IEEE Robotics & Automation Society

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ICRA 2016 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION

Lecture 2:
Kinematics and Control of Medical Robots

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1891

ICRA 2016 Tutorial on Medical Robotics

lecture objectives

- Understand the kinematic structures of medical robots
- Identify common types of sensors and actuation technologies used in medical robots
- Identify control strategies used for human-in-the loop medical robots

Kinematics

suggested references

- Introduction to Robotics : Mechanics and Control
  John J. Craig
- Robot modeling and control
  Mark W. Spong, Seth Hutchinson, M. Vidyasagar
- A mathematical introduction to robotic manipulation
  Richard M. Murray, Zexiang Li, S. Shankar Sastry
- Springer handbook of robotics
  B. Siciliano, Oussama Khatib (eds.)

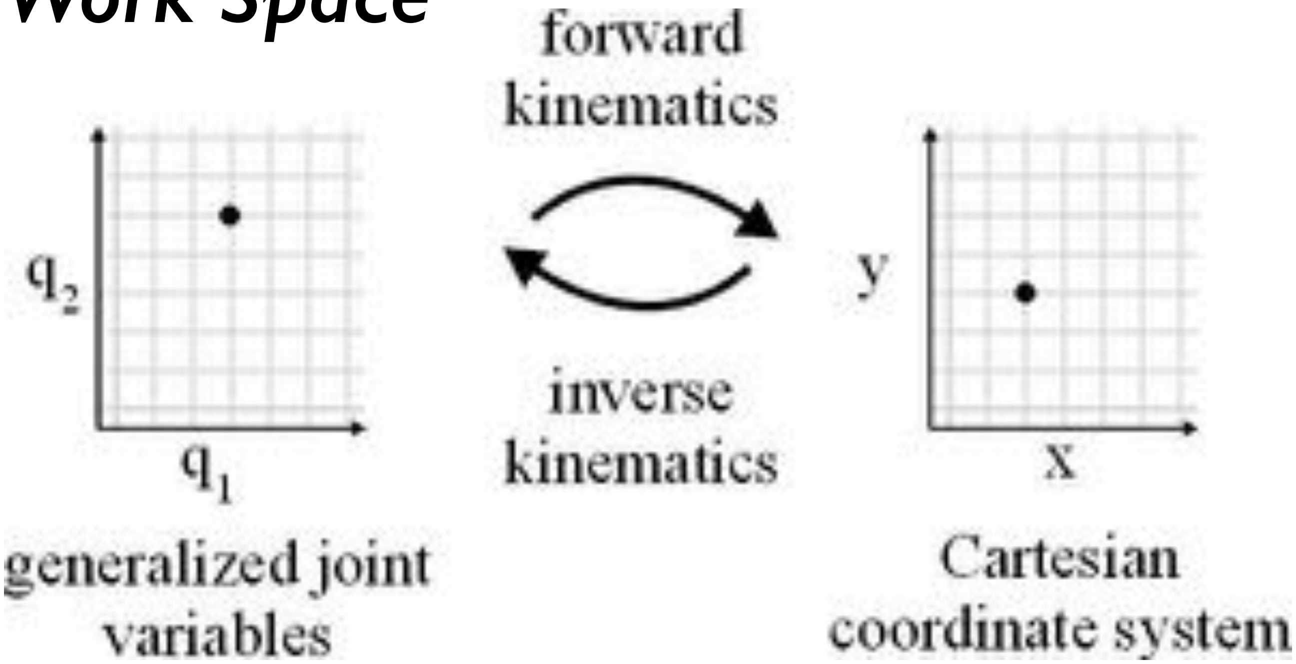
kinematics

The goals of kinematics in medical robots are to:

- Determine endpoint position and/or joint positions and their derivatives for control (forward kinematics and Jacobian)
- Determine the required joint positions for endpoint placement with respect to anatomy (inverse kinematics)
- Calculate force-torque relationships to enable control in workspace coordinates and generate force constraints (Jacobian transpose)

kinematics for robots

- Allows you to move between *Joint Space* and *Cartesian/Work Space*



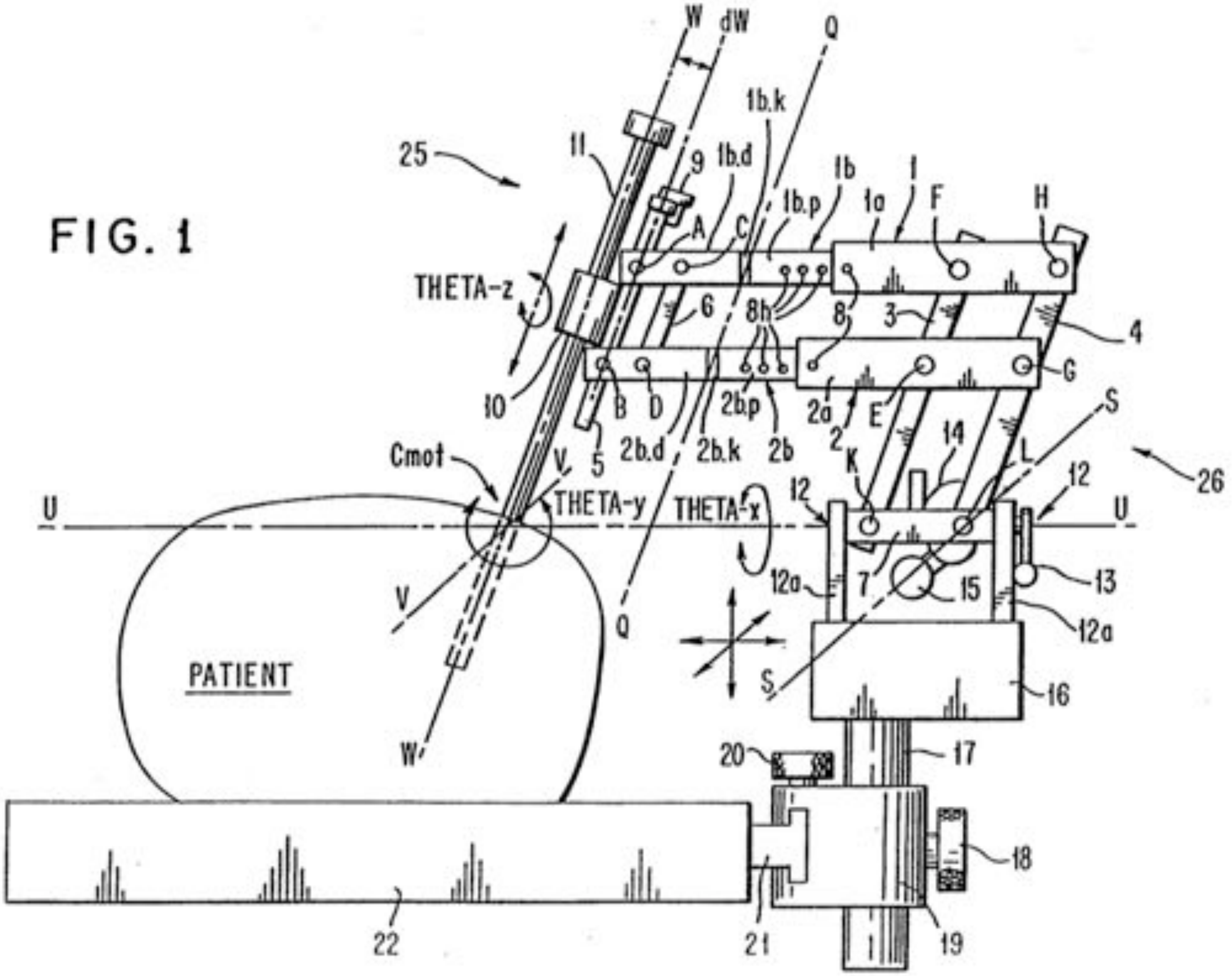
- Jacobian: $\dot{\mathbf{x}} = J\dot{\theta}$ $\dot{\theta} = J^{-1}\dot{\mathbf{x}}$ $\tau = J^{T}\mathbf{F}$

a note about degrees of freedom

- Number of independent position variables needed to in order to locate all parts of a mechanism
- DOF of motion
- DOF of sensing
- DOF of actuation
- The DOF of a mechanism does not always correspond to number of joints

a remote center of motion (RCM) robot

FIG. 1

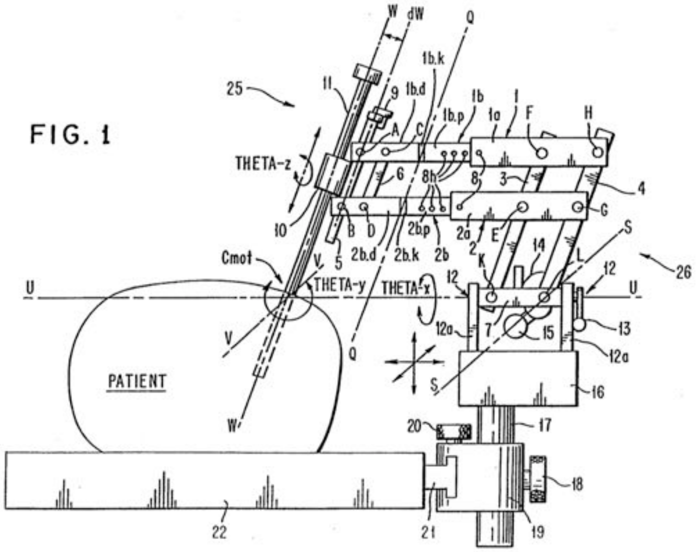


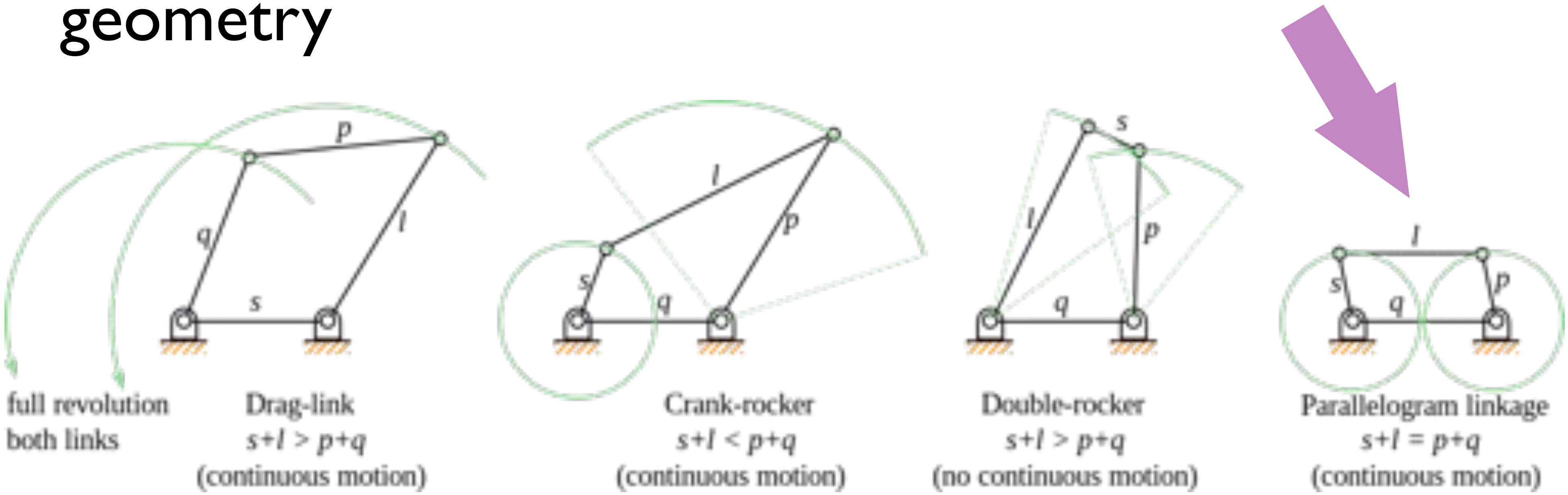
US patent 5397323 (Taylor, et al.)

