Developing Medical Robotic Systems for Research and Clinical Use

Peter Kazanzides

Research Professor

Johns Hopkins University

Honorary Professor

Obuda University

Personal History

1989-1990 Postdoctoral research at IBM

1990-2002 Co-Founder of ISS

- Commercial development of ROBODOC® System
- Commercial sales in Europe (CE Mark)
- Clinical trials in U.S. and Japan
- ISO 9001 certification

2002-present Research Professor at JHU

- Medical and space robotics
- Mixed reality
- da Vinci Research Kit (dVRK)

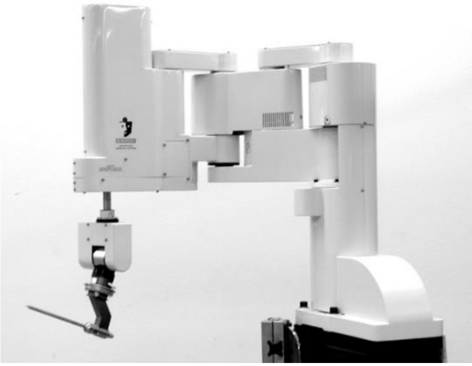
ROBODOC Canine System, 1990

dVRK Challenge at ICRA, 2026

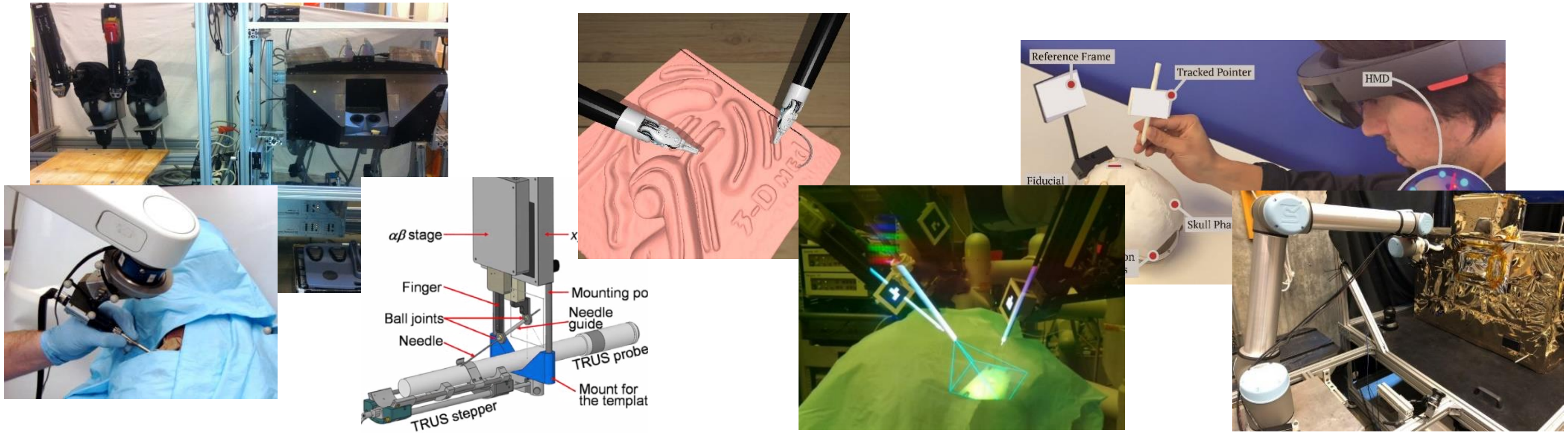
Industry vs. Academia

- In industry, I worked for 12 years on 1 project
- In academia, every year I work on 12 different projects

Industry (Robodoc)



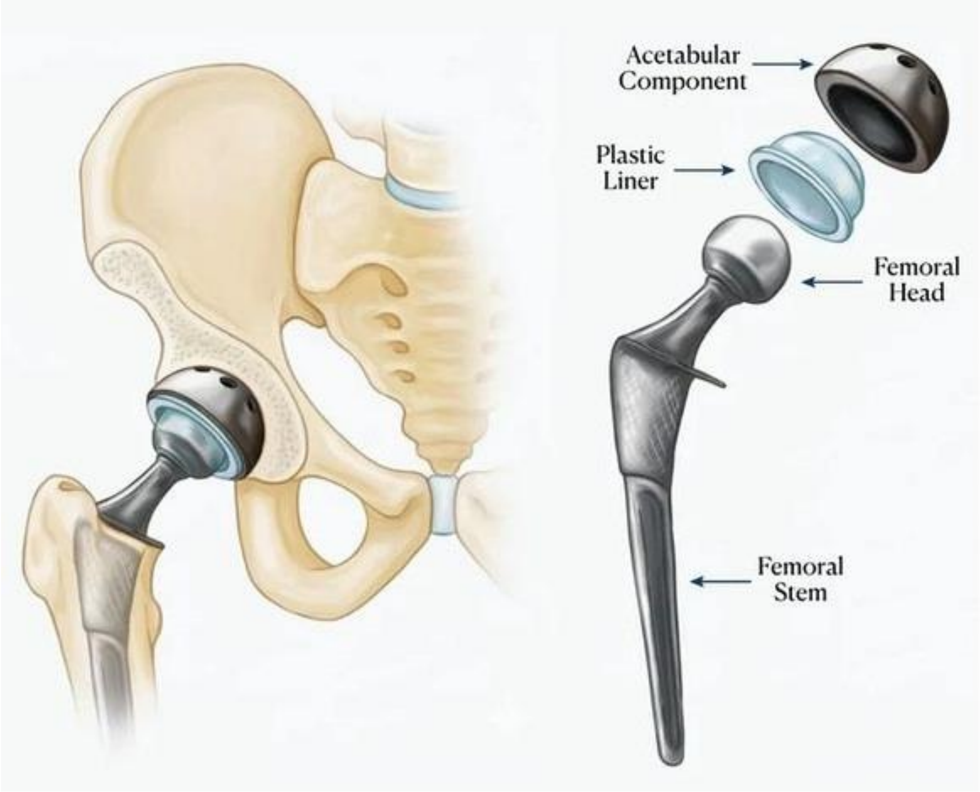
Academia (dVRK and more)

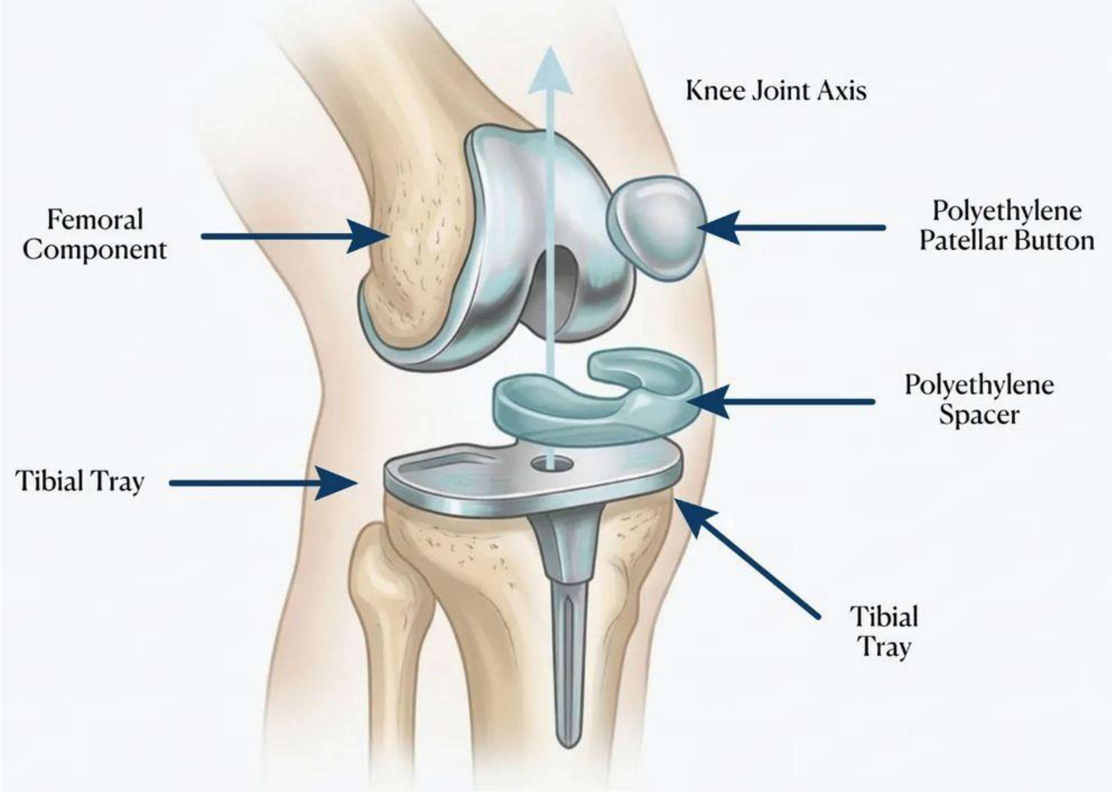


Themes for Today

- ROBODOC as a case study in commercial translation
  - Overview of development process and lessons learned
  - Final lesson: commercial success is difficult and depends on more than just good engineering
- da Vinci Research Kit for medical robotics research
  - A well engineered platform to enable worldwide medical robotics research
  - Hopefully, at least some of that research will lead to clinical impact and commercial success

Orthopedic Surgery





Total Hip Replacement (Arthroplasty)

cementless
prosthesis

Total Knee Replacement (Arthroplasty)

Initial ROBODOC Application

Image credits: https://corycalendinemd.com

Conventional hip surgery: mallet and broach

Preoperative planning

Content Warning
(Surgical Video)

Intraoperative procedure

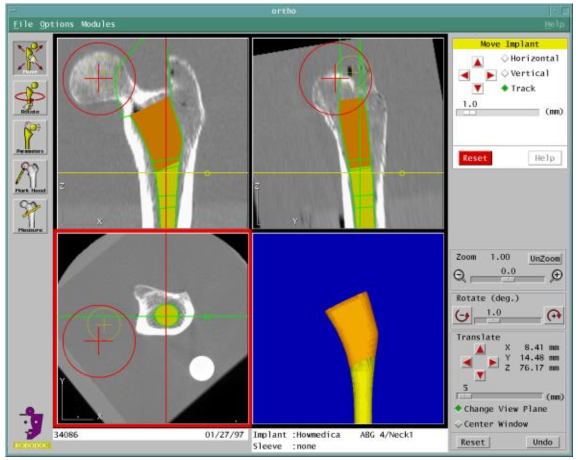
Conventional hip surgery: mallet and broach

