Institute for Process Control and Robotics (IPR)

URL: http://wwwipr.ira.uka.de

1. Introduction

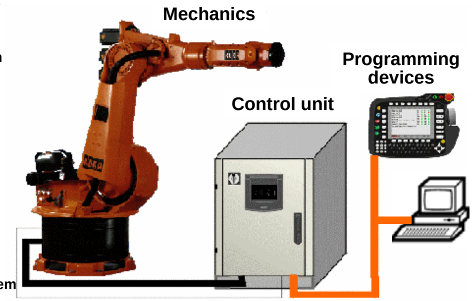
Common definitions of robots

- An **industrial robot** is an automatically controlled, **freely programmable moving mechanism** with **three or more axes**. Its purpose is to grasp and/or move objects for **industrial production of goods**.
- A service robot is a **freely programmable moving mechanism**, which performs semi or fully automated **service tasks**.
- An **autonomous medical robot** is an automatically controlled **freely programmable moving mechanism**. Its purpose is to handle tools / grippers in the medical field (operating theatre) with the goal of performing diagnosis and therapy at the human being.
- A **telemanipulated medical robot** is a robot (usually with several arms), which is controlled by the surgeon in “tele mode”. Its purpose is to handle tools / grippers in the medical field (operating theatre) with the goal of performing diagnosis and therapy at the human being.
- **The semi autonomous mode** of robots represents a modus, in which a robot is **controlled** directly **via contact with the operator** using automatic control technical methods.

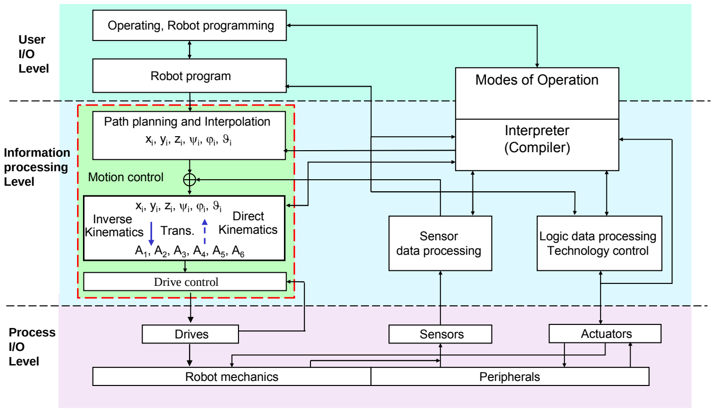
Characteristic components of an autonomous medical robot

Characteristic components of robots

- ***Mechanics, Kinematics***
  - **Drive configuration**
  - **Measurement system**
  - **Materials**
- ***Control***
  - **Control unit**
  - **RC-Control**
  - **Drive unit**
  - **Teach pendant**
  - **Interfaces**
  - **Software**
    - **Operating system**
    - **Robot functions**

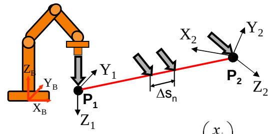


Information flow of an autonomous Robot Control (RC)

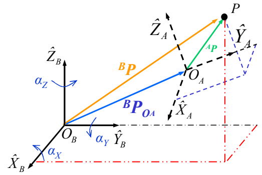


Pose and frame

Frame represents poses and TCP´s of an object with 6 dof.
Frame = 4x4 matrix = Relation between two coordinate systems = pose of a coordinate system (B), relative to another coordinate system (A)



$$ {}^B F_A \triangleq \begin{bmatrix} R_{3\times3} & P_{3\times1} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} \cong \begin{pmatrix} x_i \\ y_i \\ z_i \\ \varphi_i \\ \theta_i \\ \psi_i \end{pmatrix} $$

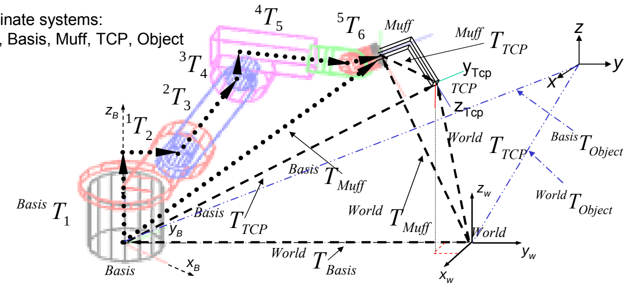


$$ {}^B P = {}^B F_A \, {}^A P $$

Poses P_i are represented as frames related to the robot base B coordinate system. A pose has 6 components according to 6 dof.
Rotation and Translation of poses are performed via a homogenous matrix (frame) multiplication

