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Medical Robotics

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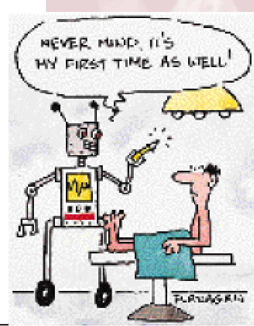
Outline

- Introduction to Robotics
  - Terms and Definitions
  - General Structure of a Robot System
- Medical Robotics - Overview
- Selected Application Examples
- Summary and Outlook



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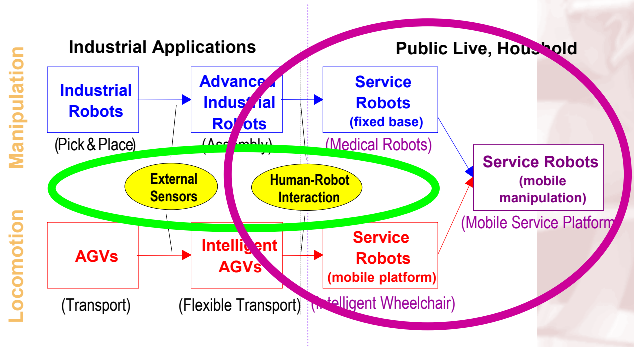
Intelligent Robotic Systems



Terms and Definitions

- **Links and Joints**
  Links are the solid structural members of a robot, and joints are the movable couplings between them

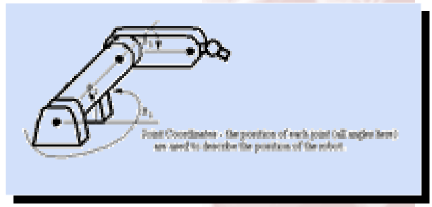
- **Degree-of-Freedom (DOF)**
  Each joint on the robot introduces a degree of freedom. Each DOF can be a slider, rotary, or other type of actuator. Robots typically have 5 or 6 degrees of freedom. 3 of the degrees of freedom allow positioning in 3D space, while the other 2or 3 are used for orientation of the end effector.

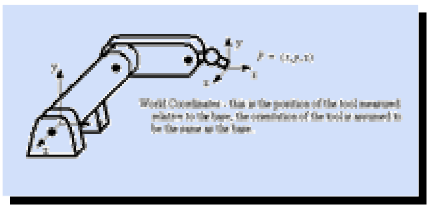
- **Work Envelope, Workspace**
  The work envelope is the boundary of positions in space that the robot can reach. The workspace is defined by the kinematic configuration of the robot (type of DOFs, orientation of joints) as well as by the ROM of each joint.

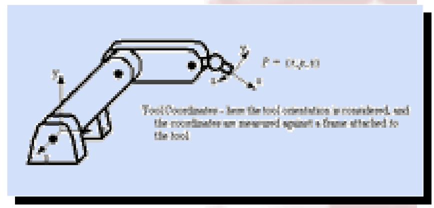
Terms and Definitions

- **Coordinates**

  Coordinates are a combination of both the position of the origin and orientation of the axes







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Terms and Definitions

- **Accuracy**
  - "How close does the robot get to the desired point"
  - This measures the distance between the specified position, and the actual position of the robot end effector.
  - Accuracy is more important when performing off-line programming, because absolute coordinates are used.

- **Repeatability**
  - “How close will the robot be to the same position as the same move made before"
  - A measure of the error or variability when repeatedly reaching for a single position.
  - This is the result of random errors only
  - Repeatability is often smaller than accuracy.

Terms and Definitions

- Accuracy and Repeatability are functions of ...
  - Resolution - the use of digital systems, and other factors mean that only a limited number of positions are available. Thus user input coordinates are often adjusted to the nearest discrete position.
  - Kinematic modeling error - the kinematic model of the robot does not exactly match the robot. As a result the calculations of required joint angles contain a small error.
  - Calibration errors - The position determined during calibration may be off slightly, resulting in an error in calculated position.
  - Random errors - problems arise as the robot operates. For example, friction, structural bending, thermal expansion, backlash/slip in transmissions, etc. can cause variations in position.