four-bar linkage

- commonly used 1-DOF mechanism
- relationship between input link angle and output link angle can be computed from geometry

FIG. 1



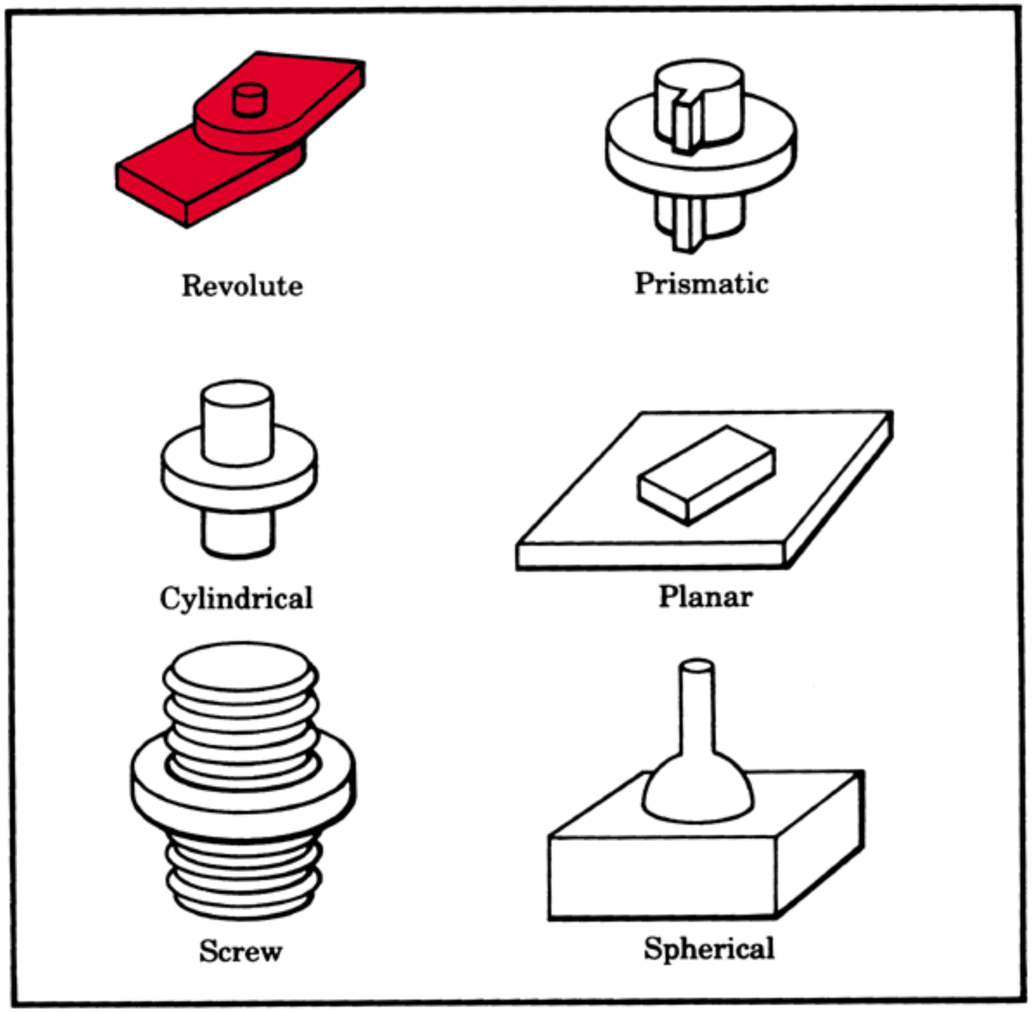


Types of four-bar linkages, *s* = shortest link, *l* = longest link

wikipedia.org

joints

- A robot manipulator a set of bodies connected by a chain of joints
- **Revolute** is the most common - why?



From Craig, p. 69

continuum robots

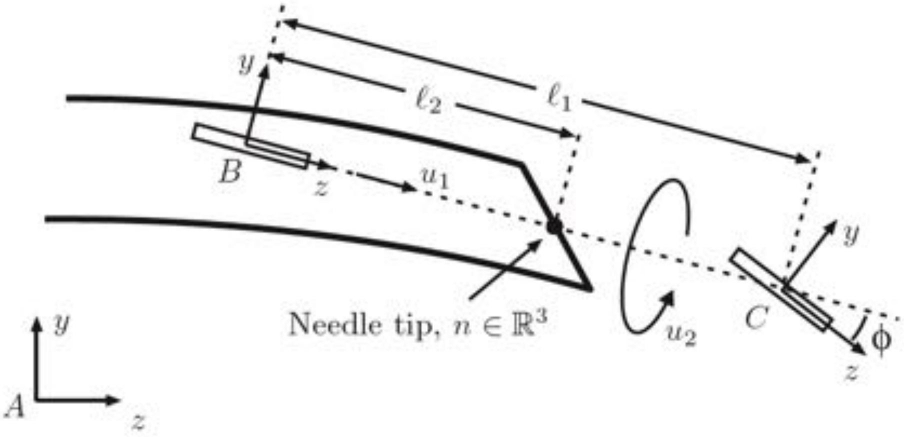
R. J. Webster III and B. A. Jones, "Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review," International Journal of Robotics Research, 29(13):1661-1683, 2010.
doi: 10.1177/0278364910368147

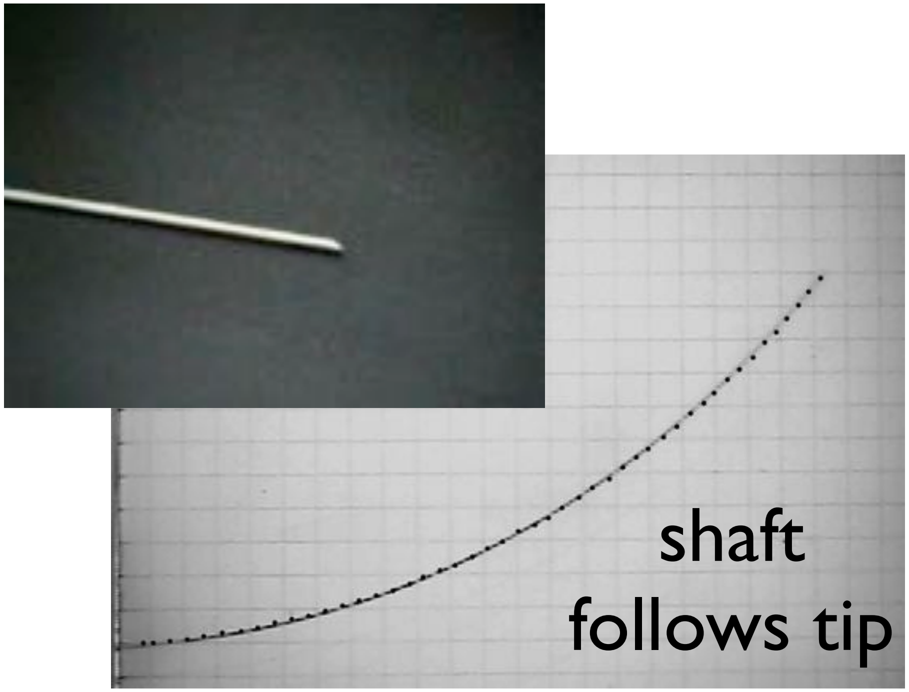
J. Burgner-Kahrs, D. C. Rucker, H. Choset, "Continuum Robots for Medical Applications: A Survey", IEEE Transactions on Robotics, 31(6):1261-1280, 2015.
dos: 10.1109/TRO.2015.2489500

steerable needles

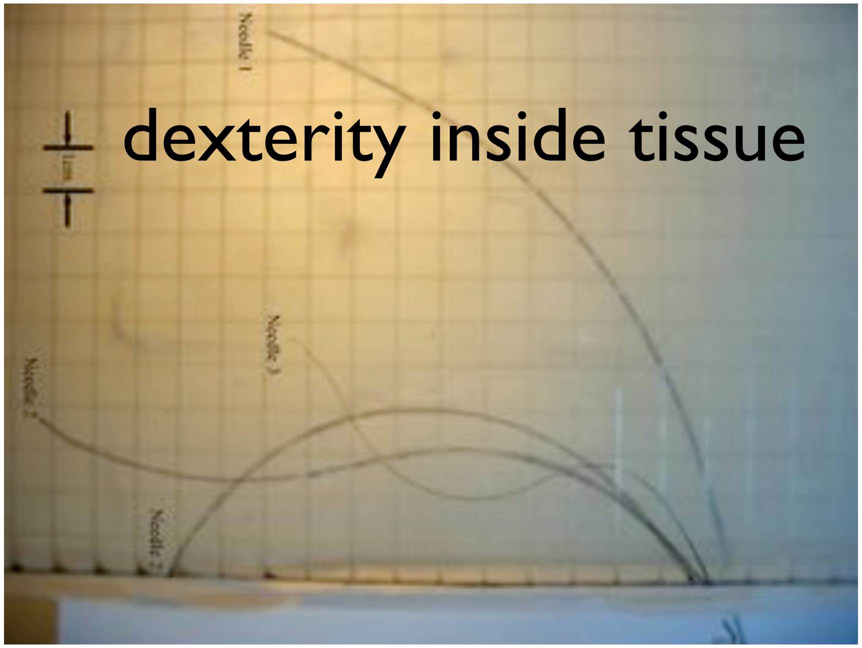
classic nonholonomic
“bicycle” model

the system is controllable
(nonholonomy degree 4)





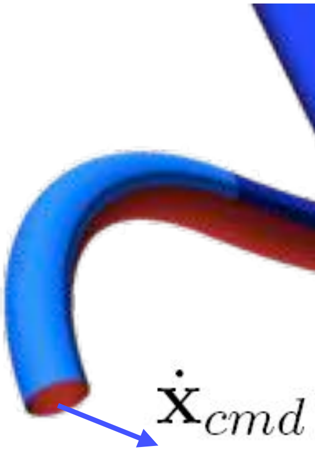
shaft
follows tip

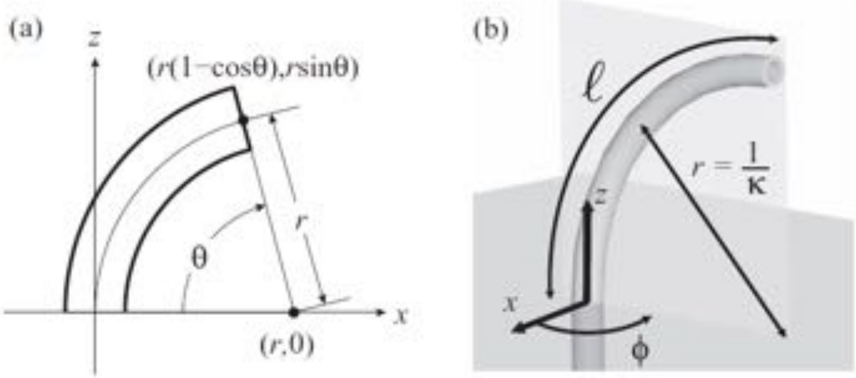


dexterity inside tissue

tendon-driven

- $\mathbf{x} = f(\mathbf{y})$ non-linear task-space kinematics
- $\boldsymbol{\tau} \geq \mathbf{0}$ actuation limitation
- Tendon driven systems often redundant