Coordinate systems and Frame arithmetic in Robotics

Coordinate systems:
World, Basis, Muff, TCP, Object

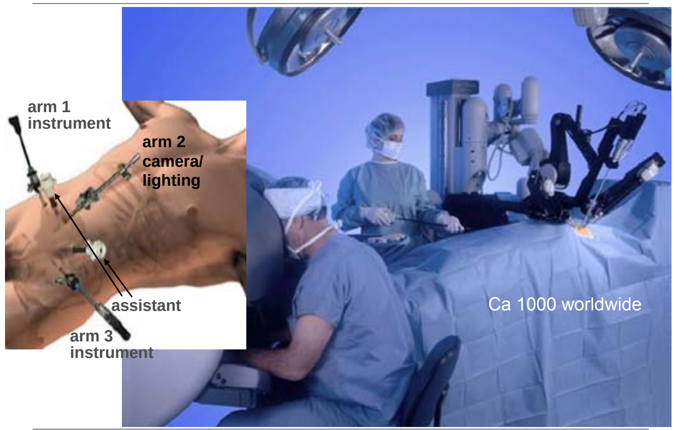


$$ {}^{World}T_{TCP} = {}^{World}T_{Basis} \cdot {}^{Basis}T_{TCP} $$

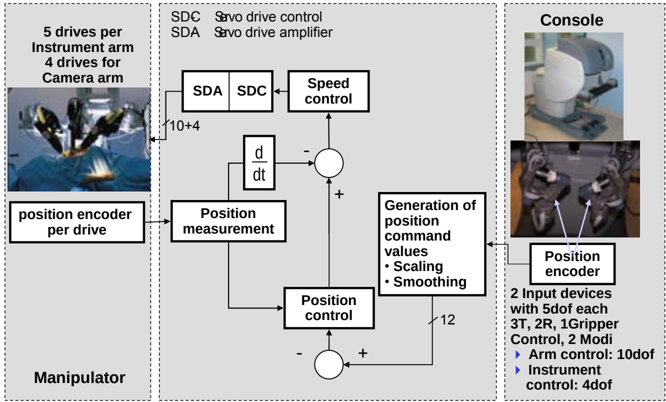
$$ {}^{World}T_{TCP} = {}^{World}T_{Basis} \cdot {}^{Basis}T_1 \cdot {}^1T_2 \cdot {}^2T_3 \cdot {}^3T_4 \cdot {}^4T_5 \cdot {}^5T_6 \cdot {}^{Muff}T_{TCP} $$

$$ {}^{World}T_{Basis} = {}^{World}T_{TCP} \cdot \left({}^{Basis}T_{TCP}\right)^{-1} $$

Teleoperated medical robot daVinci for MIS

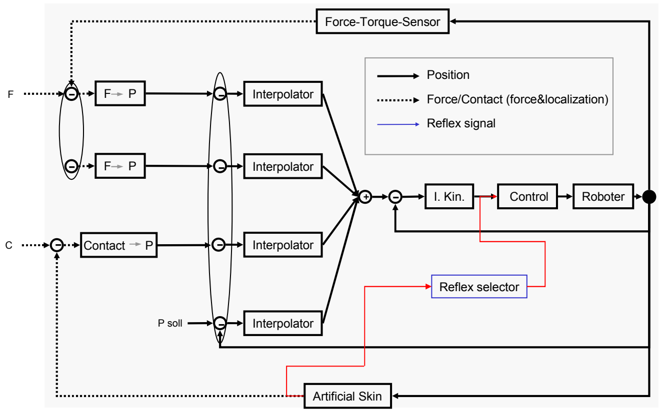


Simplified control of a telemanipulator



Semi autonomous mode - Force controlled robotic system Kinemedic

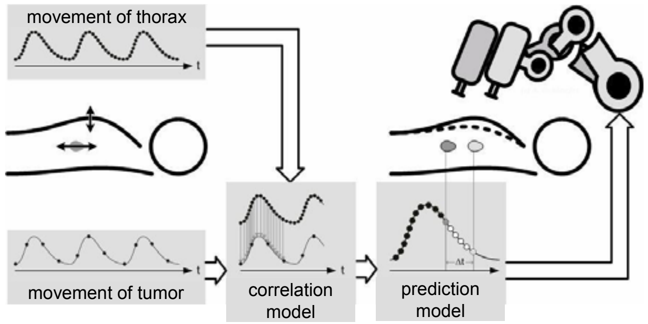
Semi autonomous mode – Force controlled robot control



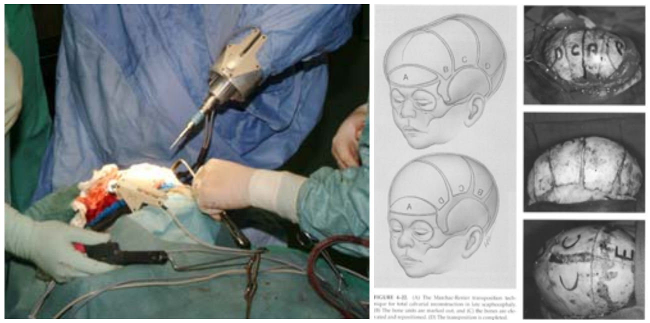
2. Robot assisted Surgery with program controlled autonomous robots