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Main Components of a Robot System

- **Mechanical structure (links, base, etc).**
  Required mass to provide enough structural rigidity to ensure minimum accuracy under varied payloads.
- **Actuators**
  Motors, cylinders, etc. that drive the robot joints. This might also include mechanisms for a transmission, locking, etc.
- **Main Controller**
  This computer interfaces with the user, and in turn controls the robot joints.
- **Effector, “End of Arm Tooling”**
  Designed for specific tasks.
- **Handheld Operation Unit, “Teach pendant”**
  Popular method for programming the robot. Small hand held device that can direct motion of the robot, record points in motion sequences, and begin replay of sequences.

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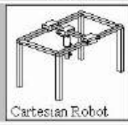
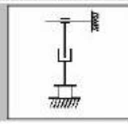
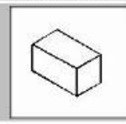
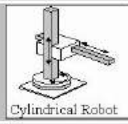
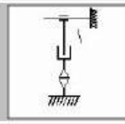
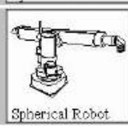
Kinematic Configurations

Roboter	Achsen		Beispiel
Prinzip	Kinematische Struktur	Arbeitsraum	Photo
			
			
			

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Kinematic Configurations

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	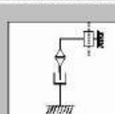		
			
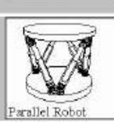			

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Special Configurations for Medical Robotics

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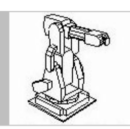
Serial vs. Parallel Kinematik Chain?

Eigenschaften		
Nutzlast / Gewicht	1:10 bis 1:20	1:1 bis 1:2
Kin. Struktur	anthropomorph	kompakt
Steifigkeit	gering	hoch
Intraoperatives Handling	schwierig	einfach
Arbeitsbereich	groß	klein
Genauigkeit	gering	hoch
Positionsfehler	akkumuliert	gemittelt
Technische Komplexität	groß	gering
Verhalten in Singularität	große Bewegungen große Beschleunigungen	große Kräfte

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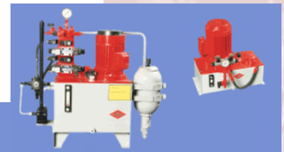
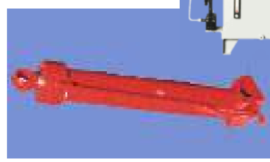
Actuators

- **Pneumatics**
  - Simple, low maintenance
  - Light, least expensive
  - Low payload
  - Noisy operation
  - Compressibility of air → hard to do continuous control



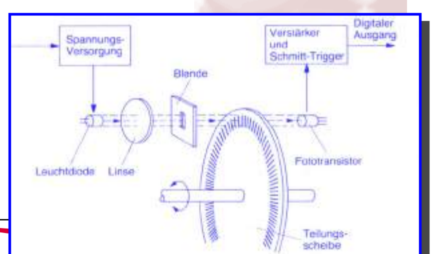
- **Hydraulic**
  - Large payload
  - High power/weight ratio
  - No breaks required
  - Leakage
  - Noisy
  - Thermal influence → position drift



- **Electrical**
  - No significant time delay for control
  - Quiet, clean, safe
  - High rotation speed + small torque → Gears!
  - Low power/weight ratio

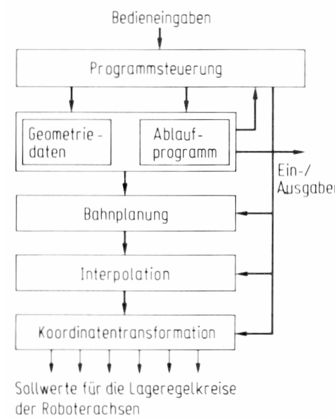
Internal Sensors

- Measurement of current position during programming and execution of movement
- Key factor for robot accuracy
- High bandwidth of speed and acceleration → robustness
- Analog / Digital Sensors
- Relative / Absolute Sensors