Preoperative planning

Intraoperative procedure

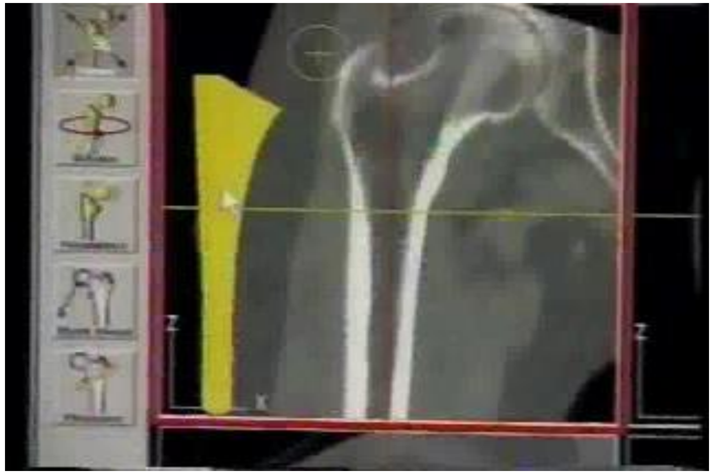
ROBODOC Procedure Overview

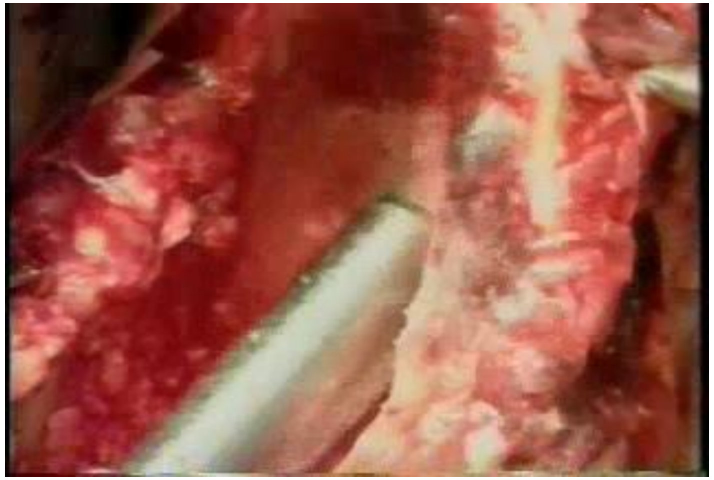
- Preoperative CT scan
- Preoperative planning
- Intraoperative registration (CT to patient/robot, initially using implanted bone screws)
- Robotic machining of bone (autonomous)



Conventional procedure: mallet and broach

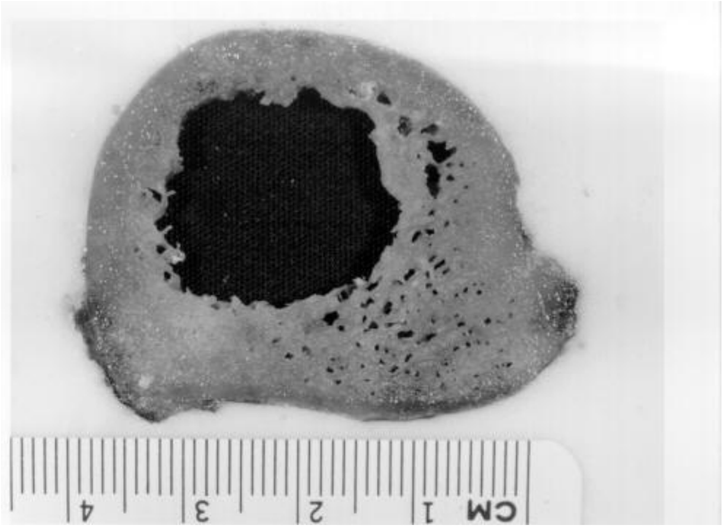
ROBODOC: Computer-assisted planning and execution



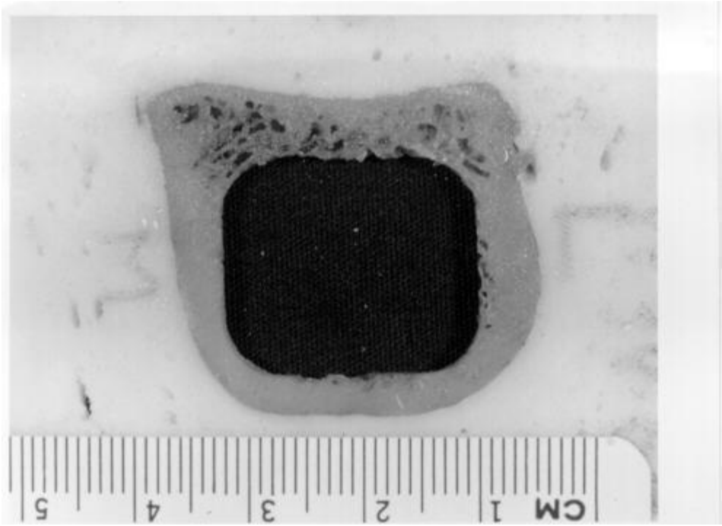


ROBODOC Benefits

- Increased dimensional accuracy
- Increased placement accuracy
- More consistent outcome



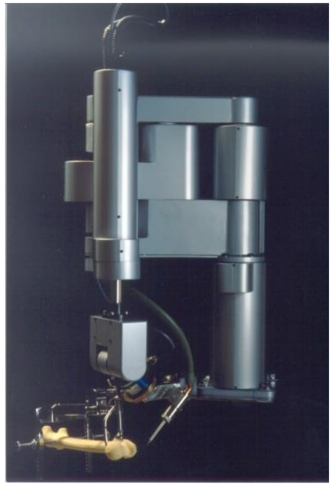
Broach

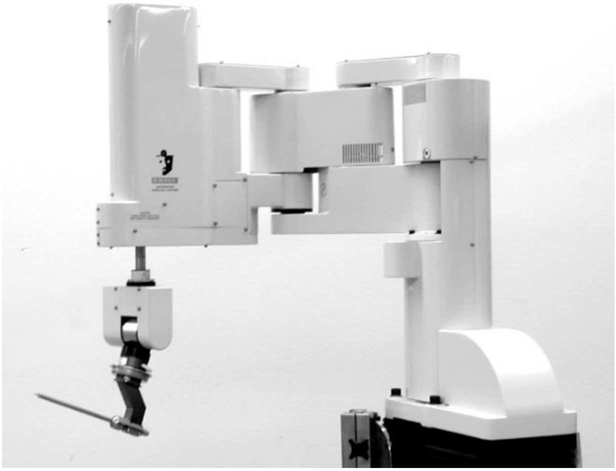


Robot

ROBODOC Generations

- Alpha: Canine System (1990)
- Beta: Human clinical prototype
  - Version 1: 10 patient study (1992)
  - Version 2: Multi-center trial (1993)
- Commercial Product
  - C System: First version (1996)
  - D System: Custom electronics (1999)



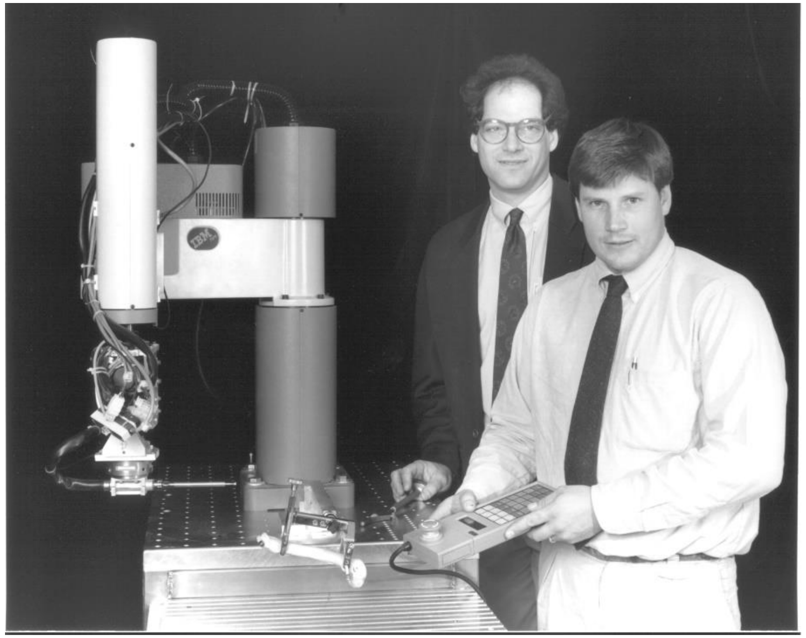


Canine System Goals

- Proof of concept
  - procedural flow (workflow)
  - high accuracy (small bones)
  - operating room compatibility (sterility)
- Focus on application, not system design
  - Use primarily off-the-shelf hardware
- Rely on engineering supervision in OR
- Research mode: no formal design process

Canine System Design

- Prototype appearance (external cables, etc.)
- Primitive (text-based) user interface
  - Engineer operated robot for all 26 surgeries
  - Graphical display during cutting (RTM)
- Primitive computer hardware (286/386)
- Did not use some safety systems during surgery



First Veterinary Surgery - May 2, 1990

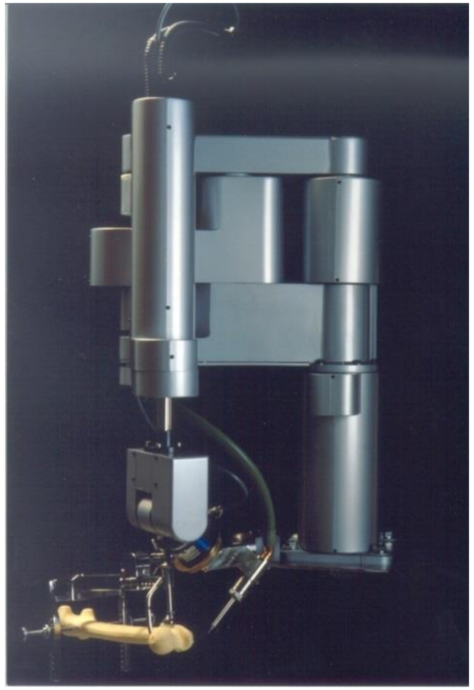
Sacramento Animal Medical Group (SAMG)

Canine System Lessons

- The procedure works!
- The user interface needs improvement
- Error recovery can be complex
- Bone motion detection is a critical safety feature
- Avoid special power requirements

Human Clinical Prototype (Beta System), 1990-1995

- Nov 1, 1990 Formation of ISS
- Nov 7, 1992 First human surgery, Sutter General Hospital
- Aug 1994 First European surgery, BGU Frankfurt

