Space Shuttle Support Flight Surgeon covering two space shuttle flights and flew combat medical evacuation missions in Operation Desert Storm with the U.S. Marine Corps. Clark qualified as a Naval Flight Officer, Naval Flight Surgeon, Navy Diver, U.S. Army parachutist and Special Forces Military Freefall Parachutist. He was Chief Medical Officer for Excalibur Almaz, an orbital commercial space company, from 2007 to 2012, and since 2013 is Chief Medical Officer for the Inspiration Mars Foundation. Clark was Medical Director of the Red Bull Stratos Project, a manned stratospheric balloon freefall parachute flight test program, which on 14 October 2012 successfully accomplished the highest stratospheric freefall parachute jump (highest exit altitude) from 127,852 feet, achieving human supersonic flight (Mach 1.25) or maximum vertical speed without a drogue chute at 843.6 miles per hour/1357.6 kilometers per hour. His professional interests focus on the neurologic effects of extreme environments and crew survival in space.

SHANE FARRITOR

Shane Farritor is the David and Nancy Lederer Professor of Mechanical Engineering at the University of Nebraska-Lincoln. His research interests include space robotics, surgical robotics, and biomedical sensors. Farritor has founded two venture funded startup companies based on his research at UNL. He co-founded Virtual Incision Corporation with his surgeon colleague Dr. Dmitry Oleynikov at the University of Nebraska Medical Center. Virtual Incision is developing miniature robotic devices that are placed inside the body during laparoscopic surgery. These new devices could have a significant impact on surgical procedures such as colon resection. Farritor's second startup, MRail, is developing a method to improve railroad maintenance by the measurement of vertical rail deflection. Farritor holds more than 60 patents with approximately 50 pending applications. He is a fellow of the National Academy of Inventors. Farritor received a B.S. degree in Mechanical Engineering from the University of Nebraska-Lincoln in 1992, and M.S. and Ph.D. degrees in Mechanical Engineering from the Massachusetts Institute of Technology, Cambridge, in 1998. Farritor is a past chairman of the AIAA Space Robotics and Automation technical committee and past member of the ASME Dynamic Systems and Control Robotics Panel. Farritor is a native of Nebraska. His wife is a physician at St. Elizabeth's and they have four children. He enjoys building things especially woodworking, golf, basketball, and running.

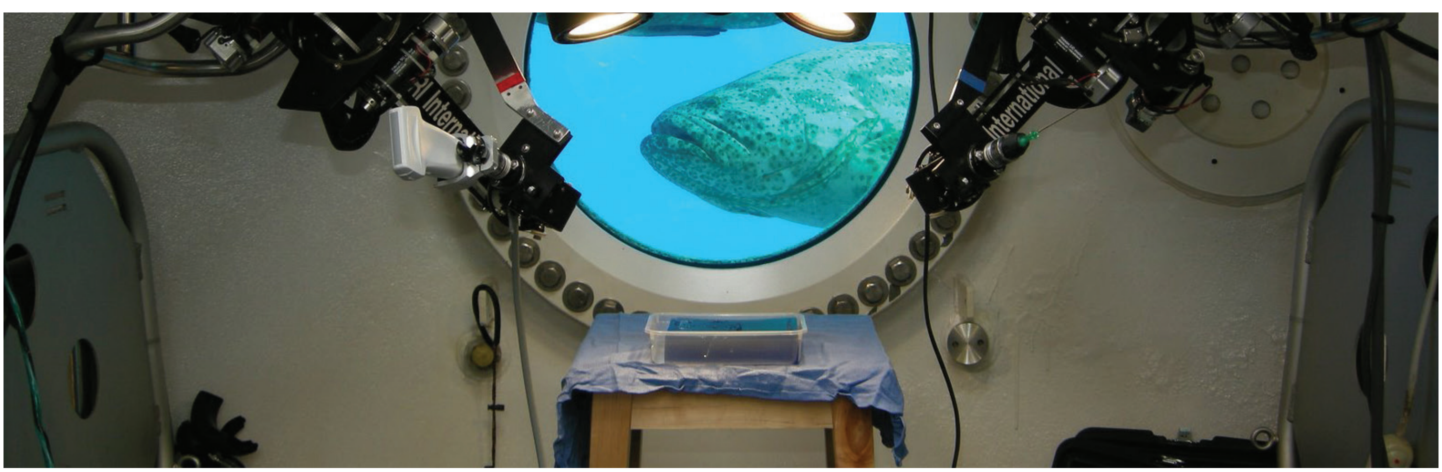


KENNETH FORD

Kenneth Ford is Founder and Chief Executive Officer of the Florida Institute for Human & Machine Cognition (IHMC) — a not-for-profit research institute located in Pensacola, Florida. IHMC has grown into one of the nation's premier research organizations with world-class scientists and engineers investigating a broad range of topics related to building technological systems aimed at amplifying and extending human cognition, perception, locomotion and resilience. Richard Florida has described IHMC as "a new model for interdisciplinary research institutes that strive to be both entrepreneurial and academic, firmly grounded and inspiringly ambitious." IHMC headquarters are in Pensacola with a branch research facility in Ocala, Florida. In 2004 Florida Trend Magazine named Ford one of Florida's four most influential citizens working in academia. Ford is the author of hundreds of scientific papers and six books. His research interests include: artificial intelligence, cognitive science, human-centered computing, and entrepreneurship in government and academia. Ford received his Ph.D. in Computer Science from Tulane University. He is Emeritus Editor-in-Chief of AAAI/MIT Press and has been involved in the editing of several journals. Ford is a Fellow of the Association for the Advancement of Artificial Intelligence (AAAI), a charter Fellow of the National Academy of Inventors, a member of the Association for Computing Machinery, a member of the IEEE Computer Society, and a member of the National Association of Scholars. Ford has received many awards and honors including the Doctor Honoris Causas from the University of Bordeaux in 2005 and the 2008 Robert S. Englemore Memorial Award for his work in artificial intelligence (AI). In 2012 Tulane University named Ford its Outstanding Alumnus in the School of Science and Engineering. In 2015, the Association for the Advancement of Artificial Intelligence named Ford the recipient of the 2015 Distinguished Service Award. Also, in 2015, he was elected as Fellow of the American Association for the Advancement of Science (AAAS). In 2017 Ford was inducted into the Florida Inventor's Hall of Fame. In January 1997, Ford was asked by NASA to develop and direct its new Center of Excellence in Information Technology at the Ames Research Center in Silicon Valley. He served as Associate Center Director and Director of NASA's Center of Excellence in Information Technology. In July 1999, Ford was awarded the NASA Outstanding Leadership Medal. That same year, Ford returned to private life and to the IHMC. In October of 2002, President George W. Bush nominated him to serve on the National Science Board (NSB) and the United States Senate confirmed his nomination in March of 2003. The NSB is the governing board of the National Science Foundation (NSF) and plays an important role in advising the President and Congress on science policy issues. In 2005, Ford was appointed and sworn in as a member of the Air Force Science Advisory Board. In 2007, he became a member of the NASA Advisory Council and on October 16, 2008, Ford was named as Chairman – a capacity in which he served until October 2011. In August 2010, Ford was awarded NASA's Distinguished Public Service Medal – the highest honor the agency confers. In February of 2012, Ford was named to a two-year term on the Defense Science Board (DSB) and in 2013, he became a member of the Advanced Technology Board (ATB) which supports the Office of the Director of National Intelligence (ODNI).

ALEJANDRO GARBINO

Alejandro "Alex" Garbino is a Research Associate at IHMC, an Attending Physician in Emergency Medicine at UCHealth in Denver, and an EVA Research Scientist at NASA Johnson Space Center. He has extensive experience practicing medicine in challenging environments. His work focuses on physiological responses to such environments, including work and research on dive medicine, oxygen toxicity and space suit injury management. Garbino's work experience includes serving as Lead Physiological Monitor on the Red Bull Stratos high altitude jump, leading the medical consulting and medical support team for the subsequent StratEx record breaking high altitude jump, a two month medical support and transport rotation in Antarctica. He also completed the NOAA/UHMS Physician Dive Medicine Program. He serves as Vice President of the Aerospace Medicine Association where he is also an Associate Fellow. Garbino first obtained a B.S. in Physics with Honors from the University of Houston in 2005. In 2012 he graduated from Baylor College of Medicine with an M.D. and a Ph.D. in Translational Biology. In 2015 Garbino completed his Emergency Medicine Residency at Baylor College of Medicine, where he also served as Chief Resident from 2014 to 2015. In 2017 Garbino completed his Aerospace Medicine Residency at the University of Texas Medical Branch/NASA Program. During his residency, he completed the US Air Force Flight Surgeon and Critical Care Air Transport training program, and rotated aboard the aircraft carrier USS Eisenhower (CVN-69) and with the Navy Experimental Dive Unit. He now lives in Houston, Texas, but divides his time between there and Denver, CO. He is licensed to practice in Texas, Colorado, Florida, and California. Garbino also holds Private Pilot, Skydiving and SCUBA diver certifications.

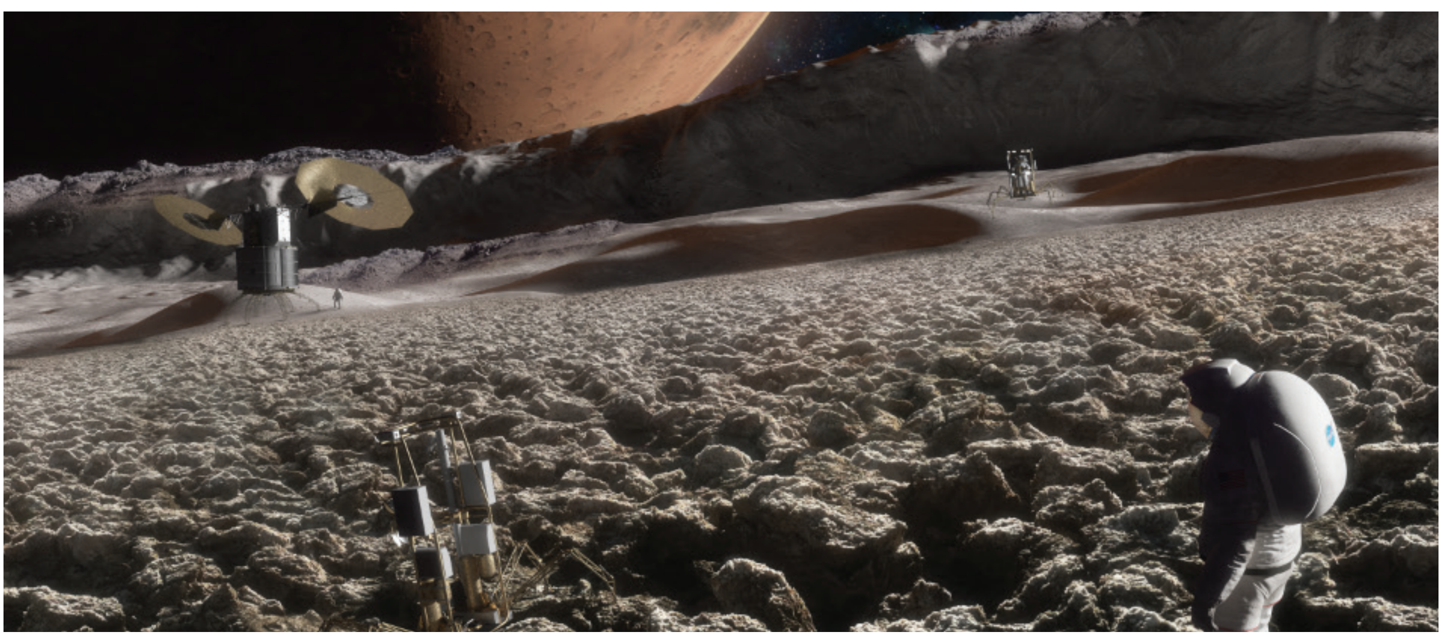


KIMBERLY HAMBUCHEN

Kimberly Hambuchen is currently the NASA Space Technology Mission Directorate's (STMD) Principal Technologist for Robotics. As Principal Technologist, she serves as the STMD technical expert and advocate for robotics across all NASA centers for STMD programs. She works with STMD managers and field center leads to maintain and update the directorate's portfolio of robotics projects across the range of Technology Readiness Levels. She has spent the last 20 years developing software and applications to advance the intelligence, usefulness and operational intuitiveness of robots. As a robotics engineer in the Robotics Systems Technology branch of the Software, Robotics and Simulation division of engineering at NASA Johnson Space Center, Hambuchen developed expertise in novel methods for remote supervision of space robots over intermediate time delays and has proven the validity of these methods on various NASA robots, including JSC's Robonaut and Centaur robots. She participated in the development of NASA's Space Exploration Vehicle (SEV) and bipedal humanoid, Valkyrie (R5), to which she extended her work developing human interfaces for robot operations. Hambuchen is currently a member of the International Space Exploration Coordination Group's (ISECG) Telerobotics Gap Assessment team, providing gap analysis in the field of operating space robots for the international space community, and in 2016 was named "One of the 25 Women in Robotics to Know" by RoboHub.

STEVEN S. HONG

Steven S. Hong is a Head and Neck Oncologic and Microvascular Reconstructive Surgeon at Walter Reed National Military Medical Center in Bethesda, Maryland. Hong is spearheading the efforts at USAMRMC to enable safe and effective robotic telesurgery in austere operational environments as part of the US Army's Science and Technology Man/Machine Teaming and Medical Robotics. Hong is a graduate of Miami University of Ohio, where he received undergraduate and Master's degrees in political science. He attended the University of Toledo College of Medicine, receiving his medical degree in 2009. He completed his residency in Otolaryngology and Head and Neck Surgery at Tripler Army Medical Center in Honolulu, Hawaii in 2014. Following residency, he served as a staff otolaryngologist at Ft. Campbell, Kentucky where he earned his air assault badge in the famed 101st Airborne Division. From 2016-2018, Hong completed a research and clinical fellowship focused on surgical robotics in Head and Neck Oncologic and Microvascular Reconstructive Surgery at Stanford University. In addition to medical robotics, Hong also has a special interest in benign and malignant tumors of the head and neck, and the complex reconstruction that comes with their treatment. He also has multiple publications related to fluorescence-guided surgery using molecularly-targeted compounds and analyzing medicolegal outcomes and issues pertaining to head and neck surgery.



JAMES HURY

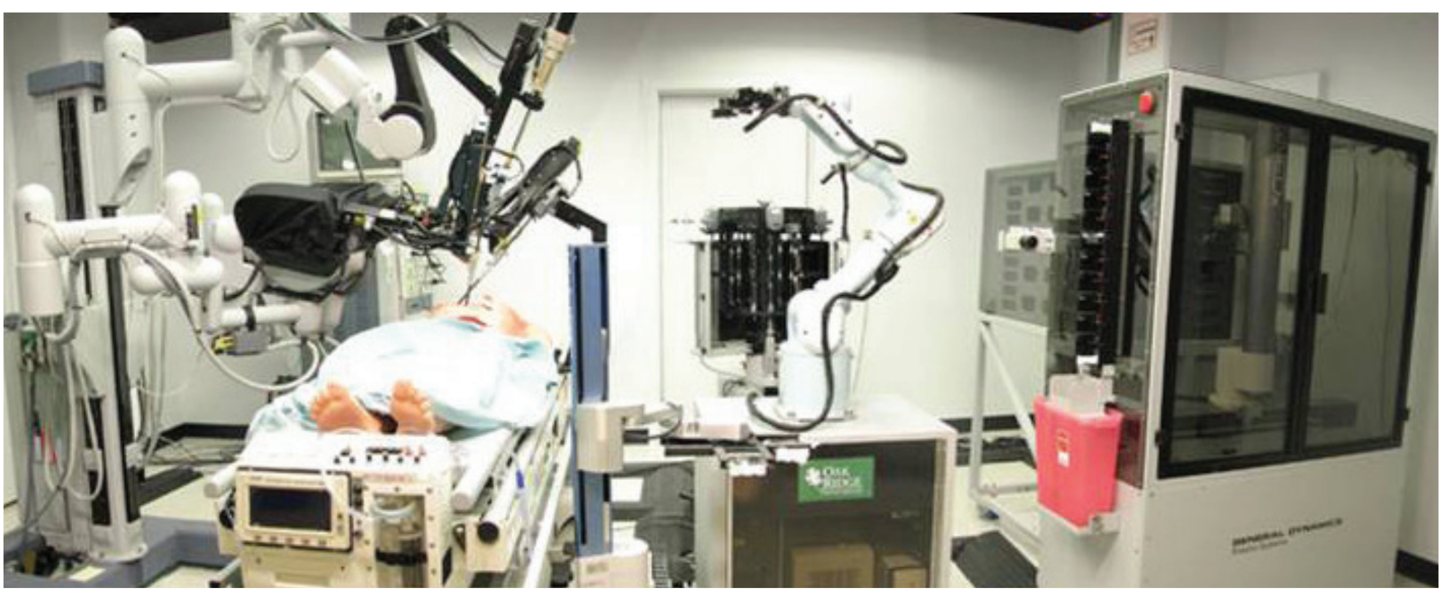
James Hury is the Deputy Director and Chief Innovation Officer of the Translational Research Institute for Space Health (TRISH). Hury sources innovation and partnerships by exploring out-of-the-box structures, mechanisms, and human workflows for space. Leveraging his expertise of fostering emerging technologies to advance patient care in the world's leading pediatric and maternal care system, Hury will translate these skills to accelerate the institute's mission of improving astronaut health and performance. He received his M.B.A. from Rice University, as well as undergraduate degrees from both the University of Houston and the University of Texas Medical Branch. Prior to joining TRISH, he led innovation for the Texas Children's Health System. Hury built his foundation for healthcare management at Rice University's Jones School of Business M.B.A. program and currently teaches Healthcare Ventures eLab at the Jones School.

MATTHEW JOHNSON

Matthew Johnson is a research scientist who has worked at the Florida Institute for Human and Machine Cognition since 2002. He received his B.S. in Aerospace Engineering from the University of Notre Dame, a M.S. in Computer Science from Texas A&M – Corpus Christi, and his Ph.D. in Computer Science through Delft University of Technology in the Netherlands. Prior to working for IHMC, he flew both fixed and rotary wing aircraft in the Navy, retiring after 20 years of service. Johnson has worked on numerous projects including the Oz flight display for reducing the cognitive workload in the cockpit, Augmented Cognition for improving human performance, and several human-robot coordination projects for both NASA and the Department of Defense. He has worked on advanced robotic control projects such as the DARPA Little Dog project developing walking algorithms for a quadruped robot on rough terrain and the IHMC lower body humanoid developing low-gravity walking gaits for NASA. Most recently, he played a leadership role in IHMC's 2nd place finish at the international robotics competition known as the DARPA Robotics Challenge. Johnson's research interest focuses on improving performance in human-machine systems through design of more effective human-machine teamwork.

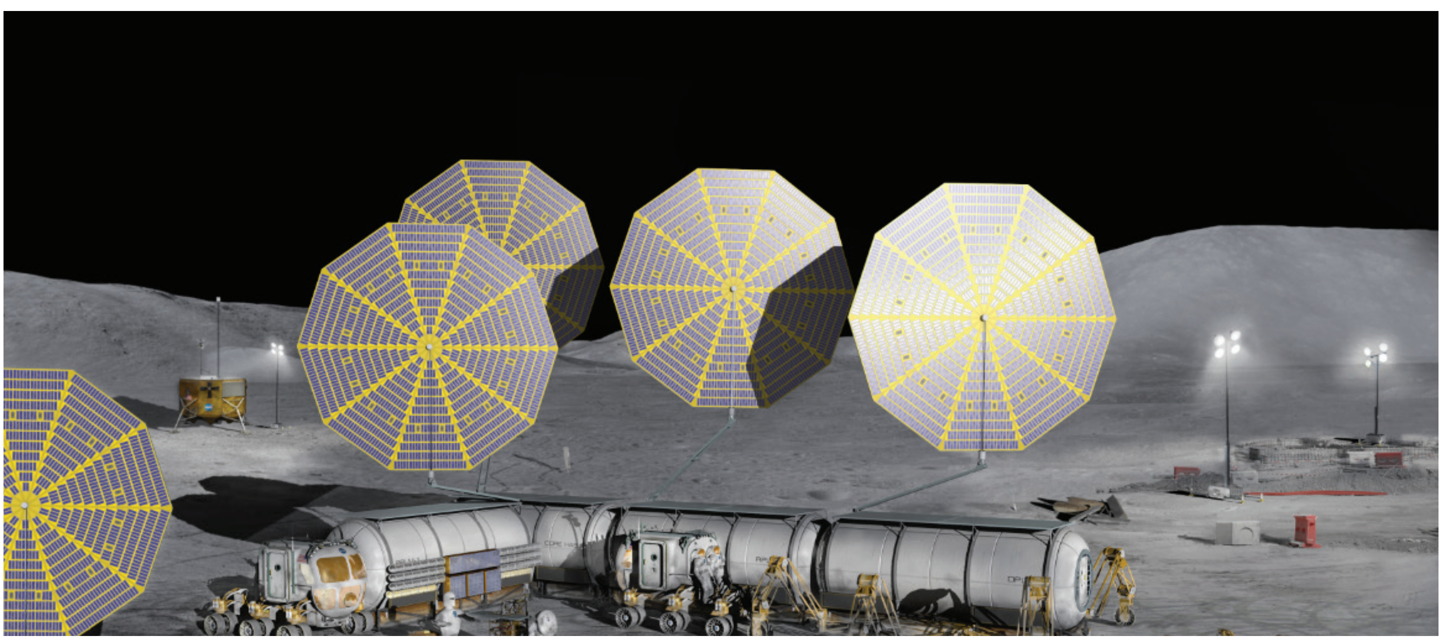
DAWN KERNAGIS

Dawn Kernagis is a Research Scientist at the Florida Institute of Human & Machine Cognition (IHMC) in the area of human performance optimization and risk mitigation for operators in extreme environments, such as those working in high altitude aviation and undersea diving. Kernagis joins IHMC from Duke University Medical Center, where her research was funded by the Office of Naval Research and the American Heart Association to identify novel approaches to protect against acute brain injury. Kernagis completed her Ph.D. at Duke University as ONR Undersea Medicine's first Predoctoral Award recipient. Her thesis research focused on gene array-based diagnostic development and how genetics may influence individual susceptibility to decompression sickness in Navy divers. Kernagis obtained her degree in Biochemistry at North Carolina State University, where she was a recipient of the Sigma Xi Undergraduate Research Award. Before pursuing her Ph.D., Kernagis held an internship at Karolinska Institute in Stockholm, where she coordinated a study investigating differential carbon dioxide retention in scuba, rebreather, and breath-hold divers. She also worked on research projects through Duke's Center for Hyperbaric Medicine and Environmental Physiology, including Flying After Diving (DAN) and EVA Oxygen Prebreathe (NASA). Kernagis has also been involved with numerous underwater exploration, research, and conservation projects around the world since 1993, including the deep underwater cave exploration team, the Woodville Karst Plain Project, for over a decade.