Robot Controller

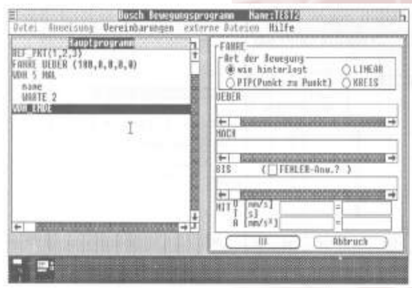
- „Transfers commands into motion“
  - Control of positioning / movement along trajectories
  - Synchronization with external events
  - Reading sensor data and starting appropriate measure
  - Permanent supervision of operating data and movement



Controller Hardware

- CPU
  - **16-bit or 32-bit micro-processor; arithmetic co-processor for trigonometric calculations**
- Memory Unit
- Position Control Modules
  - **Control of position/velocity**
- I/O Components
  - **Exchange of information with auxiliary devices; serial/parallel interface; DI/DO cards; networks (field bus, LAN)**
- Power Supply
- Teach Panel, Handheld Control Unit

Robot Programming



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Safety Regulations IR (EN 775)

Sources of Risks:

- Loss/Malfunction
  at safety system, energy supply, control system, etc.
- Moving mechanical components leading to contusion
- Stored energy
- Energy source
- Human failure
  at design and/or realization, putting into operation, functional check, operation, programming and testing, maintenance

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Safety Regulations IR (EN 775)

Safety Measurements:

- Limitation of Workspace
  - Safety zones
  - Limitation by means of hardware stops or similar measurements
- Reduced velocity
- Fences, etc.
- Emergency Stop
- Safety measurements must be “FAIL SAVE”

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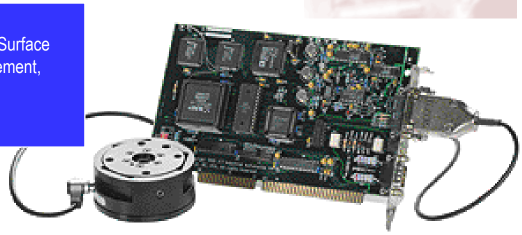
External Sensor Systems

contact

Force/Torque
Gripping/Tooling force, Trajectory Adaptation

Tactile
Switch, Surface measurement, Slipping



non-contact

Video-optical
2D-image processing (binary, grey tone), 3D-image processing, Active illumination

Distance
1D / 2D / 3D-Scanner, Sheet-of-light measurement, Photo sensor

Ultrasound
Proximity switch, Distance measurement

Inductive, capacitive magnetic
Proximity switch, Distance measurement

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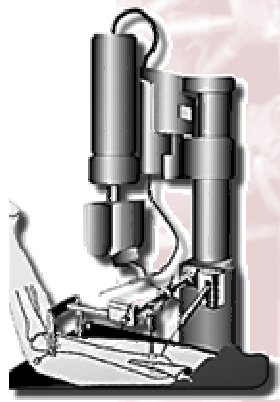
Industrial robots for medical Applications?

- Major design criteria IR:
  Working envelope ⇧, Velocity ⇧
- SEVERE modifications for system safety
  <u>(not only SW!)</u>
- Application Example:
  Orthopedics, Radiation Therapy



➔ special design for medical Applications!

- Major design criteria :
  SAFETY ⇧
- Velocity, working envelope ⇩
- Special kinematic designs
  („mechanical constraints“)

Problems to be solved ...

- **Mechanical Design**
  - Design for ACCURACY rather than repeatability
  - „Shared Control“ → backdrivable robot systems
  - Sterilization
  - Compatibility to intra-operative imaging!!!!!
  - Accessibility
- **Sensors, Control**
  - Master-Slave
  - New advanced sensor systems (nano-sensors) !!!!!
  - „Shared Control“, automation of routine operations (e.g. suturing)
  - (active) compensation of tissue movement (models for tool/tissue interaction)
  - „Visual servoing“

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Medical Robotics - Applications

- **Robots for Laboratory:**
  Pipetting, hit picking, etc.; PROs: repeated operation at high speed with high accuracy – without tiring
  → saves time & costs

- **Robots for Hospital Logistics:**
  Transport tasks at hospitals (medicine, food, laundry, ...) - discharges (high specialized) nurses from those tasks;
  - Transfer of patient (“patient handling robots”) –
    → e.g. support of nurses

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Medical Robotics - Applications

- **Robots for Rehabilitation:**
  Providing handicapped people higher degree of autonomy and mobility. “Assistive Devices”. Stationary robot systems (simple handling tasks) and/or mobile robot systems (autonomous wheelchair). Robot for post-stroke therapy!!!