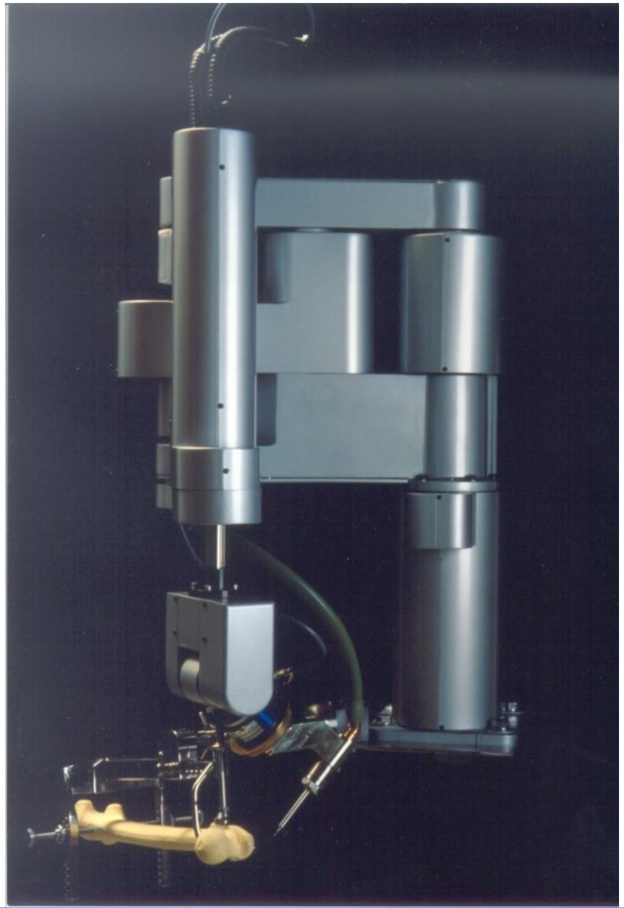


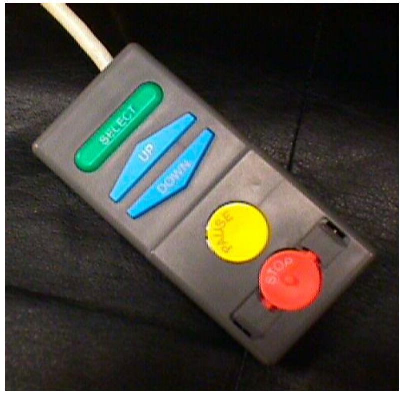
Beta System Goals

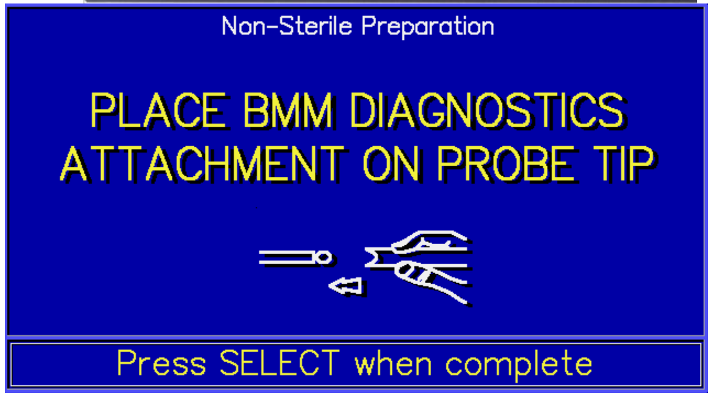
- Adapt canine system for human application
  - Support longer tools (higher stiffness)
- Re-design system for production
  - Create specifications, risk analysis, etc.
  - Improve system appearance
  - Rewrite software in industry-standard language
- Create user interface for surgeon use
  - graphical user interface and simple pendant
- Reduce cost

Beta System Design

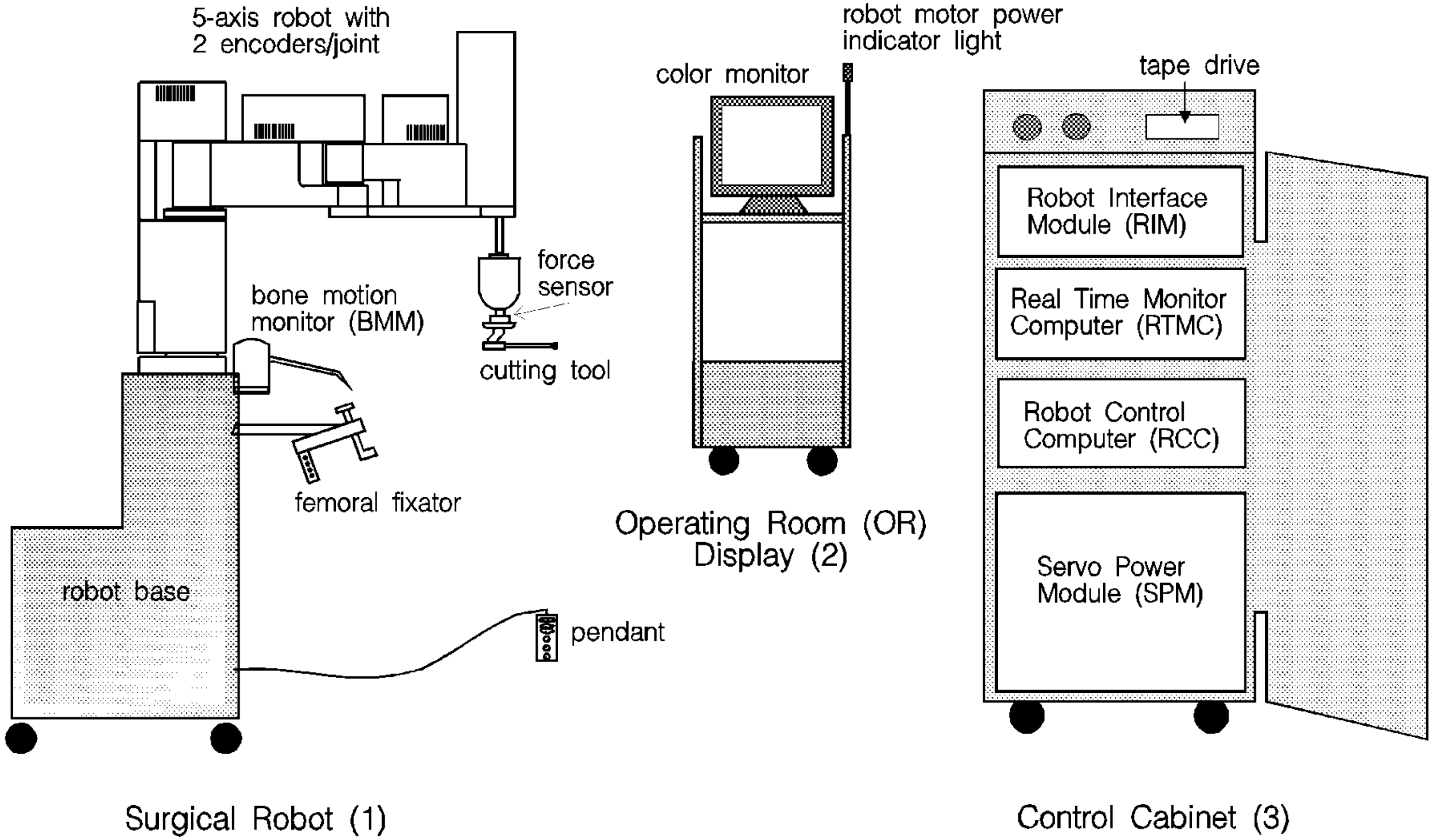
- Customized industrial robot
  - Integrated pitch axis
  - Increased stiffness for longer tools
  - Higher accuracy
  - Improved safety (redundant encoders, force/speed limits)
- Significantly improved appearance
  - Still a few external cables
- Graphical user interface and pendant
- Software written in C and C++
- Additional safety features
- Improved error handling







Beta System Design

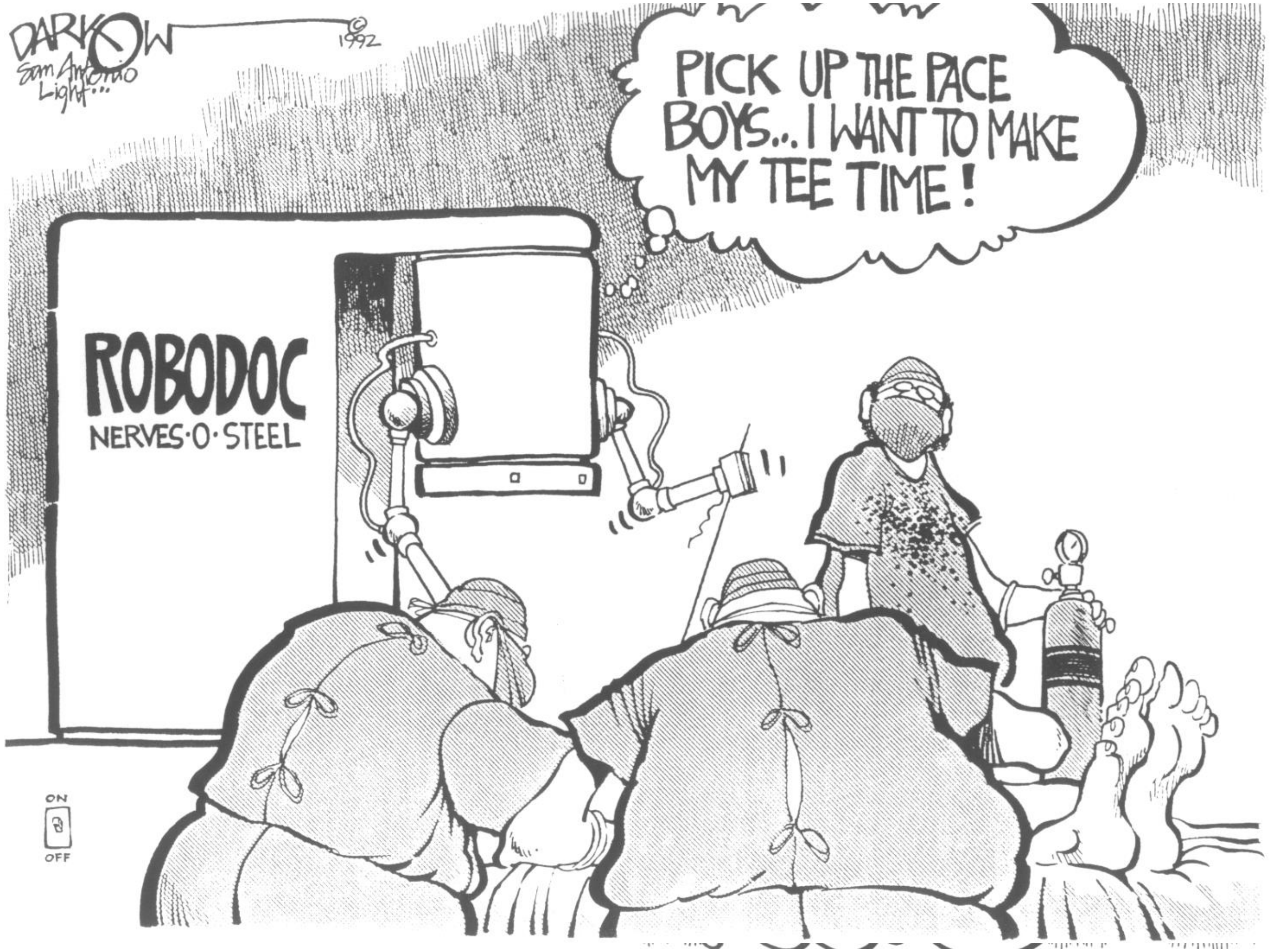


Safety Design Overview

- Completely different from industrial robots
  - Robot must share workspace with humans
  - One human (patient) is anesthetized and cannot run away
  - Robot is holding a dangerous instrument (high-speed cutter)
  - Robot must cut the patient, but only in the right place

First Human Surgery - Nov 7, 1992

Sutter General Hospital, Sacramento, CA



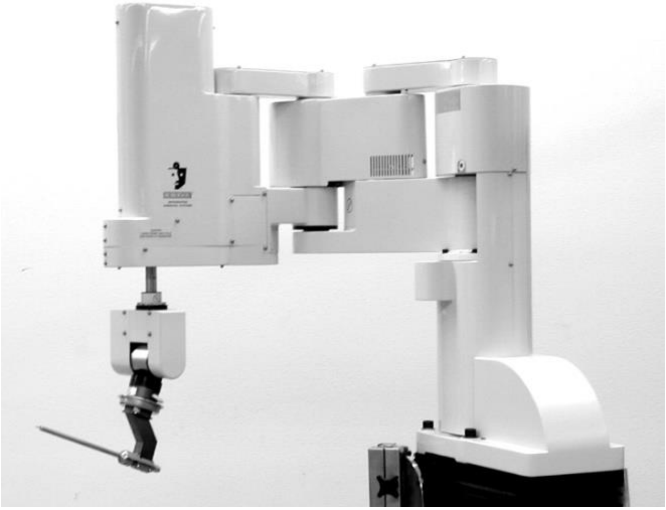
The press reacts…

Beta System Lessons

- Successfully completed clinical trials, but:
- Did not meet EMC requirements
  - Emissions marginal
  - Susceptible to interference (cautery mode)
- Required larger vertical workspace
  - Version 2 system had base encoder
- Difficult to move robot
- System too large for OR