ANDREW W. KIRKPATRICK

Andrew W. Kirkpatrick is a Professor in both the Departments of Surgery and Critical Care Medicine at the Foothills Medical Centre of the University of Calgary, and the former Medical Director of Regional Trauma Services. Kirkpatrick graduated Magna Cum Laude from the University of Ottawa, with fellowships in Surgery and Critical Care at the University of Toronto with a Master's degree in Epidemiology at the University of British Columbia. He is immediate past President of the Abdominal Compartment Society. Kirkpatrick has more than 375 peer-reviewed articles and book chapters, mainly concerning intra-abdominal hypertension, emergency sonography, hypothermia, aerospace medicine and occult pneumothoraces. He is a past-President of the Trauma Association of Canada and the Abdominal Compartment Society, as well as past executive member of the Canadian Emergency Ultrasound Society and the Canadian Association of General Surgeons Evidence Based Reviews in Surgery Committees. He has consulted for the Canadian Space Agency and the National Space and Aeronautical Agencies. Kirpatrick retains a reserve commission in the Canadian Forces and has served oversees on several occasions. He is a former Paratrooper and Flight Surgeon and currently maintains a current pilots license. He has completed over 500 parabolas of parabolic flight research.

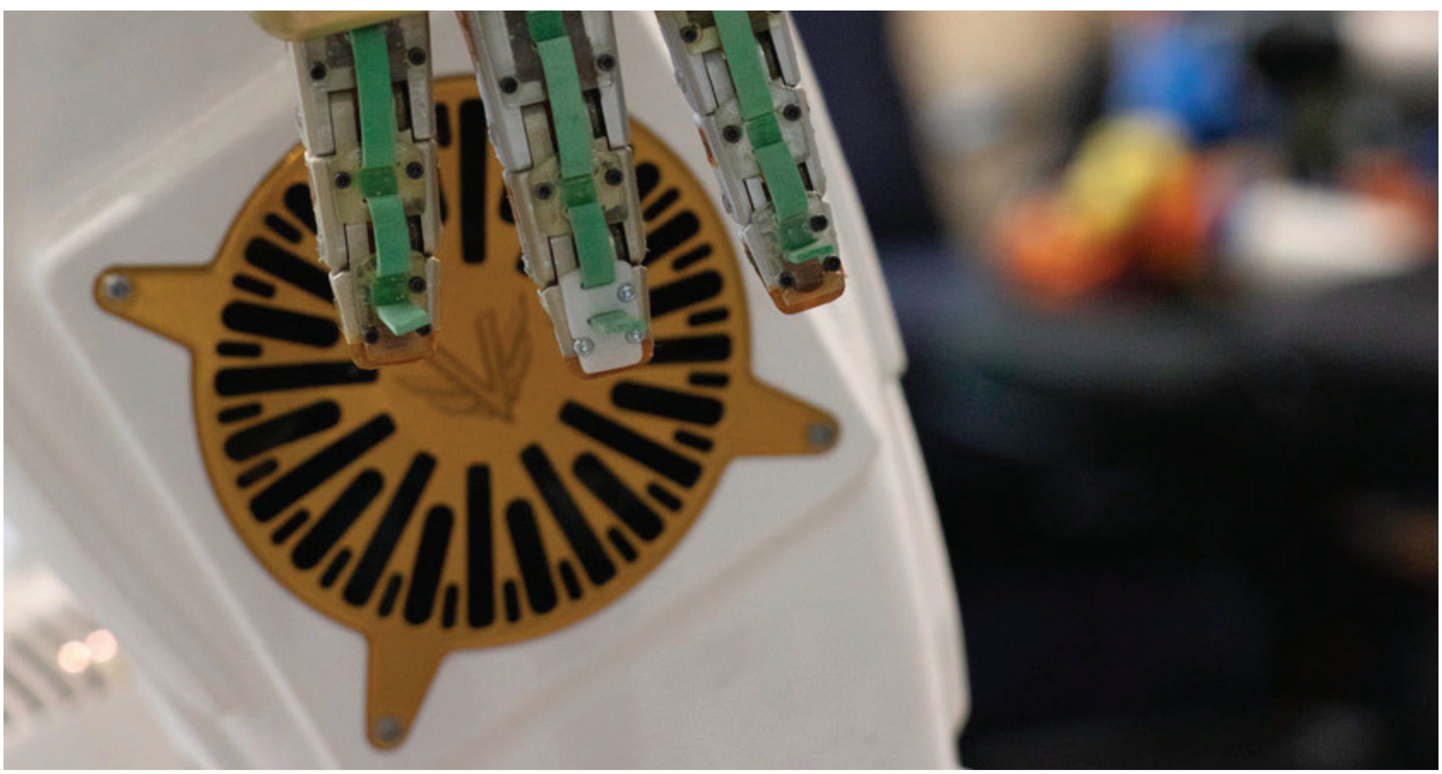


KRIS LEHNHARDT

Kris Lehnhardt is the Element Scientist for Exploration Medical Capability in NASA's Human Research Program. He has appointments as Senior Faculty with the Baylor College of Medicine in the Center for Space Medicine and the Department of Emergency Medicine). He is board-certified in Emergency Medicine in both Canada and the U.S.A., and he works clinically in the Emergency Department at the Ben Taub Hospital in Houston. Previously, Lehnhardt was an Attending Physician and Assistant Professor at The George Washington University (GWU) School of Medicine and Health Sciences. A reservist in the Royal Canadian Air Force, a private pilot, and a PADI advanced open water SCUBA diver, Lehnhardt has had an active role in NASA's Human Research Program since 2017. His main research interest focuses on the provision of medical care in extreme environments (space, military, wilderness, etc.). Lehnhardt completed his M.D. and Emergency Medicine residency at Western University in 2003 and 2008 respectively and he received his B.S. in Biomedical Sciences from the University of Guelph in 1999.

THOMAS LOW

Thomas Low serves as the Associate Director of the Robotics Programs at SRI International, of Menlo Park, CA where he has worked for the past 34 years. He earned his BSME from UC Berkeley and MSME from Stanford University. Low's three decades of technical innovation have resulted in 44 issued patents and publications in diverse fields of research, from biochemical processes to robot system design. Much of his career has been focused on effective telemanipulaton and robotically assisted surgery. He was as member of the development team that created the prototype da Vinci Robotic surgical system, and Google Verily's new Verb Surgical platform. Low led the development of the Taurus dexterous telemanipulation system for neutralizing improvised explosive devices. The Taurus is now being repurposed to support Army research activities related to battlefield remote trauma care. Recently, Low led his team to create the world's first fully autonomous humanoid robot capable of racing a motorcycle against top human riders.

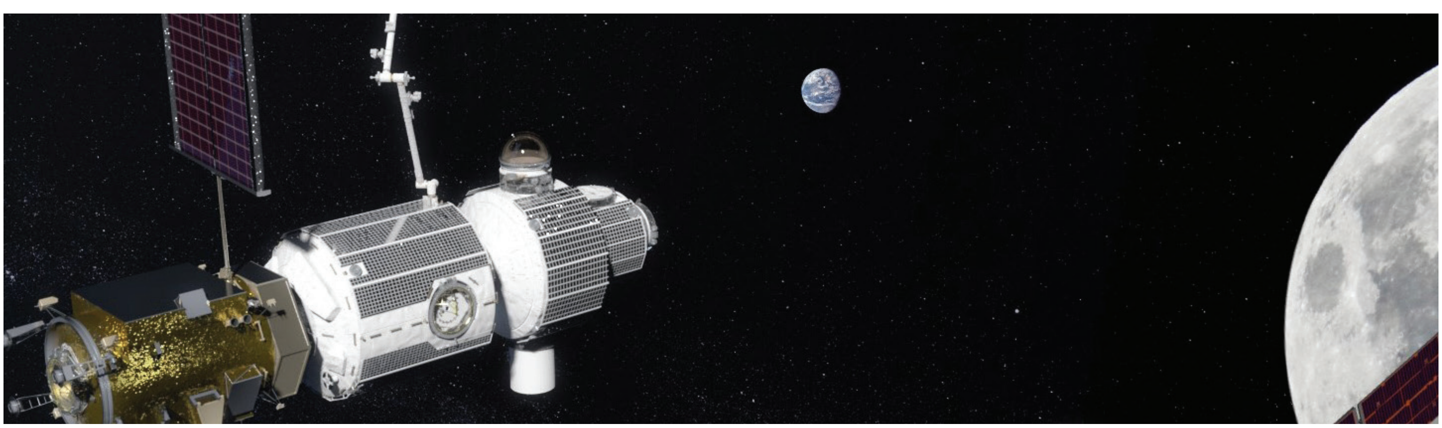


DWIGHT MEGLAN

Dwight Meglan has applied simulation and robotics to medicine for more than 25 years. He has worked with a number of high technology medical startups and established medical device companies including four efforts developing surgical robots. His early training was in orthopedic biomechanics at Ohio State with a postdoc at Mayo Clinic. Meglan left a tenure track position at Mayo for a life as a hands-on engineer focused on enhancing healthcare through building financially successful technology centric products so that patients would gain access to them. This has led to interesting combinations of technologies in simulation, robotics, image guidance and augmented reality. Some have made it to market, like the first commercial endovascular intervention simulator that was key to the FDA requirements on training for carotid stent placement, while a number of the more innovative systems have not. As of 2018, Meglan recently transitioned from being a Technical Fellow on Medtronics' surgical robotics team to working on his own cardiac robot venture as well as other projects. Prior to this, he was focused on surgical simulators spanning open incision to orthopedic surgery including an open source surgical simulation effort funded by the US Department of Defense. During that era, Meglan's group worked on multiple augmented reality-based, low cost simulators for minimally invasive surgery and enhancement of manikin-based training such as physics-based AR of bleeding for hemorrhage control training. He has written grants funded for more than $15M over an 8-year span and been a reviewer of dozens of surgical simulation and surgical robotics proposals. He is the inventor on 24 patents to date with more in the pipeline. He prefers to be a hands-on builder and has on going interests combining computation, motion measurement, and electromechanical systems to enable a more fulfilled life for the physically/cognitively challenged including his own brain injured daughter.

TANIA K. MORIMOTO

Tania K. Morimoto is currently an Assistant Professor in the Mechanical and Aerospace Engineering Department at University of California San Diego (UCSD). She obtained her undergraduate degree at MIT, followed by her Master's and Ph.D. degrees at Stanford University, all in Mechanical Engineering. She was an NSF Graduate Research Fellow, and her research interests include surgical robotics, haptics, and engineering education. Her research to date has focused on the design and control of flexible continuum robots and their associated human-in-the-loop interfaces. Current robot-assisted minimally invasive surgical systems enable procedures with reduced pain, recovery time, and scarring compared to traditional surgery. While these improvements benefit a large number of patients, safe access to diseased sites is not always possible for specialized patient groups, including pediatric patients, due to their anatomical differences. To address these unmet needs, Morimoto proposed a patient- and procedure-specific (i.e., personalized) surgical robot design paradigm. This paradigm leverages the surgeon's expertise to use preoperative medical images to design and fabricate personalized concentric tube robots-- a type of continuum robot constructed from precurved, elastic, nesting tubes. The example clinical application focused on was nonlinear renal access in pediatric patients, to access diseased sites such as kidney stones and tumors. The general principles can be applied to a range of different applications and patient groups, including patients in remote environments whose needs cannot be adequately addressed with existing systems. Morimoto is continuing this line of research at UCSD and is focusing on addressing challenges in (1) soft body mechanical design of new surgical robots and (2) human-in-the-loop interfaces for design and control, in order to help overcome accessibility, maneuverability, and safety limitations of conventional systems.

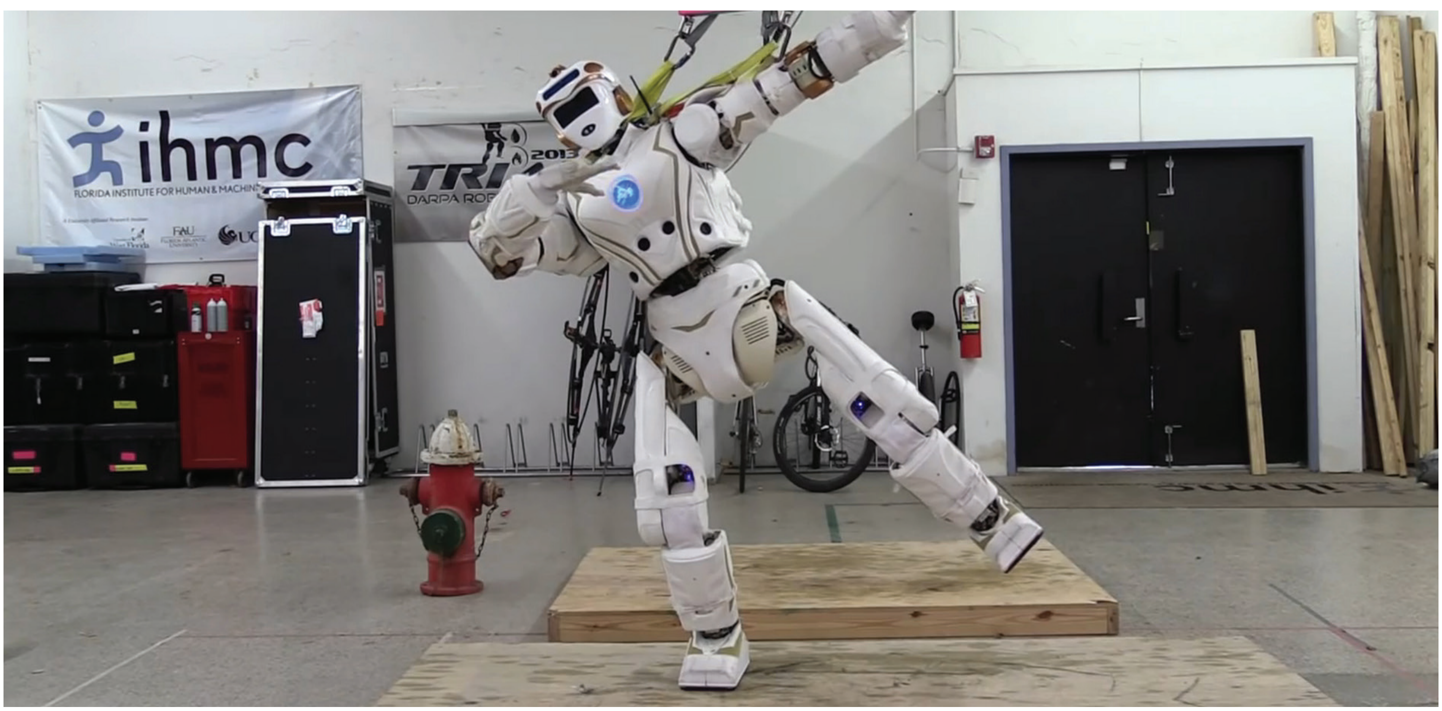


GEORGE PANTALOS

George Pantalos has been a cardiovascular explorer for over 45 years. Much of that effort has included the development of surgical devices and procedures to make the research projects possible. He has been a Professor of Cardiovascular and Thoracic Surgery and Biomedical Engineering at the University of Louisville, in partnership with Jewish Hospital and Norton Children's Hospital, since July 2000, after holding similar appointments at the University of Utah for 17 years. His efforts to investigate cardiovascular function have focused on understanding and treating heart failure with mechanical devices including artificial hearts, ventricular assist devices, and cardiopulmonary support systems which he has helped develop, test, and implement clinically in patients with two legs and with four legs, with big hearts and with little hearts. Pantalos has also collaborated with NASA for many years helping to understand cardiovascular adaptation to the weightlessness of space flight and the return to Earth. He has flown 43 research missions on the NASA parabolic flight aircraft and led the development of a cardiovascular diastolic function experiment - that included an instrumented artificial heart beating on a circulation simulator - that flew twice on the Space Shuttle Discovery. Other reduced gravity research projects have included delivery of effective chest compressions for CPR in 0-G, organ perfusion in 0-G, and the development of surgical capabilities for exploration space missions. Outside of his research and development efforts, Pantalos enjoys traveling with his family, playing basketball and biking, being a weekend percussionist, volunteering with the American Red Cross, working on federal policy development, and making baklava. With his fellow students, staff, faculty, and patients, his motto has always been, "Share the adventure!"

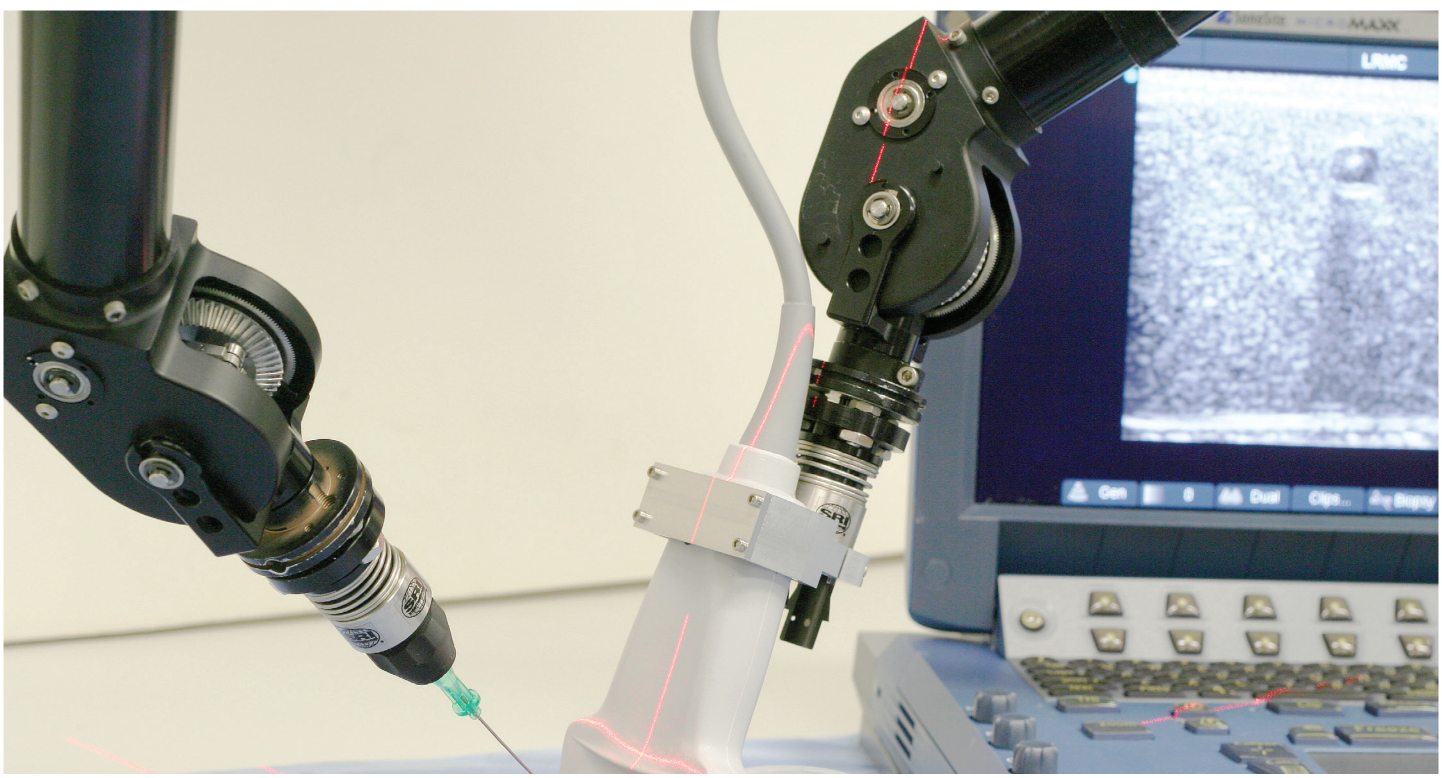
PETER PIROLLI

Peter Pirolli joined the Institute for Human & Machine Cognition (IHMC) in 2017. Previously he was a Research Fellow and Area Manager in the Interactive Intelligence Area at the Palo Alto Research Center (PARC), where he had been pursuing studies of human information interaction since 1991. Over that time, he had been a member or leader of groups that have created entirely new fields of research in the psychology of human-computer interaction, information visualization, information foraging theory, sensemaking, and social information foraging. Pirolli's current interest is in computational neurocognitive models to support artificial intelligence systems that help people change to healthier lifestyles. He received his Ph.D. in cognitive psychology from Carnegie Mellon University in 1985. Prior to joining PARC, he was an Associate Professor in the School of Education at UC Berkeley. Pirolli is an elected Fellow of the American Association for the Advancement of Science, the Association for Psychological Science, the American Psychological Association, the National Academy of Education, and the Association for Computing Machinery SIGCHI Academy. He is the author of "Information Foraging Theory: Adaptive Interaction with Information.



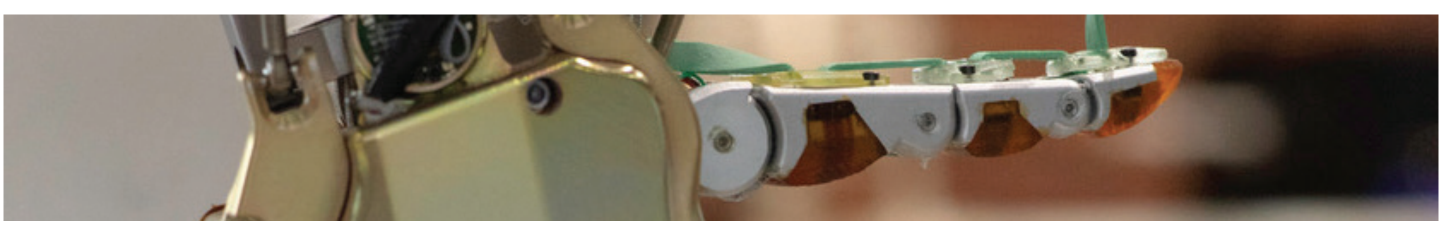
ANIL RAJ

Anil Raj is a Research Scientist at the Florida Institute for Human & Machine Cognition (IHMC). Raj received his M.D. from the University of Michigan School of Medicine in 1990. His interests in aerospace medicine research led him to the Naval Aerospace Medical Research Laboratory in Pensacola, FL, following a two-year fellowship as a National Research Council Resident Research Associate at the NASA Johnson Space Center in Houston, TX. Raj's interest focuses around the human physiologic and psychological responses to accelerative forces, particularly how changes in acceleration affect the sense of spatial orientation. He has been involved with the development, testing, and evaluation phases of the US Navy/NASA's Tactile Situation Awareness System. Since joining the Institute for Human & Machine Cognition in 1996, Raj has been involved with the development of human-centered interfaces and the development of automated systems for tracking and analyzing human response characteristics in dynamic environments.