- **Robots for Diagnosis/Therapy, “OR-Robots”:**
  Assistance during surgical intervention - (more or less) guided by robot control;
  PROs: precision, reliability, time reduction;
  CONs: extensive planning, costs ???

Types of Interaction

- Autonomous Procedures
  - Examples: THR/TKR, radiation therapy
- Interactive / Robot“assistant“
  - Robot and surgeon „share“ control („shared control“)
  - „Hands-on“ systems, „active constraints“-methods
  - Examples: Milling and/or cutting procedures in orthopaedics
- Explicit control by surgeon („Master-Slave“)
  - Supporting at minimal-invasive interventions
  - „Tele-Operation“, „Tele-Presence“

Robots for Autonomous Procedures

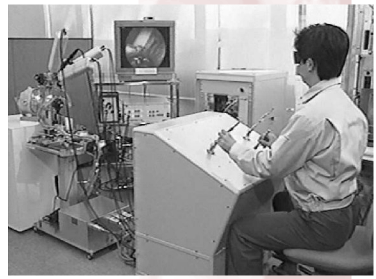
- Once positioned by a surgeon, robot removes tissue automatically
- Lack of direct surgeon involvement
- Problems with intra-operative tissue motion
- Examples: ROBODOC, CASPAR, CyberKnife

„Hands-On“ - Systems

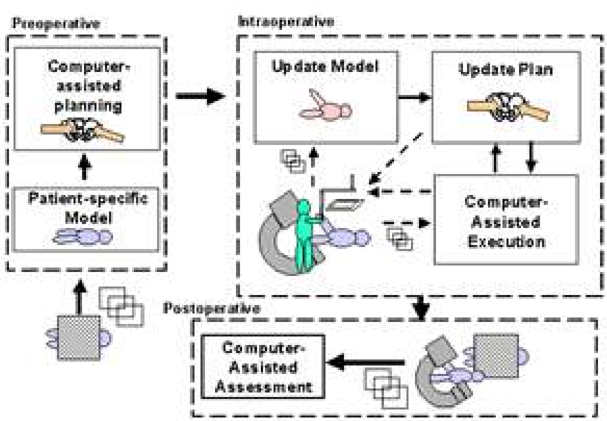
- Force - controlled joystick on end of robot; Surgeon moves joystick, back-driving under servo- assist
- Robot constrains within a pre-op plan: Surgeon judges, senses, adapts - a good synergy
- Special requirements for robot design (low impedance, no brakes, back-drivable, etc.)
- New type of surgery robot
- Example: „ACROBOT“

Master/Slave - Telemanipulation

- Generally Master near to patient in O. R. – but not “hands- on”
- Generally little tactile information
- Uses high quality imaging
- Motion scaling of Master to Slave is possible
- Examples: Zeus, daVinci



“Computer Aided Surgery” - CAS



Source: ERC-CISST / JHU

Surgical CAD/CAM

- "Surgical CAD“
  is analogous to computer-aided design in manufacturing systems. Preoperatively, medical images, anatomical atlases, and other information are combined to make a model of an individual patient. The computer then assists the surgeon in planning and optimizing an appropriate intervention.
- "Surgical CAM“
  is analogous to computer-aided manufacturing. The data from the preoperative planning step (images, models, plan geometry, etc.) is all brought into the operating room. Real time images and other sensor data are used to "register" the preoperative plan to the actual patient, and the model and the plan are updated throughout the procedure. The actual surgical procedure is performed by the surgeon with the assistance of the computer.
- "Surgical TQM“
  is analogous to "total quality management" in manufacturing, and reflects the important role that the computer can play in reducing surgical errors and in promoting more consistent and improved outcomes. It is built into the entire process.