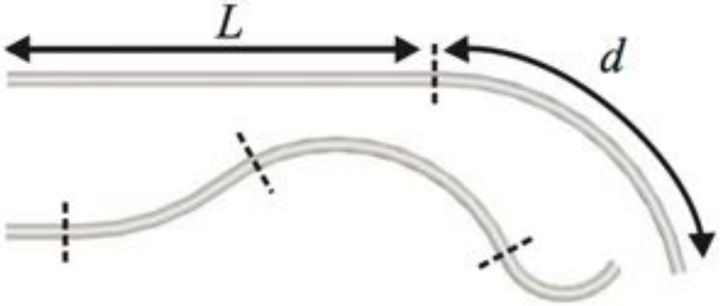


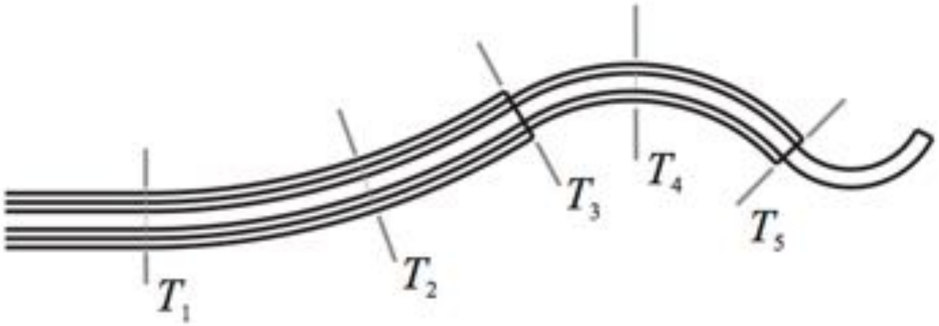


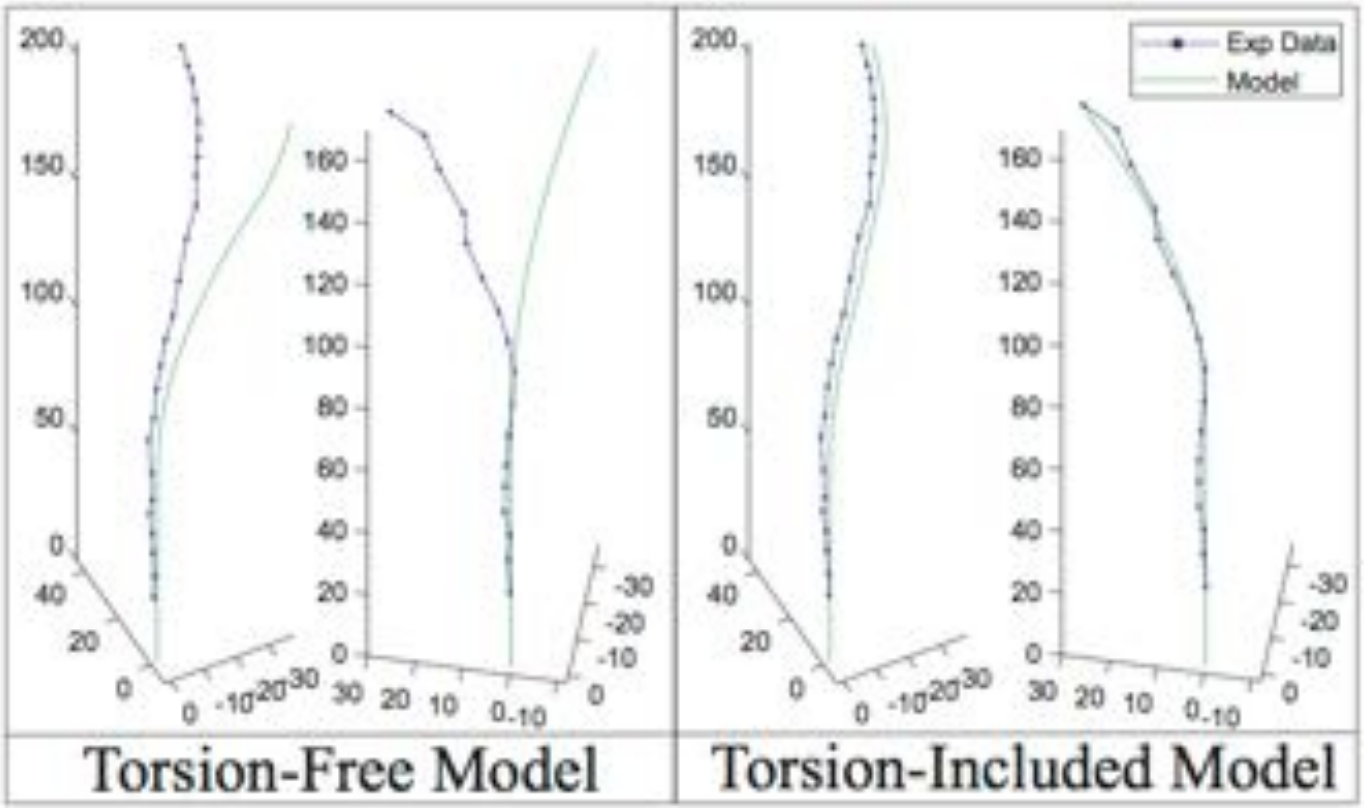
$$\begin{array}{lll}
\underset{\mathbf{y}(t+\Delta t)}{\text{minimize}} & \|\mathbf{C}_m^{-1}\mathbf{y}(t+\Delta t)\| & \\
\text{subject to} & \dot{\mathbf{x}}_{cmd}\Delta t - \left(f(\mathbf{y}(t+\Delta t)) - f(\mathbf{y}(t))\right) & = \mathbf{0}, \\
 & \mathbf{C}_m^{-1}\mathbf{y}(t+\Delta t) & \geq \mathbf{0}
\end{array}$$

David Camarillo

active cannulas

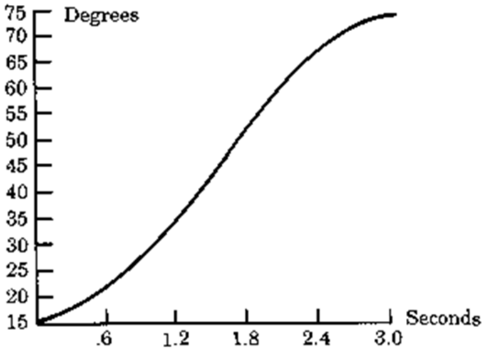






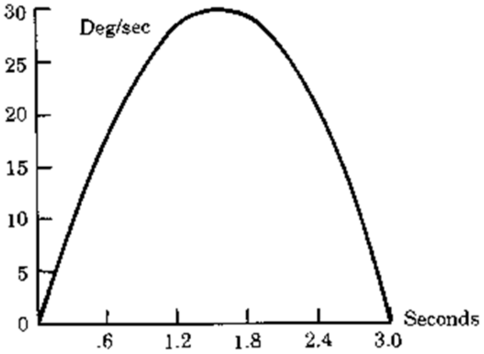
Robert Webster III

trajectory generation



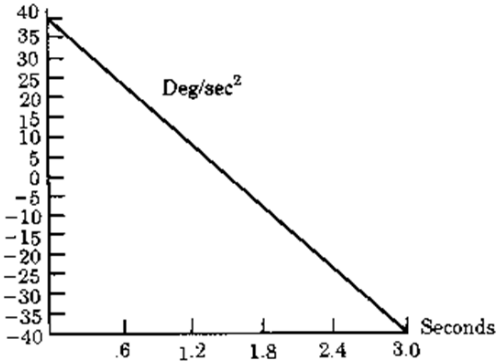
Position

position
cubic polynomial
C1 continuous



Velocity

velocity
quadratic polynomial
C0 continuous

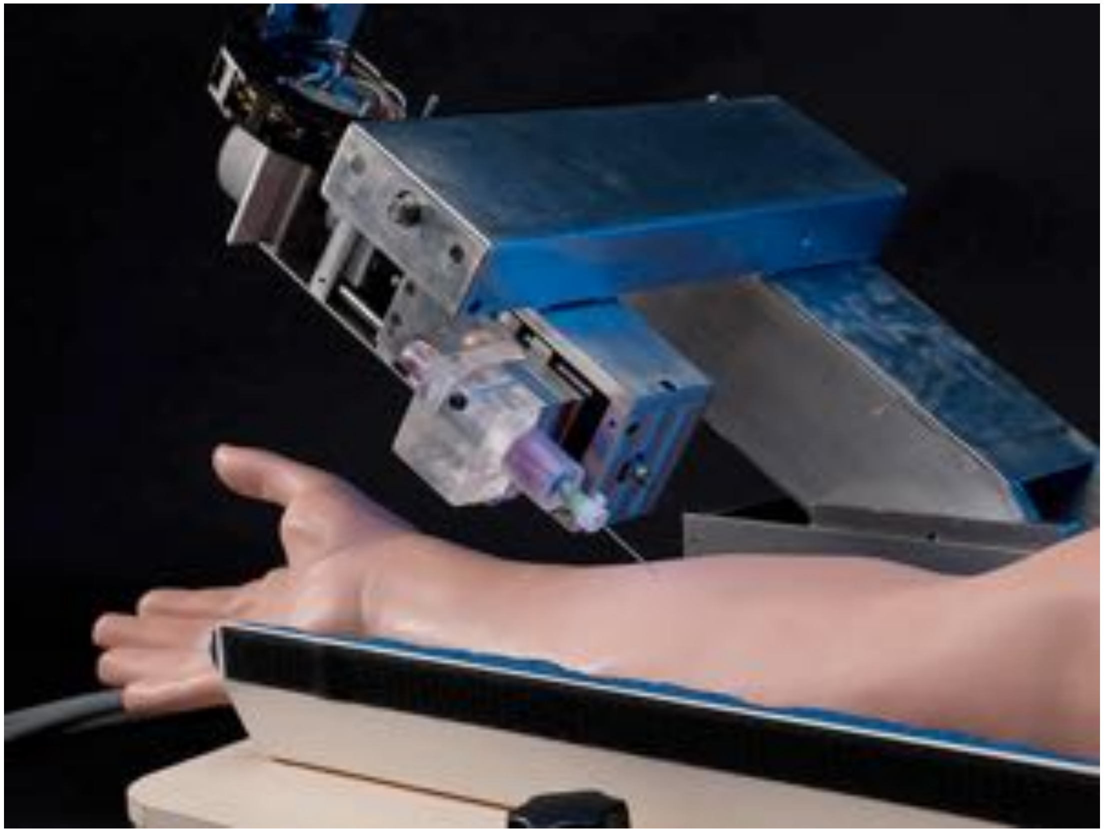


Acceleration

acceleration
quadratic polynomial
not continuous

discussion

what kind of kinematics/trajectory would you want for a robot that inserts a needle into solid tissue?

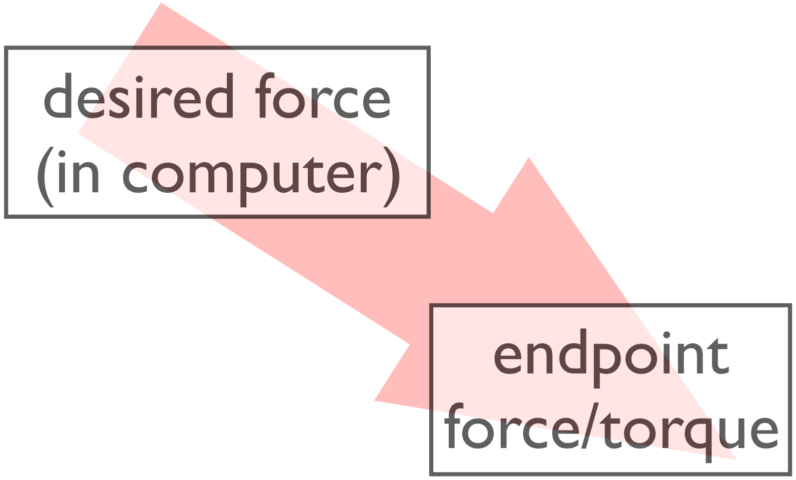


bloodbot (Imperial College of London)

controller on one end, system dynamics on the other

a controller computes
the desired force

e.g. $f = k_p * (x - x_d)$



desired force
(in computer)

endpoint
force/torque

this force and externally applied
loads result in robot motion

e.g., solve for x in $f = m\ddot{x} + b\dot{x}$

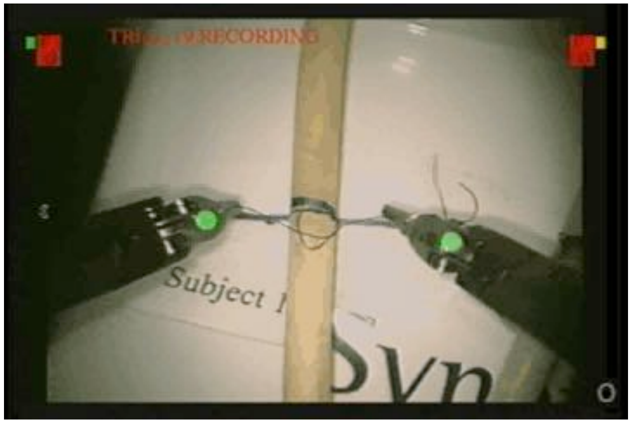
Sensors, Tracking, and Surgical Navigation