JACOB ROSEN

Jacob Rosen is a professor of medical robotics at the Department of Mechanical and Aerospace Engineering with joint appointments with the Department Surgery and the Department of Bioengineering, University of California, Los Angeles (UCLA). His research interests focus on medical robotics, biorobotics, human centered robotics, surgical robotics, wearable robotics, rehabilitation robotics, neural control, and human-machine interface. Rosen received his B.S. degree in Mechanical Engineering, M.S. and Ph.D. degrees in Biomedical Engineering from Tel-Aviv University in 1987, 1993 and 1997 respectively. From 1987 to 1992 he served as an officer in the IDF studying human-machine interfaces. From 1993 to 1997 he was a research associate developing and studying the EMG based powered Exoskeleton at the Biomechanics Laboratory, Department of Biomedical Engineering, Tel-Aviv University. During the same period of time he held a position at a startup company developing innovative orthopedic spine/pelvis implants. From 1997 to 2000 he was a Post-Doc at the departments of Electrical Engineering and Surgery, University of Washington while developing surgical robotic and medical simulation systems. During 2001- 2008 Rosen served as a faculty member at the Department of Electrical Engineering, University of Washington in Seattle with adjunct appointments with the Departments of Surgery. From 2008- 2013 he served as a faculty member at the Department of Computer Engineering, University of California - Santa Cruz (UCSC). Since 2014 Rosen serves as a full professor at UCLA, directing the Bionics lab, and serves as a member at the Center for Advanced Surgical and Interventional Technology at David Geffen School of Medicine UCLA. Rosen developed several key systems in the field of medical robotics such as the Blue and the Red Dragon for minimally invasive surgical skill evaluation that is commercialized by Simulab as the "Edge", Raven – a surgical robotic system for telesurgery that is commercialized by Applied Dexterity as an open source research platform, several generations of upper and lower limb exoskeletons and most recently the Exo-UL7 – a dual arm wearable robotic system. He is a co-author of 100 manuscripts in the field of medical robotics and a co-author and co-editor of two books entitled "Surgical Robotics – Systems, Applications, and Visions" and "Redundancy in Robot Manipulators and Multi-robot systems" published by Springer.



ERICA R. H. SUTTON

Erica R. H. Sutton is currently a tenured Associate Professor in surgery at the University of Louisville School of Medicine. She is President of Surgery on Sunday Louisville, Inc., a nonprofit she founded in 2013 to provide free surgery to people who are uninsured or underinsured. Sutton is a graduate of Indiana University Bloomington ('97) and The Johns Hopkins University School of Medicine ('01). She completed her surgical training and fellowship in minimally invasive surgery at the University of Maryland School of Medicine Department of Surgery in Baltimore before relocating back to the midwest in 2011.

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Appendices

Appendix A: Welcome Slide – G. Pantaolos

Welcome to the Blue Sky!

Mass, Power, Volume, Time, Money, Risk, & Crew Competence

Appendix B: Astronaut's Perspective on Robotic Surgery – M. Barratt

Astronaut's Perspective on Robotic Surgery

Michael Barratt / NASA Astronaut Office

October 2018

Skipping to the end:

Eventually robotic surgery will be an enabling capability for space flight. Just like on the ground. And in the movies.

But there are filters and gates……

Medical Capabilities Constraints for Space Flight: The Stuff you Already Know (Gates)

Remote

Hardware Limitations (mass, volume, power, shelf life)

Communications Latency (telerobotic surgery beyond lunar vicinity unlikely)

Anesthesia limitations (enclosed atmosphere, TCCS)

CMO training issues (whether hands on or systems operator)

Medical Capabilities Constraints for Space Flight: The Stuff We Think About for Exploration (Filters)

Trades! E.g. state of art robotic surgery suite vs. redundant ECLSS

Proven Capability A solid ground pedigree is a must; we do not necessarily want cutting edge technology

Battlefield mentality We will do what we have to do

Holistic Risk Equation How we view the overall mission risk and how that factors into view of medical capability

Someone's gonna die.

Meaning of course you cannot prepare for everything.

Medical officer will have broad duties for foreseeable future*

Environmental Control and Life Support System!

Countermeasures system

Diet / Nutrition

Medical Monitoring

Behavioral Health

***Pending a critical mass of crew size and remoteness**

The Astronaut Perspective: Separating the Concepts

Robotic **Surgery**

On Board Medical Procedures ('Pre-surgical')

Basic medical procedures are easy. (It's all about zero-G stuff management.)

- **IM injection**
- **Phlebotomy**
- **IV placement (for serial sampling, fluid infusion)**
- **Foley and straight cath**
- **Minor wound care (non-suture)**
- **Eye foreign body removal**
- **Ultrasound imaging**

Non-medically trained crewmembers have routinely performed most of these.

Onboard Rodent Research

On Board Animal Research

Animal (rodent) research skills now mandatory for ISS flight assignment. Good experience base built:

- **anesthesia, euthanasia**
- **blood sampling**
- **organ / tissue sampling and handling**
- **survival surgeries**

Tissue handling, surgical instrumentation use, sterile procedures, management of blood and body fluids exercised on small animal model on a moderate to large scale of numbers / hours

Not difficult to envision surgical wound repair or other real time guided procedure

Along this path, simple surgical procedures seem attainable with skill sets and hardware within an exploration class mission crew

Wound repair
U/S guided cyst / abscess drainage
Peripheral amputations

Space Flight Robotics

Deeply ensconced into human flight operations and definitively multiplies our capability. But there are issues…..

NEEMO VII Crew

Busted surface rover.

One day on Expedition 19……
Uncommanded robotic arm motion.

Steve Bowen, STS-133
SSRMS froze during EVA with crewmember attached

Re-converging to the Astro Perspective of Robotic Surgery (Filters)

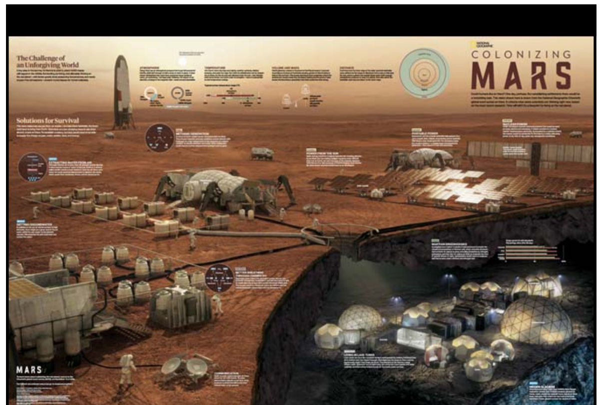
System must be as simple as possible, oriented toward a reasonable set of likely but / and manageable surgical problems

Must be a proven reliability, validated field history

Criticality determination is essential (defines redundancy requirements)

Failure modes must be understood
    Fail Operational / Fail Safe approach

Must be integrated into a holistic medical suite (not vice versa)

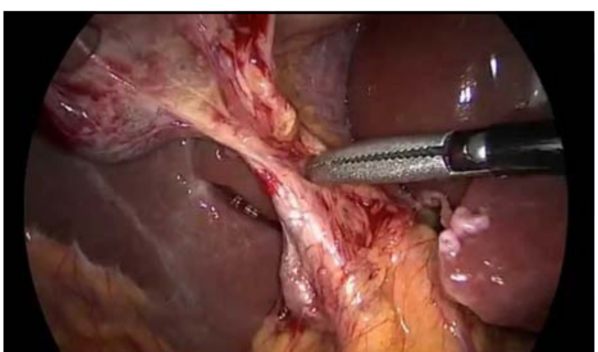


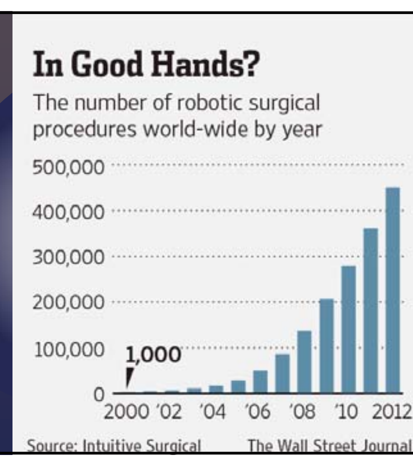

Questions?

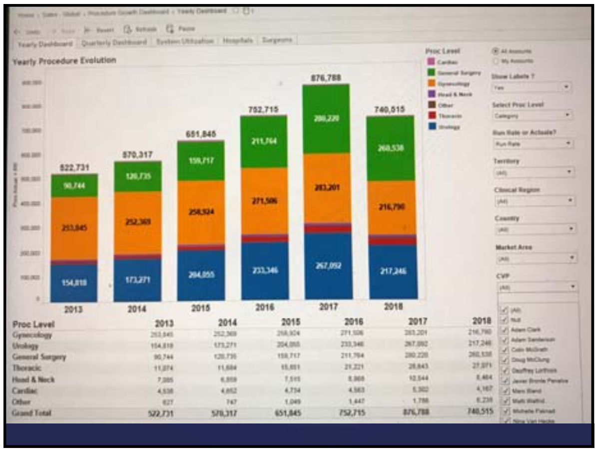
Appendix C: The Future is Here – M. Campbell

Robotic General Surgery 2018 – Implications for Surgical Care in Space

- Robotic surgical experience in U.S.
- Rapid adoption\expansion of robotic surgery in the U.S.
- Objective data shows no improved results
  - No increase in complications (safe)
  - Increased Cost and Op time
  - Maybe less LOS
- Idea of the <u>subjective</u> assessment of robotic surgery among surgeons
- Benefits and problems of robotic surgery







Robotic General Surgery – Paris Regional Medical Center

	Gen Surg	Gyn	Total
2014 (4\2)	202	98	310
2015	327	164	491
2016	402	192	594
2017	418	190	608
2018 (Proj)	412	204	616

Robotic General Surgery – Individual Statistics

	Chole	Hernia	Total
2014 (4\2)	99	8	109
2015	156	14	170
2016	185	14	201
2017	194	26	237
2018 (Proj)	240	52	292

Robotic General Surgery- Subjective Assessment

- Prostatectemy +++++
- Hysterectemy ++ (++++)
- Colecystectemy + (+++)
- Hiatal Hernia Repair ++++
- Inguinal Hernia Repair ++ (++++)
- Incisional Hernia Repair ++ (+)
- Colon Resection ++ (+)

District	Open surgery	Laparoscopic surgery	Robotic
Esophagus	+	++	+++
Reflux disease	−	+++	+++
Stomach (proximal)	+	+	++
Stomach (distal)	+	++	+++
Liver (major resection)	+	−	++
Liver (minor resection)	+	++	+
Liver (posterolateral segments)	+	−	++
Gallbladder	−	+++	+
Biliary tree	+	++	++
Pancreas (head)	+	−	+++
Pancreas (body–tail)	+	++	++
Pancreas (body–tail spleen preserving)	+	++	+++
Small bowel	+	+	+
Colon	−	+++	++
Rectum	−	++	+++

Robotic General Surgery- Benefits

- Better visualization (stereoscopic, mag, res)
- More stable camera control (surgeon directed)
- Wristed instruments (articulated end-effectors)
- Low maintenance (high level of support)
- Only slight increase in actual operative time (highly experienced OR crew)
- More precise surgical technique (dexterity, precision, accuracy, tremor reduction)
- Haptic feedback not important

Robotic General Surgery- Problems

- High cost of complex equipment
- Only applicable to a few specific operations
- Increased training (experience) of surgeons
- Increased training (experience) of OR crew
- High level of support (70% of revenue of Intuitive Surgical)
- Requires a large amount of ancillary supplies
- No objective data showing better outcomes

Surgical Care System in Space

- LEO does not need much surgical
- capability as med evacuation to
- Earth best surgical option (24 hr DMCT)
- Long duration (greater than 3 months)
- Long distance (Mars or cis-Lunar)
- Implemented in next 25 years (not next 100 years)

Surgical Care System in Space- Desired Characteristics

- Minimal weight, volume and power
- Maintenance free or high ability to repair
- Applicable to general situations and not only to specific procedures
- Minimal training requirements - CMO unlikely to be a surgeon (MD?).
- Not requiring a large amount of supplies
- Not dependent on telementoring - long communication delay
- No Radio Frequency Interference

Robotic General Surgery in Space- Future Challenges

- Miniaturization !!! – Weight, Volume
- Simplification (equipment and training) !!!
- Equipment – fault free
- Automatous segments
- Segmented procedures with stop points for telementoring (cis-Lunar)
- Person delivering surgical care will be at the level of a First Assistant
- No latency greater than 500 ms for telerobotic use

NASA Technology Readiness Level

Technology Readiness Levels

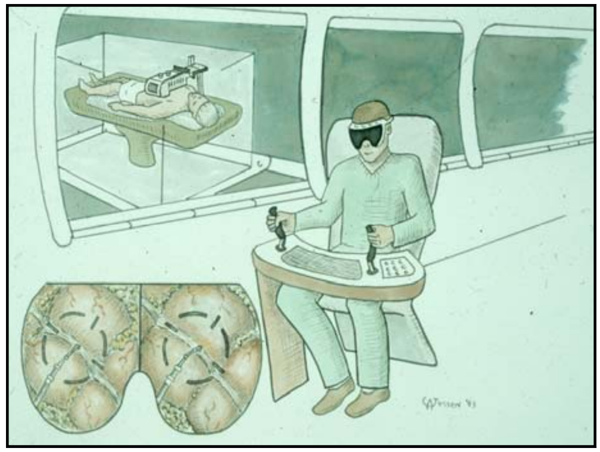
TRL 0: **Idea.** Unproven concept, no testing has been performed.
TRL 1: **Basic research.** Principles postulated and observed but no experimental proof available.
TRL 2: **Technology formulation.** Concept and application have been formulated.
TRL 3: **Applied research.** First laboratory tests completed; proof of concept.
TRL 4: **Small scale prototype** built in a laboratory environment ("ugly" prototype).
TRL 5: **Large scale prototype** tested in intended environment.
TRL 6: **Prototype system** tested in intended environment close to expected performance.
TRL 7: **Demonstration system** operating in operational environment at pre-commercial scale.
TRL 8: **First of a kind commercial system.** Manufacturing issues solved.
TRL 9: **Full commercial application**, technology available for consumers.

Technology Readiness Level

(Michelle Noguez)

- Robotic Surgery
  - TRL 9. Full Commercial Application. Technology
  - available for consumers.
- Surgery in Space
  - TRL 6. Prototype System. Tested in intended
  - environment with expected results.
- Robotic Surgery in Space
  - TRL 1: Basic Research. Principles postulated
  - and observed but no experimental data.

- Surgical robotic systems do not replace the need for a surgeon.
- Robotic surgery enhances and enables the existing skills of the surgeon, but does not replace the need for those skills.
- Any surgical procedure can be done faster and easier, with less training, and with less equipment without robotic surgery.
- Currently, robotic surgery in space flight is a complex liability (Michele Noguez).
- Goal : At least partially autonomous, miniaturized robotic system that could perform surgical procedures with minimal human assistance.



Appendix D: Roles for Humanoid Robots – R. Ambrose

Some (Old) Humanoid Videos

Roles for Humanoid Robots

Minimally Invasive Expeditionary Surgical Care using Human-Inspired Robots

Dr. Rob Ambrose
NASA JSC Engineering

Many Forms : Many Functions

Why Build Humanoids?

Definitions

humanoid. adjective.

Definition of humanoid : having human form or characteristics

human. noun.

Definition of human : a bipedal primate mammal (Homo sapiens)

Definitions

Primate. Noun.

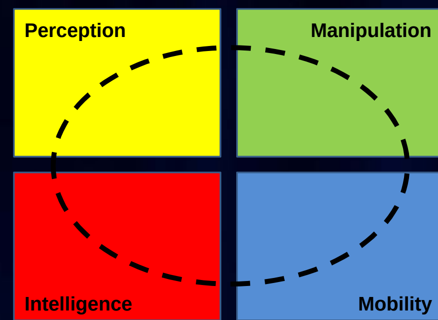
Definition of primate: any of an order (Primates) of mammals that are characterized especially by advanced development of binocular vision resulting in stereoscopic depth perception, specialization of the hands and feet for grasping, and enlargement of the cerebral hemispheres and that include humans, apes, monkeys, and related forms

Historical Definitions

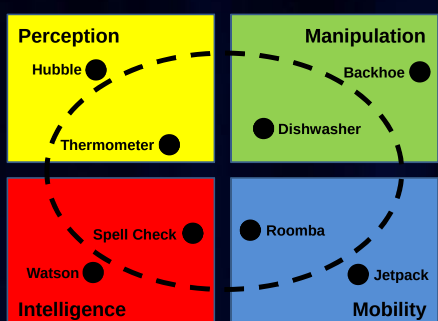
Mivart in 1873 Primate

Unguiculate, claviculate, placental mammals, with orbits encircled by bone; three kinds of teeth, at least at one time of life; brain always with a posterior lobe and calcarine fissure; the innermost digit of at least one pair of extremities opposable; hallux with a flat nail or none; a well developed caecum; penis pendulous; testes scrotal; always two pectoral mammae.

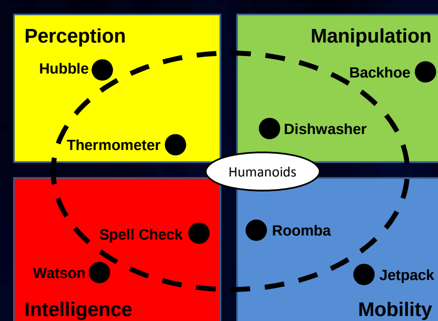
To Be Human



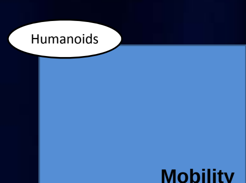
Single Purpose Robots



To Be Human*oid*



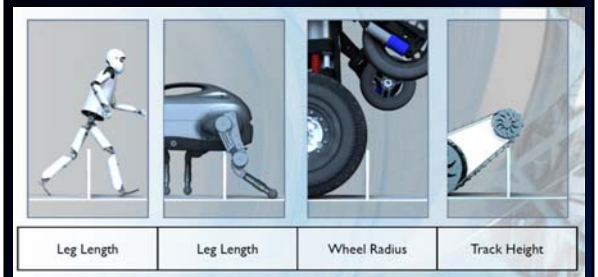
Focus on Legs



Thin Passage: Legs Win

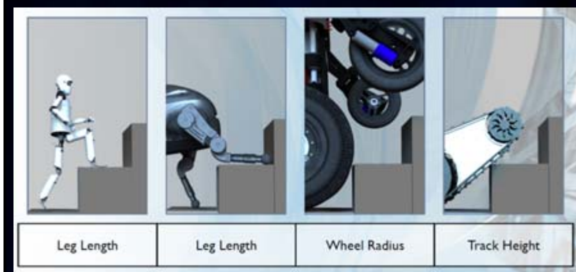
Jerry Pratt

Barriers: Legs Win



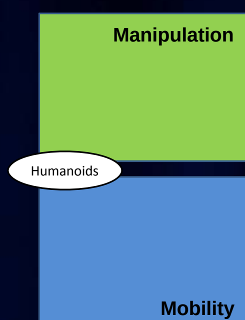
Jerry Pratt

Steps: Legs Win

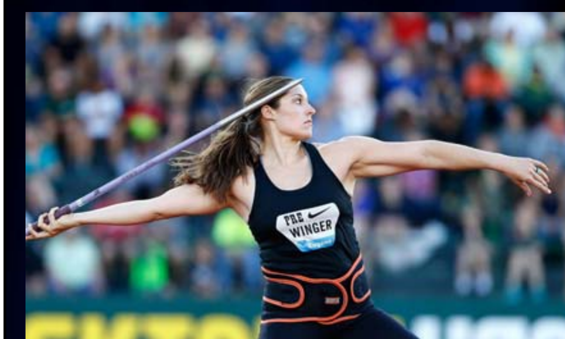


Jerry Pratt

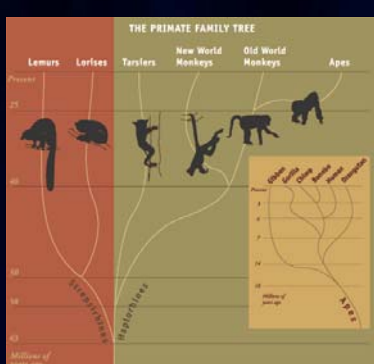
Focus on Arms and Legs



Manipulation and Mobility, Combined



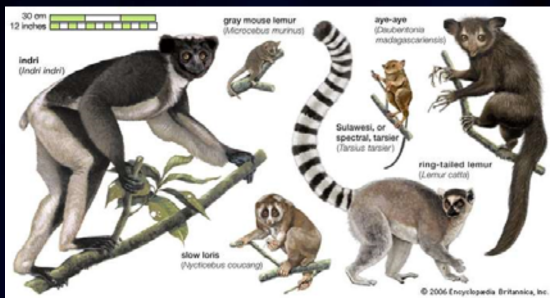
Primate Order



Primate Order

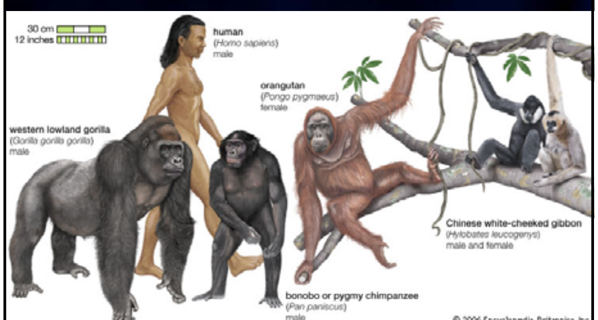
Order	Sub Order	Infra Order	Super Family	Family	Sub Family	Tribe	CommonName
Primate	Prosimians						Loris Lemur Tarsier
	Anthropoidea	Platyrrhini					New World Monkey
		Catarrhini	Cercopithecoidea				Old World Monkey
			Hominoidea	Hylobatidae			Gibbon
				Hominidae	Ponginae		Orang
					Homininae	Panini	Gorilla Chimp
						Hominini	Human

Prosimians and New World Monkey



Old World Monkey

Great Apes

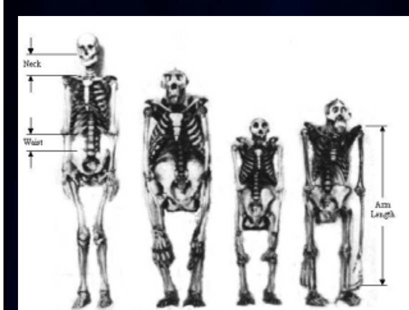


Hominidae Waist

Species	Average Lumbar Joint		# of lumbar vertebrae	Lumbar-Sacral Joint	
	Flexion	Extension		Flexion	Extension
Monkey	15	8	7	28	11
Rabbit	17	17	7	20	40
Badger	14	14	6	15	30
Wallaby	18	8	6	35	15
Sheep	5	8	6	15	30
Seal	16	0	6	18	0
Tiger	7	0	7	15	0
Human	7	5	5	10	8