Commercial Product, 1995-2002+

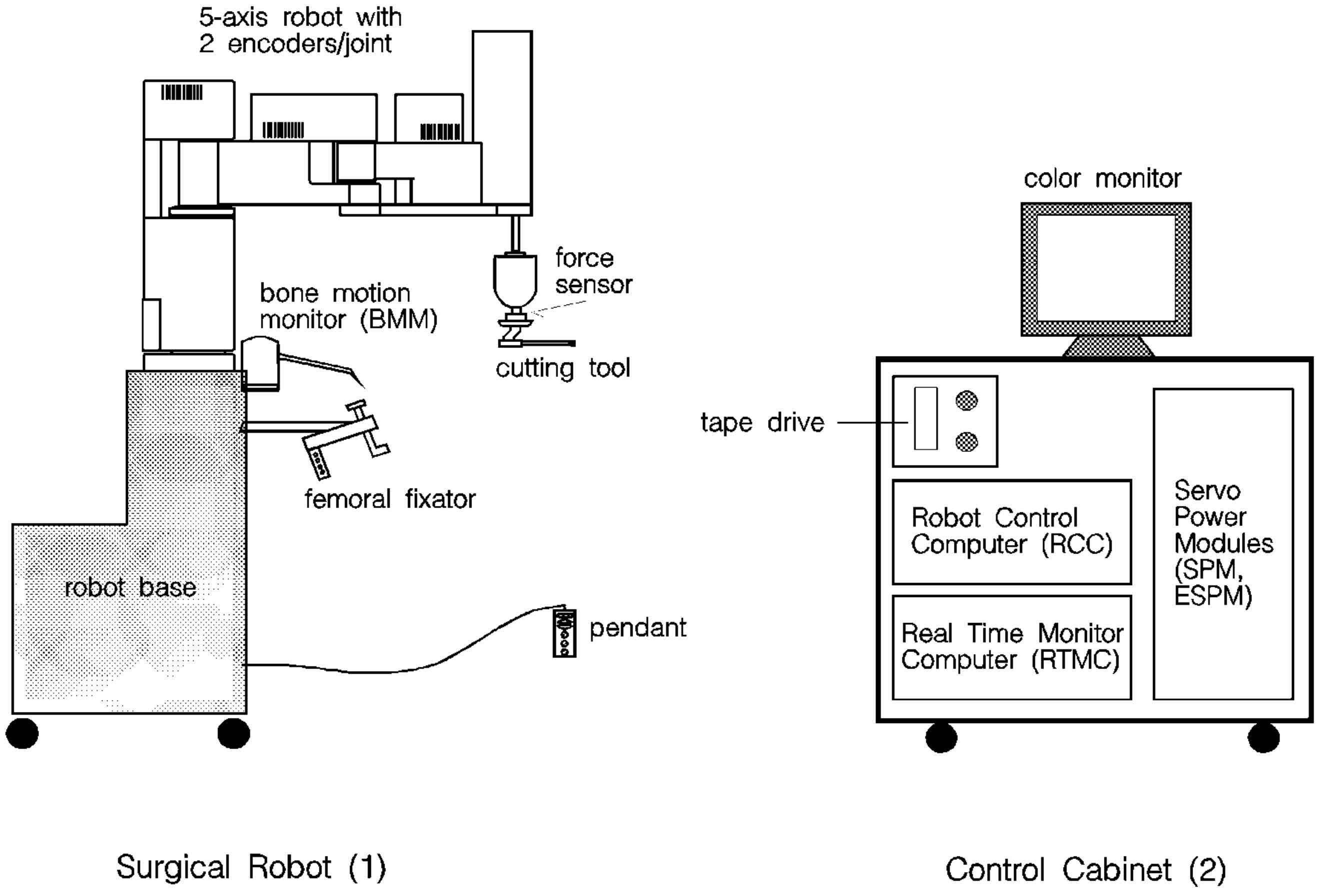
- March 1996 CE Mark
- April 1996 First 2 installations (Germany)
- Nov 1996 ISS initial public offering (NASDAQ)
- March 1998 First hip surgery with pinless registration
- Feb 2000 First knee replacement surgery



Commercial System Goals

- Meet regulatory requirements
  - CE Mark
  - UL/CSA
- Improve maneuverability
- Reduce size
- Improve system appearance
- Support local languages

Commercial System Design



Commercial System Status

- Approximately 70 systems were installed worldwide
  - Europe (Germany, Austria, Switz., France, Spain)
  - Asia (Japan, Korea, India)
  - U.S. (Clinical trial for FDA approval)
- Over 20,000 hip and knee replacement surgeries
- FDA approval in Aug 2008
- ROBODOC (now TCAT) acquired by Think Surgical
  - Recently discontinued in favor of TMINI

Commercial System Lessons

- Robot should save time (money) and/or provide substantial clinical benefit (enable new procedures)
  - Avoid increasing cost by adding new imaging (CT) or additional procedures (pin implantation) if possible
  - Can take a long time to prove clinical benefit due to expected life of implant
  - Pay more attention to marketing
- Develop a good business model
  - Recurring revenue (consumables) is a better business than capital equipment sales
  - Example: Hospital paid \$600K for Robodoc and performed 1000 cases per year, resulting in \$3M annual revenue to implant company

Robotic Minimally Invasive Surgery

- The da Vinci Surgical System is the most successful surgical robot in the world

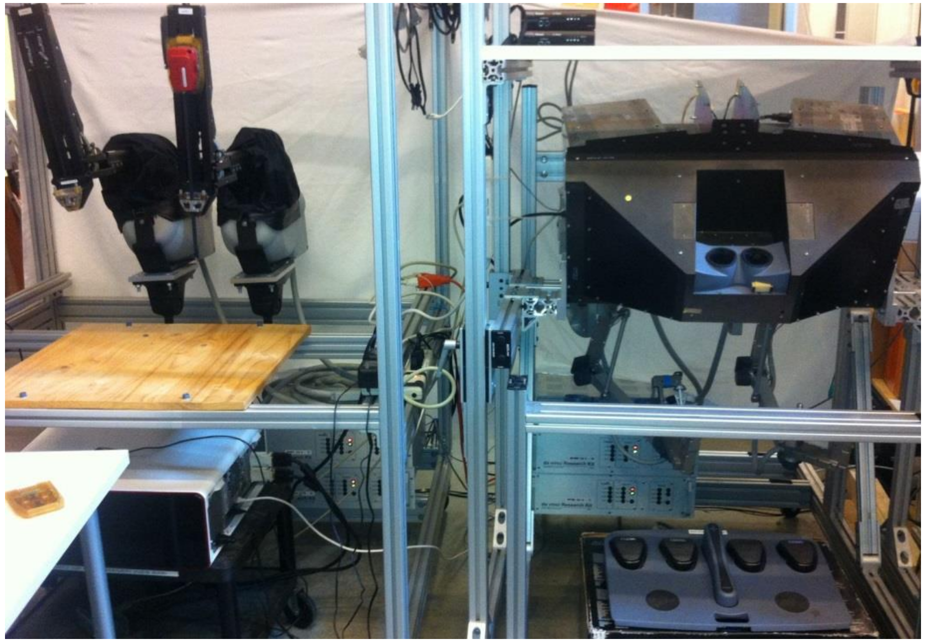
da Vinci Surgical System, © 2022 Intuitive Surgical, Inc.

- More than 12,000 da Vinci robots in hospitals
- More than 20 million surgeries performed
- Intuitive Surgical market cap ~ $130B
- Annual revenue ~ $11B (instrument sales ~60%)

- What is available to researchers?

da Vinci Research Kit

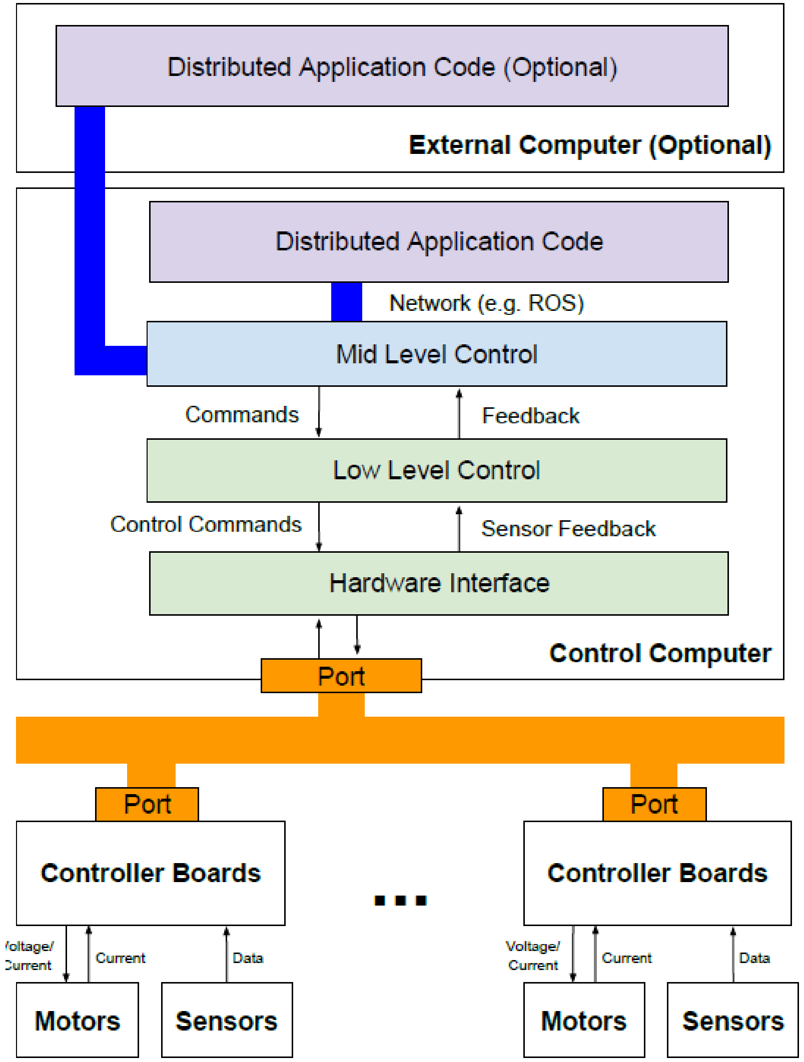
- Mechanical components from decommissioned da Vinci surgical robots
- Consortium for “open source” controllers
  - JHU: software, controller electronics
  - WPI: controller power, packaging, assembly
  - ISI: Interface electronics



P. Kazanzides, Z. Chen, A. Deguet, G. Fischer, R. Taylor, S. DiMaio, “An open-source research kit for the da Vinci® surgical system”, ICRA 2014.