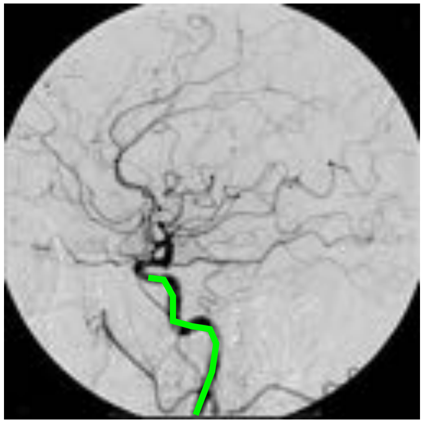
tracking

goal: to determine the position and orientation of tools and anatomical structures in image-guided procedures

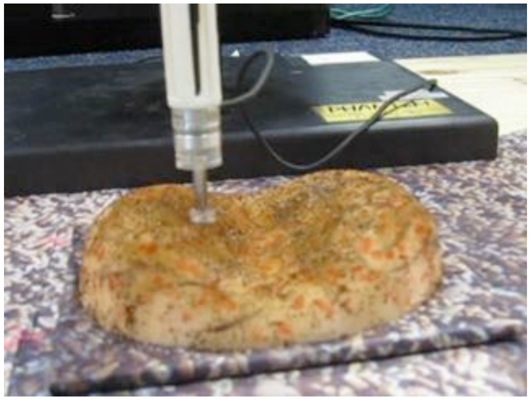
typical purposes:

1. display a dynamic virtual representation on screen relative to real images (e.g., augmented reality)





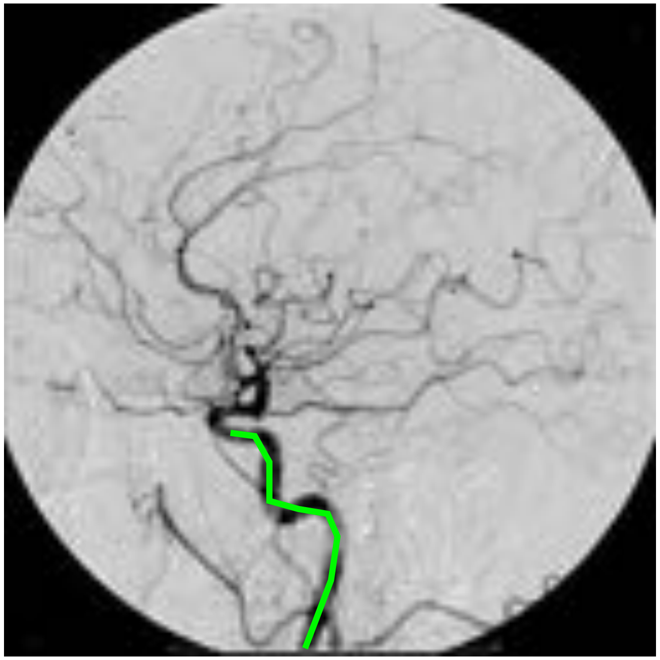
2. control a robot based on pose changes of tools and anatomical structures



goal1: information display

display a dynamic virtual representation on screen relative to real images (e.g., augmented reality)

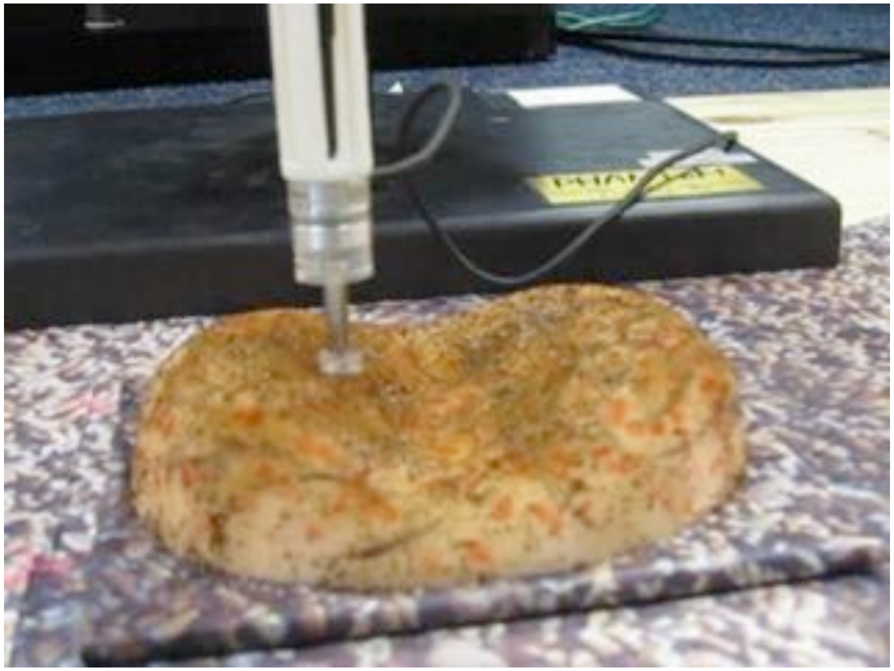
here, instruments are tracked so that "force dots" can be placed on them to prevent occlusion of the workspace

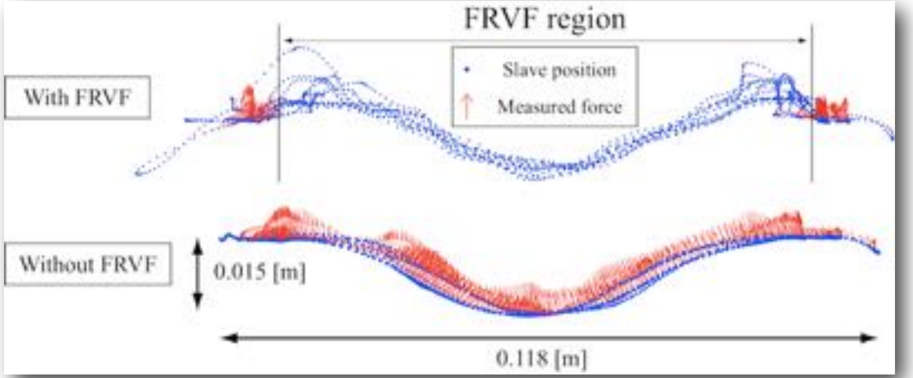


here, a dynamic graphical image of a catheter is overlaid on a static DSA image

goal 2: robot control

control a robot based on pose changes of tools and anatomical structures





in this example, virtual fixtures are created to keep the instrument away from the tissue surface

Yamamoto et al. (2011)

tracking requirements

1. Refresh rate: refresh rate of ~100Hz with a latency of less than 1ms, regardless of the number of tracked objects.
2. Concurrency: tracks up to *n* sensors concurrently.
3. Working volume: meets the needs of the procedure
4. Obtrusiveness: sensors are wireless and can function for several hours, all hardware components can be positioned so that they do not restrict the physical access to the patient, and the system does not have any effect on other devices used during the procedure
5. Completeness: sensors are small enough to embed in any tool and provide all 6DOF
6. Accuracy: resolution less than 0.1mm and 0.1°
7. Robustness: not affected by the environment (light, sound, ferromagnetic materials, etc.)
8. Cheap: costs less than ~$5000

G. Welch and E. Foxlin. Motion Tracking: No Silver Bullet, but a Respectable Arsenal. IEEE Computer Graphics and Applications, 22(6):24-38, 2002.

slide from Ziv Yaniv, Sheikh Zayed Institute for Pediatric Surgical Innovation Children's National Medical Center

mechanical tracking

method: robot kinematics combined with joint sensing is used to compute an end-effector position (this comes for free with a robot!)

caution:

- accuracy depends on correct kinematics
- limited workspace, obtrusive

stereotactic frame

coordinate measuring machine (e.g. Faro Arm)

robot (e.g., Mako)

optical tracking

method: use camera rigs to track fiducial markers that are attached to the instrument or anatomical structure of interest

passive markers: spherical markers reflect infrared light, emitted by illuminators on the position sensor

active markers: infrared-emitting markers are activated by an electrical signal (example: Polaris, NDI)

what are the advantages and disadvantages over mechanical trackers?

what about “traditional” computer vision?

electromagnetic tracking

method: a transmitter (magnetic field generator) is used to induce a current in sensor coils that can be embedded into the tracked objects

Aurora, NDI

transmitter

sensor coils

TrakStar, Ascension

what are the advantages and disadvantages over optical trackers?

SurgTrak: Affordable Motion Tracking and Video Capture for The da Vinci Surgical Robot

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OBJECTIVE

Robotic surgery provides high resolution video and instrument movement data useful in assessing surgical skill. This data could enable the development of training algorithms to accelerate learning curves. However, only a few research centers have access to the instrument data housed within the da Vinci robot's Application Programming Interface (API). Here we present a hardware and software solution that obviates the need for da Vinci API access during dry, cadaver, and animal lab training: SurgTrak. Our method achieves comparable data (all degrees of freedom of the tool and wrist and camera) to the da Vinci API at a far lower cost and without the intellectual property agreements needed to license API access from Intuitive Surgical. Our hardware and software is highly configurable and does not put the robot at risk of damage or malfunction. Further, it is deployable to any unmodified da Vinci robot.

FIGURE 1 Our modified tool next to a standard da Vinci Si instrument. Both motion tracking and grasper tracking are achieved within the tool body and outside the surgical field.

FIGURE 2 The da Vinci grasper is driven by four spindles in the tool body. By measuring the angle of these spindles we know the pose of the tool.

FIGURE 3 LEFT: Internal components of SurgTrak including potentiometers to measure spindle angle, and electrical connection to tool-tip for contact sensing. CENTER: Spacer featuring tracker receptacle positioned to optimize signal quality and strain relieved signal wiring receptacle. RIGHT: Internal view of modified tool showing final product.

DESCRIPTION

Our system consists of synchronized video and surgical tool motion recording unified by custom software. Video is recorded at up to 30Hz from the da Vinci master console using an Epiphan DVI2USB device, Epiphan Systems Incorporated, Ottawa, Ontario, Canada. Tool position and orientation are captured with a 3D Guidance trakSTAR magnetic tracking system, Ascension Technology Corporation, Burlington, VT, USA. Grasper and wrist position is recorded by measuring the angular position of the four spindles driving the four tool degrees of freedom (See figures 2 and 3). Custom USB-enabled hardware based on PhidgetInterfaceKit 8/8/8 (Phidgets Incorporated, Alberta, Calgary, Canada) was developed, including a set of inexpensive potentiometers that extract absolute spindle angle and additional environmental signals. Data streams from the video recording, position recording and wrist signal recording are united by purpose-built Visual C++ software running on a Windows 7 based laptop computer utilizing the windows multimedia timer.

RESULTS

SurgTrak requires no modification of the da Vinci surgical robot and no access to its inner workings. It can be adapted to da Vinci standard, da Vinci S and da Vinci Si surgical robots.

The addition of SurgTrak recording equipment is transparent to the surgeon. It requires only one wired connection to each tool and camera. Data is recorded to compact, manageable files for later analysis. Video data can be analyzed manually via an Objective Structured Assessment of Technical Skills protocol or via automated methods. SurgTrak is currently in use in a multicenter study to validate robotic surgical education curricula. Two complete systems have been constructed and deployed: one to the University of Washington Institute for Simulation and Interprofessional Studies (ISIS) and the second to Madigan Army Medical Center. To date, over 750 iterations of surgery-like tasks have been logged. These include tasks such as FLS Block Transfer and a new, more challenging rocking peg-board task. Figure 4 depicts the system and typical results.