Ambrose & Ambrose, IJHR, 2003

Design Observation



Biped Mobility

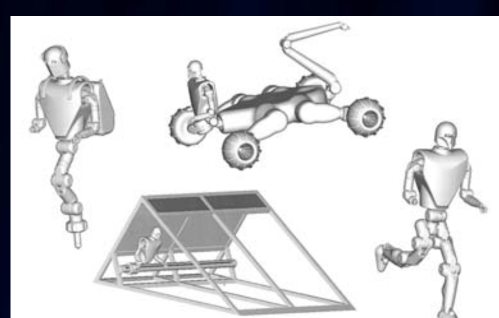
+

Waist

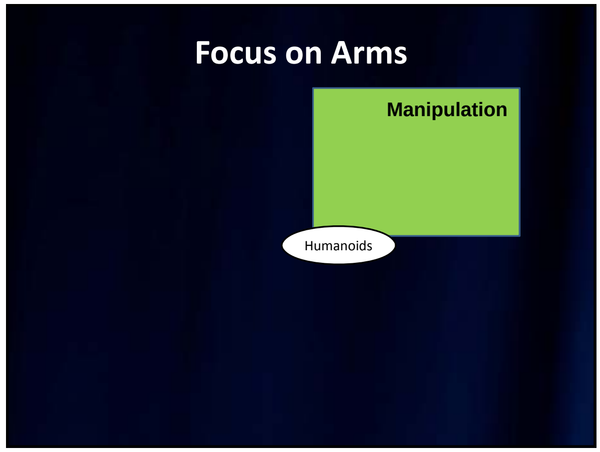
=

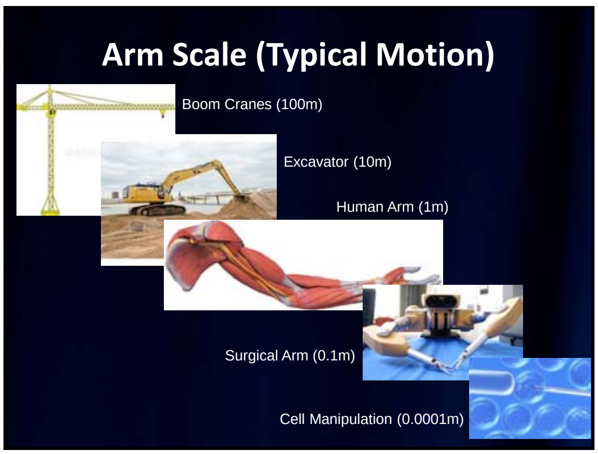
Shorter Arms

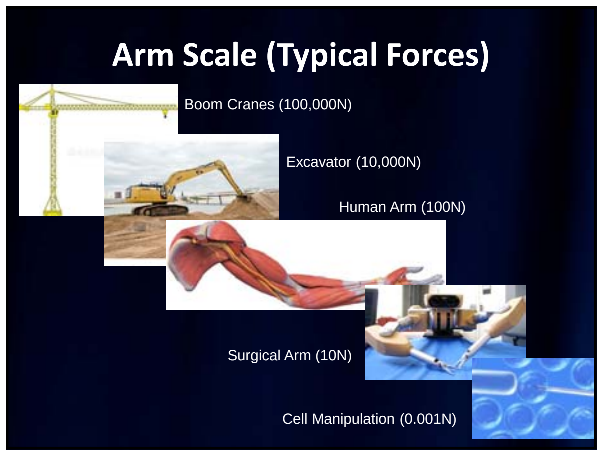
Arms on Non-Human Mobility

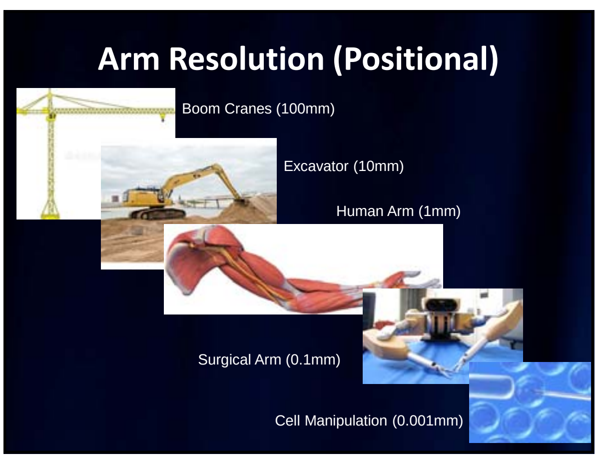


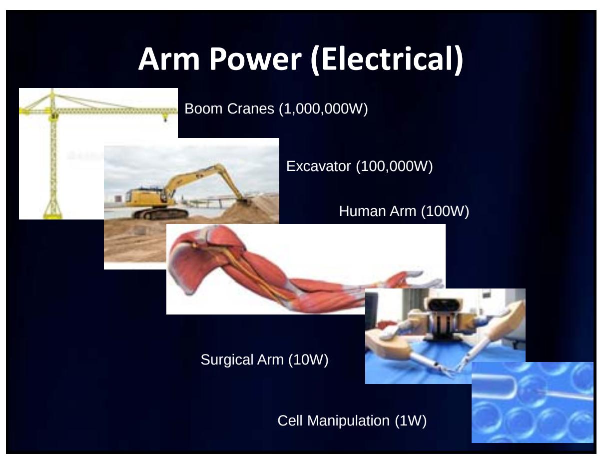

Arms on Non-Human Mobility


Focus on Arms
Manipulation
Humanoids

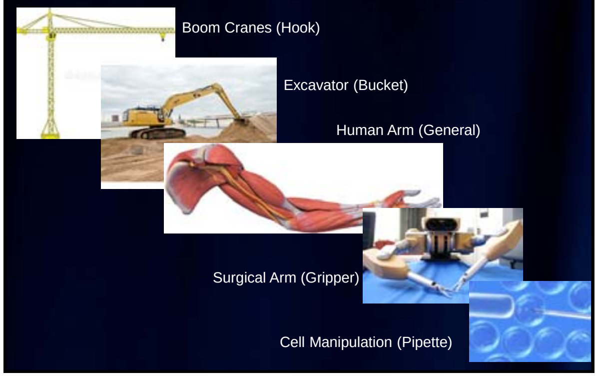

Arm Scale (Typical Motion)
Boom Cranes (100m)
Excavator (10m)
Human Arm (1m)
Surgical Arm (0.1m)
Cell Manipulation (0.0001m)


Arm Scale (Typical Forces)
Boom Cranes (100,000N)
Excavator (10,000N)
Human Arm (100N)
Surgical Arm (10N)
Cell Manipulation (0.001N)

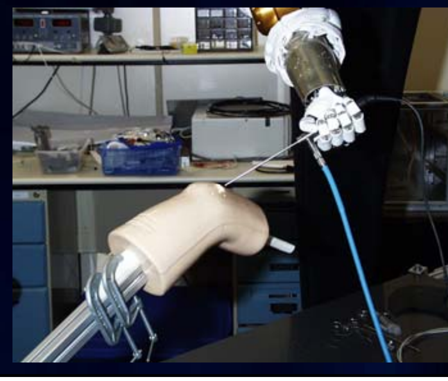

Arm Resolution (Positional)
Boom Cranes (100mm)
Excavator (10mm)
Human Arm (1mm)
Surgical Arm (0.1mm)
Cell Manipulation (0.001mm)


Arm Power (Electrical)
Boom Cranes (1,000,000W)
Excavator (100,000W)
Human Arm (100W)
Surgical Arm (10W)
Cell Manipulation (1W)

Arm Tooling (Interfaces)

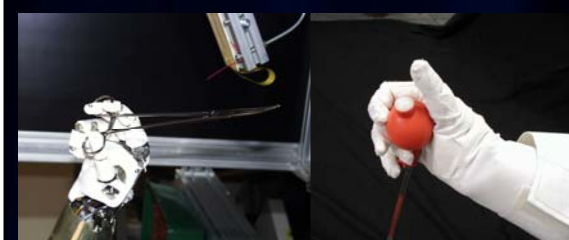


Humanoids Handling Objects



Humanoids Handling Objects

Humanoids Handling Objects



Humanoids Handling Objects

Humanoids Handling Objects

Capabilities for Humanoids

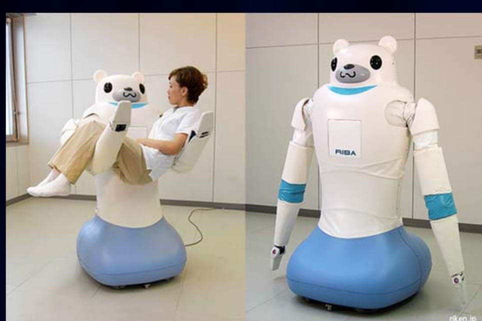
Arms
- 1m Typical Motions
- 100N Forces
- 1mm Resolution
- 100W Power
- General Tooling

Mobility
- Legged, or
- Non-Human

Roles for Humanoids: Orderly

M13 AEUP
Bed Mover

Roles for Humanoids: Palliative Care



Riken

Roles for Humanoids: Radiology

Roles for Humanoids: Therapist

Riken

Roles for Humanoids: Bedside Visits

Roles for Humanoids: Surgical Nurse

Purdue

Roles for Humanoids: Midwife

Star Wars Midwife

Summary

A Humanoid robot is a good fit if…..

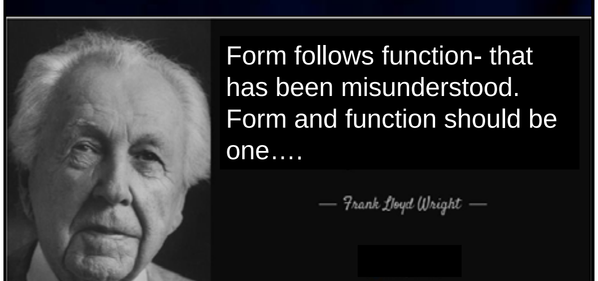
- You need to move into position to work
- And do human scale tasks

Autonomy and perception are catching up…

- These capabilities today with telepresence
- And soon autonomously

Backup

Form Follows Function, Sort of….



Poles: Legs Win

Jerry Pratt

Overall Themes

Common Needs for NASA and Nuclear Cleanup Robotics

- Radiation tolerant systems
- Dirty environments
- Dangerous tasks
- Handling high consequence materials
- Wearable robotics
- Remote operations

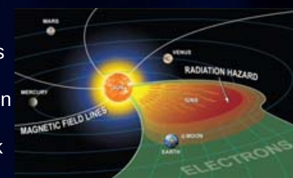
Other Observations on Cleanup Applications

Radiation Tolerant Robotics

NASA and DOE are rare in dealing with radiation

Both have key needs

- Avionics challenges
- Material degradation
- Clean up after work



Both challenge human health

Dirty Environments

NASA and DOE-EM need outdoor (field) robotics

Operating in dirt

- Mechanisms challenges
- Material degradation
- Clean up after work
- Handling dirt

Both challenge human health

Dangerous Tasks

Dangerous Chemicals

Dangerous Radiation

Dangerous Sharps

Distance to Safety

- Airlocks, Tunnels, Suits
- Extraction Difficulties
- Transport to Medical Treatment

Handling High Consequence Materials

Dangerous Materials

Expensive Objects

One-of-a-Kind Samples

Avoiding Inadvertent Drops

- Explosions
- Contaminations
- Cleanup Costs

Wearable Robotics

Improve Safety

Extend Careers

Level Playing Field

Embraced by Workers

- This is unusual in my history
- Aging workforce
- Medical/legal costs

Remote Operations

Communications Challenges

- Distance
- Noise
- Denied Areas

Employ Human Judgement

- Provide Data
- Context
- Decision Making Options

DOE-EM Robotics Applications

DOE-EM Study Team Site Visits

WIPP

- Tunnel mobility, inspection, monitoring, logistics
- Manipulation with long reach, pallet handling

Idaho Falls

- Dry material handling, "silo" access, barrel processing
- Liquid handling, monitoring, processing

Savannah River

- Canyon operations, inspection, and D&D
- Tunnel access, glove box operations, manipulation

Hanford (so, so many….)

- Underground tank inspection, material handling, D&D
- PUREX tunnel inspection, access, D&D, emergency response
- Canyon operations, inspection, servicing, life cycle planning

Case Study: Human-Robot Teams

- NASA GM Partnership
  - Safe robot for working with people
  - Focused on jobs that hurt workers
- Robonaut 2 Development
  - What if you could work next to a robot, safely
  - Developed multiple Robonaut 2's
- Applications to Cleanup
  - Glovebox manipulation
  - Assembly, decommissioning, contingency tasks

Case Study: Robotic Gloves

- NASA GM Partnership
  - Safe robot for working with people
  - Focused on jobs that hurt workers
- Glove Spin Off
  - What if you could wear the robot hand?
  - Developed the Robo Glove
- Partnered with DOE
  - How would DOE workers use a glove?
  - Now working other applications.

Case Study: Robotic Off Road Vehicle

- NASA Lunar Rover
  - Pressurized Cabin
  - Radiation Shielded
  - 2 Crew for 2 Weeks
  - 200 Km Range
  - Can carry robots on outside
  - Humans egress thru suit ports
- 2nd Generation in Design
  - Able to operate in contamination
  - Looking for partnerships

https://www.youtube.com/watch?v=xSVupWflmG4

Case Study: Small, Agile Vehicle

- Modular Robotic Vehicle
  - Separate Wheel Modules
    - Steering
    - Suspension
    - Drive
  - Drive-by-wire Cockpit
  - All electric design
  - Intrenisic safety by design
- Cleanup Applications
  - Maneuverable inside tunnels, buildings
  - Able to carry manipulators, forklifts
  - Manned and unmanned operations

Thank You

robert.o.ambrose@nasa.gov

Appendix E: Dexterous Robotic Caretaking on the ISS and its Applications to Remote Surgical Care –J. Badger

Dexterous Robotic Caretaking on the ISS and its Applications to Remote Surgical Care

Julia Badger, PhD
Project Manager, Robotics and Intelligence for Human Spacecraft Team
NASA- Johnson Space Center

2 October 2018

Robonaut 2 (R2)

- Started in 2007 with GM
  - Leveraged Robonaut 1 technology (1998-2006)
- Common goals
  - Use humans' tools
  - Safely share humans' workspace
  - Do real (useful) work
- Launched on STS-133 in Feb 2011

Robonaut 1, Units A & B

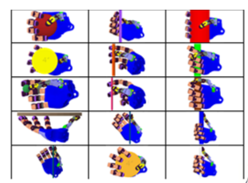
Overview

- *Mechanical Features*
- ISS Timeline & Tasks
- R2 Mobility System
- Supervised Autonomy for Robotic Caretaking
- Surgical Tasks

Hand Dexterity

- 4 DOF Thumb
- Dexterous fingers
- Grasping fingers
- Approaching human joint travel
- High friction grip surface
- Fine motion
- Tendon Tension
- Wide range of grasps

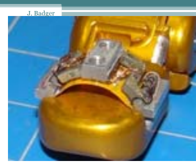
Human Like Grasps: Pen



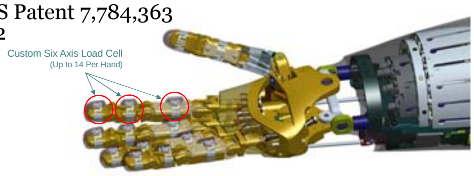
Cutkosky Grasps

Tactile System

- Extremely Small
- Integrated Load Cells
- 6 Axis
- Up to 14 per Hand
- Serialized Data
- Gram sensitive
- US Patent 7,784,363 B2



Load Cell



Arm Control

- Series Elastic Control
  - Embedded Springs
    - US Patent App. 20100145510
  - High resolution absolute position sensing
  - Joint level torque control
    - 10Khz loop
  - Variable compliance
- Modular Joint Electronics
  - Highly integrated
  - Redundant processing
  - Local A/D
    - Noise reduction

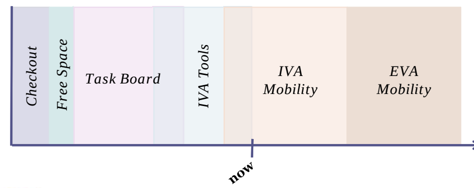
Torsional Spring

Plug-in SuperDriver

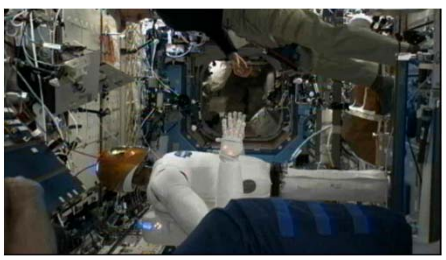
Overview

- Mechanical Features
- *ISS Timeline & Tasks*
- R2 Mobility System
- Supervised Autonomy for Robotic Caretaking
- Surgical Tasks

R2 ISS Task-Level Timeline

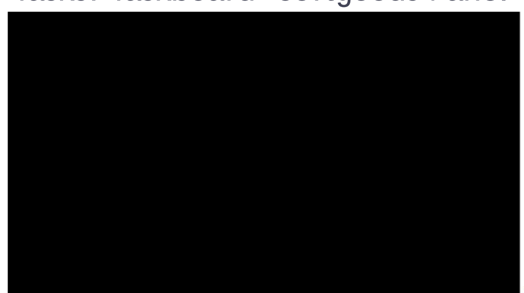


Tasks: Free Space



First R2-Astronaut Space Handshake

Tasks: Taskboard- Softgoods Panel



Tasks: Tele-operation

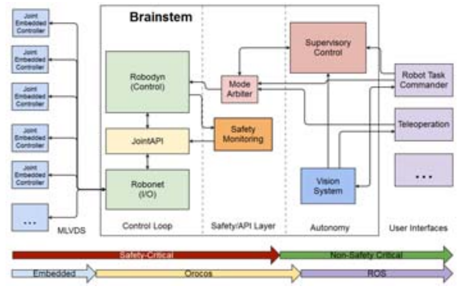
Overview

- Mechanical Features
- ISS Timeline & Tasks
- *R2 Mobility System*
- Supervised Autonomy for Robotic Caretaking
- Surgical Tasks

R2 Mobility System

- Upgrades include:
  - Robotic “legs”
    - 7 DOF each + gripping end effector
    - Vision package (camera + TOF sensor) in each end effector
  - Increased processing ability
  - New helmet for increased vision capabilities
- Interfaces with the following:
  - IVA handrails
  - Lab wireless network

Overall Architecture



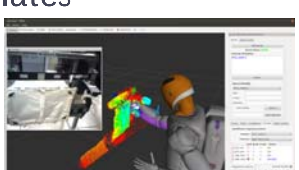
Overview

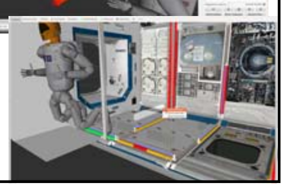
- Mechanical Features
- ISS Timeline & Tasks
- R2 Mobility System
- *Supervised Autonomy for Robotic Caretaking*
- Surgical Tasks

Future Exploration Goals

Affordance Templates

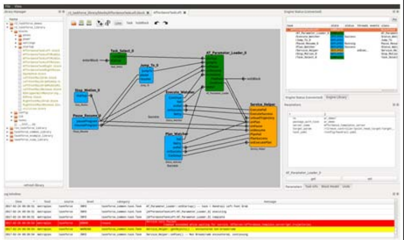
- Adopted this approach to move from supervised control to autonomous robotic behaviors
- Adapted from concept attempted during first DARPA Robotics Challenge
- Framework upgrades and improvements:
  - Embedded collision data & checking
    - Allowable Collision Matrix
    - Obstacle Avoidance
  - Planner Plugins
    - Customizable planners and trajectory generators
  - Active supervisors
    - QR Code Detection
    - Automatic Object Recognition





Autonomous Caretaking Demonstration

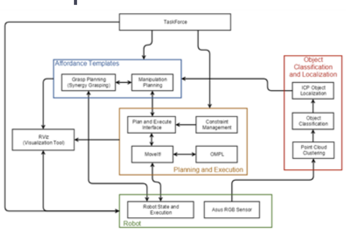
TaskForce



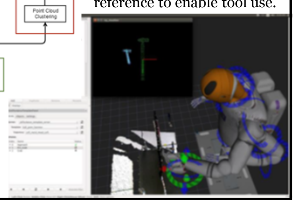
- General-purpose algorithm design and execution framework that can serve as an Integrated Development Environment (IDE) for complex task development
- Includes options for procedure execution, deployments of task supervisors

Autonomous Logistics Demonstration

Manipulation Framework



Affordance Templates- framework that uses models of objects encoded with afforded grasps and manipulations registered to the robot's frame of reference to enable tool use.



- Centers around Affordance Template framework and Planning and Execution engine

Cognitive Grasping

Overview

- Mechanical Features
- ISS Timeline & Tasks
- R2 Mobility System
- Supervised Autonomy for Robotic Caretaking
- *Surgical Tasks*

Robotic Surgical Explorations

Conclusions

- Robonaut 2 is a premier testbed for autonomous dexterous robotic technology development
- Born of an industrial partnership, it has garnered over 40 patents and several spin-off technologies
- Next steps involve developing caretaking technologies for dangerous, hard-to-access locations (dormant spacecraft, off-shore oil rigs)
- Medical tasks certainly has cross-over technology!

Appendix F: What Makes a Good Robotic Surgery Assistant – M. Johnson

What Makes a Good Robotic Surgery Assistant?

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Florida Institute for Human and Machine Cognition

Presented by Matthew Johnson (mjohnson@ihmc.us)

02 OCT 2018

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Expeditionary Robotic Surgery Issues

- Environmental
  - e.g. contamination, liquid containment
- Biological
  - e.g. 0g
- Anesthetics and other drug use
- Size, weight , space limitations
- Available equipment
  - e.g. robotic assistant

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Expeditionary Robotic Surgery Issues

- Environmental
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- Anesthetics and other drug use
- Size, weight , space limitations
- Available equipment
  - e.g. robotic assistant

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Why Robotic Surgery?

- Shorter hospitalization
- Reduced pain and discomfort
- Faster recovery time and return to normal activities
- Smaller incisions, resulting in reduced risk of infection
- Reduced blood loss and transfusions
- Minimal scarring

- No local surgeon?
- Under-manned surgical staff?
- Under-trained surgical staff?
- No human staff available?