Autonomous medical robot Cyberknife

Research: Motion compensation

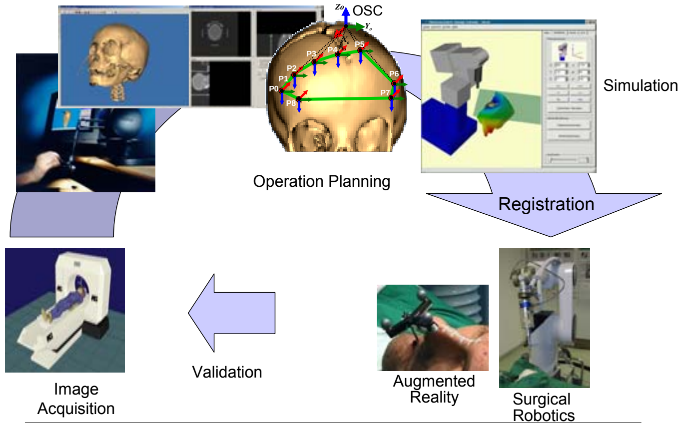


Autonomous Robots for Osteotomy (IPR)



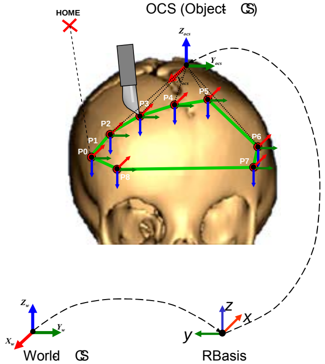
RobaCKa

Computer- and Robot- Aided Head Surgery-Workflow (IPR)



Transfer of the planned Trajectory to a robot program (IPR)

The robot points are represented relative to an object coordinate system, which is located at the head of the patient




```
PTP HOME  ;Home position
PTP P0    ;P0={x-100, y 100, z 0, a 0, b 90, c 0}
          ;Start position on bone surface
LIN P1    ;P1={x-100, y 100, z-10, a 0, b 90, c 0}
          ;Move into bone z 10
LIN P2    ;P2={x-120, y 120, z-10, a 0, b 90, c 0}
LIN P3    ;P3={x-150, y 155, z-10, a 0, b 90, c 0}
:
:
LIN P8    ;P8={x-20, y 125, z-10, a 0, b 90, c 0}
LIN P1    ;Move out z=0
LIN P0    ;Back to start position
PTP HOME
```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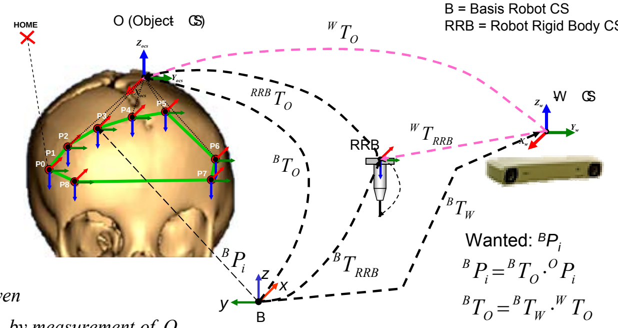
Registration (IPR)

W = World
CS = Coordinate System
B = Basis Robot CS
RRB = Robot Rigid Body CS



Wanted: $^{B}P_i$

$$^{B}P_i = {}^{B}T_O \cdot {}^{O}P_i$$

$$^{B}T_O = {}^{B}T_W \cdot {}^{W}T_O$$

$$^{B}T_W = {}^{W}T_{RRB} \cdot {}^{B}T_{RRB}^{-1}$$

Given

$^{W}T_O$ *by measurement of O*

$^{B}T_{RRB}$, $^{W}T_{RRB}$

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Patient registration with markers (IPR)

Preoperativ marker (4screws) identification:

Monitoring and localization with a navigation system

Intraoperativ marker identification:

Least-squares fitting

With the help of the markers the actual object coordinate system of the patient in the OR is calculated

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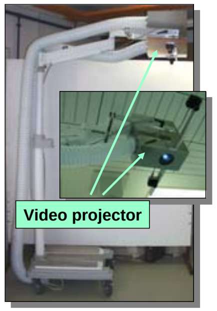
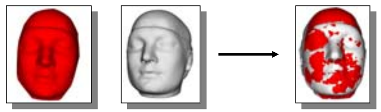
Alternative non-invasive, markerless registration with surface matching (IPR)



OR prototype

Scan with coded light approach and registration with surface matching:



Scan **CT/MRT**

Tracking with a dental adapter:

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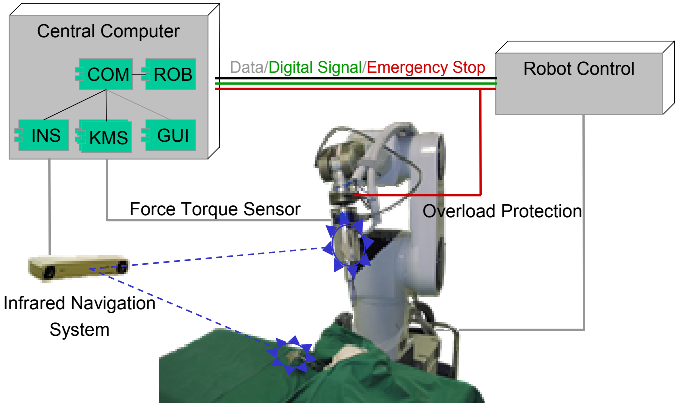
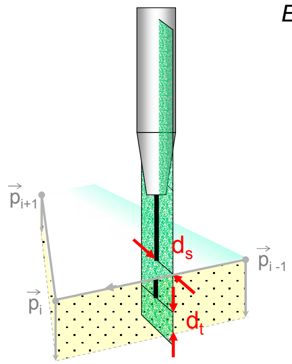
Assistive Robot System *RobaCKa* (IPR)



Monitoring to get a high safety (IPR)



Exact cutting of trajectories

- Surgeon
  General surveillance
- Force torque sensor
  feed control
  monitoring of limits
- Infrared navigation system
  lateral deviance d_s
  deviance in depth d_t

Clinical Evaluation of the Surgical Robot (IPR)

Autonomous Medical Robot for precise drilling for Cochlea Implantation (IPR)

Advantages of future bone cutting methods for robots (IPR)

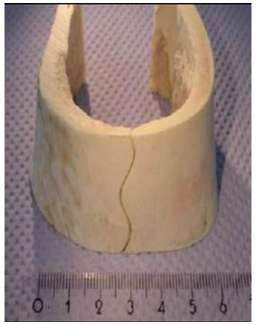
Milling:

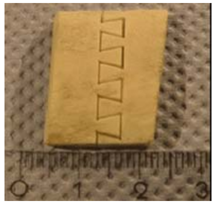
- Force control
- Bone meal

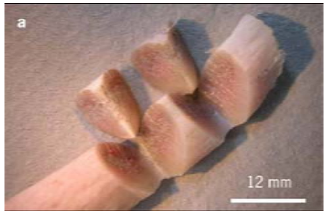
Laser:

- No forces
- No vibrations
- No necroses
- No metal attrition
- Less loss of bone
- Finer cuts

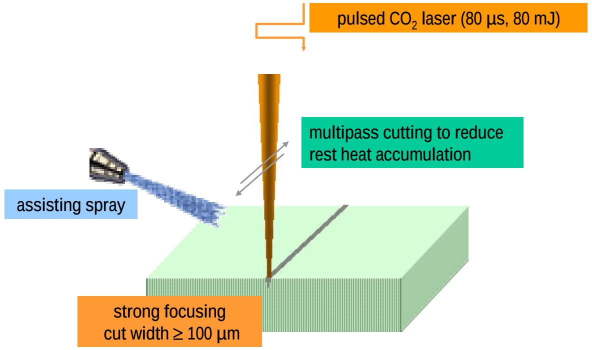
New Cutting Opportunities with Laser (IPR)







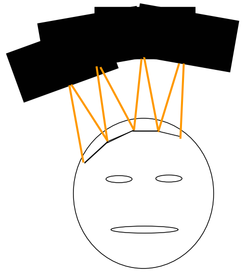
CO_2-Laser cutting (IPR)



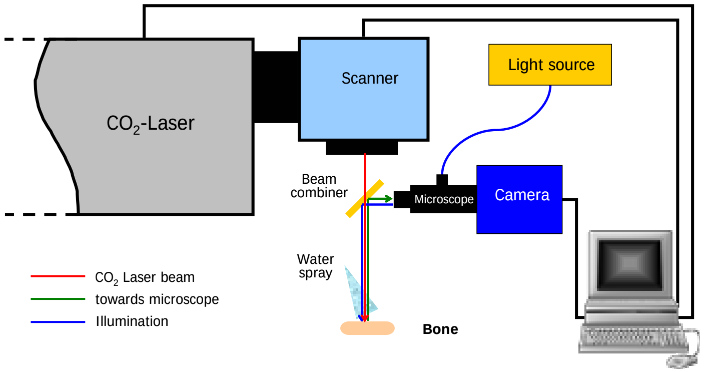
Robot with Laser (IPR)

Experiments (IPR)

Repositioning of Scanning Head (IPR)

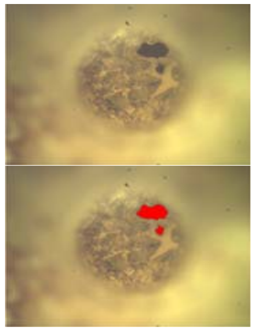


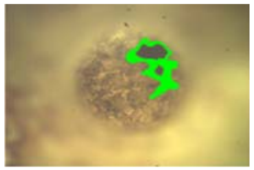
New Vision control method for laser ablation (IPR)



Visual detection of the membrane for Cochleostomy (IPR)

- Automatic detection of the areas of break through (red) (fast marching algorithm)
- Challenge: additional detection of the membrane (green)