System Architecture

Layer	**Key Concerns**
Application	Interoperability (ROS)
Real-time Control	Performance, ease of programming
Fieldbus	Scalability, performance
Hardware/Firmware	Low latency



Z. Chen, A. Deguet, R Taylor, P. Kazanzides, "Software architecture of the da Vinci Research Kit," IEEE Robotic Computing, 2017

da Vinci Systems and dVRK Controllers

(V1, V2, V3)

dVRK

(V3)

dVRK-Si

(some)

da Vinci "Classic"

da Vinci S

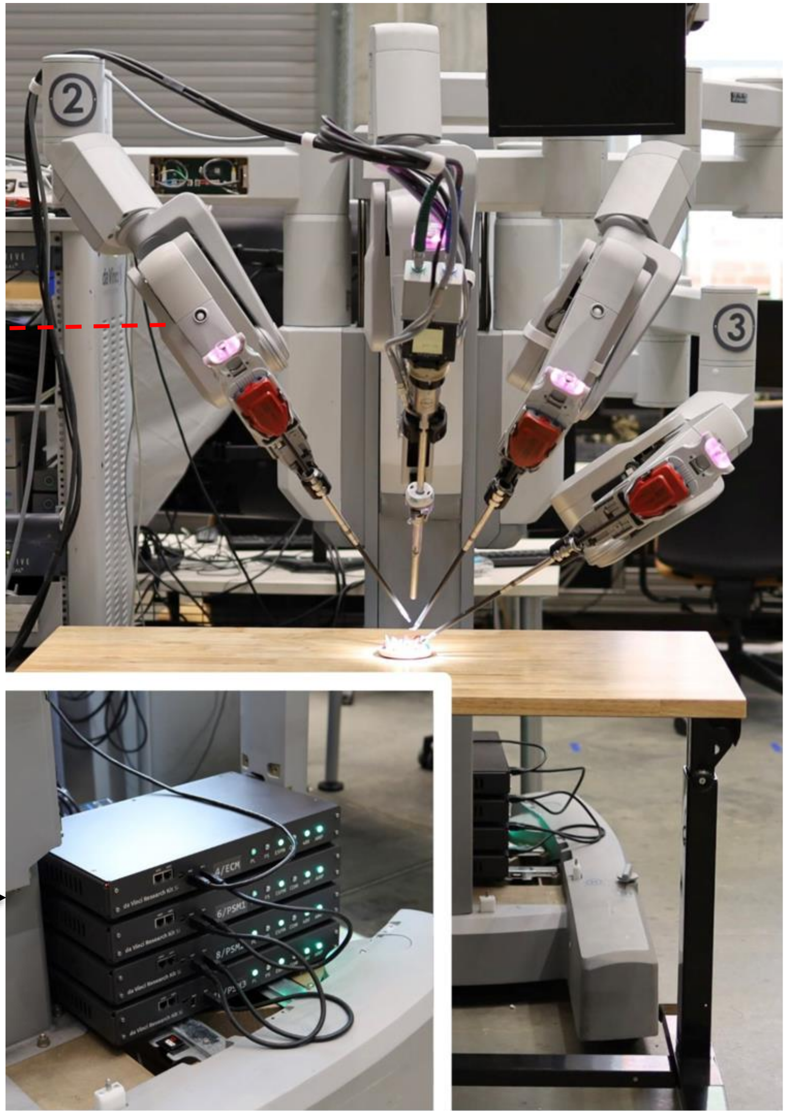
da Vinci Si

Next Generation: dVRK-Si

Problem: proprietary embedded electronics to serialize data via LVDS (serial network)

Solution: alternative firmware (closed source) with open protocol via LVDS

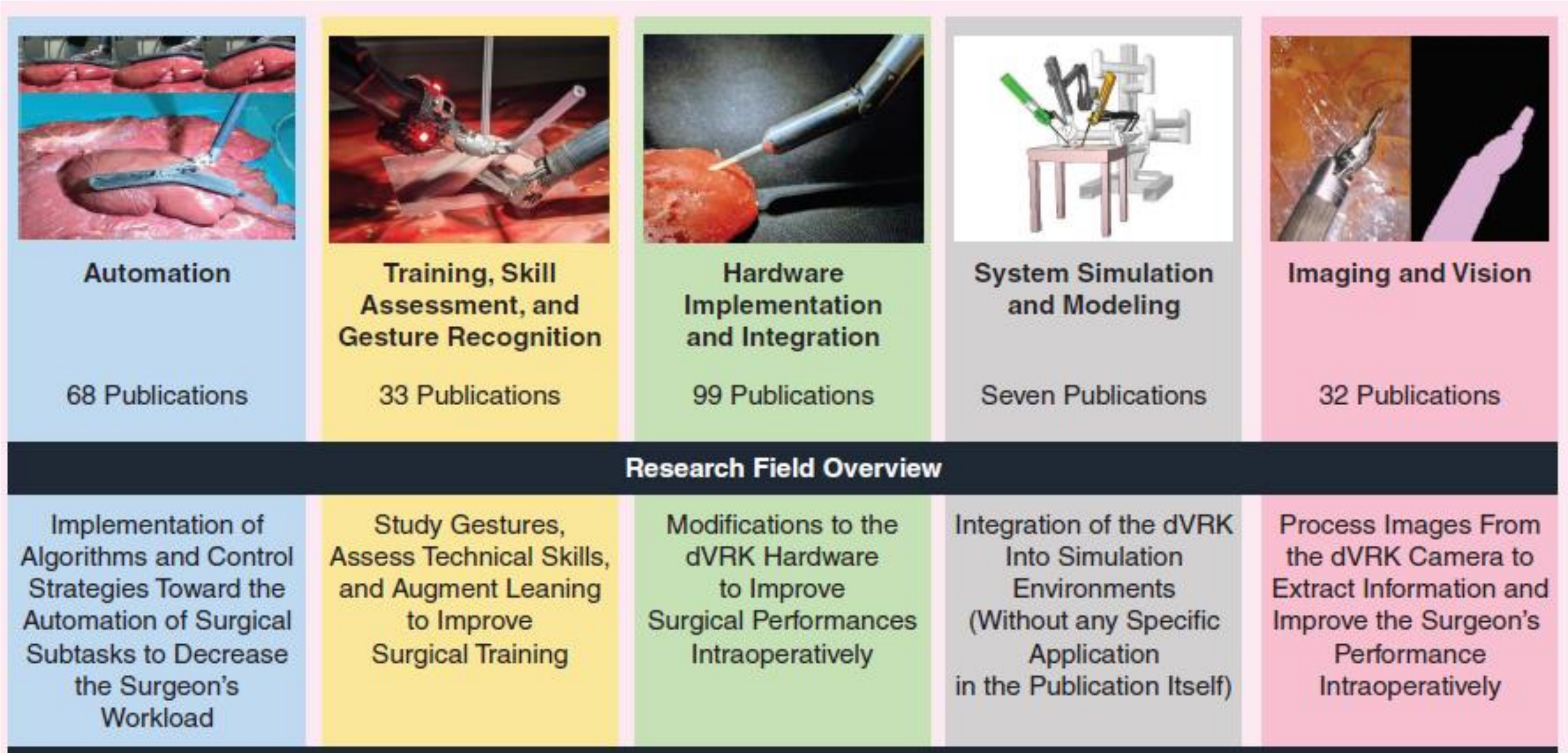
dVRK-Si Controllers



Credit: Jie Ying Wu, Keshuai Xu

dVRK Research Review

C. D'Ettorre *et al*., "Accelerating Surgical Robotics Research: A Review of 10 Years With the da Vinci Research Kit," *IEEE Robotics & Automation Magazine*, Dec. 2021.



+14 review papers

253 total publications

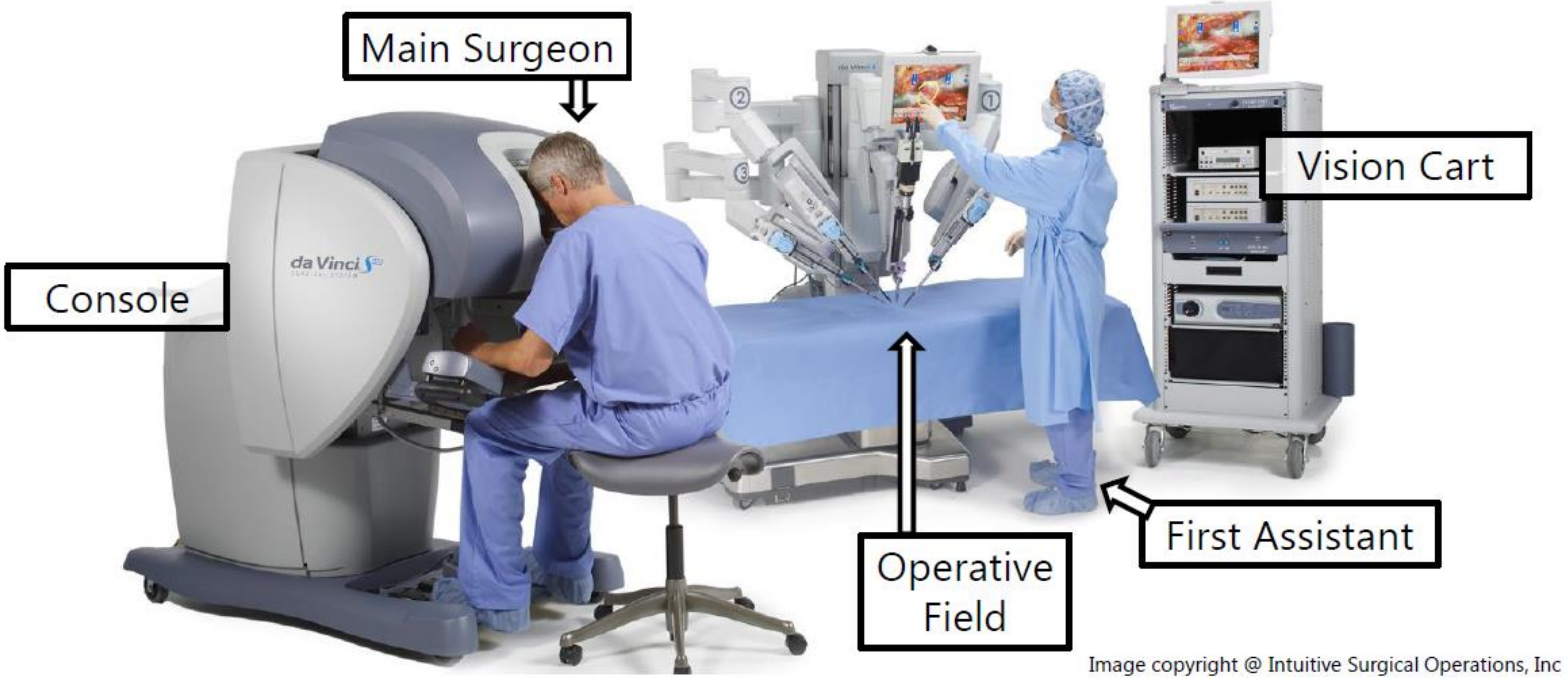
Google scholar,
September 5, 2026

An open-source research kit for the da Vinci® Surgical System
P **Kazanzides**, Z Chen, A Deguet... - ... on robotics and ..., 2014 - ieeexplore.ieee.org
We present a telerobotics research platform that provides complete access to all levels of control via open-source electronics and software. The electronics employs an FPGA to enable ...
Save Cite Cited by 749 Related articles All 17 versions