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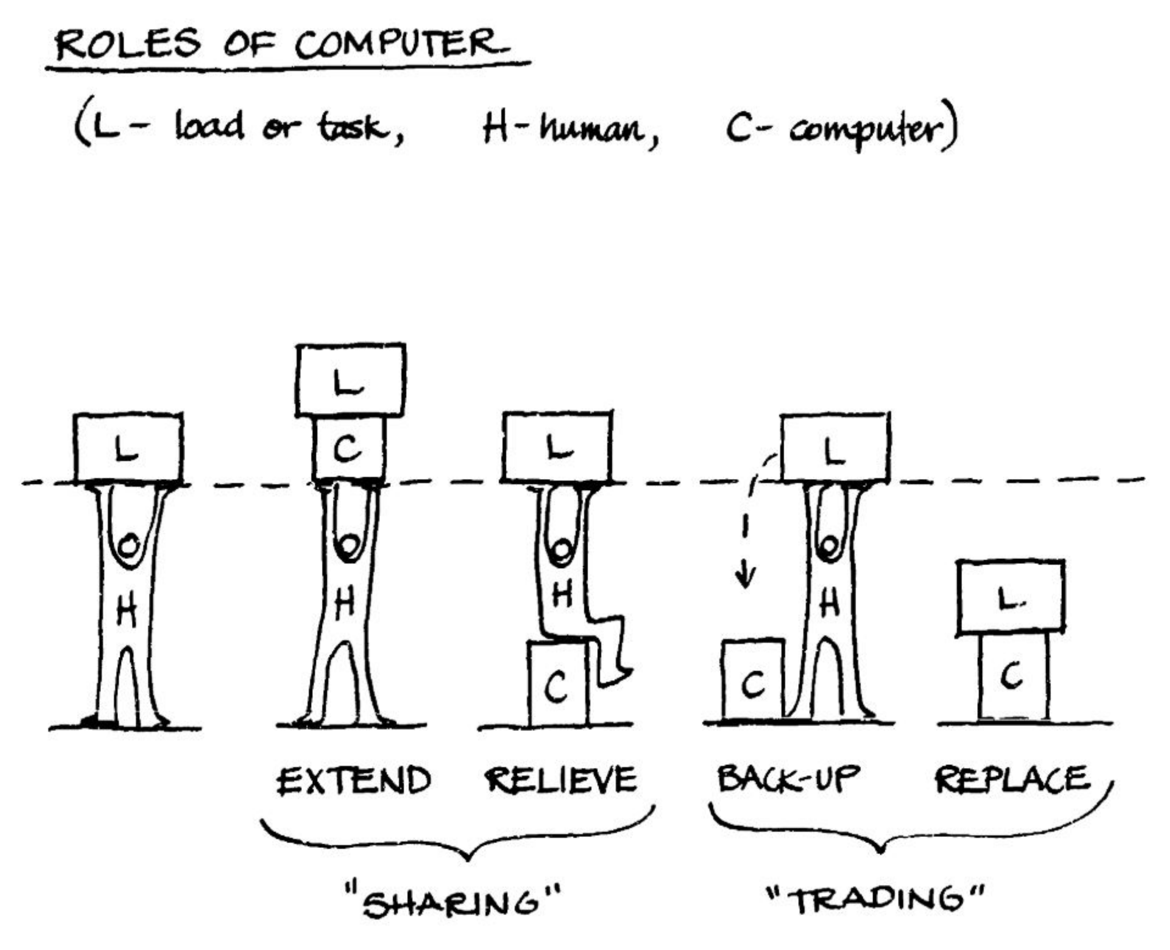
What is the Role of a Surgery Assistant?



[1]Sheridan, T. B., & Verplank, W. (1978). Human and Computer Control of Undersea Teleoperators. Cambridge, MA: Man-Machine Systems Laboratory, Department of Mechanical Engineering, MIT.

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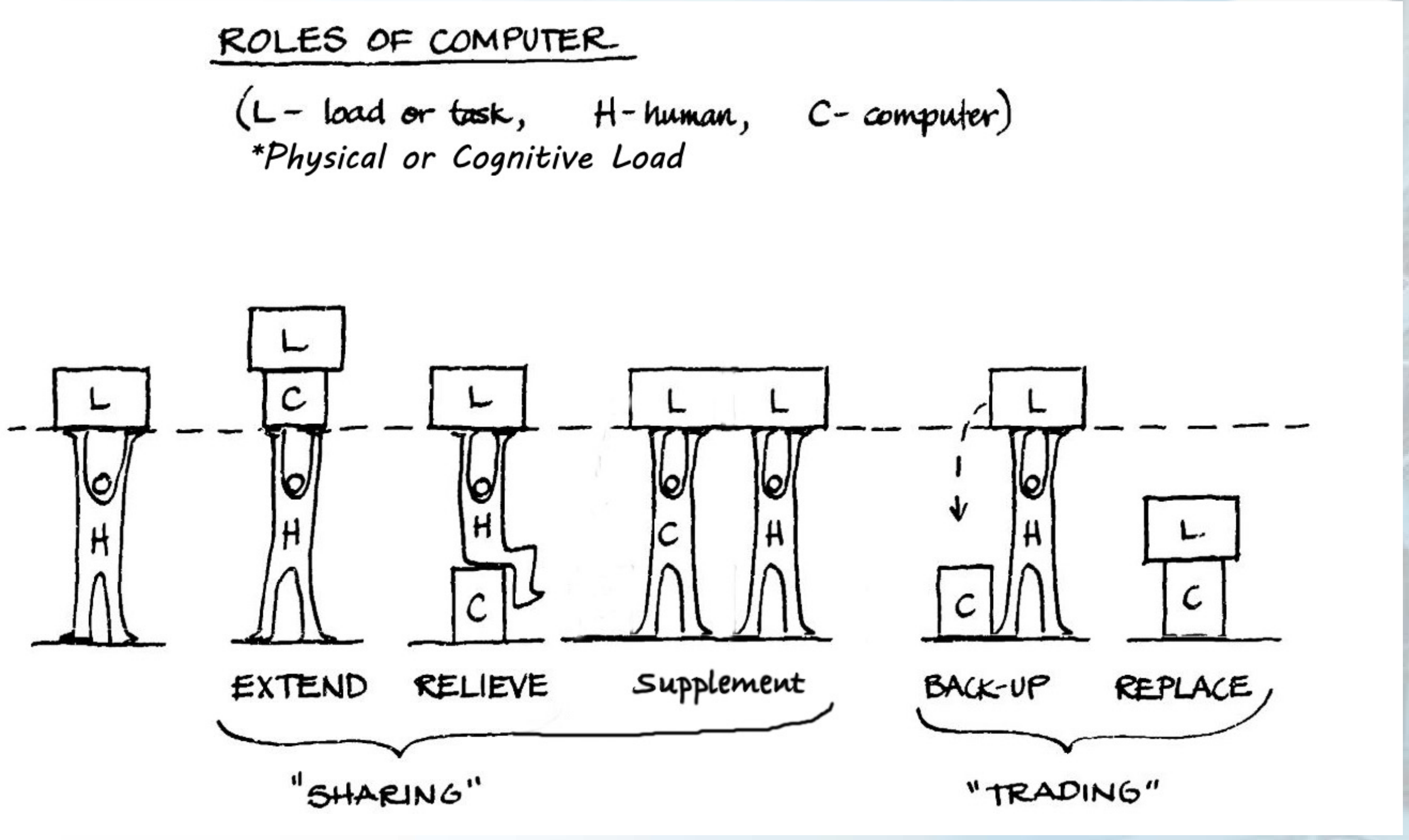
What is the Role of a Surgery Assistant?



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Advantages and Disadvantages (Da Vinci)

Advantages

- Minimal incision[2]
- Decreased postoperative morbidity[2]
- Reduction in total hospital stay[2]
- Greater visualization[1]
- Enhanced dexterity[1]
- Greater precision[1]

Disadvantages[2]

- Long surgical instruments
- Loss of depth perception
- Loss of tactile sensation
- Amplified motion vibrations

With the addition of new technology to provide enhancements comes the potential for correlated disadvantages

[1] https://uchealth.com/services/robotic-surgery/patient-information/benefits
[2] ROBOTIC SURGERY IN SPACE (2018) Michelle Noguez Ceron

Advantages and Disadvantages (Da Vinci)

Advantages

- Minimal incision[2]
- Decreased postoperative morbidity[2]
- Reduction in total hospital stay[2]
- Greater visualization[1]
- Enhanced dexterity[1]
- Greater precision[1]

Disadvantages[2]

- Long surgical instruments
- Loss of depth perception
- Loss of tactile sensation
- Amplified motion vibrations
- Loss of natural hand-eye coordination
- Loss of intuitive movement
- Loss of dexterity

New technology, if not carefully designed,
can inhibit human capabilities

[1] https://uchealth.com/services/robotic-surgery/patient-information/benefits
[2] ROBOTIC SURGERY IN SPACE (2018) Michelle Noguez Ceron

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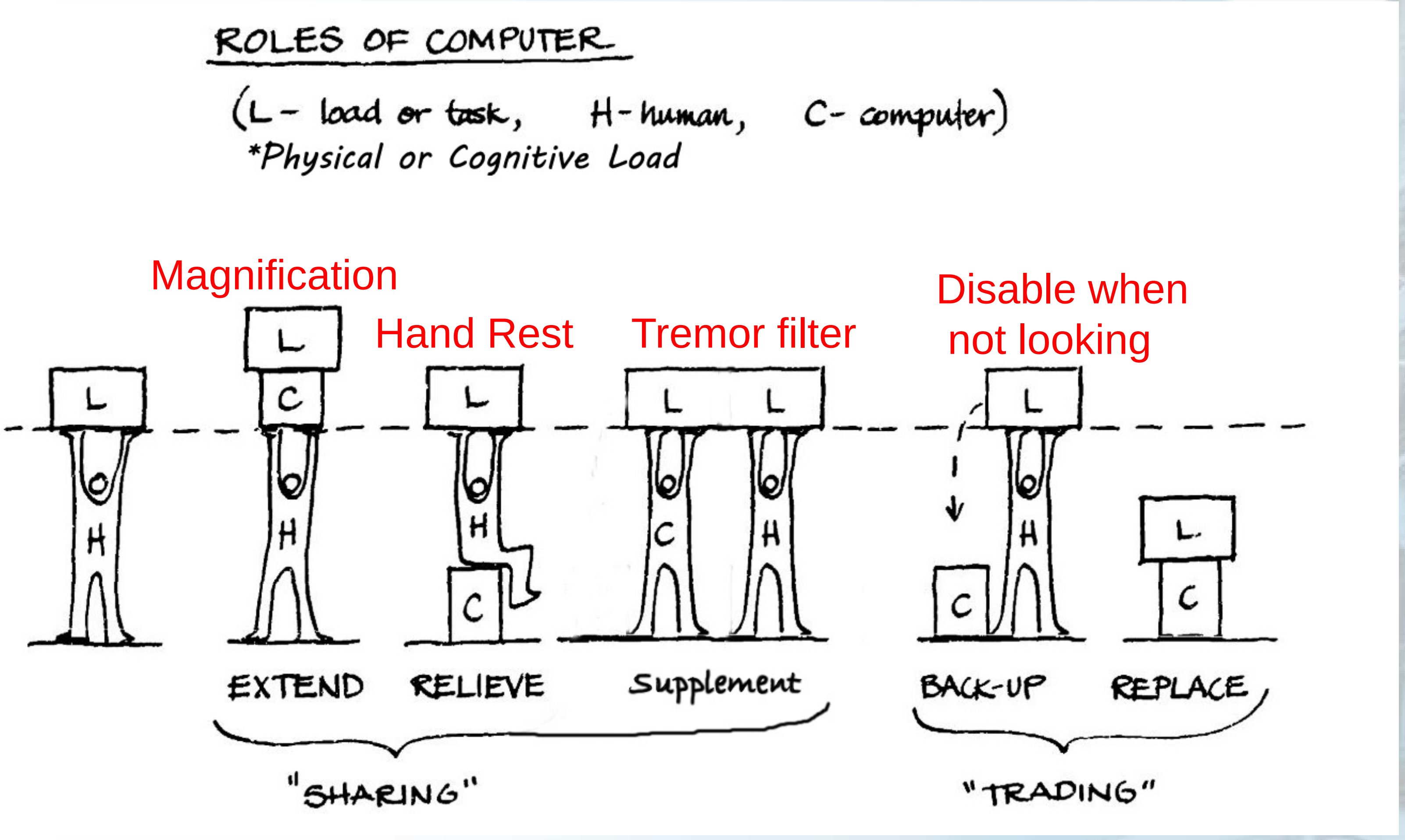
What is the Role of a Surgery Assistant?



What about Autonomy and Artificial Intelligence?

Although counter-intuitive,
the greater the individual competence (autonomy/intelligence),
the greater the need for more sophisticated collaborative skills.

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Dependent *-Autonomy-* **Independent**

Dependent *-Autonomy-* **Independent** *-Teamwork-* **Interdependent**

Coactive Design is about enabling autonomy to reach its pot
by designing for interdependence.

Dependent *-Autonomy-* **Independent** *-Teamwork-* **Interdependent**

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Coactive Design is about enabling autonomy to reach its pot
by designing for interdependence.

Dependent *-Autonomy-* **Independent** *-Teamwork-* **Interdependent**

“Robotics will need to work around a medical suite – not the other way around”

– Mike Barratt

“Robotics will not replace the need for a surgeon”

– Mark Campbell

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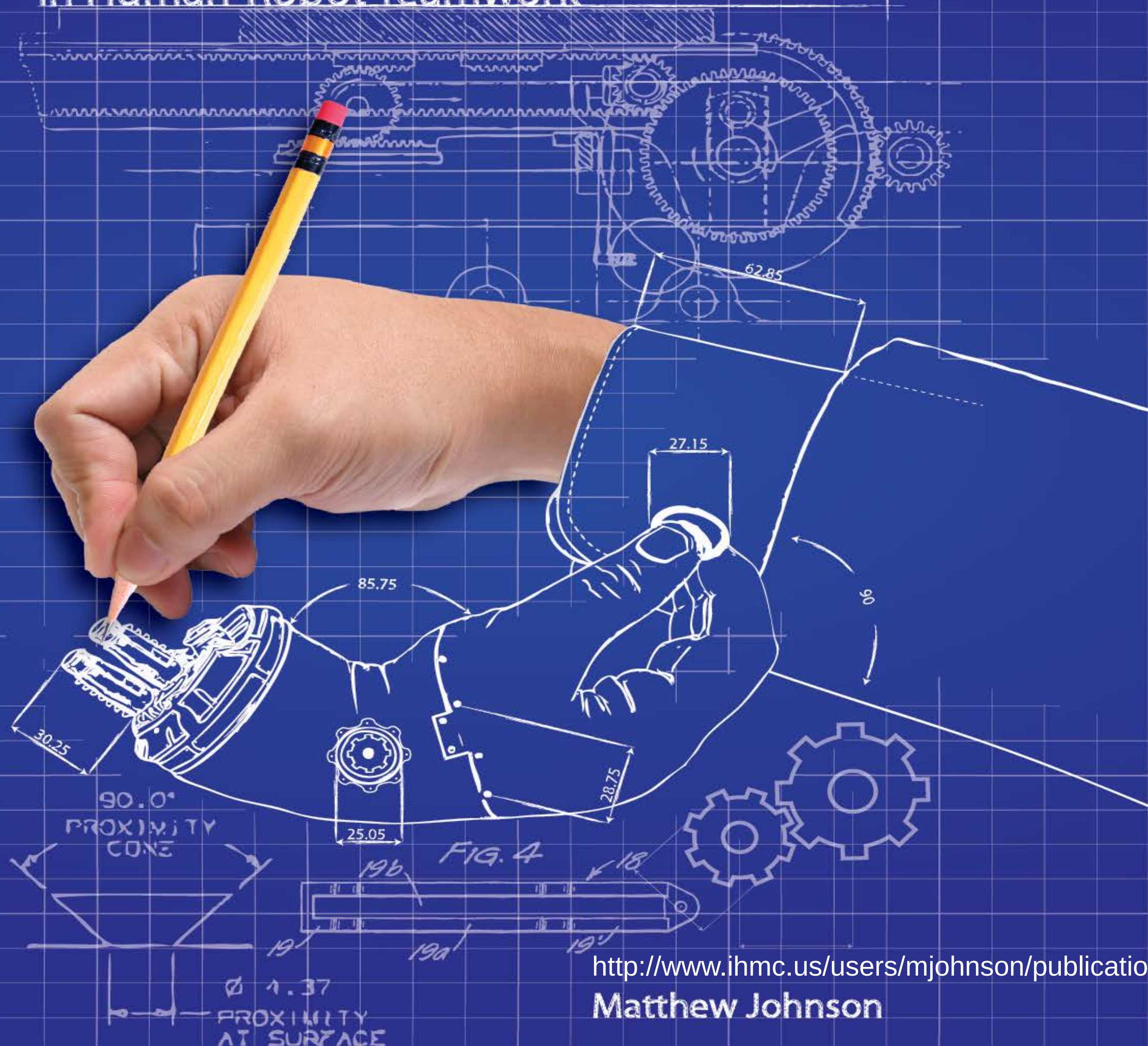
Coactive Design

Designing Support for Interdependence in Human-Robot Teamwork



http://www.ihmc.us/users/mjohnson/publications.html

Matthew Johnson

Key Observations

- Designing for interdependence is not a call to develop a new capability, rather, it should be viewed as an approach to how and what capabilities are built such that they are imbued with teaming competence.

- Approaches based on function allocation simplify work to task decomposition and do not create designs that allow dealing with the contingencies of teamwork.

"When it comes to the job itself, however, the problem is not to dissect it into parts or motions but to put together an integrated whole."

– Peter Drucker *The Practice of Management* (1954)

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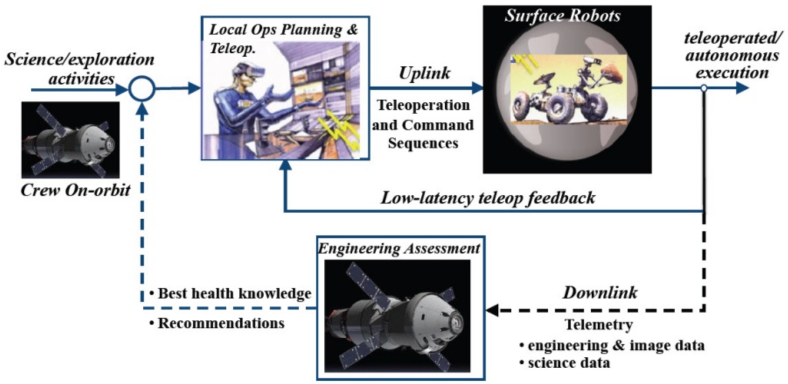
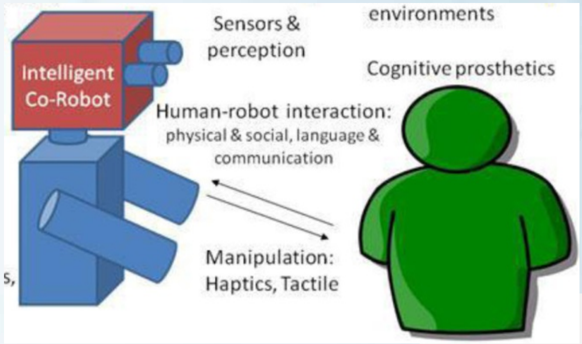
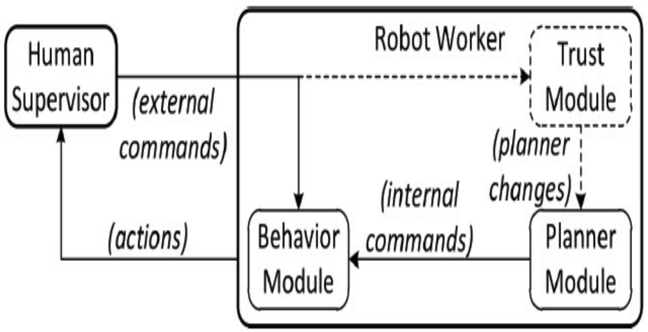


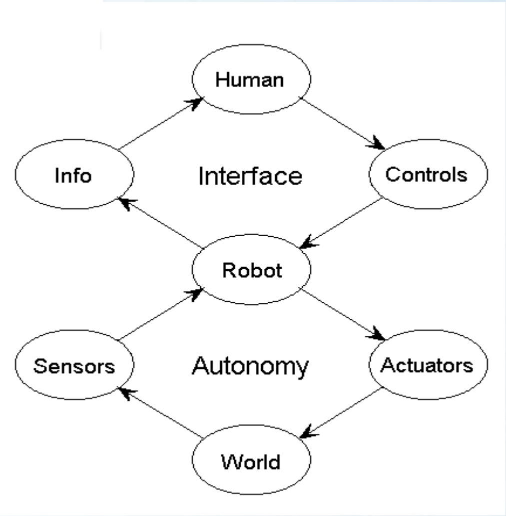
Science/exploration activities
Crew On-orbit
Local Ops Planning & Teleop.
Uplink
Teleoperation and Command Sequences
Surface Robots
teleoperated/ autonomous execution
Low-latency teleop feedback
Engineering Assessment
• Best health knowledge
• Recommendations
Downlink
Telemetry
• engineering & image data
• science data



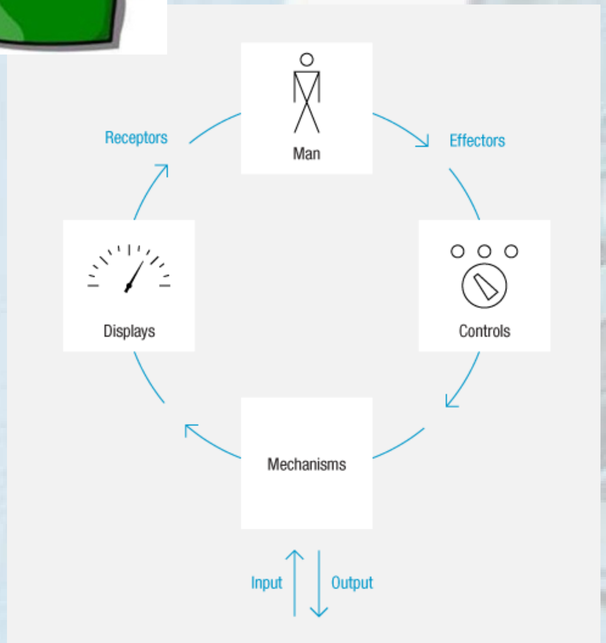
Intelligent Co-Robot
Sensors & perception
environments
Cognitive prosthetics
Human-robot interaction: physical & social, language & communication
Manipulation: Haptics, Tactile



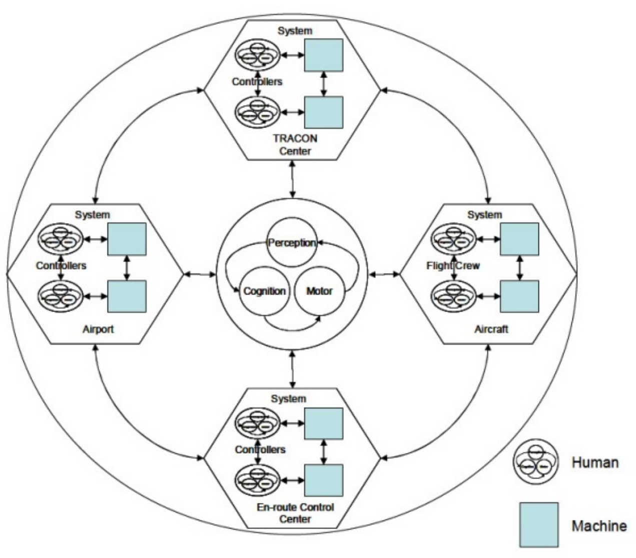
Human Supervisor
(external commands)
(actions)
Robot Worker
Trust Module
(planner changes)
(internal commands)
Behavior Module
Planner Module