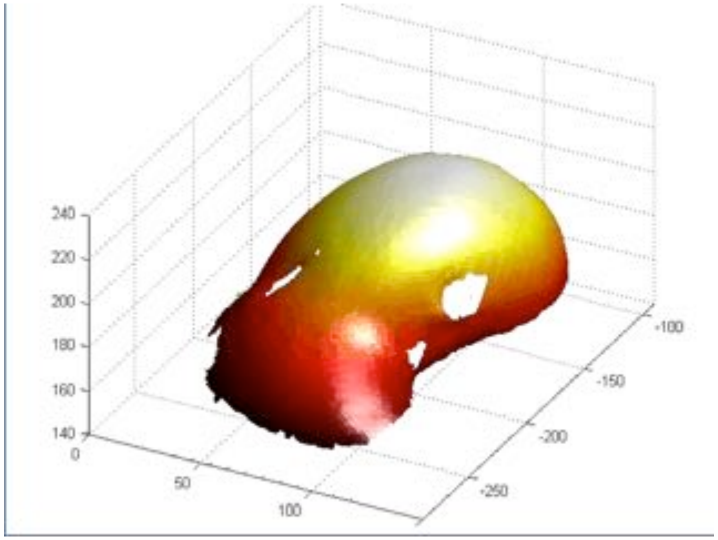
Surgical Data Capture Using SurgTrak

FIGURE 4 As surgeons perform tasks, the video stream they view and motions they produce are recorded at 30 Hz and stored to a hard drive. All tracking occurs outside the surgical field, with the position sensors and instrumentation located at the back of the tool body (seen also in Figure 1).
Data collected includes spindle angle (tool-tip pose), tool position and orientation in space, tool contact with tasks, and video of the entire task or procedure.

surface imaging
(computer vision, depth sensing)

Bumblebee Firewire Stereo Vision Camera

Microsoft Kinect

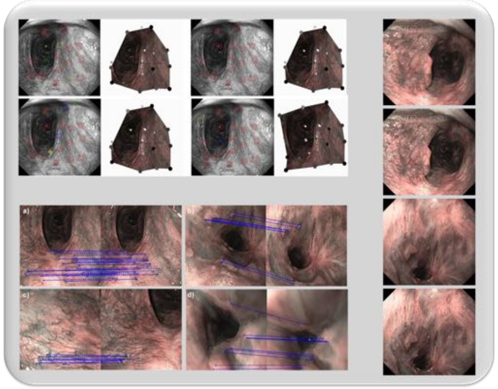


Optimet Conoprobe surface scanning (Vanderbilt)

Sick Laser Measurement Sensor

image: Microsoft

other trackers



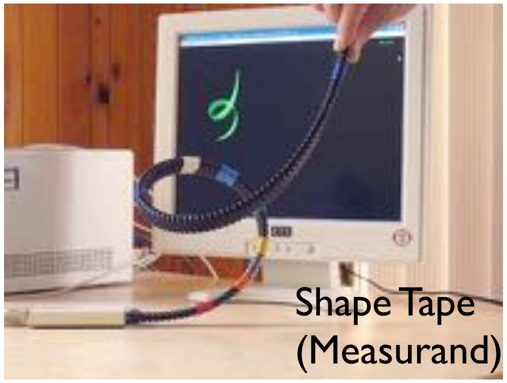
optical ego-motion (self-motion) computes camera motion; appropriate for endoscopes

Technische Universität München

ultrasonic systems: sound point sources are attached to the objects; time of flight between the source and a number of detectors is used to estimate the location of the source

inertial measurement units use accelerometers and gyroscopes to detect acceleration and orientation

Shape Tape uses fiber optics to estimate the location and orientation along its length



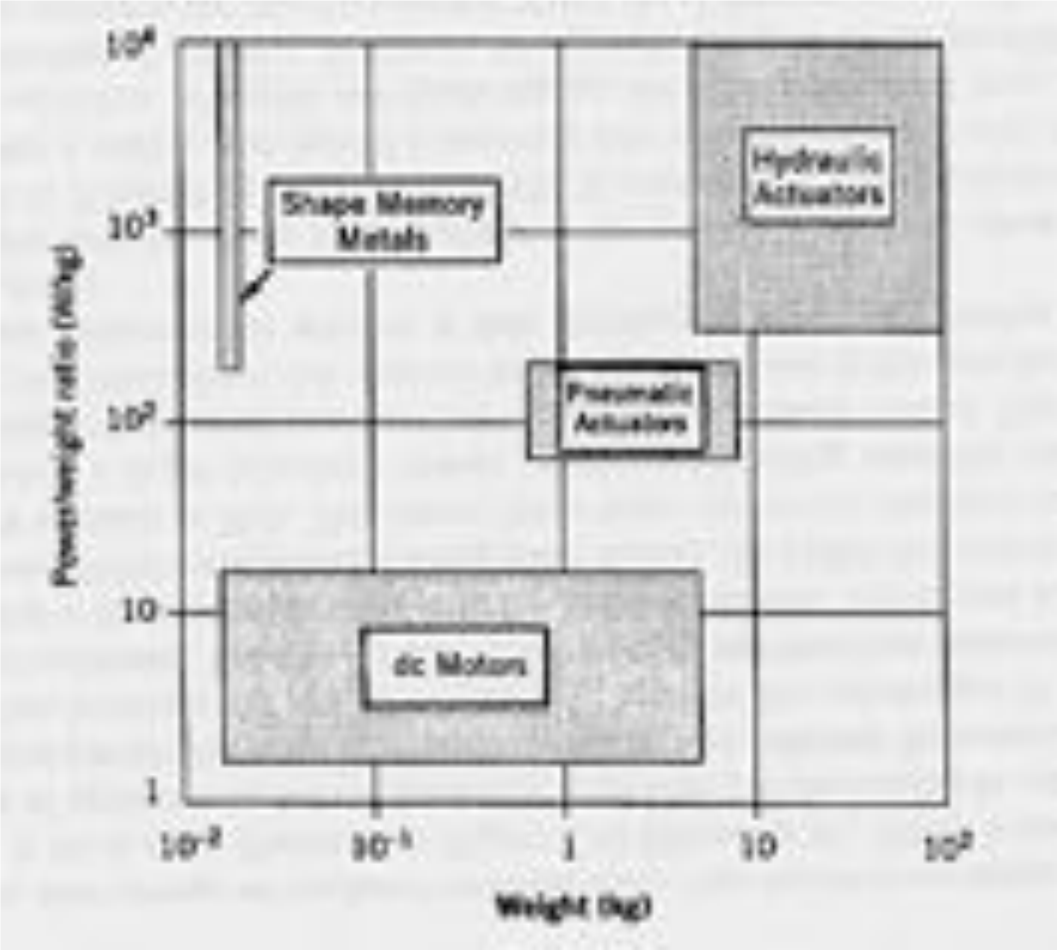
Shape Tape (Measurand)

Virginia Tech Shape Tape example: http://www.youtube.com/watch?v=ZMZr1jNDVGY

Actuators

actuator types

- Electric motors
  - –DC (direct current)
  - –Brushed
  - –PM (permanent magnet)
- Pneumatic Actuators



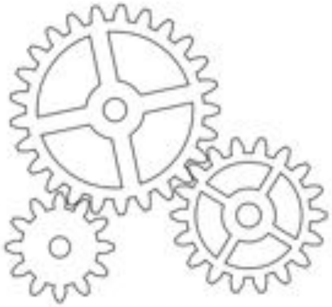
Burdea

Pneumatic Actuators

- How do they work?
  - Compressed air pressure is used to transfer energy from the power source to haptic interface.
- Many different types
- Concerns are friction and bandwidth

transmission

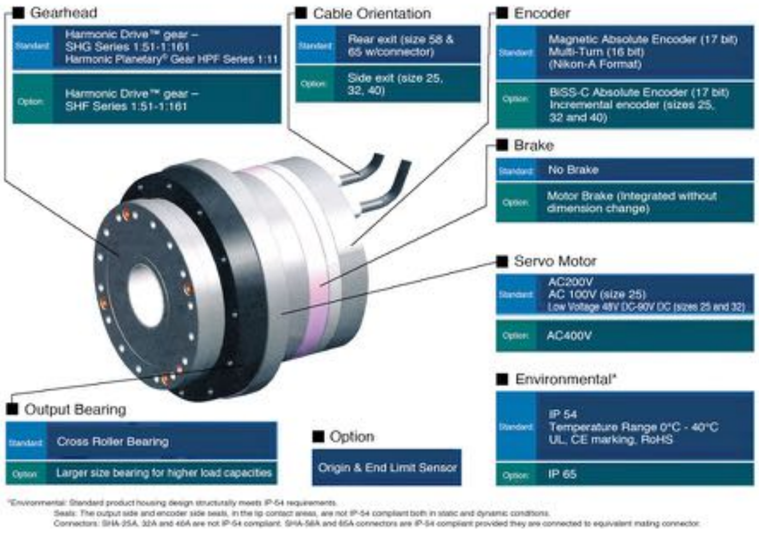
- Transfers/amplifies force/torque from motor
- You don’t want to feel or see the effects of the transmission!
- Types:
  - Gears
  - Belts/pulleys
  - Capstan Drive
  - None (direct drive)



harmonic drive

- mechanical gear system
- advantages:
  - no backlash
  - compactness and light weight
  - high gear ratios
  - high torque capability
  - coaxial input and output shafts

wikipedia.org



*Environmental: Standard product housing design structurally meets IP-54 requirements.
Seals: The output side and encoder side seals, in the lip contact areas, are not IP-54 compliant both in static and dynamic conditions.
Connectors: SHA-25A, 32A and 40A are not IP-54 compliant. SHA-58A and 65A connectors are IP-54 compliant provided they are connected to equivalent mating connector.

harmonicdrive.net

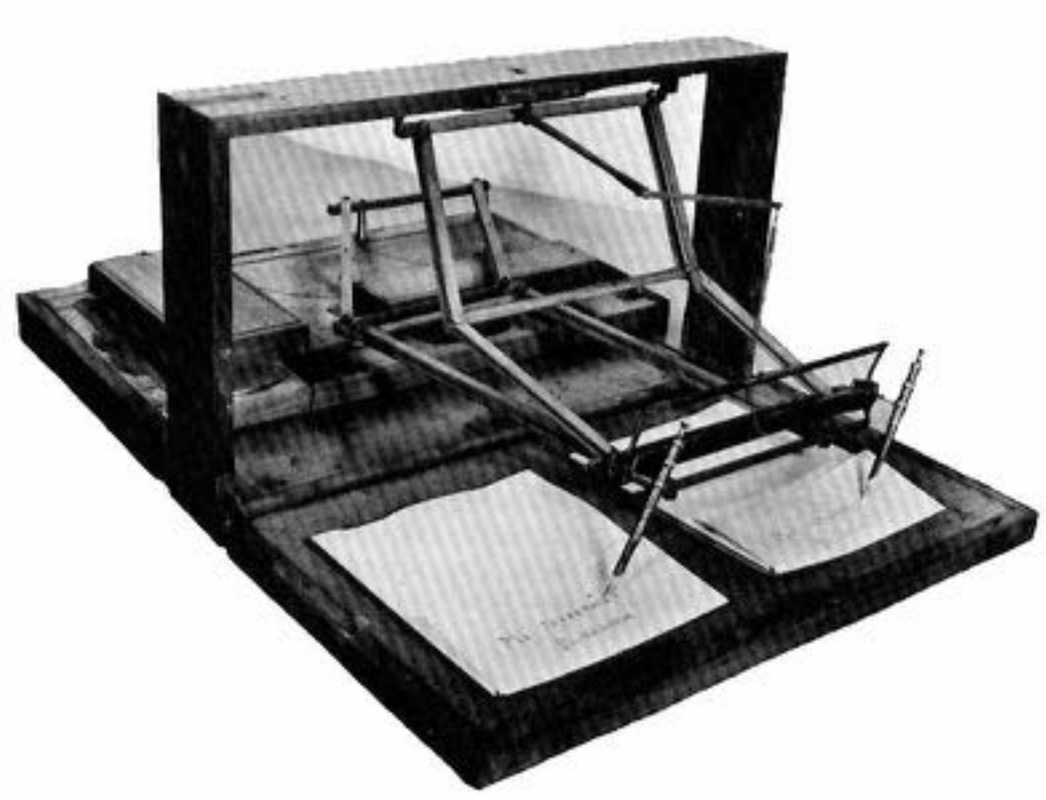
capstan drive

- High force
- Low friction
- Make sure it doesn't slip!