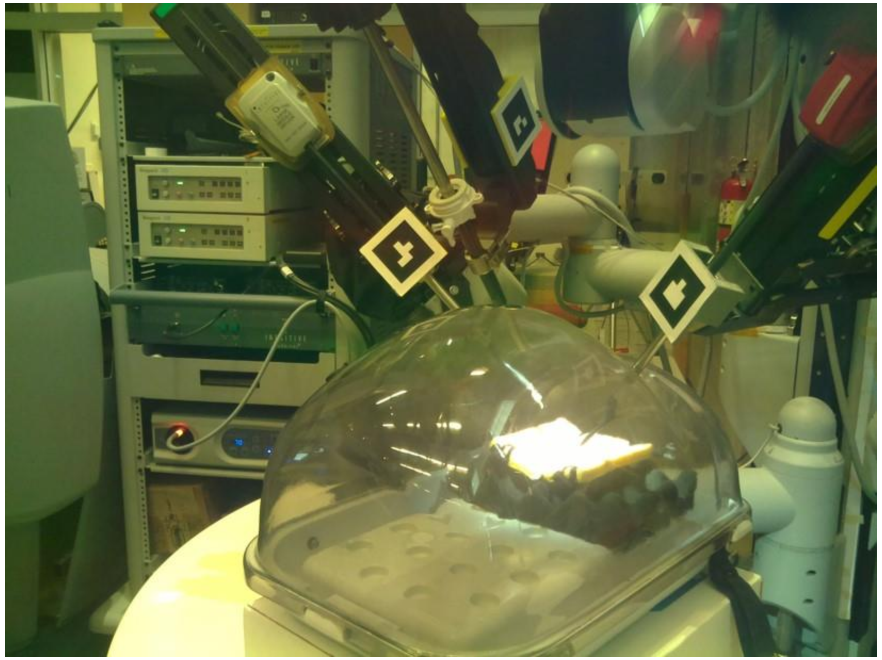
Some dVRK Research Highlights

- Augmented reality for robotic surgery
- Force estimation and haptic feedback
- Autonomous endoscope control
- Surgical Robotics Challenge

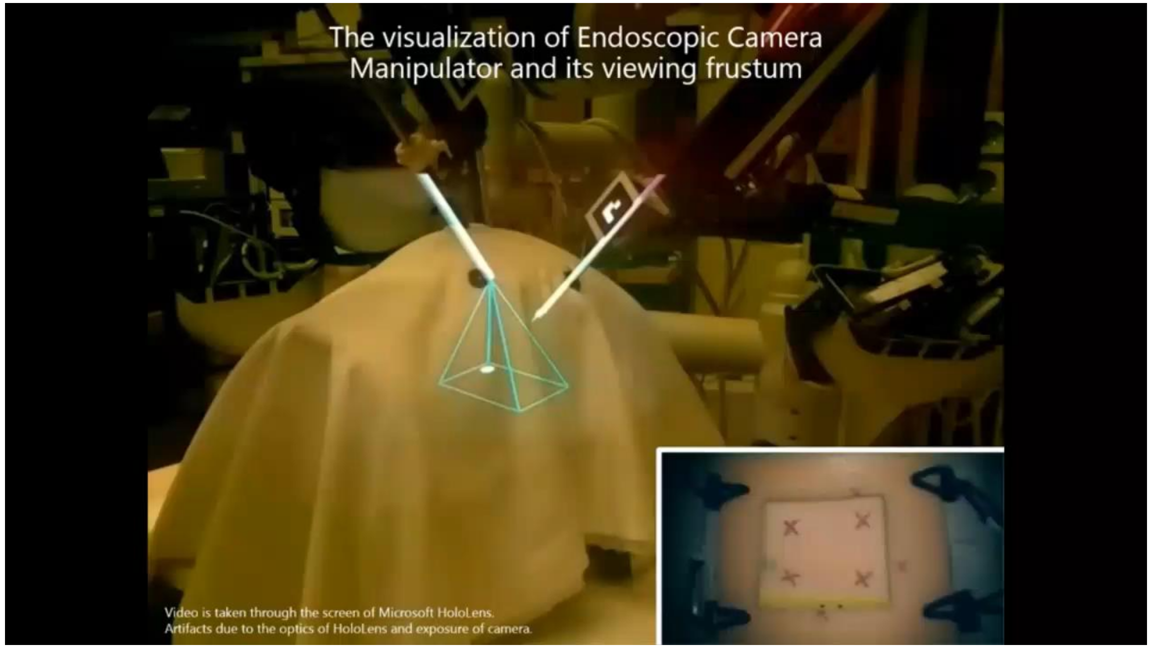
Augmented Reality for Robotic Surgery



Augmented Reality for da Vinci Assistant



Setup with transparent abdominal phantom



View through HMD (HoloLens)

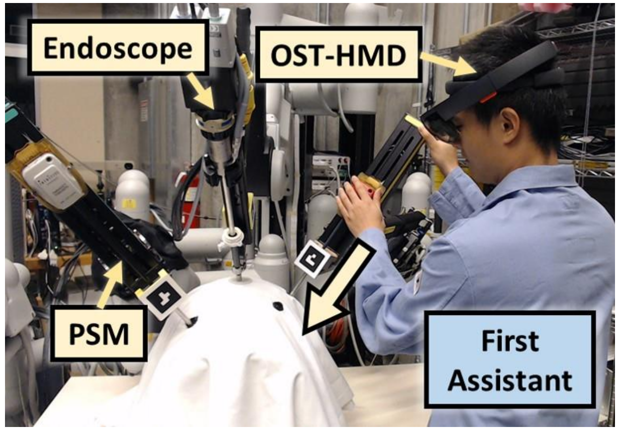
L. Qian, A. Deguet, P. Kazanzides, "ARssist: Augmented Reality on a Head-Mounted Display for the First Assistant in Robotic Surgery", IET Healthcare Technology Letters, Oct. 2018

L. Qian, A. Deguet, Z. Wang, Y. Liu, P. Kazanzides, "Augmented Reality Assisted Instrument Insertion and Tool Manipulation for the First Assistant in Robotic Surgery", IEEE ICRA, May 2019.

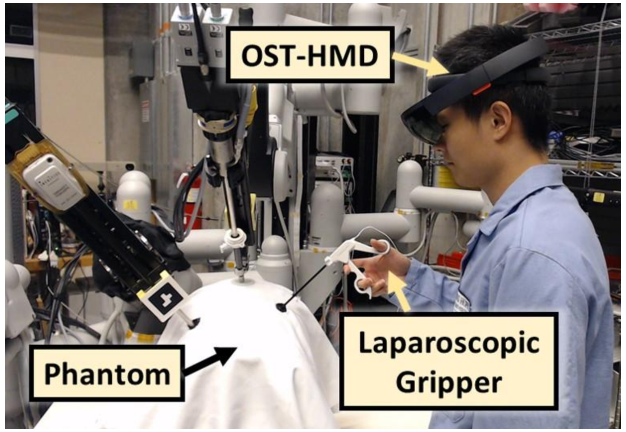
Supported by Intuitive Surgical Technology Research Grant, 2018

ARssist Evaluation

Instrument Insertion

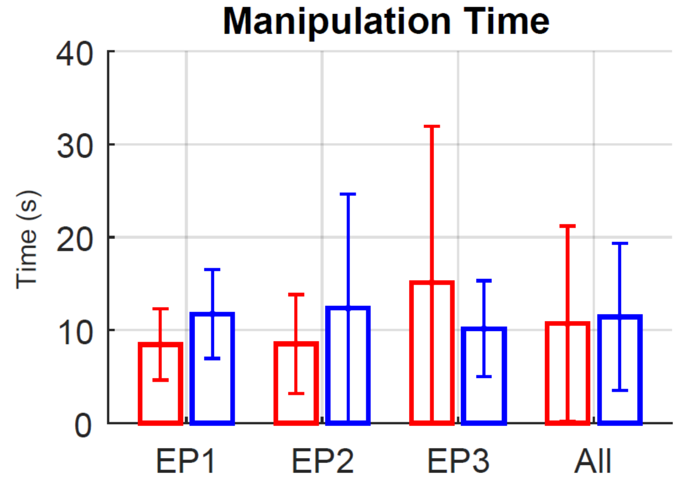


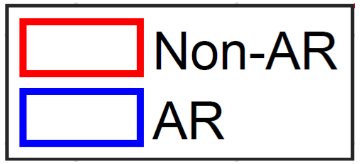
Tool Manipulation



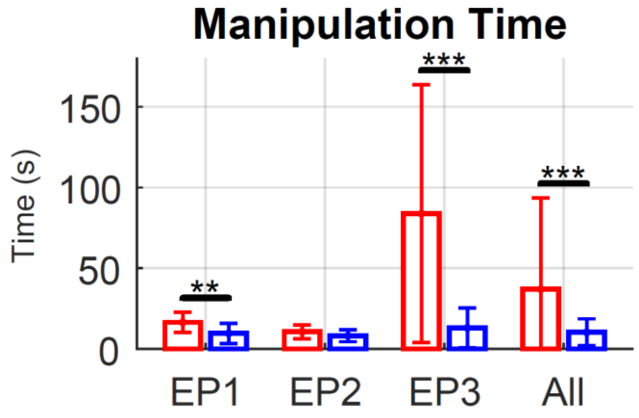
3 Endoscope Positions: EP1, EP2, EP3 (easy to hard)

Experts (N=10)



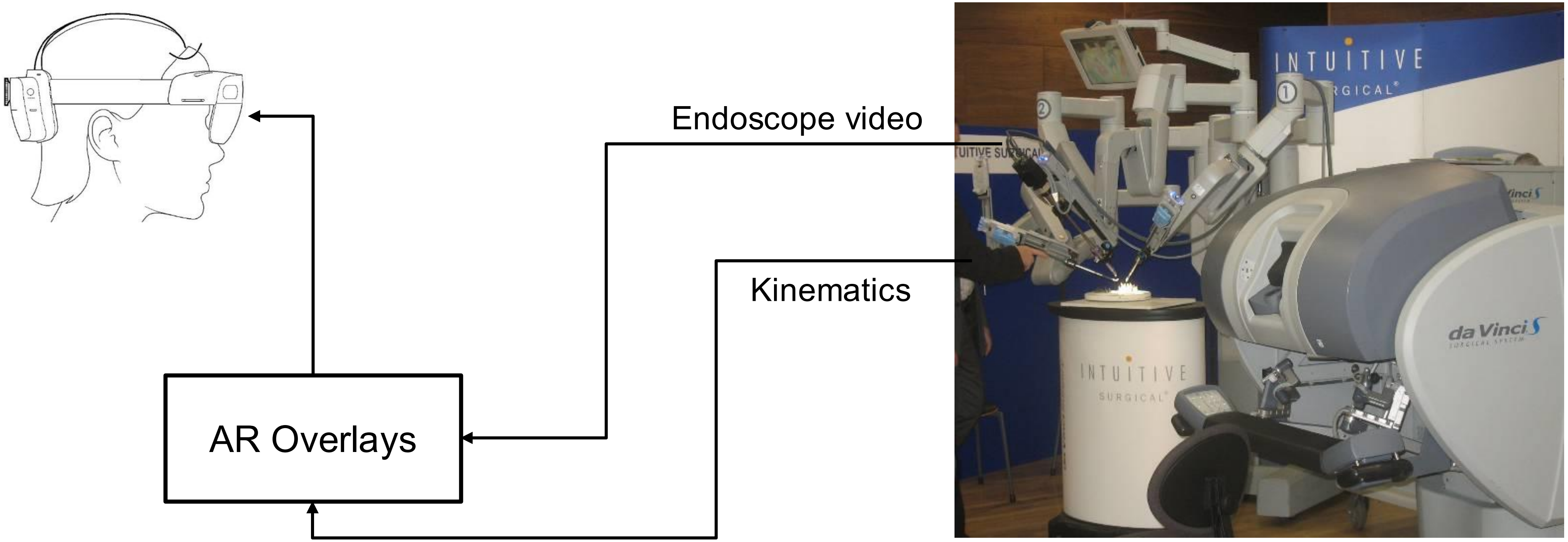


Novices (N=20)