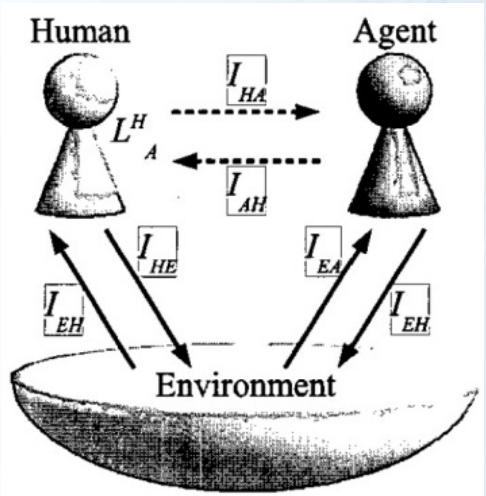
Human
Info
Interface
Controls
Robot
Sensors
Autonomy
Actuators
World



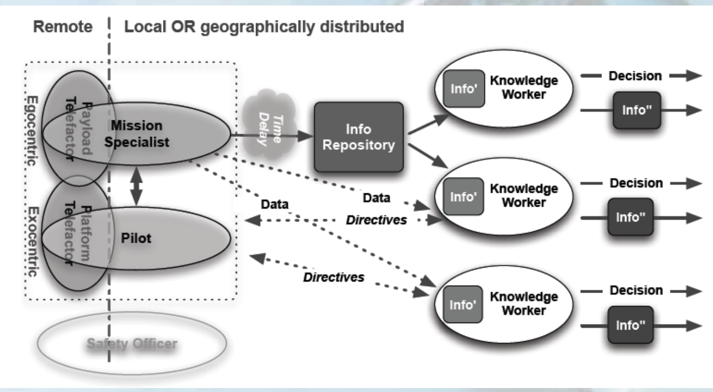
Man
Receptors
Effectors
Displays
Controls
Mechanisms
Input
Output



System
Controllers
TRACON Center
Airport
Flight Crew
Aircraft
Perception
Cognition
Motor
En-route Control Center
Human
Machine

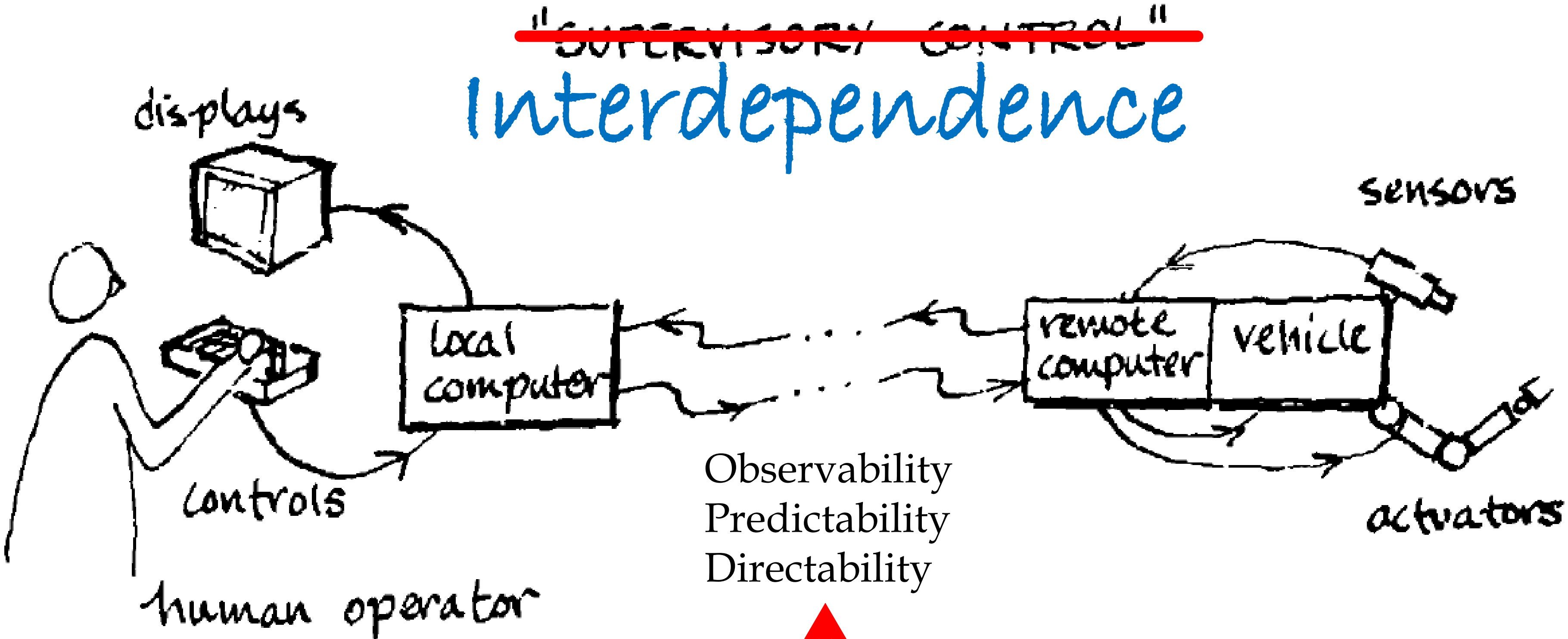


Human
Agent
Environment



Remote
Local OR geographically distributed
Egocentric
Exocentric
Payload Telefactor
Platform Telefactor
Mission Specialist
Pilot
Safety Officer
Time Delay
Info Repository
Data
Directives
Knowledge Worker
Info'
Info"
Decision

The Theory of Interdependence



Interface Design and Human Factors

Autonomy and Control Theory

(Sheridan & Verplank, 1978)

These are where the requirements for supporting interdependence come from.

Core Issues with Robotic Support

Human Needs
What is the robot doing?
What is the robot going to do next?
How can we get the robot to do what we need?

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Core Issues with Robotic Support

Human Needs	Issues
What is the robot doing?	Observability
What is the robot going to do next?	Predictability
How can we get the robot to do what we need?	Directability

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Core Issues with Robotic Support

Human Needs	Issues	Robot Needs
What is the robot doing?	Mutual Observability	What is the intent of the human?
What is the robot going to do next?	Mutual Predictability	What does the human need from me?
How can we get the robot to do what we need?	Mutual Directability	Can the human provide help?

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What Makes a Good Robotic Surgery Assistant?

- Being observable, predictable and directable is a major part of being a good teammate.

- Higher level teaming capabilities like trust and explainability are built from these foundational interdependence relationships.

Mike Barratt examples

- Rover that failed and it was a system we did not understand. Nothing worse than having no means of recovery.
- Robotic arm - Nothing scarier than uncommanded motion
- Robotic arm – It froze. We don't understand the failure. It did not make me comfortable

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Factors Effecting Performance

- Latency
  - The highest latency at which telerobotic surgery has been performed is 500 ms. Surgeons are still capable of completing surgical tasks but at higher completion times and with higher error rates (Anvari, et al., 2005).
- Force Feedback
  - (Da Vinci) Surgeons have demonstrated that force or tactile feedback is not necessary for microsurgery, as the range of motion in the operational field is minimal and as such the haptic feedback is barely perceptible (Liverneaux, et al., 2013).
- Control Mapping
  - I had to get used to the master controls' workspace range and resistance, the correct arm and wrist positioning, and to the finger gripping. (ROBOTIC SURGERY IN SPACE - Michelle Noguez Ceron)
- These are only factors related to telerobotic surgery and do not address additional factors that will come with higher levels of automation (e.g. perception, planning, decision making)

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Examples of Human-Machine Teaming

Examples of Human-Machine Teaming

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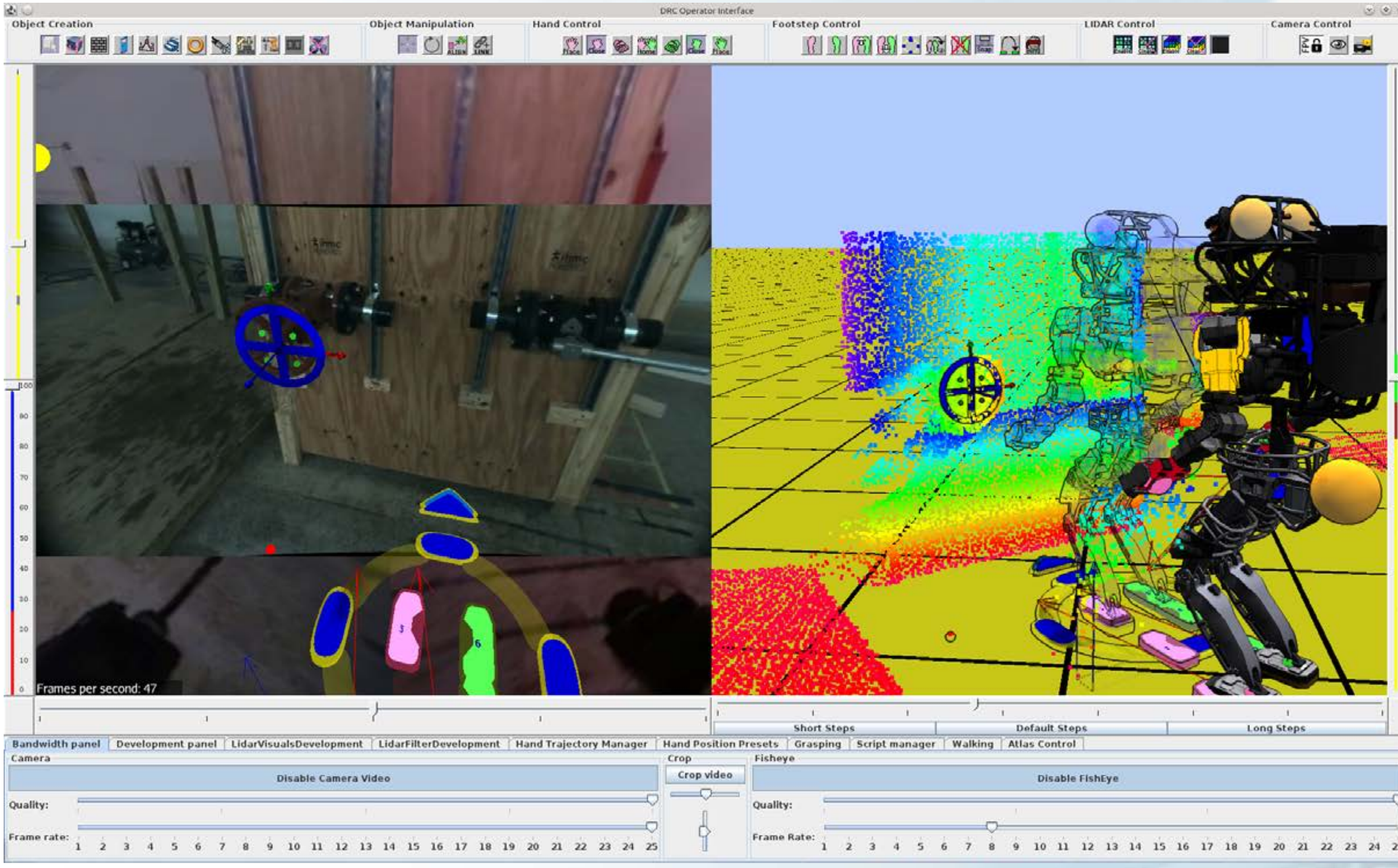
Examples of Human-Machine Teaming

Our Interface

Our Interface



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Remote Driving

- Relation to surgery
  - real-time motion control
- Predictability
  - The projected path the vehicle will follow
- Latency
  - The robot motion is slower than operator input
- Control Mapping
  - control your desired (no human constraints)
  - see the difference from actual

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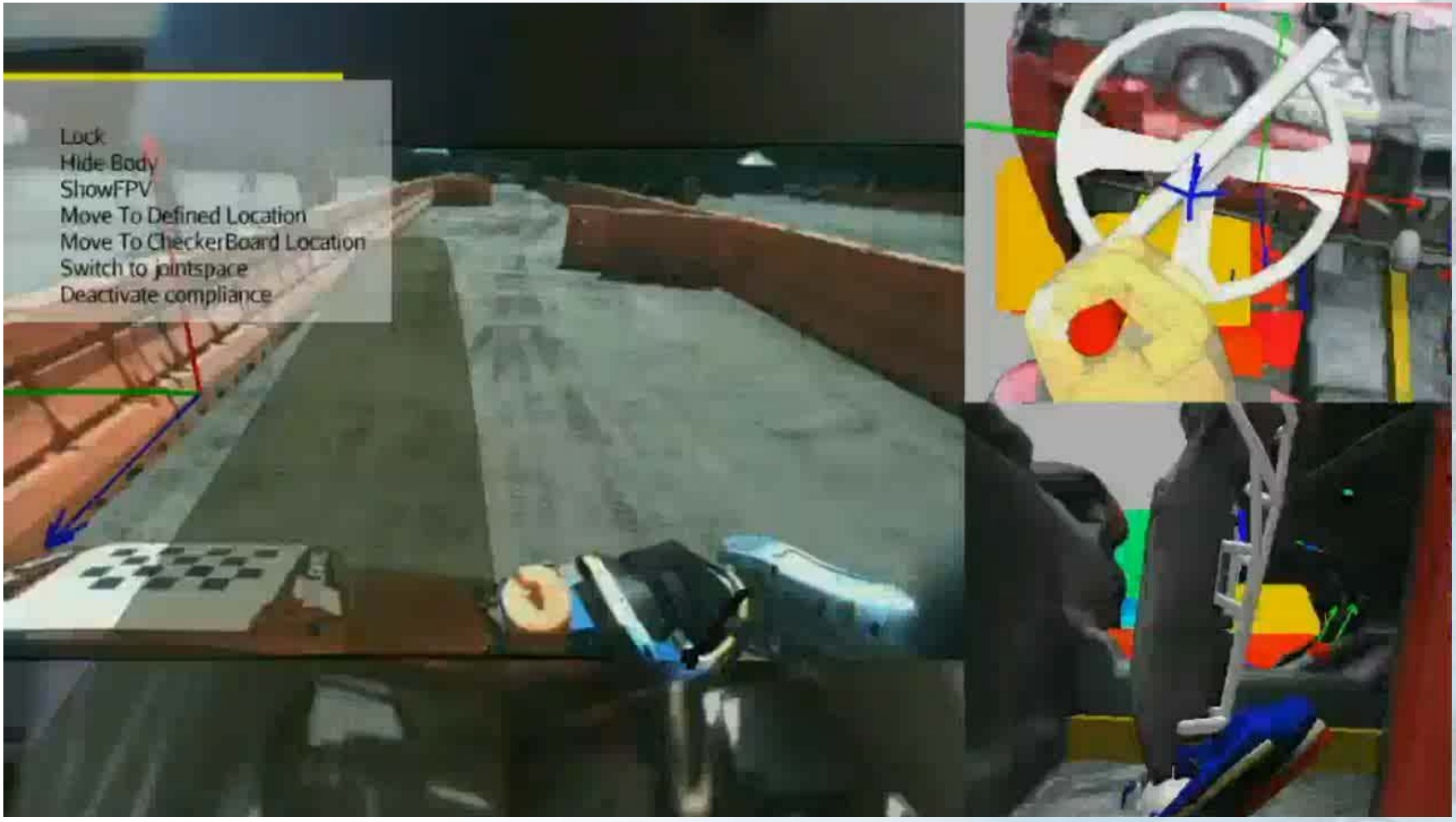
Remote Driving



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Remote Valve Operation

- Relation to surgery
  - Higher-level behavior with latency
- Latency
  - 20-30 seconds of latency
- Control Mapping
  - No direct control
  - Use of interactable objects
- Observability
  - Use of controllable third person view constructed from sensor data

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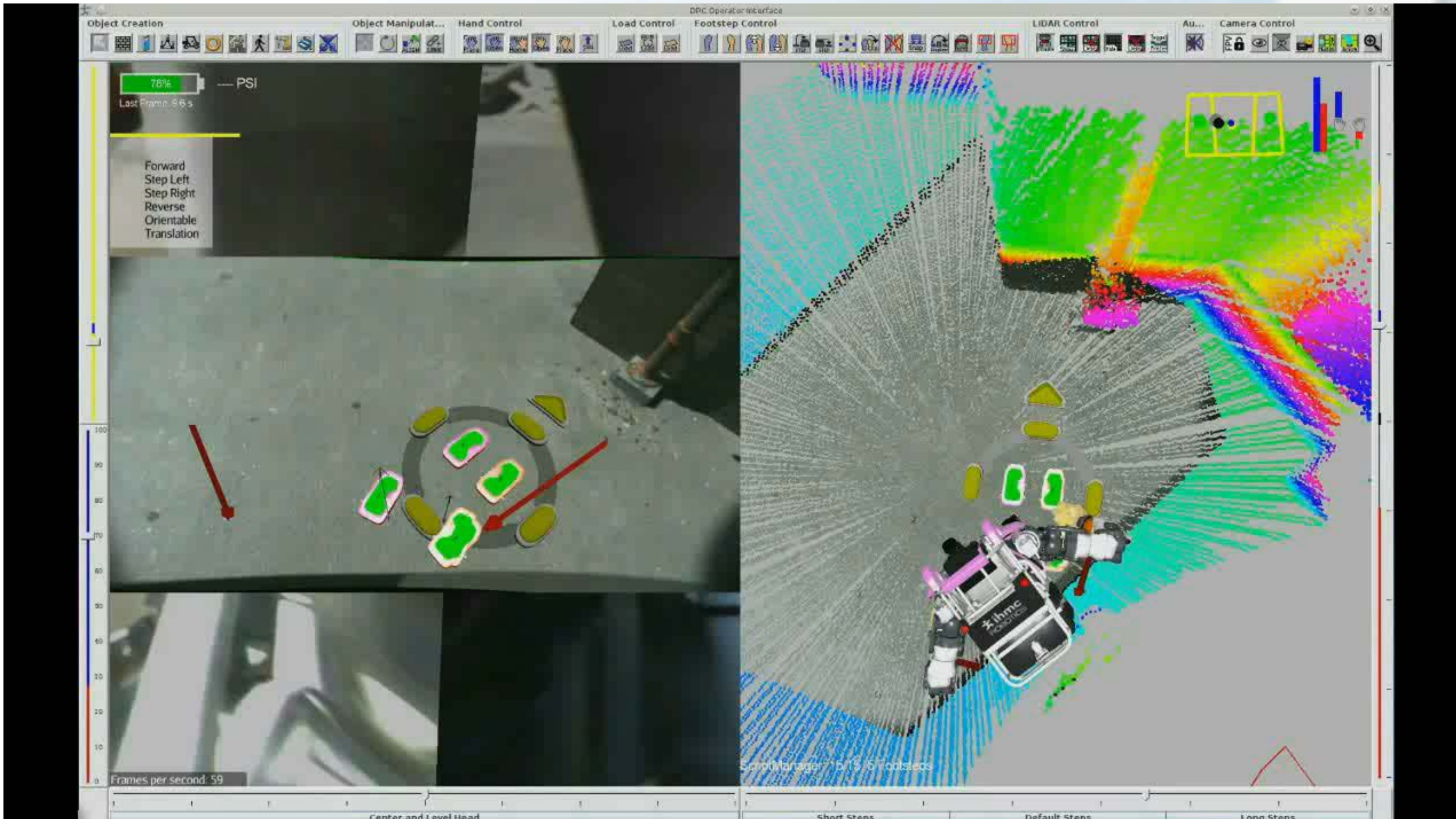
Remote Valve Operation



Remote Wall Cutting

- Relation to surgery
  - Parameterize a higher-level behavior with latency
- Directability
  - Depth adjustment on interactable objects
- Predictability
  - Preview of arm motion
- Latency
  - 20-30 seconds of latency
  - Simulation allows continuous operation with delays

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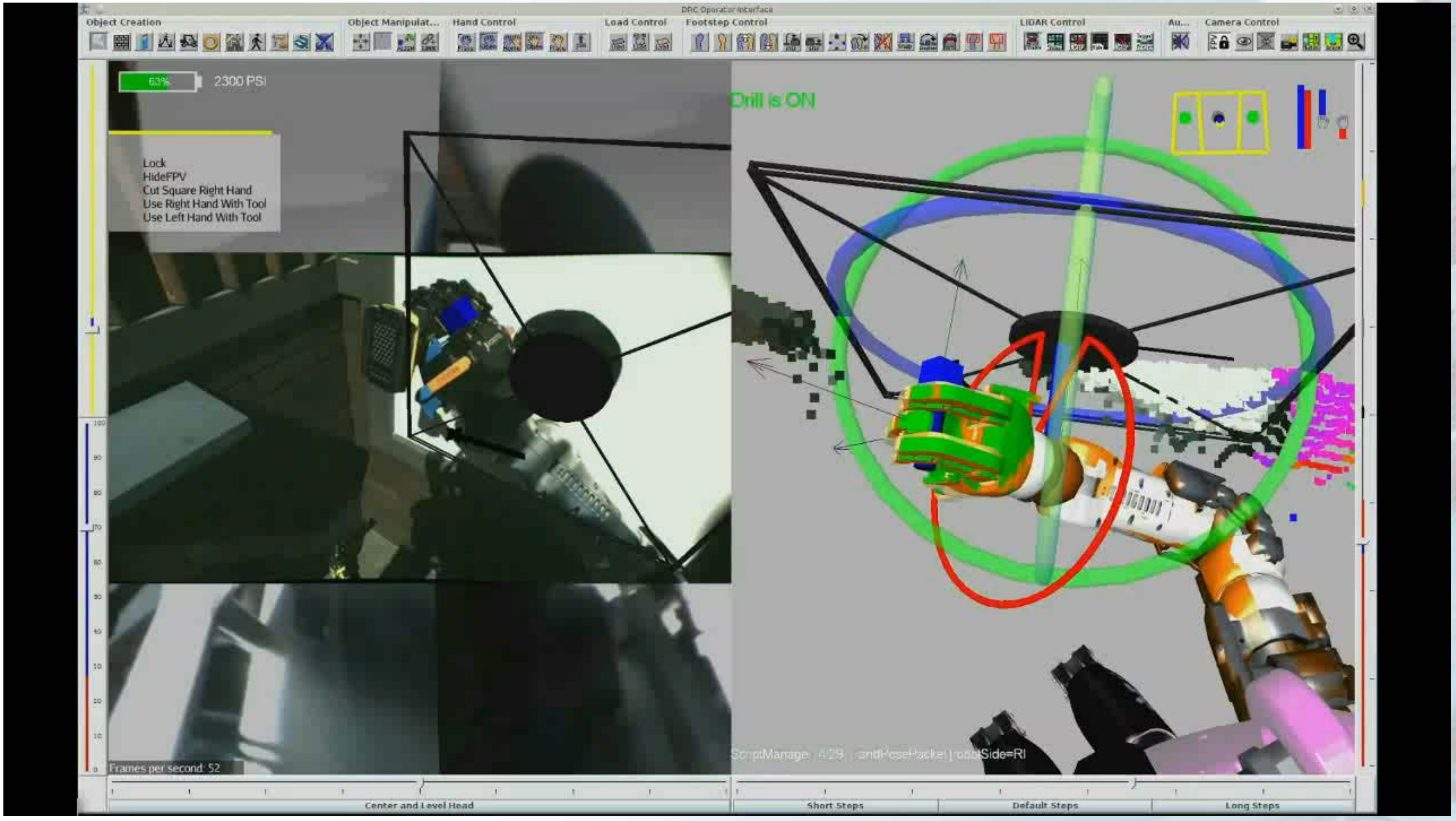
Remote Wall Cutting



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Examples of Human-Machine Teaming

- We spent a lot of time designing the system to be observable, predictable and directable
- This gave the operator confidence and properly calibrated their trust in the system
- It also made the system flexible

  "If you fail to plan, you are planning to fail."