Medical Robotics vs. „Augmented Reality“

- Why to use a robot? Is „Augmented Reality“ a better choice?
- Are there any advantages from the use of a robot which justify the higher cost / complexity?
- Who is in charge?
- Clinical acceptance?

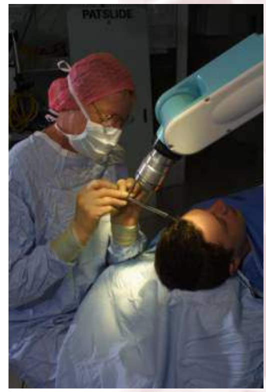
Clinical Applications

- Neurosurgery
  - Frameless stereotactic applications ➔ high spatial accuracy and precise targeting
- Orthopedic Surgery
  - THR, TKR, spine interventions ➔ autonomous procedures due to rigid nature of bone
- General and Thoracic Surgery
  - Camera holder for laparoscopic surgery
  - Active instruments
  - Percutaneous interventions

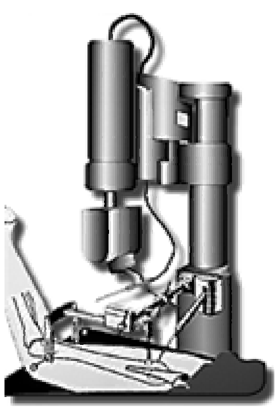
PathFinder: Armstrong Healthcare, Ltd.

- Precise „localizer“ for neurosurgery - positioning of surgical instruments along pre-defined trajectory
- Removes the need for a stereotactic frame and its associated calculations; robot serving as a precision tool localizer
- Head supported by standard Mayfield clamp during surgery, in any convenient position
- Automatic registration of images and patient
- DICOM3 Interface for CT und MR data

PathFinder: Armstrong Healthcare, Ltd.



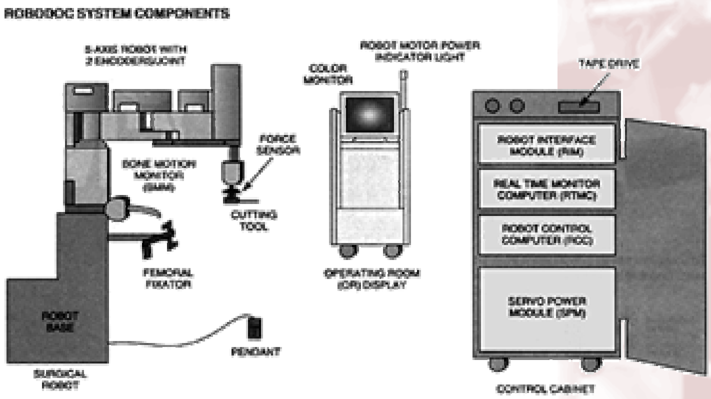
ROBODOC: Integrated Surgical Systems Inc.



- Components: Planning workstation (OrthoDOC), robot, control system
- Target: Cementless implantation → natural bone growth into implant → long-term improvement of implant fit

→ Robotic system for precise cutting of the femoral cavity

ROBODOC: Integrated Surgical Systems Inc.



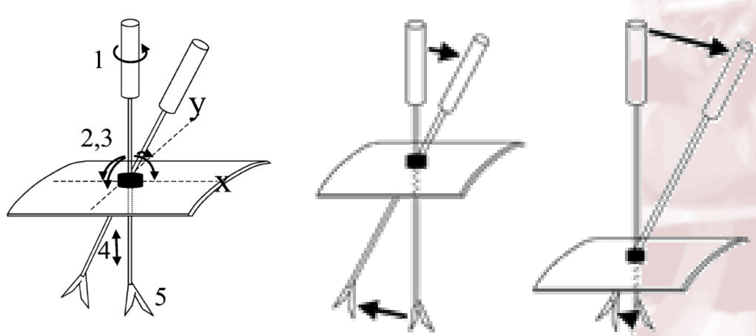
ROBODOC: Integrated Surgical Systems Inc.