Conclusion (IPR)

- Laser superior to conventional drilling
- Only useful with *robot guided* laser and a beam scanning head

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Orthognathic surgery for the correction of Dentofacial skeletal irregularities with an autonomous robot (IPR)

- Today: Experience for repositioning the bone segments to create a good outlook of the patient, manual measurements
- Idea: Assistive robot system for holding the bone segments in the preplanned position during fixation procedure
  1. Acquire initial and target position of the maxilla in the articulator
     - Store relative transformation
  2. Build individual maxillary splint from light curing resin (leicht aushärtendes Harz)

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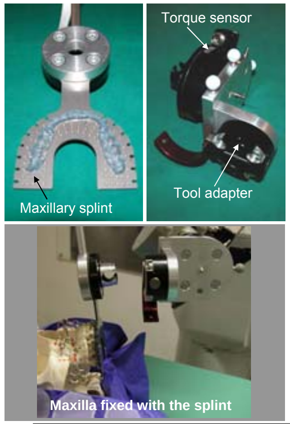
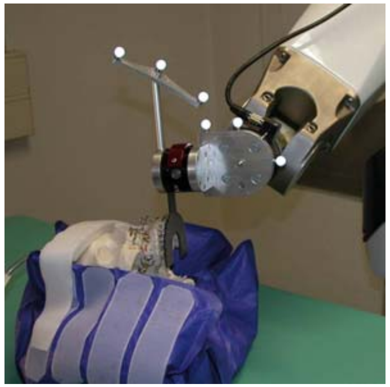
Developed devices for orthognathic surgery (IPR)





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Robot Assisted Fracture Reduction (TUB/IRP) with an autonomous robot

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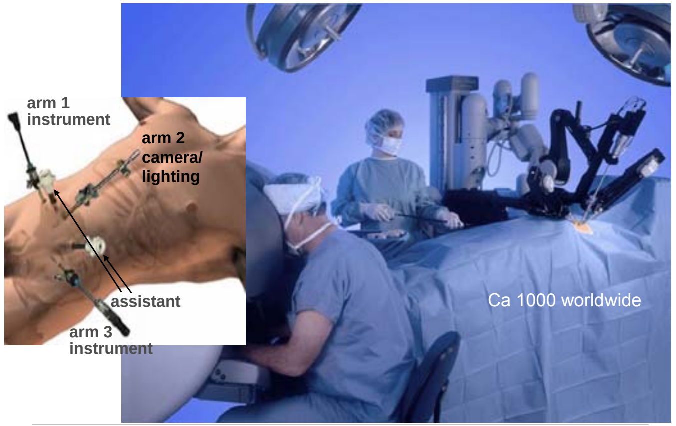
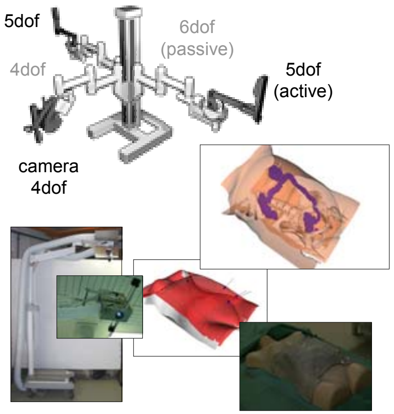
3. Teleoperated medical robots

Teleoperated medical robot daVinci for MIS



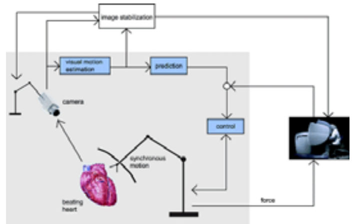
Current Research at IPR: port & pose planning

- Problem: Best poses of the arms and ports
- Planning
  - Instrument/ Robot modeling
    - Geometry
    - Kinematics
  - Patient modeling
    - Situs (insufflated)
    - Obstacles
    - Critical structures
    - Access area
- Transfer
  - projector based augmented reality

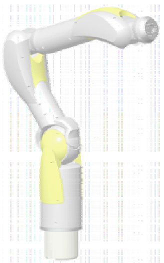


General research fields: Motion controlled Telemanipulation

- Movement compensation of organs (beating heart, ...) for interaction and Augmented Reality (Vessels, blood flows...)
  - Robot tracking control
  - Sensors
  - Prediction (q.v. GK 1126)
- Haptics
  - Instruments (tracking) (Ø<8mm)
  - Input device (force, detect)
- New Instruments



Objectives of AccuRobAs, EU FP6 STREP (10.06 –09.09)



- Modular robotic system for autonomous and teleoperated modes
- Increaset system accuracy through
  - Adaptive Soft-tissue models
  - Online motion prediction
  - Sensors
- Autonomous robot with new techniques for laser osteotomy
- Teleoperated robotic system with kinaesthetic feedback