  -Benjamin Franklin

  "In robotics, If you don't plan to fail, you are failing to plan."

  -Matthew Johnson

- This in turn made it resilient in the face of unexpected circumstances

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Examples of Human-Machine Teaming

	Terrain	Ladder	Debris	Door	Wall	Valve	Hose	Total falls and/or resets	Total other critical incidents
Team A	---		---	S	---	F	---	1	1
Team B		F	H	F, T, H		M	S, D	2	6
Team C	F, F			S, S	M	---	M, M, M, M	2	7
Team D	F, F, H	F		R, F	D	H	H, H, H, H, H, D	5	9
Team E	F, F, M	R, F		F, F, H, H	---	S	---	6	4
Team F	F	F	F, F			R, F, F	---	7	0
Team G	F		H, H, H, M, M	F, S		F		3	6
Team H	R, R			S, S, S	R, R, R	R, R, H, H, H, H, H, S, S, S		7	11
Total falls and/or resets	10	5	2	6	3	7	0	**33**	
Total other critical incidents	2	0	6	11	2	11	12		**44**

Table 3. All critical incidents observed per team per task. Dashes indicate that no critical incidents were observed for a team on that task. A gray cell indicates that the team was not observed on that task or, in the case of Team B on Terrain, the data could not be included.

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Examples of Human-Machine Teaming

	Potential Error	Cause	Solution
Day 1	Possible hand flip	Machine specified poor solution	Machine warned/Human adjusted
	Possible hand flip	Human chose a poor solution	Machine warned/Human adjusted
	Arm striking door frame	Machine did not recognize obstacle	Machine preview/Human adjusted
	Estimation drift	Machine estimation drift	Observable in interface/Human Corrected
	ICP approaching limits	Machine exceeding capability	Machine warned/Human adjusted
	Footsteps below LIDAR	Machine failed to recognize ground	Observable in interface/Human aborted and re-planned
	Is the drill on?	Human & Machine uncertainty	Concurrence of automated detection and human observation
	Is that step too far?	Human & Machine error	None (Fall)
	Sensor data is wrong	Hardware damage from fall	Human judgement
	Exceeding control authority	Failure to recognize approaching stability limit	None (Fall)
	Potential Error	**Cause**	**Solution**
Day 2	Autonomous behavior failed	Door latch was stiffer than expected	Human adjusted
	Sensor error	Hardware damage from fall	Human judgement
	ICP approaching limits	Machine exceeding capability	Machine warned/Human adjusted
	Is the drill on?	Human & Machine uncertainty	Concurrence of automated detection and human observation
	Missed attempt at surprise task	Human judgment	Human re-try
	Poor hardware performance	Hardware damage from fall	Human judgement and caution
	Linguistic confusion	Human spoke incorrectly	Other people corrected
	Arm striking hand rail of stairs	Machine did not recognize obstacle	Machine preview/Human adjusted
	Footstep did not land where commanded	Controls error possibly due to damage	Observable in interface/human adjusted and re-step

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Robotic Copilot

- Relation to surgery
  - Surgical assistant
- Observability
  - Difficult to know what machine was doing
- Predictability
  - Difficult to predict what machine would do
  - Pilots expressed surprise at robot motion
- Directability
  - Limited options (Start/Stop)
  - Interferes with the pilot

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Examples of Human-Machine Teaming

Examples of Human-Machine Teaming

- Did not spend any time designing the system to be observable, predictable or directable
- This concerned the operator who had little trust in the system
- It also made the system inflexible
- Early design decisions inhibited enabling support for interdependence
- Worst of all, it gave the work the pilot wanted to do (flying) to the machine and relegated the pilot to menial activity (e.g. radio tuning) and robot-sitting
  - Example from surgery: The patient-side surgeon assisted with positioning/repositioning the robotic arms on the operative field

Jacob Rosen: A pilot can follow a checklist, but would not know what to do in a surgery if things go wrong.

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What Makes a Good Robotic Surgery Assistant?

- Being observable, predictable and directable is a major part of being a good teammate.
- Higher level teaming capabilities like trust and explainability are built from these foundational interdependence relationships.
- As systems take on more challenging activity themselves and become "more intelligent" they will need corresponding increases in "teaming intelligence."
- Designing a robotic surgical assistant to support appropriate interdependence relationships, such as these, is the key to making a good robotic assistant.

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What Makes a Good Robotic Surgery Assistant?

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Florida Institute for Human and Machine Cognition

Presented by Matthew Johnson (mjohnson@ihmc.us)

02 OCT 2018

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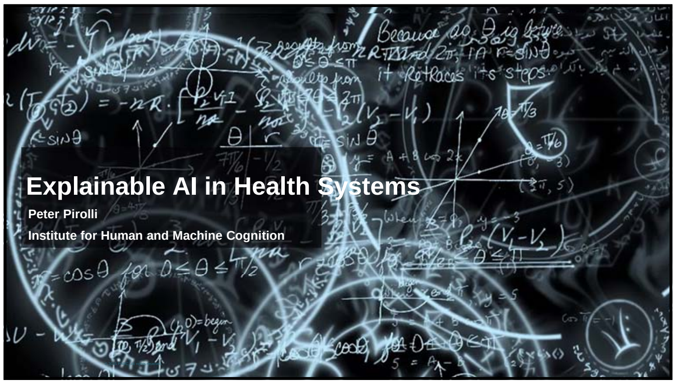
Appendix G: Explainable AI in Health Systems – P. Pirolli



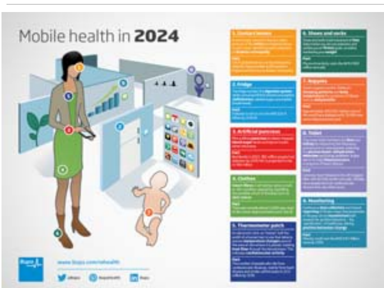
Explainable AI in Health Systems

Peter Pirolli
Institute for Human and Machine Cognition

Human-AI Digital Health Platforms

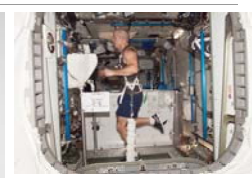
- Behavioral and environmental factors account for more deaths than genetics
- 70% of health care costs are due to changeable behavior (diet, fitness, smoking)

Digital Pervasive Health: Monitoring and Interventions in the Ecology of Everyday Life



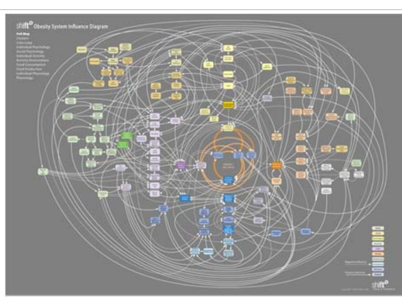
While not exactly the same as health & performance in space—it is *very* complex and presents many of the same challenges

Digital Pervasive Health: Monitoring and Interventions in the Ecology of Everyday Life



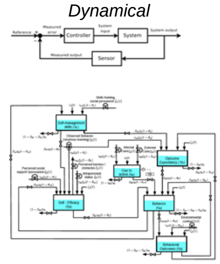
- Pervasive, ubiquitous sensing, intense interaction
- AI/ML is improving operations and safety via Crew Resource Management (CRM)
- In spaceflight AI/ML based CRM might expand to include health maintenance and eventually emergency medical/surgical care

Complexity Example: Obesity System Influence Diagram



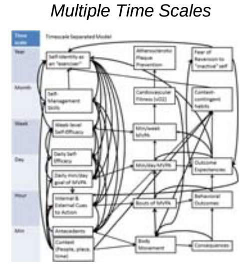
Complexity Example: Social-Psychological Mechanisms

Dynamical



Martín, C. A., Rivera, D. E., Riley, W. T., Hekler, E. B., Buman, M. P., Adams, M. A., & King, A. C. (2014). *A dynamical systems model of Social Cognitive Theory*. Paper presented at the American Control Conference, Portland, OR.

Multiple Time Scales

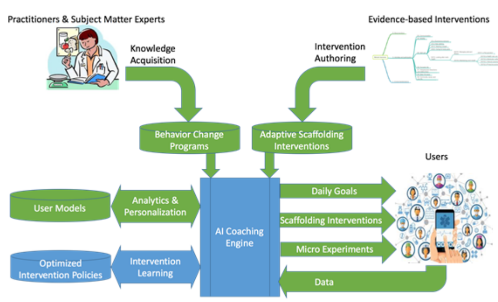


Spruijt-Metz, D., Hekler, E., Saranummi, N., Intille, S., Korhonen, I., Nilsen, W., . . . Pavel, M. (2015). Building new computational models to support health behavior change and maintenance: New opportunities in behavioral research. *Translational behavioral medicine, 5*(3), 335-346.

Aims

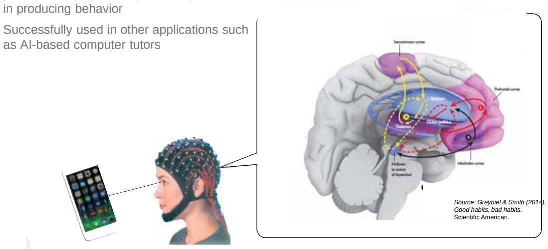
- **Interventions to build healthy habits**. Smartphone platforms to integrate behavior-change techniques into everyday life to improve diet & fitness
- **Integrated fine-grained predictive theory and methods**. Computational cognitive models to understand and predict habit change
- Support **artificial intelligence coaching**

A Recent Implementation of Fittle+



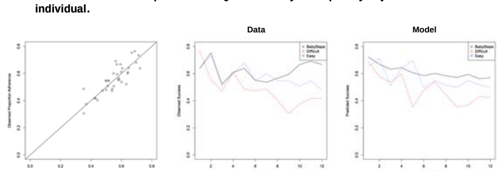
Individual Psychology and Behavior Change Modeled by Fine-grained Computational Neurocognitive Models

- How brain modules (goal, memory, perception,...) operate dynamically over time in producing behavior
- Successfully used in other applications such as AI-based computer tutors



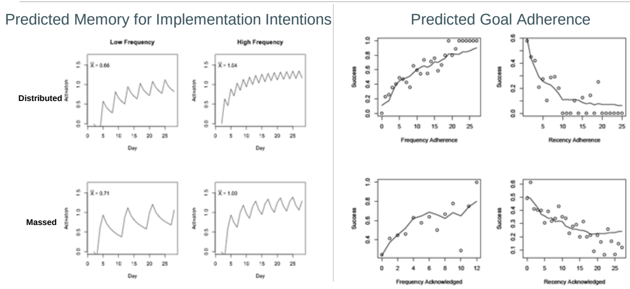
Fit of ACT-R-Based Model
28-day Study of Personalized Goal Adjustment

- ***Instance-based Learning*** **provides day-by-day, exercise-by-exercise predictions for each individual**
- **Exercise adherence improves when goal difficulty is adaptively adjusted for each individual.**



Instance-Based Learning + ***Utility Learning***

Predict Each Individual's Memory for their Self-generated Plans
+ Strength of Habit Formation
+ Goal Achievement



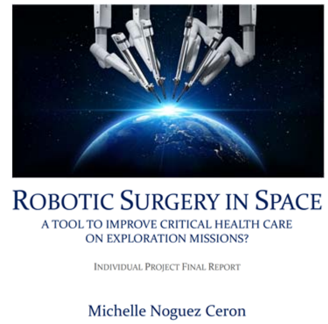
Human-AI Digital Health Platforms

- **Optimal health & performance.**
- **Preventative healthcare**
- **Readiness, resilience**
- Preoperative diagnosis and management
  - If dx = appendicitis then initial course of antibiotics

- Intraoperative (supervised) autonomous task performance
- Post-operation management and prognosis
  - Optimized curative care. Drug adherence, physical therapy.
  - Transition to comfort care

Some Challenges of Engineering Interdependent Human-AI Systems

- “Ideally, the surgical robotic system would be an autonomous intelligent system, … it would require the robot to be reactive and have the knowledge and skills of a surgeon with 10+ years of medical and surgical training”



Some Challenges of Engineering Interdependent Human-AI Systems

- **Autonomy Paradox**
  - Often creates new tasks and training requirements

U.S. Navy Littoral Combat Ship

- Designed to support multiple unmanned systems
- Still require 60 sailors
- 3X typical training time
- Typically older (30 yr as opposed to 21) & more senior

Some Challenges of Engineering Interdependent Human-AI Systems

- **Autonomy Paradox**
- **Causal Understanding** (J. Pearl)
  - *Prediction/Associations*
  - Reasoning about ***interventions***
  - *Counterfactual* reasoning about what would have happened if…

Pearl, J. (2018). *The book of why.* New York: Basic Books.

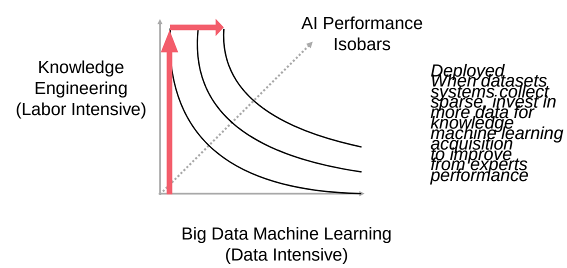
Some Challenges of Engineering Interdependent Human-AI Systems

- **Autonomy Paradox**
- **Causal Understanding**
- **Suitable for Machine Learning** problem

- Well-defined task
- Well defined function with well-defined inputs and outcomes
- Large digital data sets available for input-output training
- Clear goals, feedback, and evaluation functions
- No long chains of reasoning or need for common sense/background knowledge
- No need to provide a clear explanation of what, how, and why
- Tolerance for error and suboptimal solutions
- Phenomena or to-be-learned function do not change with time

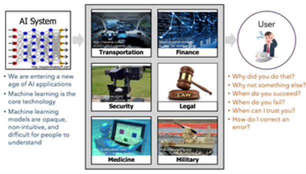
Brynjolfsson & Mitchell (2017). What can machine learning do? Workforce implications. *Science.*

Knowledge Engineering vs Big Data Tradeoff



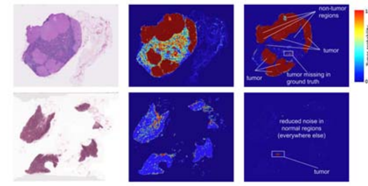
Some Challenges of Engineering Interdependent Human-AI Systems

- **Autonomy Paradox**
- **Causal Understanding**
- **Suitable for Machine Learning** problem
- **Explainable AI**

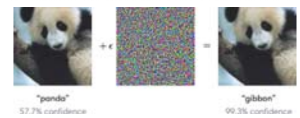


Source: Dave Gunning

Image-based Diagnosis



Left: Images from two lymph node biopsies. **Middle**: earlier results of our deep learning tumor detection. **Right**: our current results. Notice the visibly reduced noise (potential false positives) between the two versions.

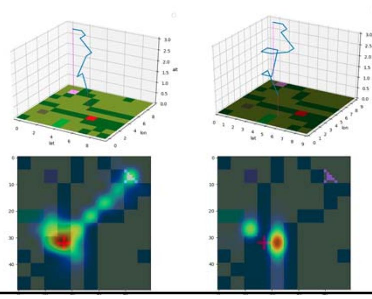


https://ai.googleblog.com/2017/03/assisting-pathologists-in-detecting.html

Simulated Drone Learning "Drop the Package Competency"

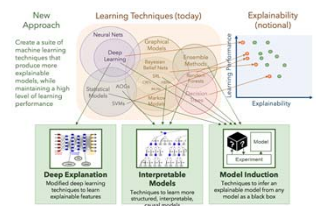
- Find a lost hiker and drop needed supplies
- Effective control of descent path
- Selection of drop altitude and location
- Emergent corkscrew descent pattern that maximizes efficiency

Carnegie Mellon



Some Challenges of Engineering Interdependent Human-AI Systems

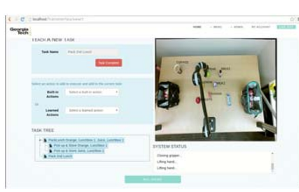
- **Autonomy Paradox**
- **Causal Understanding**
- **Suitable for Machine Learning** problem
- **Explainable AI**



Source: Dave Gunning

Some Challenges of Engineering Interdependent Human-AI Systems

- **Autonomy Paradox**
- **Causal Understanding**
- **Suitable for Machine Learning** problem
- **Explainable AI**
- **Interactive Task Learning**



- Robot instruction in one shot
- Digital assistants taught new task in one shot

Some Challenges of Engineering Interdependent Human-AI Systems

- **Autonomy Paradox**
- **Causal Understanding**
- **Suitable for Machine Learning** problem
- **Explainable AI**
- **Interactive Task Learning**

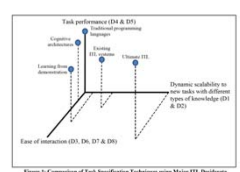
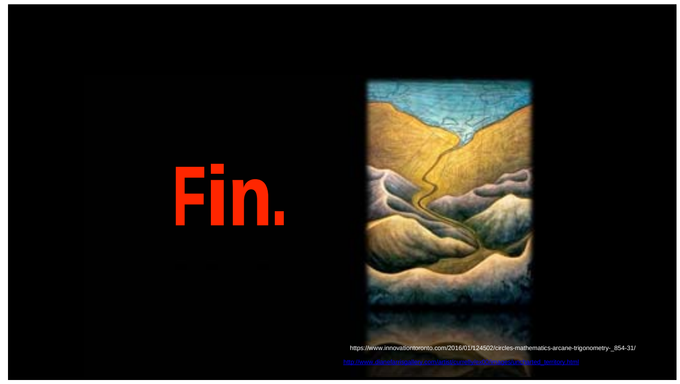


Figure 1: Comparison of Task Specification Techniques using Major ITL Desiderata

Credit:
Ernst Strungmann Forum on Interactive Task Learning
John Laird (University of Michigan), Kevin Gluck (Air Force Research Laboratory), John Anderson (Carnegie Mellon University), Ken Forbus (Northwestern University), Odest Chadwicke Jenkins (University of Michigan), Christian Lebiere (Carnegie Mellon University), Dario Salvucci (Drexel University), Matthias Scheutz (Tufts University), Andrea Thomaz (University of Texas), Greg Trafton (Naval Research Laboratory), Robert Wray (Soar Technology), Shiwali Mohan (PARC), James Kirk (University of Michigan)

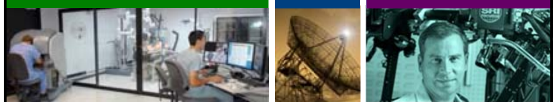
Summary

- AI-based optimization of health as part of holistic medical suite
  - Could integrate as part of larger system that includes surgery
  - Exercise, diet/nutrition, behavioral health, medical monitoring…
  - Prevention, readiness, resilience, pre-op, post-op…
- AI coaches/tutors/trainers
- Supervised autonomy, interdependent human-AI collaboration requires holistic system-level human-centered R&D



Appendix H: The Future of Surgical Robotics and Virtual Reality - T. Low

SRI International



The future of Surgical Robotics and Virtual Reality

Thomas Low
Associate Director, SRI Robotic Systems Program
thomas.low@sri.com

Who We Are

SRI is a community of innovation

An independent, nonprofit corporation
- Founded by Stanford University in 1946
- Independent in 1970
- Sarnoff Labs (RCA Labs) merged in 1987

R&D revenues: $580M

2,500 employees
- $^{2}/_{3}$ with advanced degrees

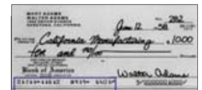
Mission:
SRI International creates world-changing solutions to make people safer, healthier, and more productive. .

SRI's innovations are found everywhere

Computer mouse

Internet TCP/IP

Siri

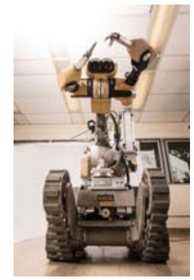


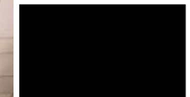
Banking

Medical Ultrasound Imaging

Who We Are

SRI Robotics is broader than surgical robotic systems





Where we fit

SRI bridges the gap from R&D to the marketplace

To see the future, it helps to see the past

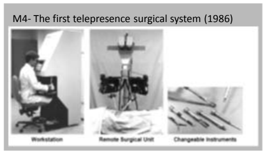
SRI International developed many of the core technologies related to robotic surgery based in pioneering work of Phil Green, John Bowersox and Richard Satava with support from NIH and DARPA.

Active in the establishment of Intuitive Surgical to refine and commercialize the system. SRI licensed its patents to the spinout.

Many other team's technology later incorporated:

- Ken Salisbury (MIT) wristed instrument
- Russ Taylor (IBM) Endoscoic Camera
- Hari Das (JPL) robotic microsurgery

M4- The first telepresence surgical system (1986)



The first MIS system and predecessor to daVinci (1988)

Recently

SRI International engaged by Johnson and Johnson Ethicon Endo-surgery to conceive and create the next-generation surgical system.

A multi-year technical development effort followed, resulting in a prototype and the establishment of Verb surgical to bring the technologies to clinical use.

The partnership brings together deep expertise in medical robotics from SRI, Ethicon advanced instrument design, and Googles machine learning prowess.