- Implanting of three locator pins in hip
- CT scan → transfer to OrthoDOC
- Planning of the implant (size, position, etc.)
- Calculation of the cutting procedure → transfer to robot controller
- Exposing hip joint
- Registration robot – patient
- Autonomous cutting; surgeon monitors process

Laparoscopic Surgery -- Problems

- MIS: advantages for patient, but challenge for surgeon
  - Working with long instruments via small incisions
  - Incision acting as pivot point for tools
  - Reduced degrees-of freedom → limited dexterity
  - Variable scaling of movement
  - Unnatural hand-eye coordination (mirrored movements)
  - No real 3D-vision
  - No (bad) tactile feedback

Laparoscopic Surgery -- Problems



AESOP (Automated Endoscopic System for Optimal Positioning)

Computer Motion Inc.

- Speech-controlled robot serving as camera holder
- Fast, easy setup at OR (about 5 minutes)
- 23 commands available
- Additional robot control: Hand- and footswitch
- Storing/Restoring of particular positions

daVinci: Intuitive Surgical, Inc.

- Master-slave system for minimally invasive surgery
- Initial clinical application: cardiac surgery
- Components: Surgeon‘s console, control unit, three-arm surgical robot
- High resolution 3D image for surgeon
- Additional DOF at surgical instruments („EndoWrist“)
- „Motion scaling“, tremor filter, „Indexing“
- Current research: Force-Feedback

daVinci: Intuitive Surgical, Inc.

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„B-Rob I“ – Percutaneous Interventions

- 4-DOF gross positioning stage
- 3-DOF fine positioning stage for secure and precise needle angulation
- Robot control system with dedicated safety features
- Dedicated hardware interface “UI”
- Navigational software “ROBUST” to define needle trajectory and to monitor robot position during intervention
- Optical tracker (NDI Polaris™)

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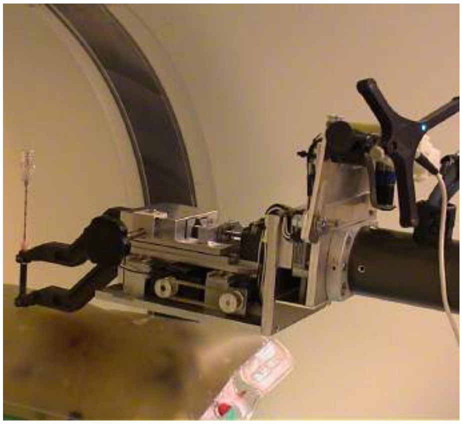
CT-guided Bx Procedure - Setup



New Development – „B-Rob II“

Safety of Medical Robot Systems

Compared to IR Systems ...

- People (patient, physician) INSIDE working area of robot
  - Additional REDUNDANT sensor systems
  - Design of special purpose robot systems (mechanical constraints)
  - Adequate, customized functionality of the robot system
  - Fail-save techniques
  - Sterilization, infection control!!
  - USER INTERFACE!!!!!!
- Non-generic applications
  ➡ **TESTS, SIMULATION**

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Medical Robotics - Disadvantages

- ☹ More costly / complex than alternatives, e.g. Computer Aided Surgery
- ☹ Is the robot safe?
- ☹ Who is in charge?
- ☹ Not able to make own decisions
- ☹ Limited flexibility
- ☹ (Currently) not able to deal with intra-operative tissue movement

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Medical Robotics - Advantages

- ☺ More accurate than manual (esp. complex trajectories and/or exact positioning in 3D)
- ☺ Minimally invasive
- ☺ Robot guides / constrains (safer?)
- ☺ Consistent quality
- ☺ Repetitive motions without tiring
- ☺ History of motions recorded
- ☺ Small movements with small forces (scaling)
- ☺ „Indexing“
- ☺ Sterilisation, resistant against germs/radiation etc.

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Major Acceptance Issue

Robots will be successful ONLY if they

→ improve patient outcome,
→ lower cost,
→ or both!!!

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