ARsisst Clinical Translation

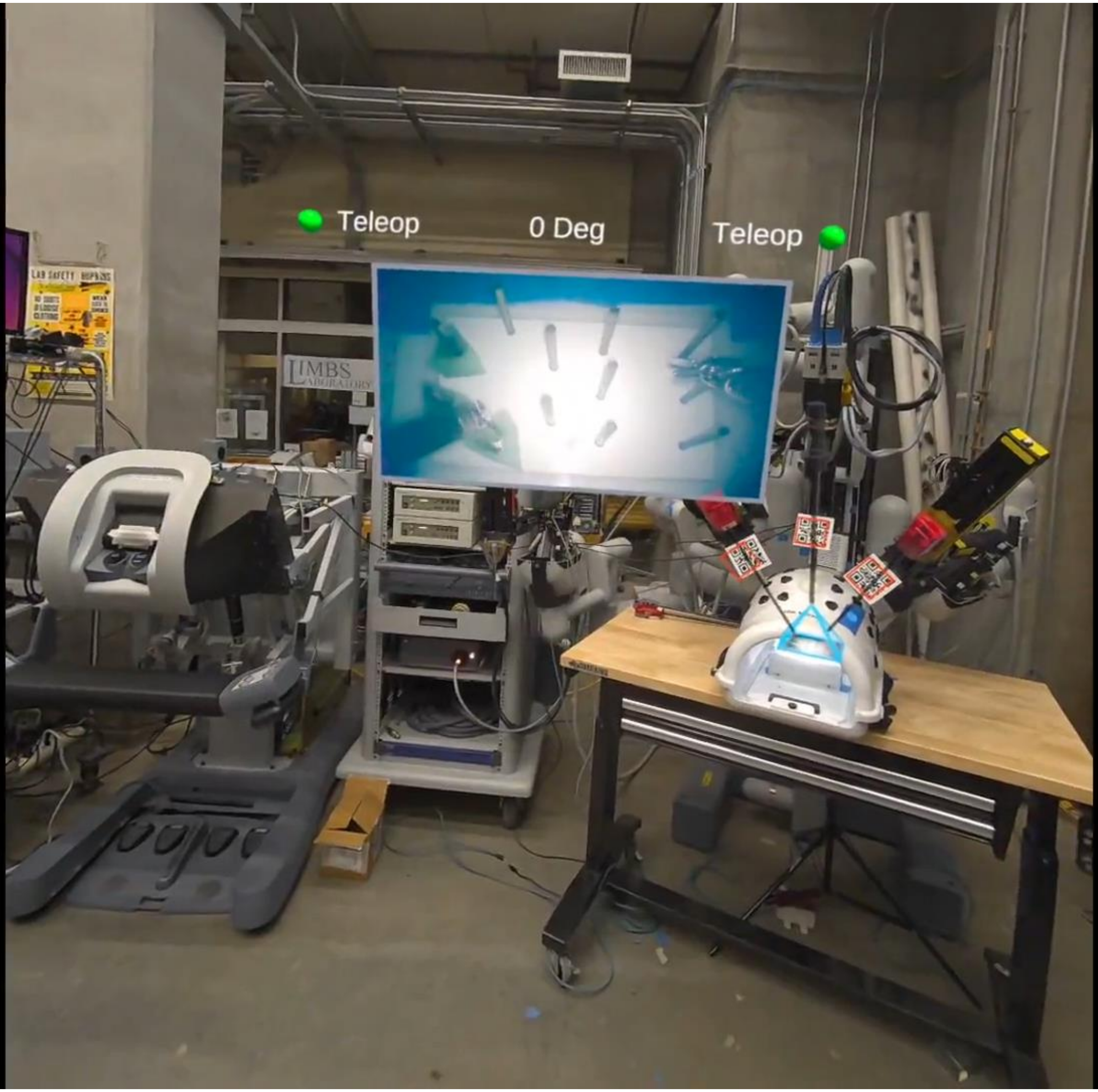
- Feasible with access to endoscope video and “read-only” research interface to obtain robot kinematics



Portable Surgeon Console

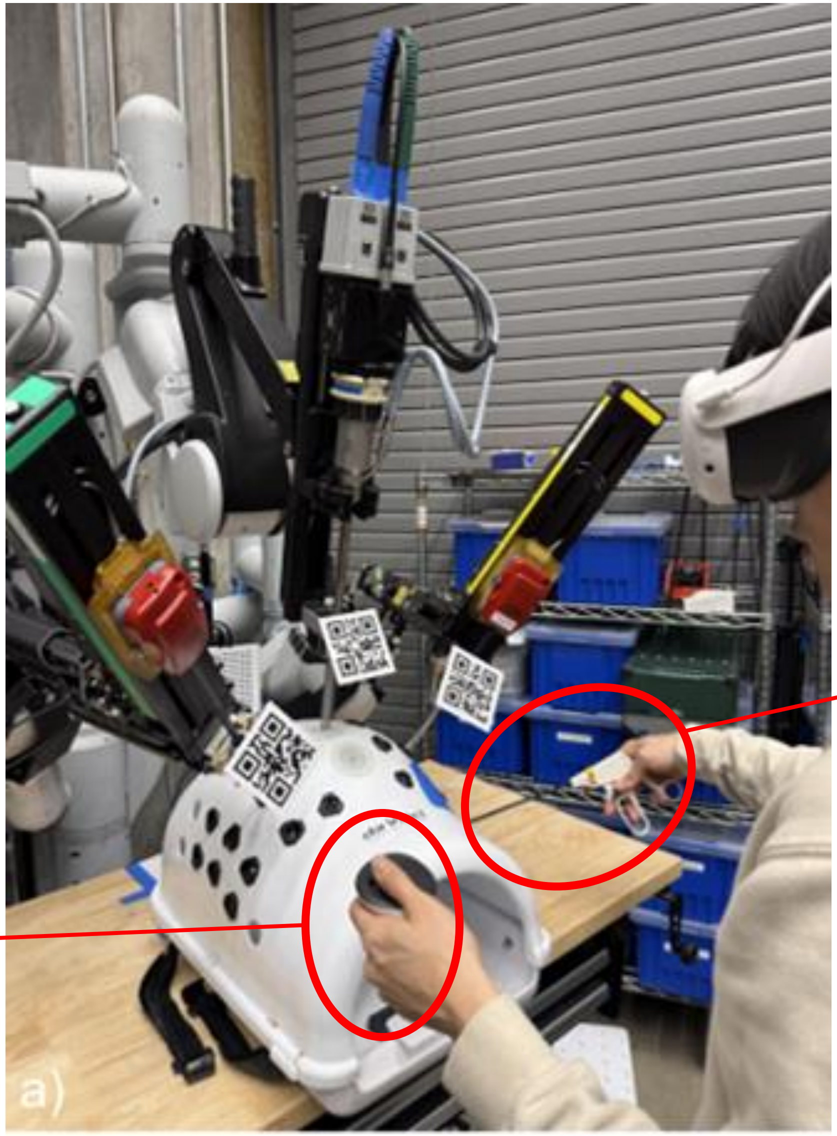
- HMD can provide stereo visualization
- Control of robotic instruments
  - Hand tracking: significant limitations
  - Tracked VR controllers
- Could enable surgeon to be at bedside
  - Assuming sterilization of VR controllers (e.g., drapes)
- Could enable "solo surgery", i.e., surgeon controls both robotic instruments and hand-held instruments
- More generally, fusion of laparoscopic and robotic surgery

Portable Surgeon Console



"Solo" Surgery

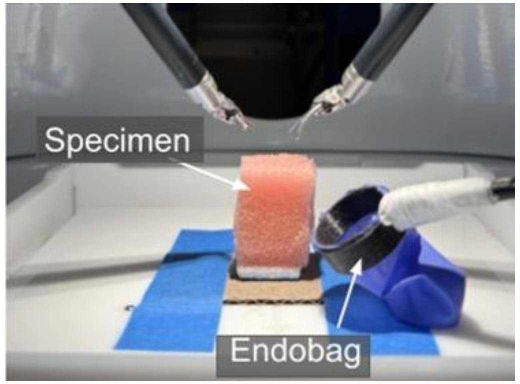
Teleoperated RAS with VR headset allows surgeon to stand at patient bedside



Can put down one controller and use hand-held instrument

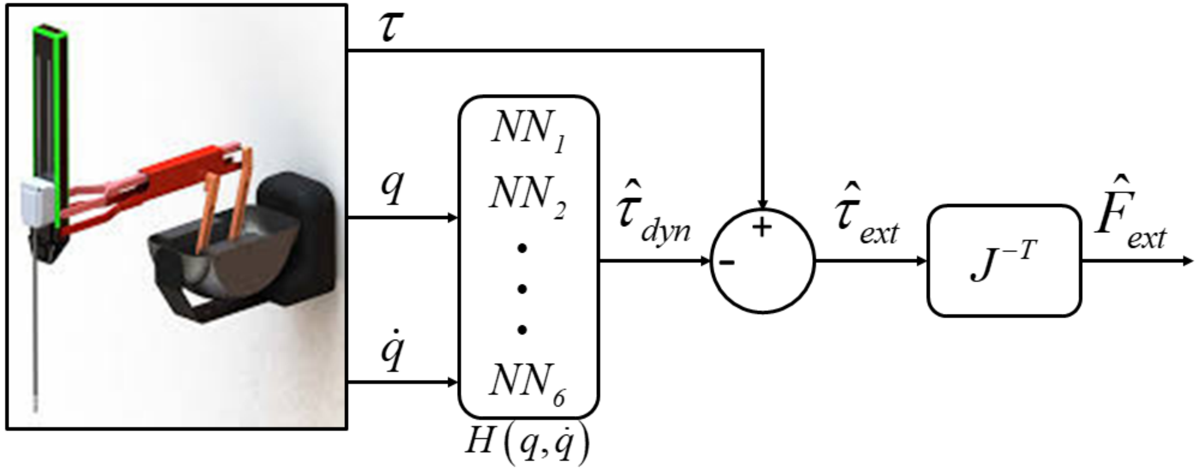
Handheld instrument

VR Controller
(PSM Teleoperation)