SensAble Technologies

Teleoperation

the genesis of teleoperation?



A Polygraph is a device that produces a copy of a piece of writing simultaneously with the creation of the original, using pens and ink. Famously used by Thomas Jefferson ~1805.

Typically uses a pantograph mechanism: a four-bar linkage with parallel bars such that motion at one point is reproduced at another point

teleoperation history

History:

- First Master-Slave Manipulator: 1948, Ray Goertz, U.S. Atomic Energy Commission
- Goal: protection of workers from radiation, while enabling precise manipulation of materials
- a device which is responsive to another device is termed a "slave" and the controlling device is termed a "master”

At first, mechanical linkages and cables

- 1954: electrical and hydraulic servomechanisms
- 1960s: Closed circuit television and HMDs

these people probably never envisioned robot-assisted surgery

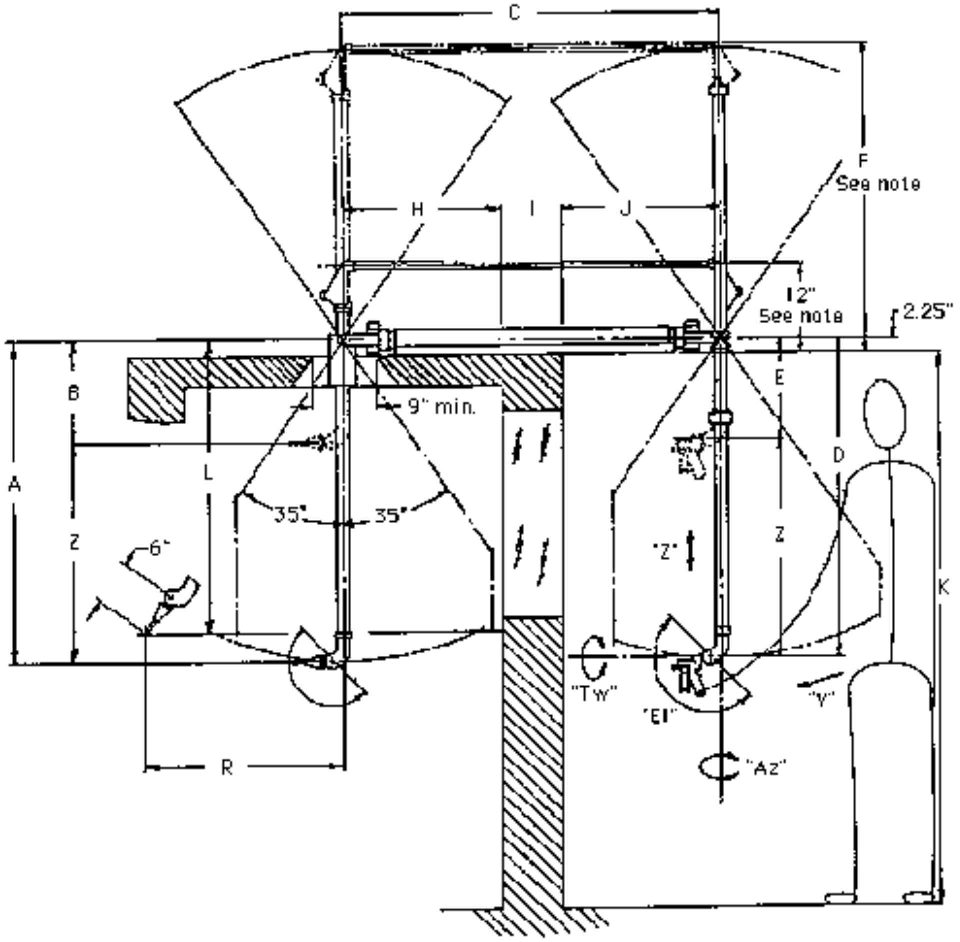
in surgery,
slave robot =
patient-side robot

bilateral control: force/haptic feedback

inherent in “mechanical” teleoperators

forces at the slave end-effector are reflected to the master end-effector

displacements produced at the slave end-effector produce a displacement at the master end-effector



modern telemanipulators

Undersea: exploration and oil acquisition

Space

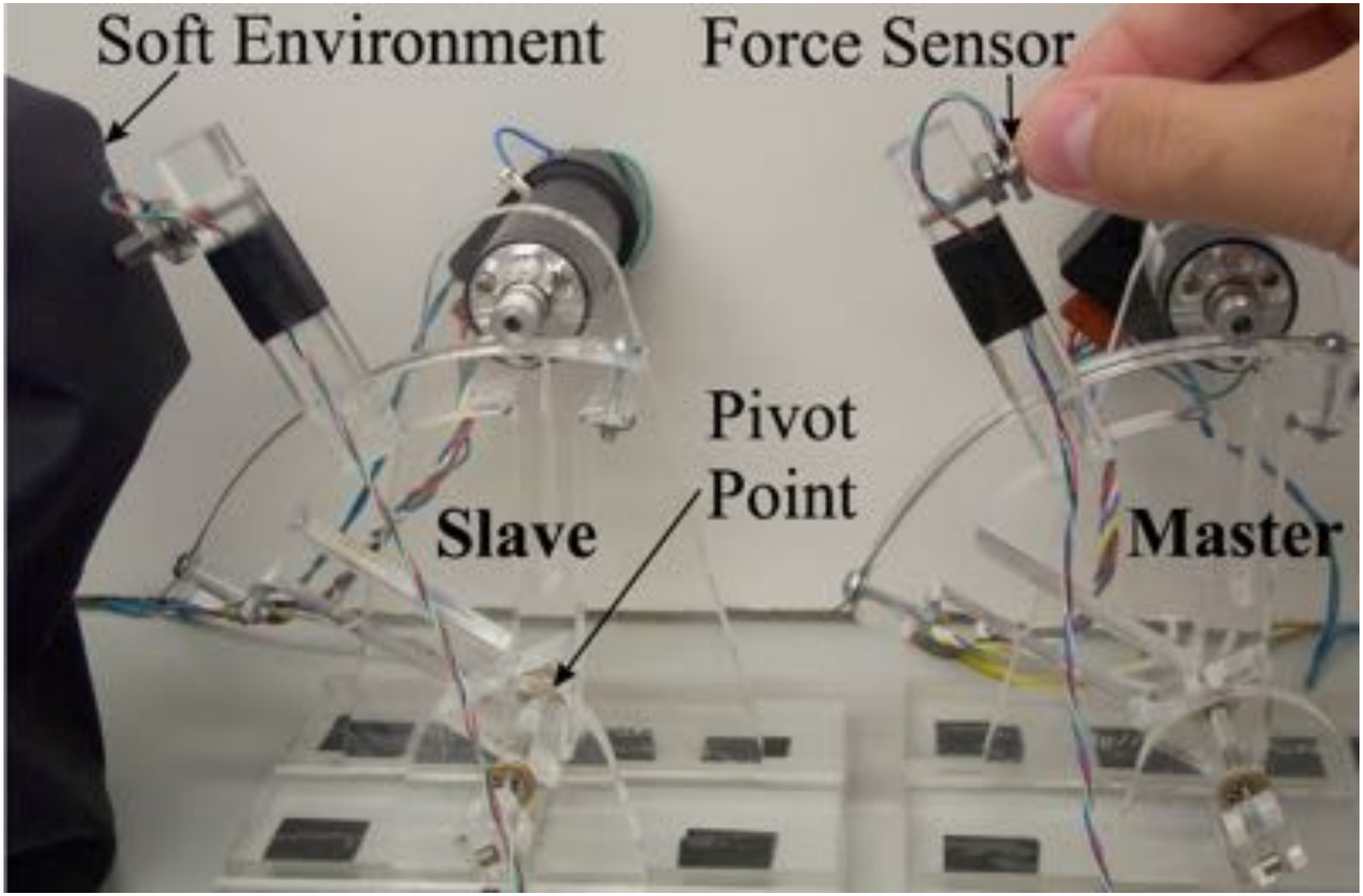
- 1967: Surveyor III landed on the surface of the Moon (a few seconds delay in the two-way transmission to earth of commands and information)
- 1976: Viking spacecraft, landed on Mars was programmed to carry out strictly automated operations
- Shuttle Remote Manipulator System (SRMS): retrieves satellites and place them in the cargo bay; mobile work platform for astronauts during space walks

even more dexterous teleoperation

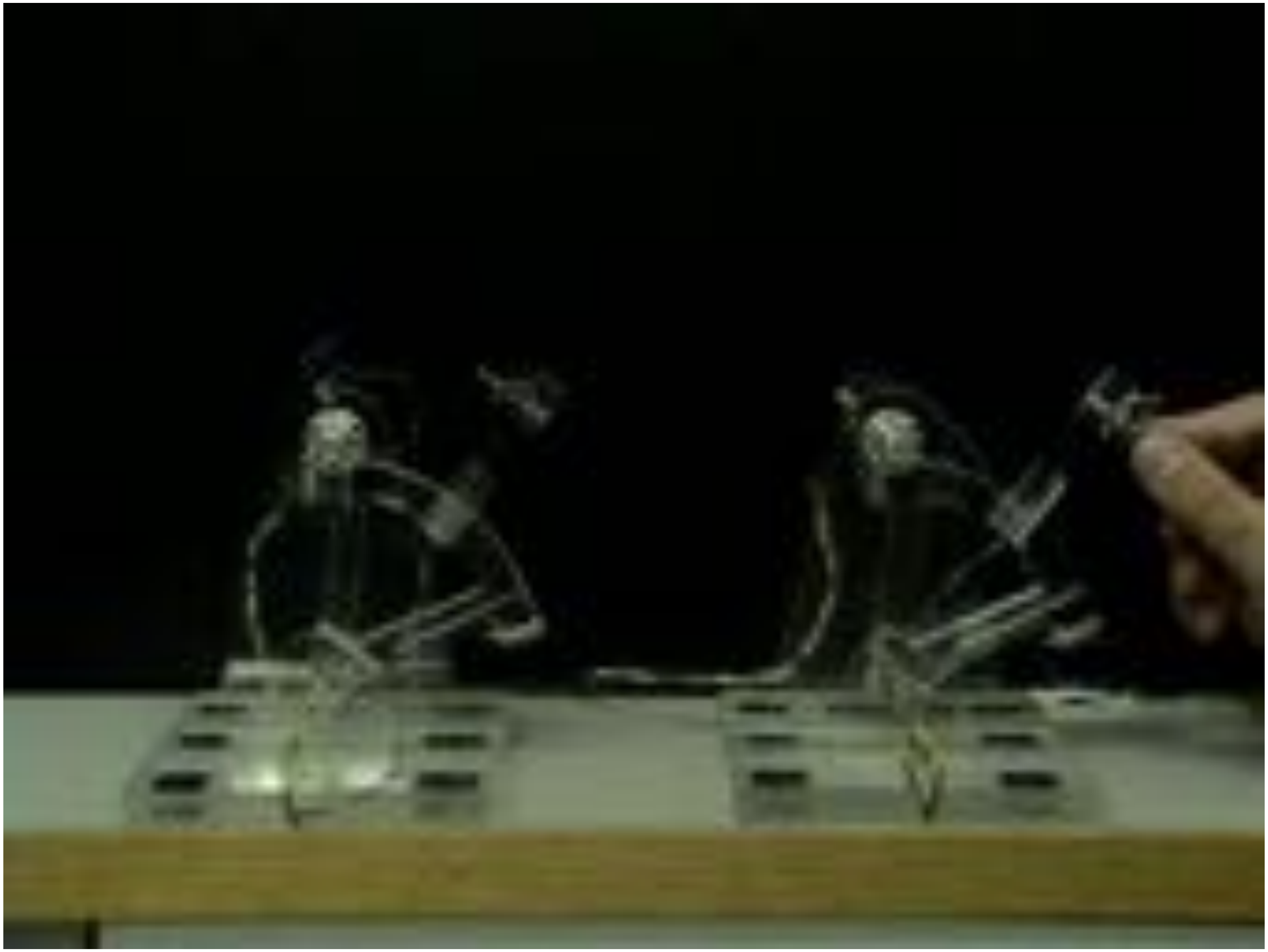
Robonaut

- Robot Systems Technology Branch at NASA's Johnson Space Center
- Purpose: Replace astronauts in dangerous missions, such as space walk, on the space shuttle and/or the space station
- Both autonomous operation and teleoperation are being developed