AccuRobAs

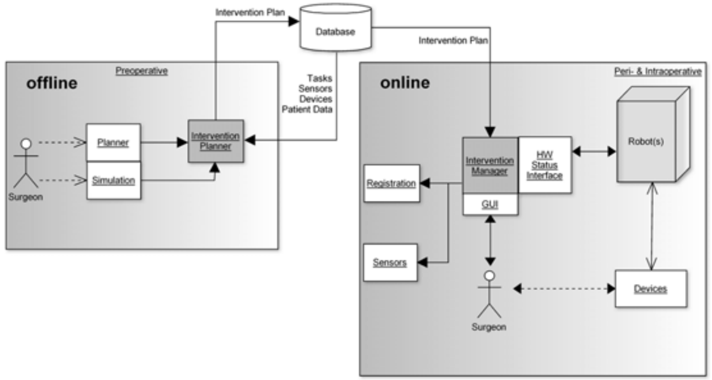
UNIVERSITE PIERRE & MARIE CURIE

DLR

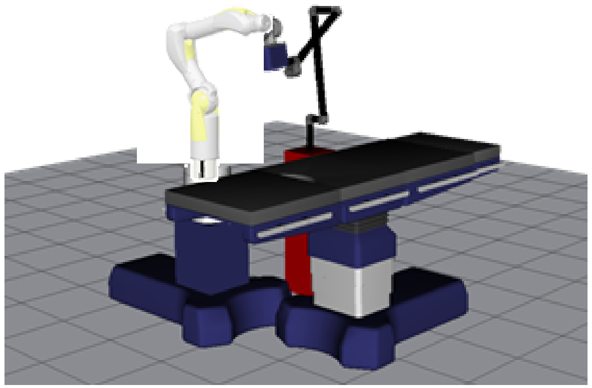
um2

BrainLAB

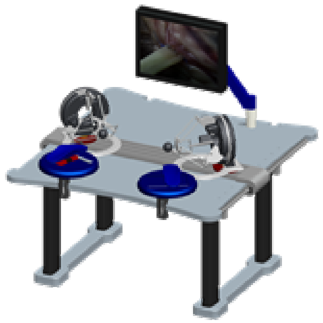
AccuRobAs System architecture

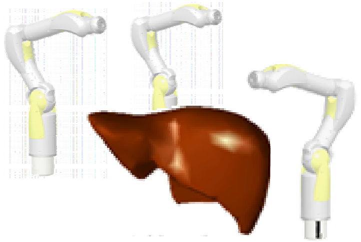


AccuRobAs-Demonstrator two: Laser osteotomy



AccuRobAs-Demonstrator one: 3 Teleoperated robot arms for Palpation





Thank You !

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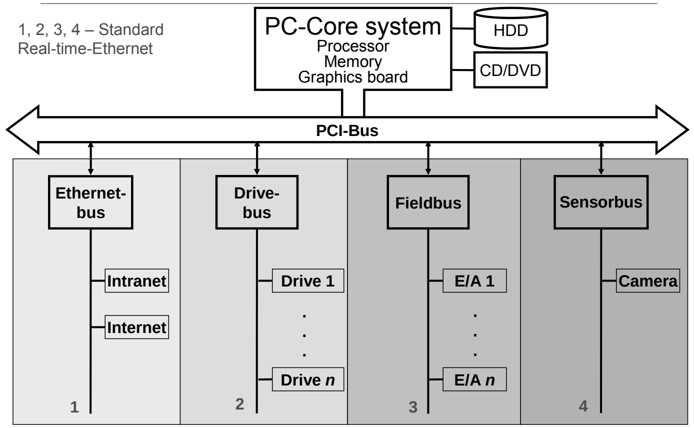
Standard structure of a PC-based Robot control

1, 2, 3, 4 – Standard Real-time-Ethernet



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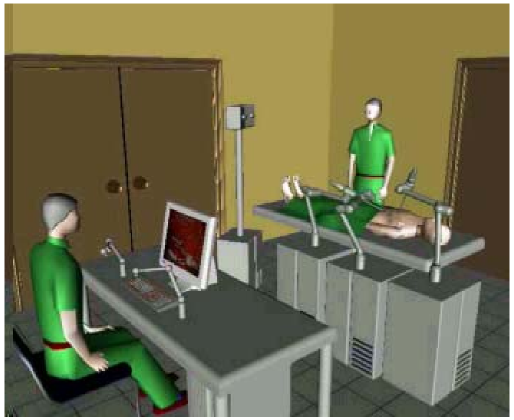
Vision of telemanipulation



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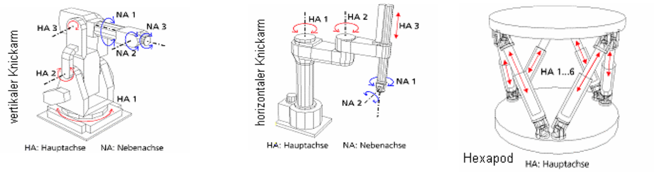
Robot kinematics for medical robots