The new Verb Surgical System

VERB SURGICAL

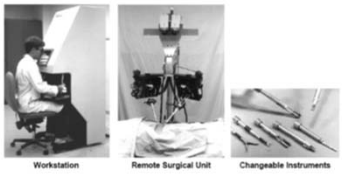
This stuff takes time

13 years to fully transition the daVinci technology (to FDA approval)

To see what could be coming next , it helps to look back at how far we have come

Historical Perspective

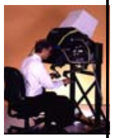
M4- The first telepresence surgical system (1986)
- 4 DOF x2 plus grip
- All haptic servos
- Intended for trauma care on the battlefield
- Stereo Video (LCD Shutter w/ Passive Glasses)
- Operated over 100 Km microwave data link
- Patent portfolio licensed to ISI in 1995



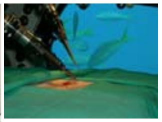
First MIS system (predecessor of the daVinci)


4 Haptic DOF + Haptic Grip x2
Developed in conjunction with ISI staff @ SRI
Developed patented coordinate transformations to preserve consistent interface.
Focus *not* on operation-at-distance, but on more “intuitive” interface than existing laparoscopic tools
ISI went on to add 2 DOF wrist

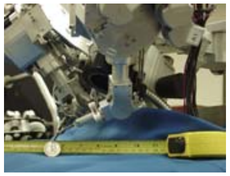
M7- NEEMO 9



First time in history an entire robotic surgical system was transported to an extreme environment and manipulated successfully from afar
First field deployable 6 DOF (+ Grip) 2 arm system
Two-monitor stereo display
Quick change tools
Force-sensor compatible wrist
Goals:
- evaluate the use of telerobotics in performing emergency diagnostic, surgical and interventional therapies in a confined and extreme environment (as is found in space flight)
- investigate open questions and operational concepts that will enable NASA to return humans to the moon as part of the President's Vision for Space Exploration.


Microsurgical Robot

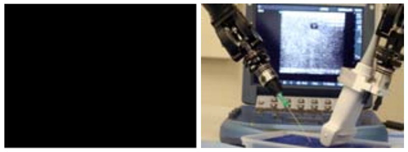


SRI Microsurgical System Specs
- 4 DOF + Grip
- 2 DOF wrist later added
- 100 mm x 100 mm x 100 mm workspace
- 2 N continuous Force
- 25 Hz Bandwidth
- 7 µm resolution
- Developed for:
  - ophthalmic surgical procedures
  - microvascular anastomosis
- Tremor Filtering and Motion Scaling


Ultrasound guided robotic vessel cannulation

Developed to demonstrate long distance tele-operation with delay
Closed loop tracking of surgeon designated features in ultrasound image
Autonomous robotic guidance

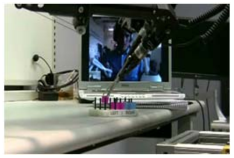
Demonstrate over 1500 km internet link to NASA undersea laboratory



Long distance telesurgery and interoperability standards (2009)

Interoperability protocol drafted by Blake Hannaford (UW) and Thomas Low (SRI) and distributed to international teams. Demonstrated interoperability of heterogeneous master and slave systems created by different research teams

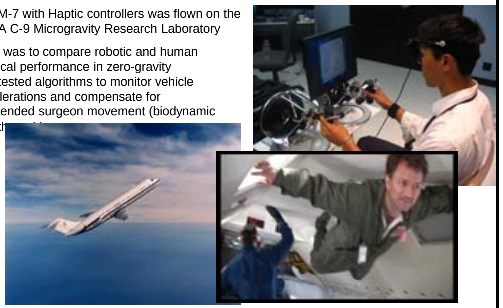
Participants included:
- University of Washington, Seattle, USA
- Imperial College London, UK
- Johns Hopkins University, Baltimore, MD, USA
- Korea University of Technology and Education, Cheonan, Korea
- Rensselaer Polytechnic Institute, Troy, NY, USA
- Tokyo Institute of Technology, Yokohama, Japan
- Technische Universität München, Munich, Germany
- University of California, Santa Cruz, USA
- SRI International, Menlo Park, CA, USA



Microgravity Experiments Studying Vehicle Induced Motion Compensation

The M-7 with Haptic controllers was flown on the NASA C-9 Microgravity Research Laboratory

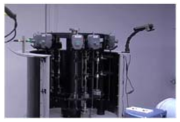
Goal was to compare robotic and human surgical performance in zero-gravity
SRI tested algorithms to monitor vehicle accelerations and compensate for unintended surgeon movement (biodynamic feedth



High level surgical support automation

Demonstrated full automation of OR team under voice and gesture control of surgeon

- Automated sterile supply depackaging and dispensing
- Automated Mayo Tray
- Automated tool changes
- Automated waste disposal
- Fully tracked supply management
- Integrated patient vitals and preop CT into DV console



Case Study: Augmentation

Enaex

RoboMiner: Safety + Productivity

Enaex collaborated with SRI to allow technicians to remotely assemble and detonate explosives in a mine.

The goal was to keep blasting technicians safe and improve their quality of life by eliminating the arduous travel required everyday. SRI combined tele-operation platforms and advanced human-machine interaction software into a mobile system able to assist in a variety of blasting tasks.

Result:
- *20 months from concept to mine*
- *Blasting companies can now offer services to mine sites previously off limits due to safety concerns*

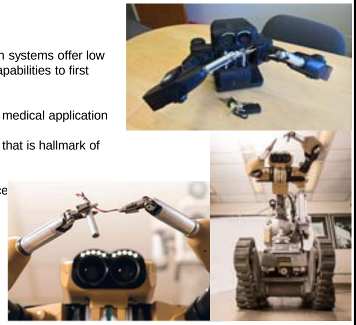
Small and light, low-cost telemanipulation solutions

Self-contained telemanipulation systems offer low cost dexterous manipulation capabilities to first responders and military.

Exploring suitability for military medical application

Same exceptional ease-of use that is hallmark of Intuitive Surgical systems.

Realistic SWaP for use in space



The next frontiers in robot-assisted surgery

What is coming

- Artificial or Machine Intelligence (AI) and deep learning, levera big data will find its place in robotic surgery
- This will require overcoming significant challenges
  - Regulatory hurdles
  - Reliability, Provability, Explainability, Liability
  - User acceptance, both by patients and surgeons
- It will be a long time before AI take direct control of our instrument
- Enhanced visualization will aid in intraoperative differentiation of healthy and diseased tissue
- AI will assist in identification of critical anatomy and provide real-time guidance.
- AI will eventually enable teleoperation-like interaction with a distant surgical robot, overcoming issues of latency and reducing the bandwidth needed for effective remote surgery.

Virtual Reality: What's the big deal?

Consumer VR systems at less than $400 US contain many of the important characteristics of our surgical master consoles.

- 3-D low latency HD video and high accuracy hand tracking.
- Added bonus is wide field of view and head tracking.

It is positioned to be a game changer for the way we will learn, interact with technology, and with each other.

Today

The visual quality available to consumers is not quite meeting our expectations for clinical use, but probably as good as first generation DV systems.

They are comparatively light and comfortable, but for all applications involving prolonged use, should be lighter.

Consumer demand for improvement will drive investments and innovation from players with deep pockets

What does VR provide that I don't get from other solutions? Why should I be excited?

- VR taps into the capability of our minds to effortlessly create mental models of what we see, with enhanced perception of space and size.
- These models are drawn upon during navigation to naturally recognize and avoid damage to critical anatomical features.
- Exploiting our minds natural ability to fuse data and coordinate our movements to effect our environment was key for the success of robotic assisted surgery. VR is simply the next step.

The challenge

Immersive VR imposes high technical demands on image response to wearer head movement. Fail to meet these demands, and the result is an uncomfortable, unnatural and perhaps nauseating experience

Alternatives to an immersive experience avoid these pitfalls, and will be introduced sooner.

.

The good news

- Applications outside of medicine, such as virtual tourism, virtual meetings and social interactions have disruptive and compelling business cases, strengthened by environmental imperatives.
- Solving these technical issues will take the resources of Facebook, Google and Apple, but they will be solved, and robotic surgery will benefit.

The path

- VR tourism and social interaction will begin with 360 video, followed by 3D, with the only interactive component being the direction of focus
- Next will come the ability to slightly alter the position of the camera in a prerecorded scene in immediate response to head movement, adding important perceptual cues.
- The final step will be a true avatar that can be inhabited by the customer who will experience and interact with a far off place in real time.

The convergence of RAS and VR is inevitable

- Early medical uses will include training simulations, but will quickly expand to include preoperative planning, surgical rehearsal.
- Procedures will be learned by med students through recorded 360 degree VR experiences from the perspective of the surgeon or at the surgeons side.
- Head worn VR displays will eventually replace the large master console, providing less isolation and improved surgeon awareness of the patient, robot and OR team through extended graphical presentation.
- Finally, it will free the surgeon from separation from the patient.

SRI Robotics
SRI International 25

Conclusion

It is you, the clinical innovators, that deserve recognition for the success of robotic assisted surgery.

Like the 15th century artist and inventor, the true genius of daVinci is the versatility it exhibits.

This versatility has allowed its "talents" to be applied in ways never envisioned by its creators, and enables pioneering surgeons to practice a new form of their art.

SRI Robotics
SRI International 26

Thank You

SRI Robotics
SRI International 27

Case Study: Understanding

YAMAHA

MOTOBOT: Performance + Safety

Yamaha Motors collaborated with SRI to rapidly design, build, and test an autonomous motorcycle-riding robot built around a fusion of motorcycle and humanoid robotics technology.

The goal was to develop a robot able to ride an unmodified stock motorcycle on a racetrack at more than 200kph. The underlying technology will lead to the creation of advanced rider-safety and rider-support systems.

Result:
- *World 1st motorcycle riding robot*
- *9 months from concept to test track*
- *Exceeded 230 kph*

Video Link: https://www.youtube.com/watch?v=mafJmMGGOXk

SRI Robotics
SRI International

Appendix E:–TRON Project- Challenges to Enabling Safe and Effective Robotic Telesurgery in Expeditionary Surgical Care – S. Hong

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TRON Project

Challenges to Enabling Safe and Effective Robotic Telesurgery in Expeditionary Surgical Care

MAJ Steven Hong MD
Head and Neck Reconstructive Surgery
Walter Reed National Medical Center

Stanford University

Disclosure Statement

"The views, opinions and findings contained in this research/ presentation are those of the author(s) and do not necessarily reflect the views of the Department of Defense and should not be construed as an official DoD/Army policy unless so designated by other documentation. No official endorsement should be made."

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"When the coun exercising its geop interests, scie piggybacks that - gain, I might add it's that has bee case forever

-Neil deGrasse

Stanford University

Telerobotics – Military Medicine Paradigm Shi

Telerobotics Aligns with DoD Strategic Goals

- Maintain Military Readiness
- Maintain Global Presence
- Enhanced Capabilities
- Strategic Operational Advantage

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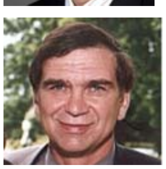
History of Telerobotic Surgery

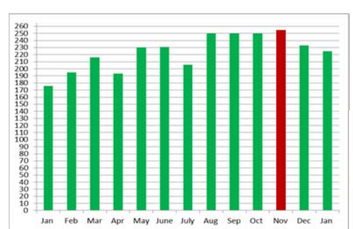
DARPA



TATRC

Stanford University

DOD Robotics Program



13 DaVinici Si systems and 7 DaVinici Xi systems in 15 Hospitals

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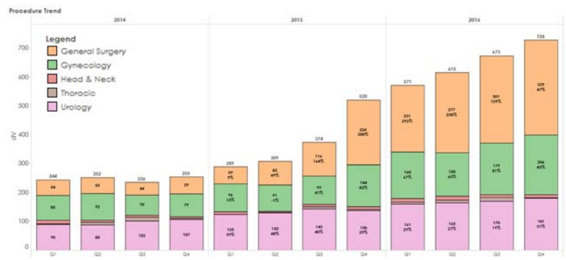
DOD Trends



Multi-Domain Battle Concept

GEN David G. Perkins, CG, TRADOC
2016 LANPAC Symposium and Exposition
(Credit: Army Staff Sgt. Christopher McCullough)

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Multi-Domain Battle Concepts
Constraints on Medical Resources

Limited freedom of movement for conventional vehicle platforms (both air and ground) to provide emergency medical resupply and casualty evacuation

- Wide Dispersion of Maneuver Units
- Area denial (e.g. CBNRE)
- Air Superiority not assured.
- 6-Dimensional threats (air, land, subterranean, maritime, space, and cyber).

Limited Medical Resources

- High risk Environments for manned assets
- Delayed Evacuation / Prolonged Field Care
- Return to duty risk of irreplaceable human resources.

UMS as Force Multipliers (PLAN B)

- When conventional manned assets are denied access
- When air superiority is not assumed
- When medical resources are severely constrained
- As UMS replace manned "vehicles of opportunity"

Advantages:

- Performance – Speed, Maneuverability, Endurance
- Smaller Landing Zones (LZs)
- Cost & Capacity***

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Prolonged Field Care the New Normal says Army, MRMC Brass

By Ramin A. Khalili, Knowledge Manager
USAMRMC Combat Casualty Care Research Program

"The battlefield of the future is already here," said Maj. Gen. Barbara R. Holcomb during her keynote speech at the 2017 Military Health System Research Symposium Aug. 28 in Kissimmee, Florida. "And so as a result, the medical force of the future must be here as well."

As the Commanding General of the U.S. Army Medical Research and Materiel Command and Fort Detrick, Maryland, Holcomb highlighted prolonged field care, which military leadership designated in a Capabilities Needs Analysis as the number one capability gap across the Army.

"We need to adjust both the way we think and the way we execute," said Holcomb. "And we need to understand that the multi-domain battlefield of the future will not always offer optimal –or even desirable– casualty care scenarios."

During her presentation, Holcomb described evolving technologies and supporting capabilities designed to support patient care in austere environments, including battlefields composed of far more dense and urban

U.S. Army Medical Research and Materiel Command and Fort Detrick Commanding General Barbara R. Holcomb delivers a keynote speech on prolonged field care at the 2017 Military Health System Research Symposium Aug. 28. (Photo Credit: Jaime Chirinos/DHA Communications)

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Medical Simulation & Information Sciences
New Army Science &Technology Task Areas

To support medical care delivery in dispersed and complex environments through futuristic technologies.

AUTONOMOUS AND UNMANNED MEDICAL CAPABILITY

VIRTUAL HEALTH

Threats

Dispersed Operations
Contested Air Space
Limited Casualty Evacuation
Delayed Definitive Patient Care
Lo/No Comm Environments

MEDICAL ASPECTS OF MAN-MACHINE TEAMING: MEDICAL ROBOTICS

Multi-Year P6.2 Army S&T POM: 2019 -2024

Gary R. Gilbert, PhD ; TATRC
MHSRS Conference, Orlando 2017

Stanford University

Similarities for Surgical Robotics in PFC and Space

Prolonged Field Care	Space Expedition
Extended medical capabilities	Extended medical capabilities
Medical force multiplier	Medical force multiplier
Logistical concerns	Logistical concerns
Signal latency, signal loss	Extreme signal latency, signal loss

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Differences for Surgical Robotics in PFC and Space

Prolonged Field Care	Space Expedition
Gravity	Microgravity
72 hours max for evac	Potential for no evac
Low Bandwidth	High bandwidth
Security / Regulatory	?

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Optimal Prototype Deployable Telerobotics

1. **Lightweight**
2. **Durable**
3. **Small logistical tail**

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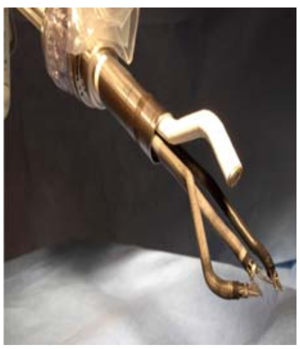
da Vinci SP



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T2 Robot

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Advantages of Virtual Reality – Interface / Simulator

- Potential for low bandwidth transmission
- Cost effective / Scalable
- Portable / Minimal logistical tail
- Situational Awareness
- Accelerated development by industry (Hooray for gamers)

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Virtual Reality Simulation Interface

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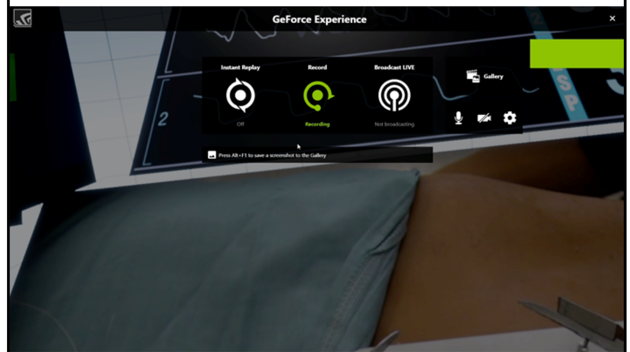

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Effects of Signal Latency Delay using Da Vinci®

Figure D1: Time Taken versus Error with and without Delay

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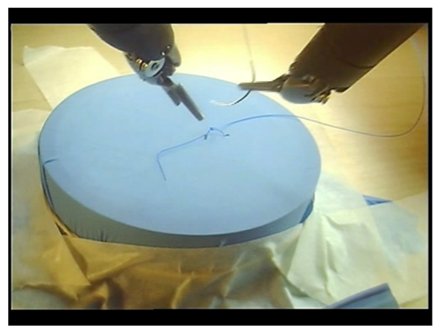
Effects of Delay: 0 sec (clean motions, fast)



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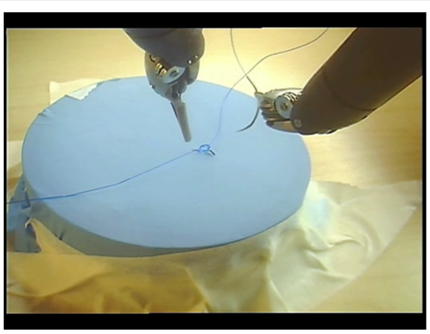
Effects of Delay: 750 msec (poor motions, tedious)



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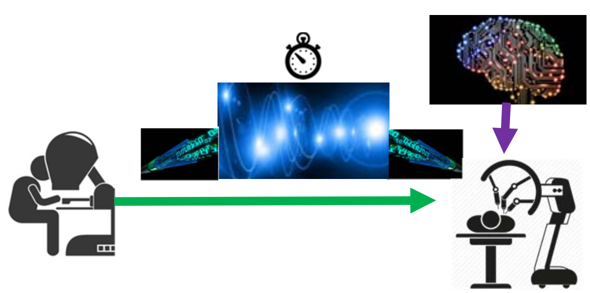
Next Step

Use machine learning to develop and implement semi-autonomous robotic surgery protocols



AI with Reinforcement Learning and Domain Adaptation

Operating Procedures

Before: the operator leads the robot to perform the tasks.

***After**: Embedded AI modules let the robot perform the tasks while the operator supervise the actions.*

- High degrees of control
- Low latency visualization

- High degrees of freedom
- High resolution sensor data

Embedded AI Module (Innovations):

- Surgical steps (prep, suturing, stitches, etc.) are trained as execution of motion plans combining Reinforcement Learning (RL) and Domain Adaptation (DA)
- Learning safe traversal policies in the visually denied setting by transfer of learning from human expert demonstrations in the visually available setting.
- Reduce communication requirements with hierarchy of learnt commands. Surgeon sends "command tasks" rather than direct control of every robotic element.

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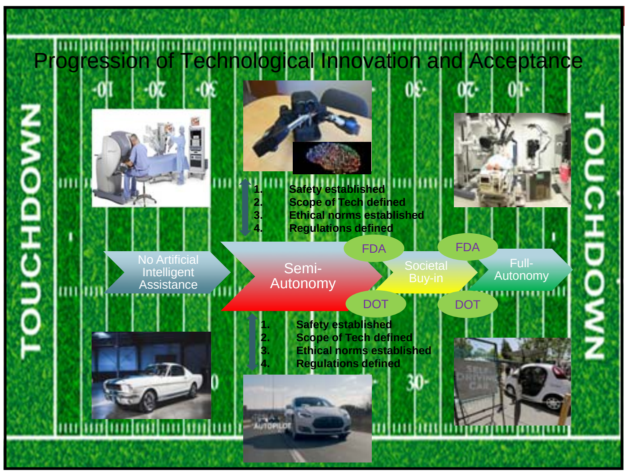
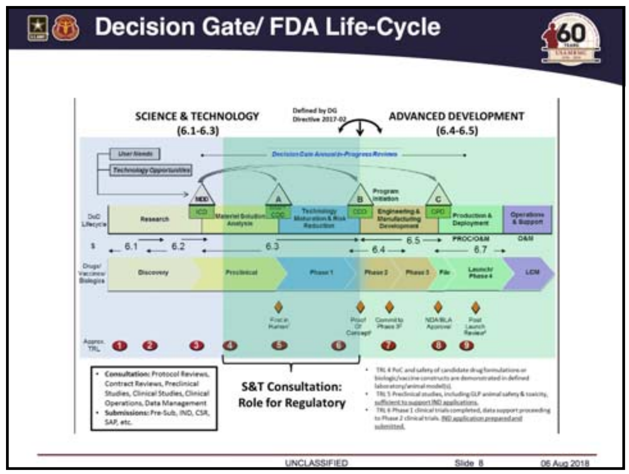
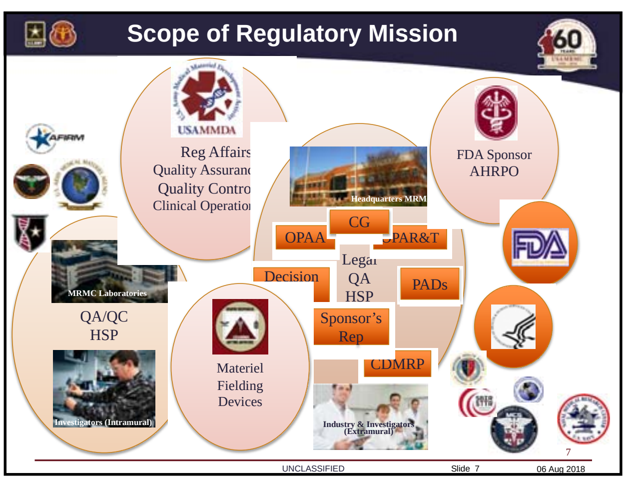
"For me, the questions I care most about are the ones I do not yet know to ask because they will only arise after future discoveries have been made. Those questions keep me awake at night because I don't even know how to pose them."

-Neil deGrasse Tyson-







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Microvascular– Ideal surgical model for telesurgery

1. Trauma relevant
2. Requires skilled assistant
3. Limited variability
4. Finite, discrete elements
5. Repetitive
6. Non-MIS

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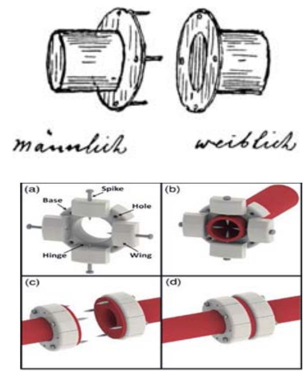

"To the man who only has a hammer, everything he encounters begins to look like a nail."

Abraham Maslow

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Principles for Expeditionary Robotic Surgical Care

- **MOVE FORWARD**
- **Define Scope**
- **Semi-autonomy**
- **Team approach**
- **Engage end-users**

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Course of Action for Surgical Robotics in Space

- **Full-autonomy**
- **Semi-autonomy**
- **Robotic assist**
- **Robotic mentor**
- **No robotic system**

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Thank you

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University of California San Diego
Walter Reed National Military Medical Center
SRI International
USAMRMC
TATRC
USAMMA
Stanford University
Brooke Army Medical Center
Madigan Army Medical Center