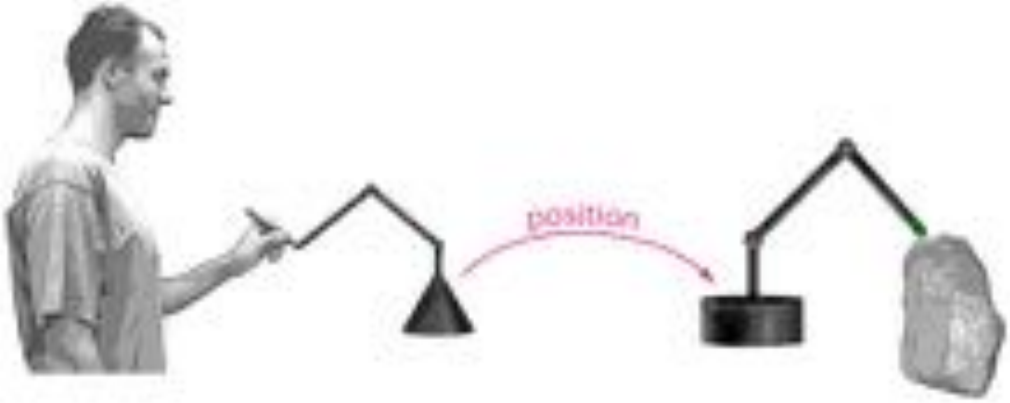
simple system example

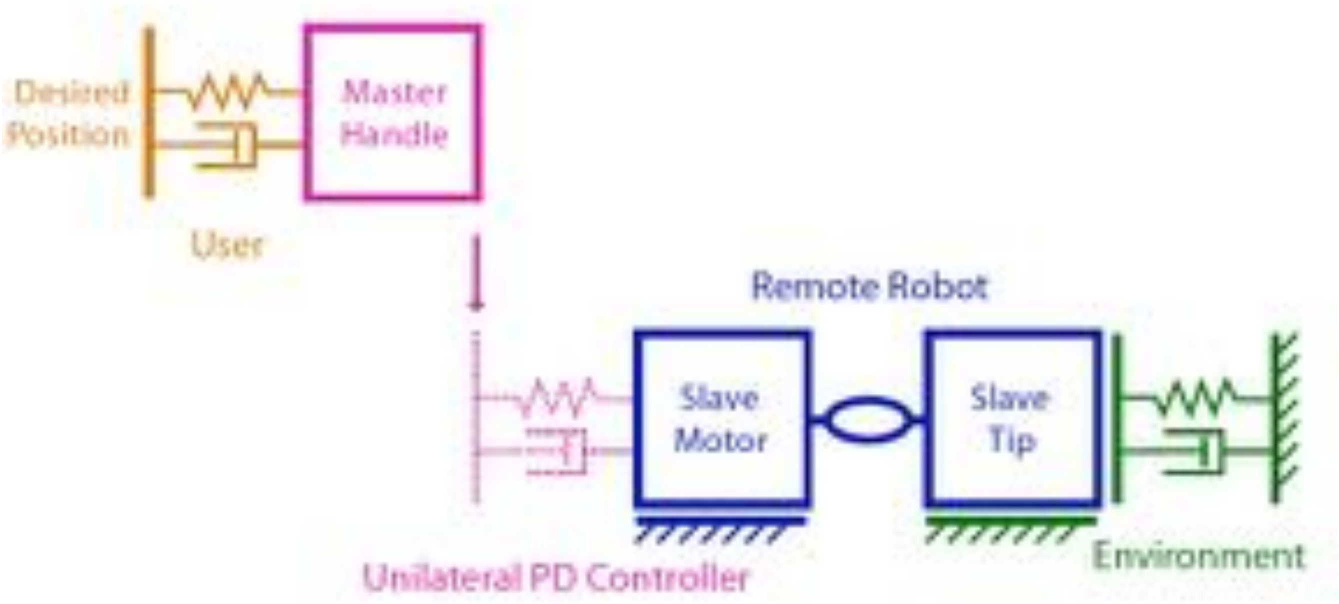


simple system example



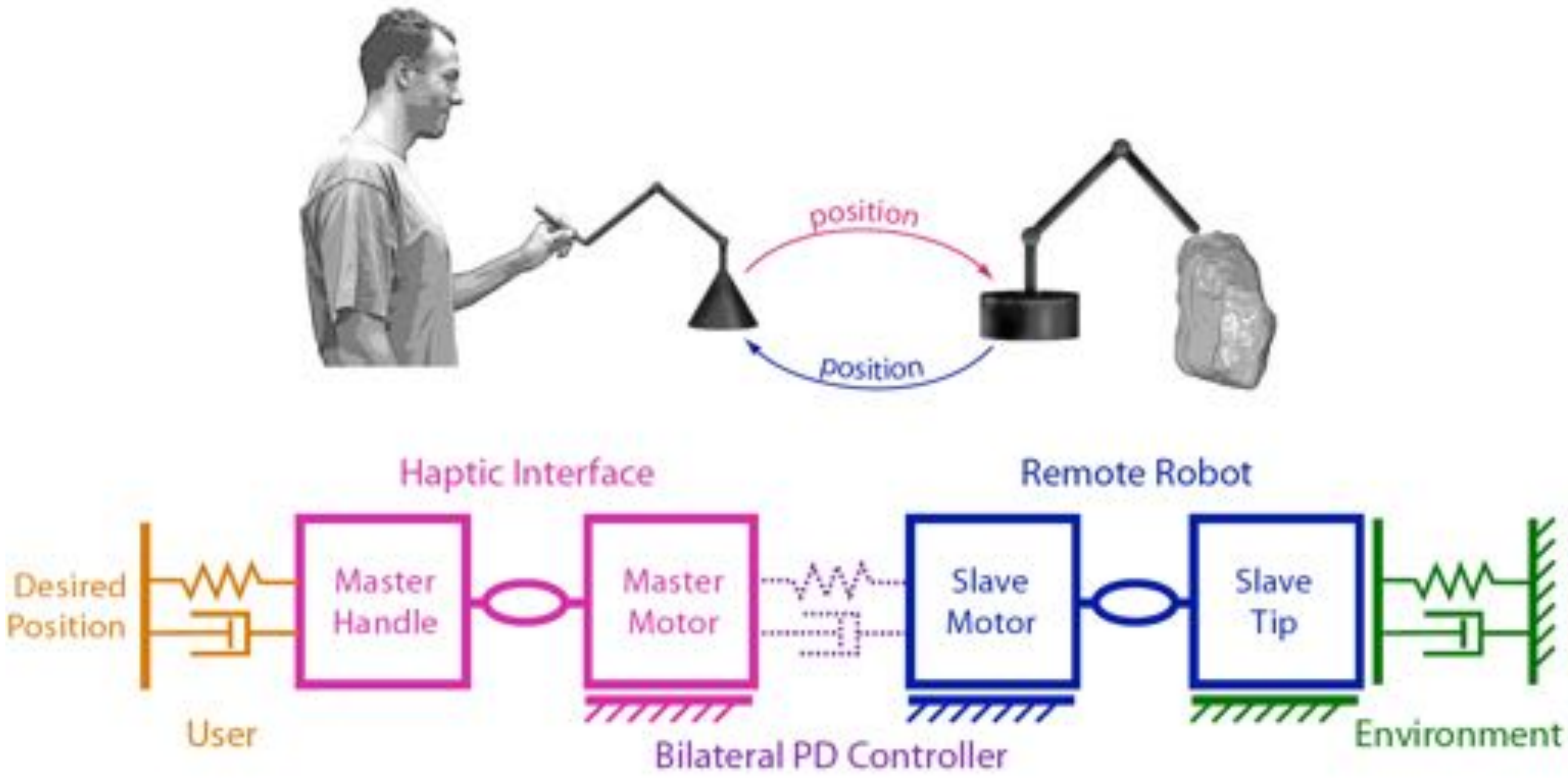
unilateral teleoperator model





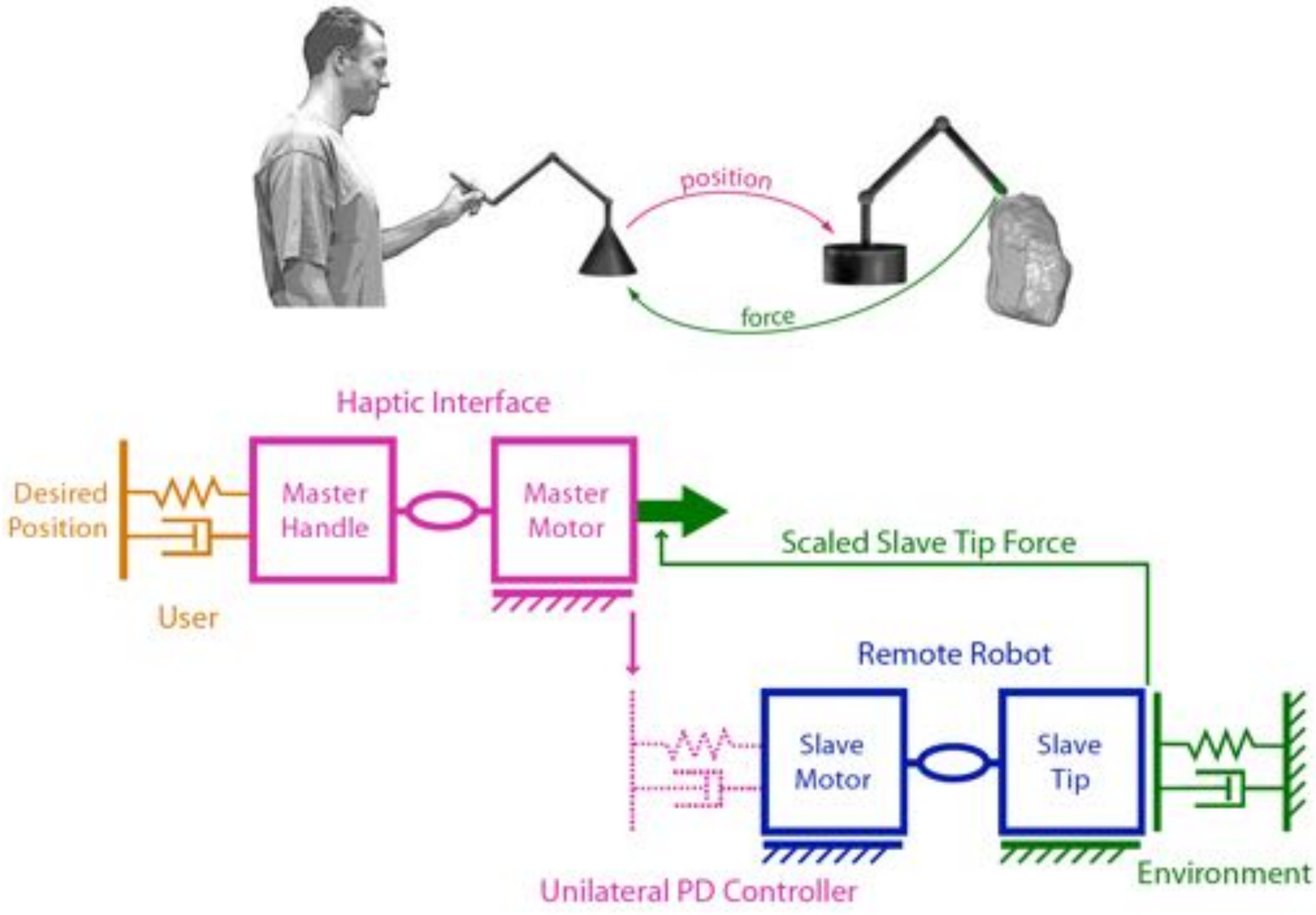
modified from Kuchenbecker Ph.D. Thesis (2006)