Serial kinematics | Parallel kinematics



Axis types: Translatory axes, Rotational Axes

Moving degrees of freedom of a robot

- Amount of movement options of the robot
- Degrees of freedom of a rotational joint: FR ≤ 3
- Degrees of freedom of a translational joint: FT = 1
- Number of joints of a robot: n, usually n ≤ 6

Spatial degrees of freedom of an object in 3D-space

- Amount of independent movements in reference coordinate system- defined by minimal amount of translations and rotations for exhaustive describing the pose of the object
- For general freely movable objects in 3D space it is:
  Degrees of freedom: f = 6 (3 translations and 3 rotations)

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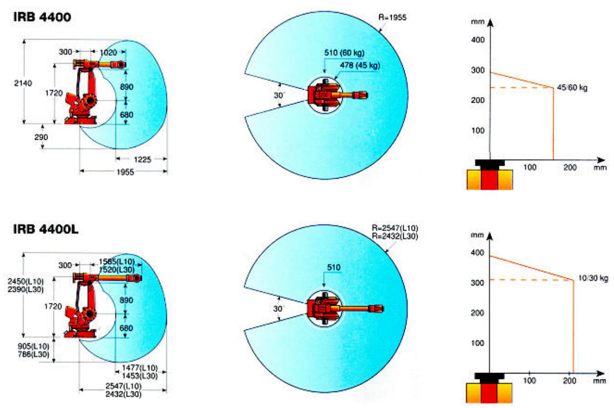
Working envelope and pay-load diagram



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1. Basics of Robotics

1.2 Motion Control for an autonomous robot

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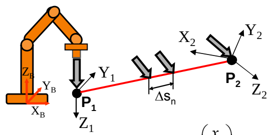
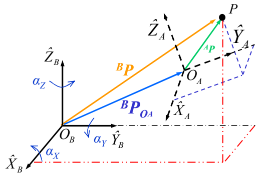
Pose and frame

Frame represents poses and TCP´s of an object with 6 dof.
Frame = 4x4 matrix = Relation between two coordinate systems = pose of a coordinate system (B), relative to another coordinate system (A)



$$^{B}F_{A} \triangleq \begin{bmatrix} R_{3\times3} & P_{3\times1} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} \cong \begin{pmatrix} x_i \\ y_i \\ z_i \\ \varphi_i \\ \theta_i \\ \psi_i \end{pmatrix}$$



$$^{B}P = {}^{B}F_{A}\,{}^{A}P$$

Poses P_i are represented as frames related to the robot base B coordinate system. A pose has 6 components according to 6 dof.
Rotation and Translation of poses are performed via a homogenous matrix (frame) multiplication

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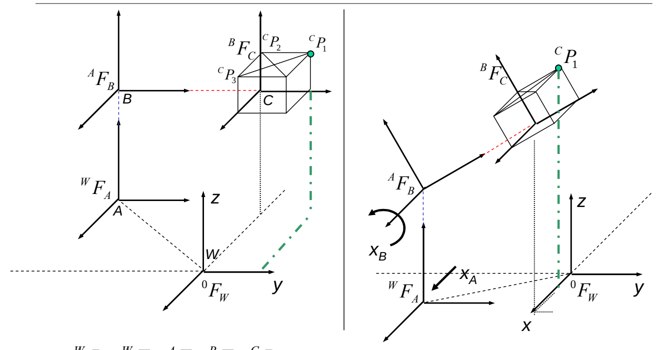
Frame arithmetic

Translation and Rotation of Poses (P_1) and Frames (F_x)



$$^{W}P_1 = {}^{W}F_A \cdot {}^{A}F_B \cdot {}^{B}F_C \cdot {}^{C}P_1$$

$^{A}F_{B}$ Frame *B* relates to Frame *A*

1) Translation $F_A(x)$
2) Rotation $F_B(x)$

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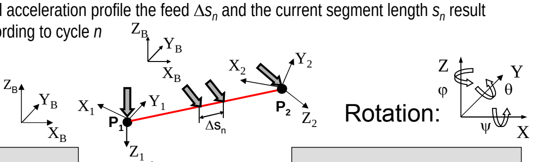
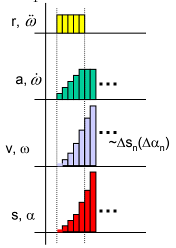
Digital motion control in 6 degrees of freedom with constant jerk

With trapezoidal acceleration profile the feed Δs_n and the current segment length s_n result recursively according to cycle n

Translation: / Rotation:



$$a_n = a_{n-1} + r\,\Delta T$$
$$v_n = v_{n-1} + a_n\,\Delta T$$
$$s_n = s_{n-1} + v_n\,\Delta T$$
$$\Delta s_n = v_n\,\Delta T$$



$$\dot\omega_n = \dot\omega_{n-1} + \ddot\omega_k\,\Delta T$$
$$\omega_n = \omega_{n-1} + \dot\omega_n\,\Delta T$$
$$\alpha_n = \alpha_{n-1} + \omega_n\,\Delta T$$
$$\Delta\alpha_n = \omega_n\,\Delta T$$

Given r, ΔT, $\ddot\omega_k$, v_{max}, a_{max}, v_{Bahn}

$\alpha = \varphi, \theta, \psi$, Orient.