Force Estimation for dVRK

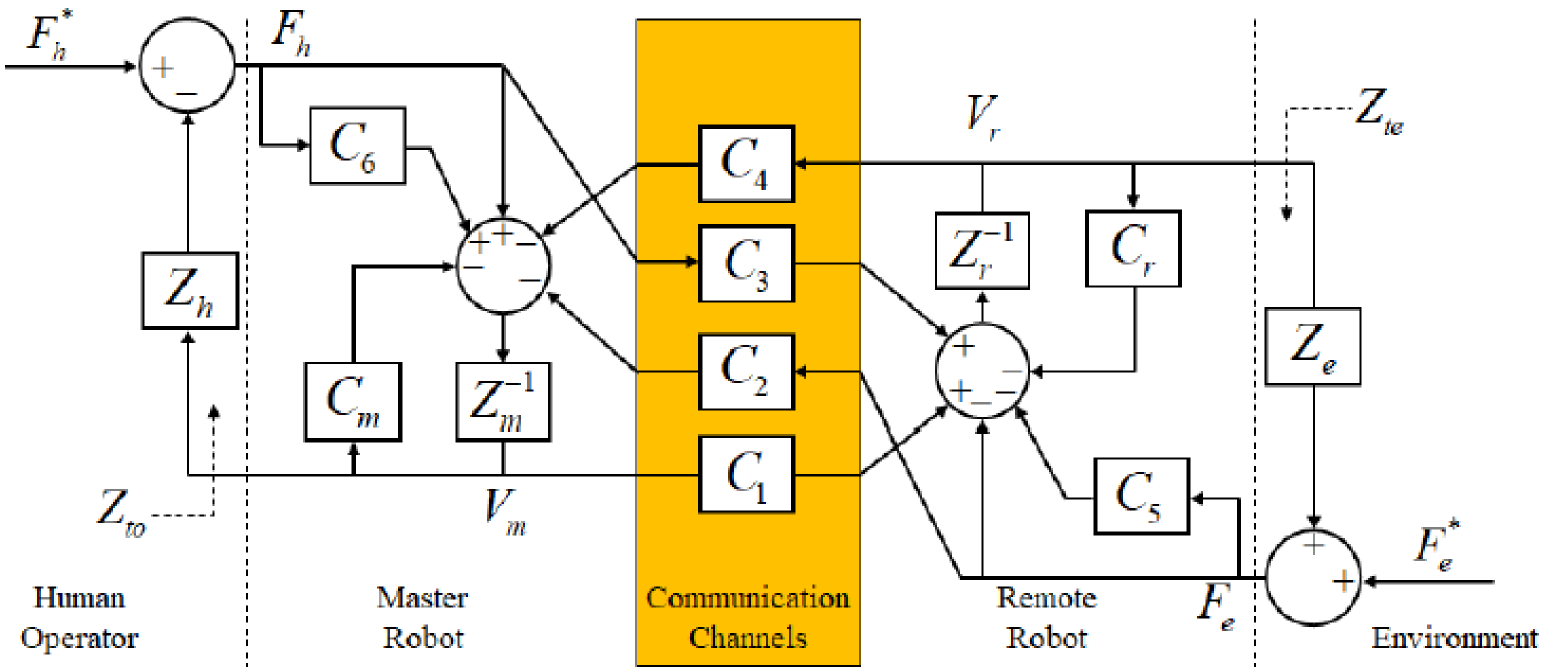
- One frequently cited limitation of robotic surgery is the lack of high quality haptic/tactile/force feedback to the surgeon
  - da Vinci 5 introduced force feedback for some instruments
- One solution: add a force sensor
- Another solution: estimate force from existing data (e.g., measured motor currents)



N. Yilmaz, J.Y. Wu, P. Kazanzides, U. Tumerdem "Neural network based inverse dynamics identification and external force estimation on the da Vinci Research Kit", ICRA 2020.

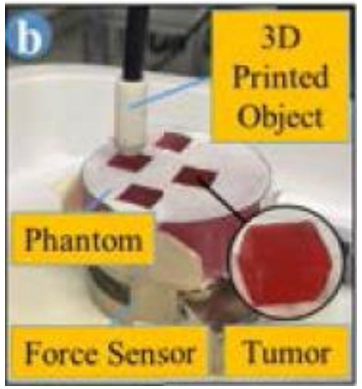
Bilateral Teleoperation

- Implemented 4-channel architecture for bilateral teleoperation



N. Yilmaz, B. Burkhart, A. Deguet, P. Kazanzides, U. Tumerdem, "Sensorless Transparency Optimized Haptic Teleoperation on the da Vinci Research Kit", IEEE RA-L 2023

Experimental Evaluation



Percentage of correct results when palpating phantom to identify stiffest one (12 subjects)

			SCALING 1:1				SCALING 1:5			
	Hand	**Inst**	**Uni**	**nDyn**	**Dyn**	**FS**	**Uni**	**nDyn**	**Dyn**	**FS**
AVG	100.00	95.83	54.17	85.42	85.42	89.58	58.33	85.42	87.50	87.50
STD	0.00	9.73	29.84	16.71	12.87	16.71	19.46	16.71	13.06	16.85

Hand Direct palpation with human hand

Inst Palpating with hand-held instrument

FS Bilateral teleoperation with force sensor feedback

Dyn Bilateral teleoperation with estimated force, with dynamic compensation (NN)

nDyn Bilateral teleoperation with estimated force, without dynamic compensation

Uni Unilateral teleoperation (no force feedback)

N. Yilmaz, B. Burkhart, A. Deguet, P. Kazanzides, U. Tumerdem, “Enhancing Robotic Telesurgery with Sensorless Haptic Feedback”, IJCARS (IPCAI) 2024

Autonomous Endoscope Control

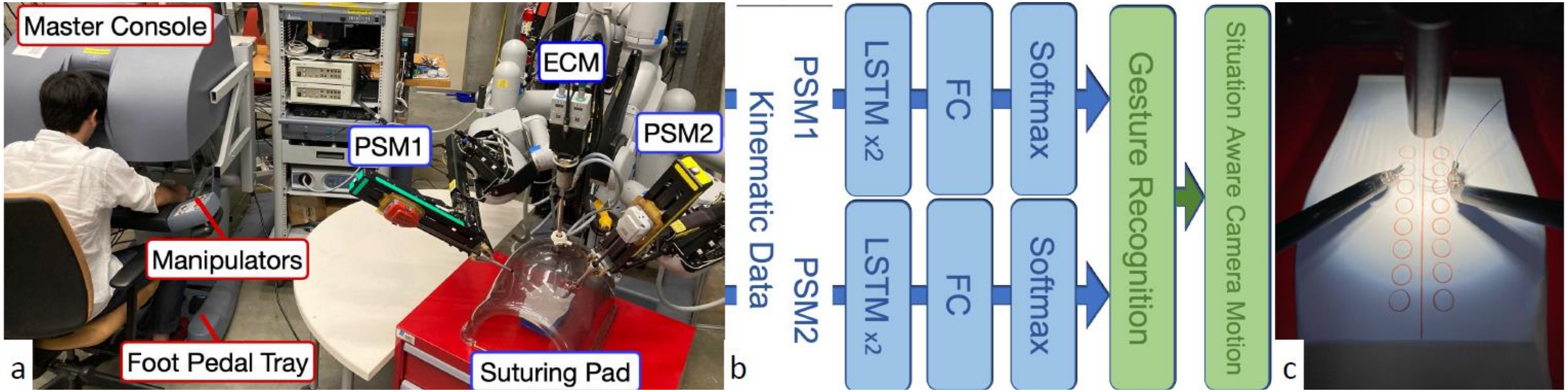
- SCAN: System for Camera Autonomous Navigation
  - Evaluated different policies for moving endoscope based on motion of one or both instruments
  - Camera motion was not optimal (for user) and too frequent
- GRACE: Gesture Recognition for Autonomous Camera-motion Enhancement
  - Establish fixed policy for each surgical subtask
  - Use ML to identify current subtask

T. Da Col, A. Mariani, A. Deguet, A. Menciassi, P. Kazanzides, E. De Momi, "SCAN: System for Camera Autonomous Navigation in Robotic-Assisted Surgery," IROS 2020.

N. Pasini, A. Mariani, A. Munawar, E. De Momi, P. Kazanzides, "A virtual suturing task: proof of concept for awareness in autonomous camera motion", IEEE Robotic Computing, 2022.

N. Pasini, A. Mariani, A. Deguet, P. Kazanzides, E. De Momi, "GRACE: online Gesture Recognition for Autonomous Camera-motion Enhancement in robot-assisted surgery", IEEE RA-L, 2023.

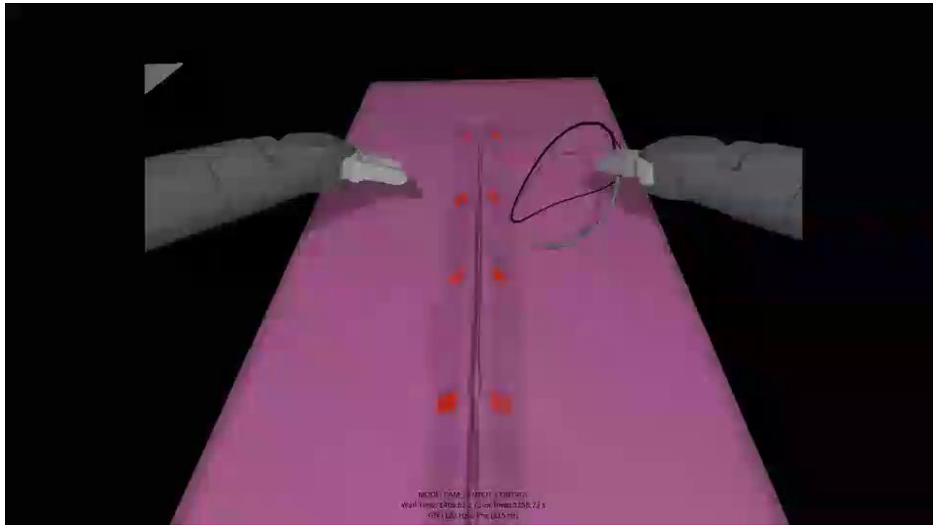
GRACE Evaluation



- Comparative evaluation of GRACE, SCAN and conventional footpedal control (novice users):
  - GRACE provided faster completion times
  - GRACE had less camera motion than SCAN, and more than footpedal
  - GRACE had better subjective ratings (NASA TLX)

Surgical Robotics Challenge

- A common dVRK platform facilitates collaboration and competitions, for example, to develop new AI algorithms



AccelNet Surgical Robotics Challenge, 2021-2022 (online)

AccelNet Surgical Robotics Challenge at ICRA, 2026
- Human teleoperation with physical and simulated dVRK
- Limited autonomous competition

https://surgical-robotics-ai.github.io

NSF 1927354 (JHU), 1927275 (WPI)

Outlook for the Future

- My life's work has primarily involved using technology to provide better tools for surgeons
  - AI can be useful here
- Lately, more interest in using AI to achieve fully autonomous surgery
  - Often justified by expected shortage of surgeons
  - One challenge is reliability. A 99% success rate means that for 20M surgeries, there will be 200K failures, even at 99.9%, it would be 20K failures.
  - Another challenge is regulatory approval. FDA and similar agencies regulate medical devices, not surgeons.
- Larger societal questions about the future of work
  - Should medicine be considered a "service", where the human connection matters?

Acknowledgments

JHU Contributors

Russell Taylor
Anton Deguet
Adnan Munawar
Jie Ying Wu
Keshuai Xu
Zihan Chen
Jintan Zhang
Brendan Burkhart
Juan Barragan
Hisashi Ishida
Irene Kim
Nick Greene
Long Qian
Ehsan Azimi
Paul Thienphrapa
Xiran Zhang
Dean Fu
Letian Ai

Visitors & Collaborators

Greg Fischer
Simon DiMaio
Ugur Tumerdem
Nural Yilmaz
Elena De Momi
Zerui Wang
Yunhui Liu
Philip W. Chiu
Zheng Li
Xin Ma
Qi Luo
Arianna Menciassi
Loris Fichera
Haoying (Jack) Zhou
Yiwei Jiang
Tamás Haidegger
Kristóf Takács
Eszter Lukacs
Nicolo Pasini
Chengzhi Song
Tommaso Da Col
Andrea Mariani
Sara Martuscelli
Matteo Magnani

Support

NSF
Intuitive Foundation
dVRK Consortium

Robodoc

Many colleagues at ISS