bilateral teleoperator model (using position)



from Kuchenbecker Ph.D. Thesis (2006)

bilateral teleoperator model (using force)



from Kuchenbecker Ph.D. Thesis (2006)

typical slave robot controller

this is a proportional-derivative controller, which attempts to make the slave follow the master's position *and* velocity

$$f_{as}(t) = k_{ps}(x_m - x_s) + k_{ds}(\dot{x}_m - \dot{x}_s)$$

$f_{as}(t)$	slave actuator force
x_m	position of master
x_s	position of slave
k_{ps}	slave proportional gain
k_{ds}	slave derivative gain

every time the master's position is recorded, the slave robot attempts to follow the master using this control law

master robot controller for unilateral teleoperation

$$f_{am} = 0$$

$f_{am}(t)$ master actuator force

the force applied by the master actuator
(if it even exists) is zero

master robot controller for bilateral teleoperation (using position)

$$f_{am}(t) = k_{pm}(x_s - x_m) + k_{dm}(\dot{x}_s - \dot{x}_m)$$

$f_{am}(t)$	master actuator force
x_s	position of slave
x_m	position of master
k_{pm}	master proportional gain
k_{dm}	master derivative gain

every time the slave's position is recorded, the master robot attempts to follow the slave using this control law

master robot controller for bilateral teleoperation (using force)

$$f_{am}(t) = f_e$$

$f_{am}(t)$ master actuator force

f_e measured environment force

every time the force between the slave and the environment is recorded, the master robot outputs this amount of force

impedance control

attempts to make the user feel a particular impedance

an assumption often made in analysis/prediction of performance both the master and slave are ideal impedance-type devices:

- linear $f(t) = m\ddot{x} + b\dot{x}$
- no multi-dof coupling
- no nonlinear friction
- no backlash
- infinite mechanical stiffness

questions

motion scaling: why would you want this, and how would you change the control laws to accomplish this?

force amplification: why would you want this, and how would you change the control laws to accomplish this?

questions

what might limit the values of the controller gains that you can choose?

what are the comparative advantages and disadvantages of position- and force-based bilateral teleoperation?

teleoperation performance metrics

tracking

the ability of the slave to follow the master

transparency

(for bilateral teleoperation only)

many definitions, but a popular one is whether the mechanical impedance felt by the user is the same as the impedance of the environment

questions

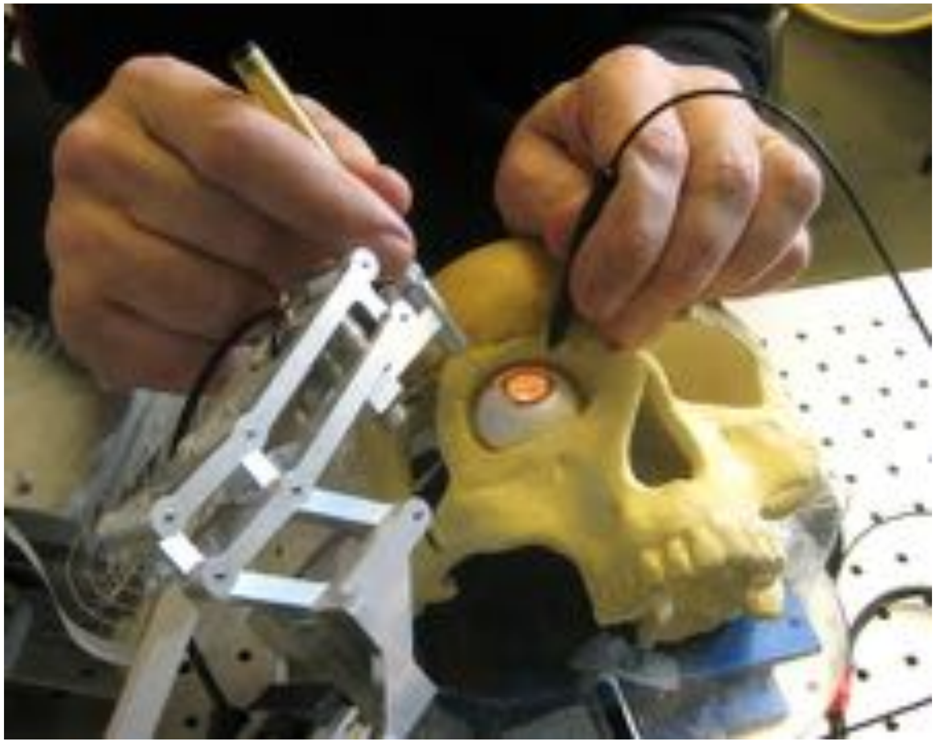
what factors might affect tracking?

what factors might affect transparency?

Cooperative Manipulation

so-called “steady-hand” robots

Mako’s RIO Robotic Arm
Interactive Orthopedic System



JHU Eye Surgery Robot

steady-hand robot behavior

Warning!

If you are sensitive to graphic images/videos of surgical procedures, please step out for about 5 minutes.

MAKO Surgical Robot (makoplasty)

Please bring back
any of our
sensitive friends
who left the room.

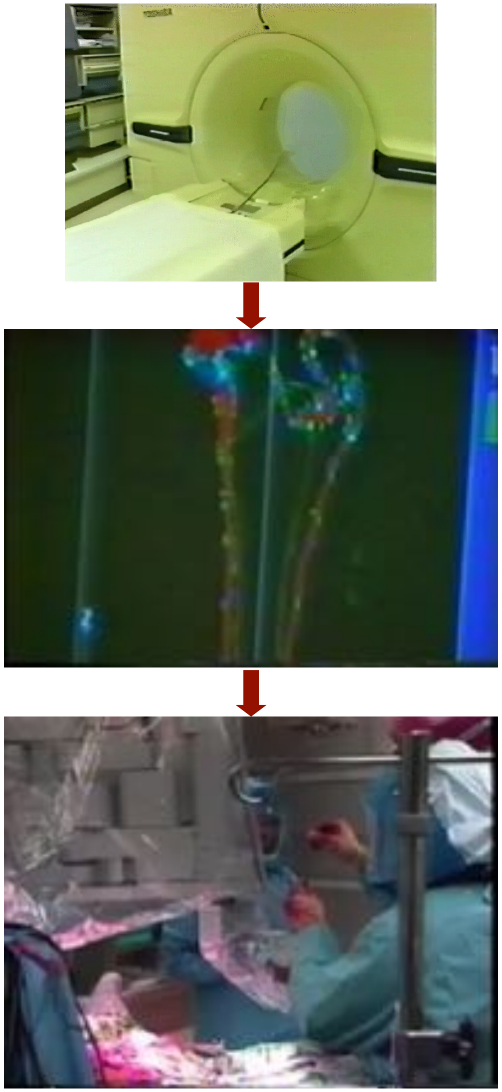
Barrett WAM Arm

The WAM and associated technologies are the basis for the MAKO surgical robot

Robodoc is a similar system (with much more history)

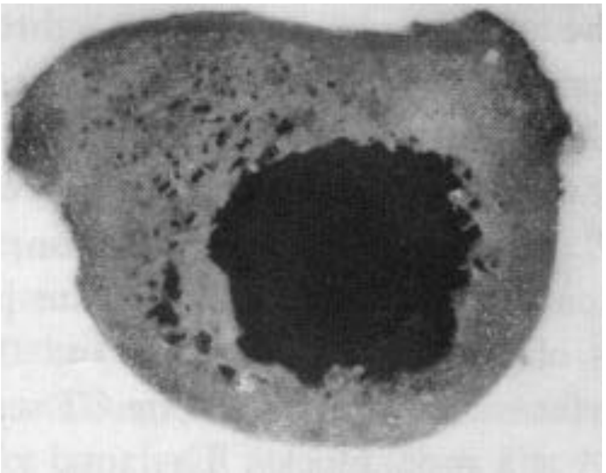
http://robodoc.com/patient_about_history.html

a more “intelligent” surgical system than the da Vinci?

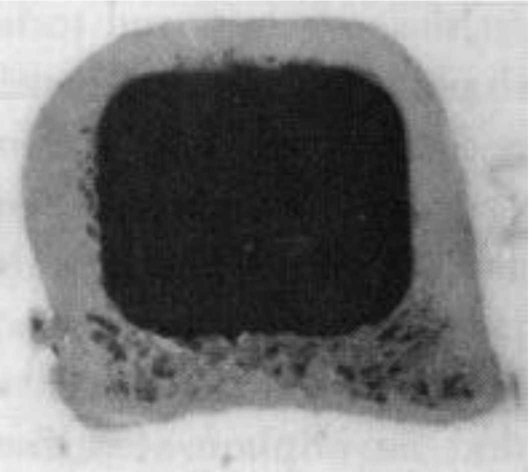


close integration with information systems

more active user assistance



Manual Surgery



Robotic Surgery

admittance control

the user’s applied force is measured, and the robot is controlled to move proportionally to that force

a typical implementation is:

$$\dot{x}_d = k_a f$$

$$f_a = k_p(x_d - x) + k_d(\dot{x}_d - \dot{x})$$

$x_d, \dot{x}_d$	desired robot position, velocity	f_a	actuator force
k_a	admittance gain	$x, \dot{x}$	robot position, velocity
f	force applied by the user (measured)	k_p, k_d	proportional and derivative gains

note: not all cooperative manipulators use admittance control, but many do...

questions

- what happens when k_a is zero?
- how would you create a virtual surface/wall using admittance control?

admittance control

enables very slow, steady motions

is a an excellent underlying control structure for applying "virtual fixtures" to guide motions

can be applied to teleoperators as well as cooperative manipulators

for cooperative manipulation,
it is best used on a very accurate,
nonbackdrivable robot

impedance

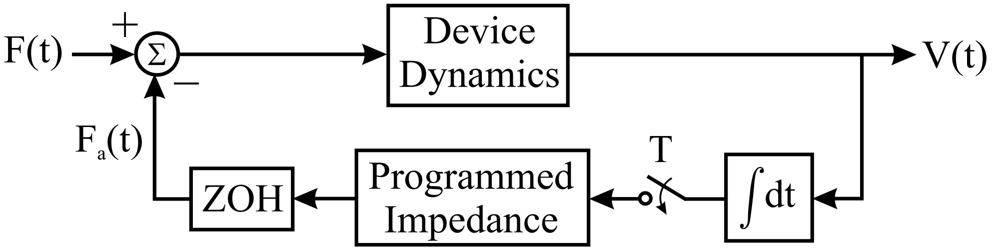
$$F(s) = Z(s)X(s)$$

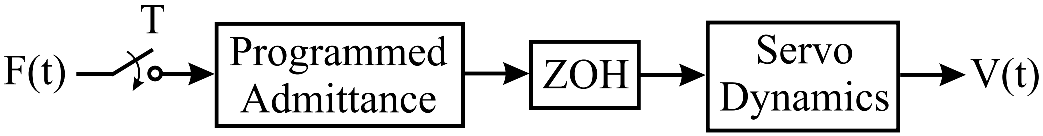
admittance

$$X(s) = Y(s)F(s)$$

dual concepts, just different causality

with implications for practical implementation on robots





questions

- what are some advantages and disadvantages of cooperative manipulation as compared to teleoperation?

- what are some advantages and disadvantages of admittance control as compared to impedance control?