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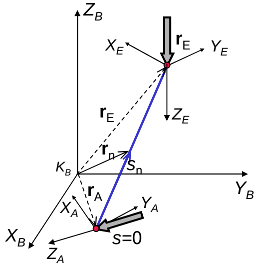
Position interpolation for linear movements



$$s_n = s_{n-1} + v_n \cdot \Delta T$$
$$\Delta s_n = v_n \cdot \Delta T$$
$$r_n = r_A + \frac{s_n}{s_L} \cdot (r_E - r_A)$$
$$s_L = \sqrt{(x_E - x_A)^2 + (y_E - y_A)^2 + (z_E - z_A)^2}$$
$$r_n = r_{n-1} + \frac{\Delta s_n}{s_L} \cdot (r_E - r_A)$$

From interpolation preprocessing:

$s_L, (r_E - r_A)/s_L$

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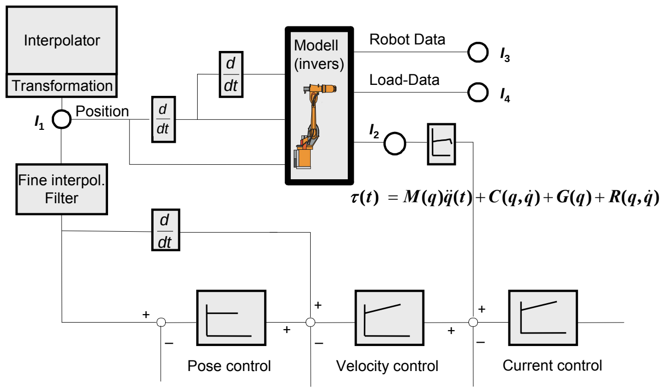
Model based Robot control



$$\tau(t) = M(q)\ddot q(t) + C(q,\dot q) + G(q) + R(q,\dot q)$$

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1. Basics of Robotics

   1.3 Robot Programming

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Robot languages KRL and PASCAL (1)

	Example	
	PASCAL	KRL
Data types	REAL CHAR ENUM	
		POS(x,y,z,A,B,C,...) AXIS(A1,A2,..A6)
Control structures	IF...THEN...ELSE REPEAT...UNTIL SWITCH...CASE WHILE...ENDWHILE	
Procedures and functions	DEFFCT...ENDFCT	
Movements		PTP LIN CIRC
Interaction with Environment		SIGNAL
Interrupt-Handling		INTERRUPT

KRL Data types: Examples (2)

Basic types and arrays

```
INT JOHN[10]                    ; Declaration
CHAR LUISE, MARTHA
...
JOHN[5] = 70                    ; Assignment
MARTHA = "Y"
```

Enumeration types

```
ENUM EN_TYPE  MALE, FEMALE      ; Definition
DECL EN_TYPE  NAME              ; Declaration
...
NAME = #MALE                    ; Assignment
```

Structures

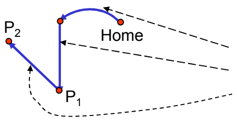
```
STRUC ST_TYPE   REAL LUISE,     ; Definition of structure with different datas types
                BOOL MARTHA
DECL ST_TYPE  JOHN              ; Declaration of a concrete structure named John
...
JOHN = {LUISE 1.5, MARTHA TRUE} ; Assignment
```


Rooters movements in KRL (3)

Movement types

Movement	Command
Point-To-Point	PTP PTP_REL
Linear (Line)	LIN LIN_REL
Circular (circular path)	CIRC

Programming example




```
AXIS PUNKT_1                          ; Declaration
POS PUNKT_2
...
PUNKT_1 = {A1 10, A3 50, A6 135}      ; Assignment
PUNKT_2 = {X 20, Y 20 ,Z 100, A 45, B 0,C 0}
...
PTP {A1 0, A2 0, A3 90, A4 0,A5 0, A6 30} ; Movement
PTP_LIN_REL  PUNKT_1
LIN PUNKT_2
```


Examples for Interaction with environment (4)

Task	Example	Description
Set output / delete output	$OUT[1] = TRUE	Set output 1 to TRUE (High).
Read input	MARTHA = $IN[13]	Set input 13 to BOOL-variable MARTHA.
Wait until input is set	WAIT FOR $IN[10] == FALSE	Wait until input 10 is set to FALSE (Low)
Pulse of defined Duration at output	PULSE ($OUT[7],TRUE,5)	Set output 7 to TRUE For 5 sec.
Path synchronous invocation of a function	TRIGGER WHEN DISTANCE= 0 DO UP() LIN P1	Do linear movement to P1 and synchronously start subprogram UP.

Robot Assisted Biopsy (DLR) with semi autonomous robot mode

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