A Few Guidelines for the Design of Surgical Robot Arms

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Surgical Robot Arms: Master & Slave
Outline

• A safety point of view

• Robot Arms
  – Classical Serial Arms
  – Not-so-classic Serial Arms
  – Parallel Arms

• Multi-purpose system?
### A Safety Point of View

#### Guidelines for Design (4)

**SURGEON**
- Efficient natural sensors
- Dexterity
- Coordination
- Capacity in reasoning and learning
- Adapting his skills

**ROBOT**
- Geometric accuracy
- Precision in controlling forces
- Possibility to work in hostile environment
- Repeatability
- No fatigue
- Stationarity
- Rapidity

- Subject to fatigue
- Stability
- Precision
- Unable to see through tissues
- Subject to radiations

- Weak capacity in deciding, learning, adapting
- Incomplete models
- Repetitiveness

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**Better accuracy**

**Safety increased**

**Trauma decreased**

**Decreasing number of interventions**

**Post operative comfort and fast recovering**
So what?

In contact with human body
- Specific functionalities
- Easily movable
- Optimal size
- Manually controllable

Specific safeties

Specific kinematics

- Unstructured environment,
- No repetitive tasks,
- Sterilization of the components…
Industrial versus medical robots

**Industrial Robots**

- Isolated from the workers (appropriate training to interact with them) by preventing machine workspace from human intrusion

- Possibility to enter in the workspace (for maintenance purpose or learning procedures) without stopping the machine:
  - Disconnecting of the protection devices
  - Activating the “manual mode” with limited speed

**Medical Robots**

- Medical robots cooperate with the human (surgeon and staff) and interact the patient

- Harsh constraints and specifications in the design itself, especially for active medical devices

- Influence of human factor and clinical constraints specific to mechanical devices for medical purpose
Typical Safety Tools in Industry
Safety: Human Factor

- Work done on human being:
  - Change in working conditions with each patient (characteristics of soft tissues, position of the patient on the operating table, size of the body and accessibility of the organs,...)
  - Task and execution specific to a patient: no “trial/error” nor “doing again” movements

- Robot directly in contact with the patient and staff:
  - Necessity of preoperative studies to plan the intervention
  - Modification of planning during the operation itself, according to the surgeon diagnostic, possible complications or patient organism behavior

- Surgeon is not “robotic specialists”:
  - Dedicated user-friendly HMI: task-oriented, allowing an easy manipulation of the system
  - Robot transparency: avoiding singularities, mechanical joint limits, reconfiguration procedures,...
Safety: Clinical Constraints

• Every component of the system in contact with the sterile field must be sterilized (generally, the robot is covered by a sterile sleeve while the tool is separately sterilized by an autoclave procedure);

• Environment is usually unstructured: operating rooms are cluttered with several other medical systems (radiology, anesthesia, surgery, etc.). The robot position with respect to the patient varies between two operations and even a single operation. Thus, its dimensions have to be reduced;

• The robot has to be easily and quickly transportable in and out of the operating room

• Required functionalities are defined according to each kind of clinical operations ➔ new medical robots have often been designed for specific operations;
• Any failure ⇒ very critical.

• Medical robots must function safely and with high reliability.

• 6 attributes of the concept of dependability:
  – Safety
  – Reliability
  – Availability,
  – Confidentiality,
  – Integrity,
  – Maintainability.
In European Community: ISO 9000 norm has been modified to comply with the specific constraints of medical devices in the European directive 93/42/CEE.

CE marking: the EN 46000 certification enacts the various criteria necessary to classify all the medical devices according to four classes.

Device classification depends on:
1. its life span use: from a few minutes (temporary) to several years (implantable)
2. its invasiveness or non-invasiveness
3. its surgical or non-surgical use
4. its activeness or inactiveness
5. the vital or non-vital body parts concerned by the device
• In these directives, the “medical device” denomination includes several kinds of products such as drugs, compresses, electrical apparatus, mechanical devices, surgical or radiological tools,…

• Elementary rules for designing a “safe” surgical robot:
  – No uncontrolled motions
  – No excessive force on patient
  – Keep the surgical tool in a predefine workspace
  – Supervision by the surgeon of any motion

• To guarantee a high level of safety, a medical device such as a robot may be designed considering the main following principles:
  – The degree of redundancy in control and sensing
  – The possibility to design an intrinsically safe system (i.e. capacity to decrease the maximum level of risk by construction)
  – The tradeoff between reliability and safety. ( … and cost )
• Safety concepts based on three rules:
  1. Redundancy in sensor and control,
  2. Intrinsically safe components
  3. Reliability in design.

• Along three axis:
  1. At the electromechanical level
  2. At the hardware level
  3. At the software level
Electromechanical concepts of safety: Intrinsically safe components (1)

- Limitation of actuator power to satisfy only the required tasks better than simply using software thresholds to restrict payload, forces, torques, velocity and acceleration.

- Use of high reduction gears such as harmonic drives (high efficiency and low backlash) reduces the robot’s velocity. But high reduction ratios ⇒ non back-drivable structures:
  - Required (in neurosurgery for instance)
  - Unacceptable (in remote MIS applications).
For systems applying effort: when the robot force becomes too important, a mechanical system ("mechanical fuse") enables to quickly drop the tool. (On AESOP, the collar linking the endoscope and the arm is quickly disconnected thanks to a magnetic connection).

Joints may also be equipped with mechanical torque limiters mounted on the motor shaft (e.g. Neurobot or Hippocrate): when a link collides with an obstacle during a motion, it stops moving while the motor shaft still rotates.
• In case of power breakdown or emergency stop, parking brakes mounted on selected joints prevent the robot from falling down under gravity effect.

• However, this technical choice presents a main drawback: when the user has to manually move the arm without actuator control, the brakes have to be released. Besides, many robots tend to vibrate a bit when brakes are applied.

• As an alternative to this solution, gravity compensation may be fulfilled by a passive counterbalancing payload or by a full irreversible structure.
Electromechanical concepts of safety: Redundancy of sensors (1)

• Decreasing the hazard rating ⇒ Increasing information and improving control by using redundant and independent components.

• Examples:
  – Stereotactic neurosurgery during the needle insertion phase ⇒ duplication of joint brakes to prevent any breakdown effect
  – In Image Guided Surgery applications ⇒ using both independent active and passive marker-based tools to improve the reliability of the tracking system (e.g. cameras coupled with a Computed Tomography system)
Electromechanical concepts of safety: Redundancy of sensors (2)

- Avoided time consuming and potentially hazardous initialization procedures by using:
  - one absolute joint position sensor
  - a combination of two relative encoders (one sensor mounted on the motor output shaft and the other mounted on the joint axis)

- Examples:
  - two resolvers (Hippocrate, SCALPP,...)
  - one incremental encoder associated with an absolute encoder (Robodoc)
  - one incremental encoder associated with potentiometer (NeuroSkill robot, SCALPP,...).

- Redundancy of sensors also used for the arm control: e.g. information on the joint velocity deduced thanks to the coarse sensor.
Electromechanical concepts of safety: Mechanical design (1)

- Avoid the risk of wrenching or cutting wires, by shielding and integrating all leads inside the links of the robot arm.
- Limiting the working envelope by using mechanical joint limits: physical threshold (+ software threshold).
- Computer Aided Design analysis for selecting robot location
- Kinematics concept:
  - Adapting the number of dof to the required task workspace
  - … or use redundant kinematics to avoid collision and increase dexterity (for instance, in MIS or in neurosurgery)
  - Fit link dimensions to preserve patient and clinical staff safety
- Kinematic models:
  - Avoid numerical or polynomial resolution methods and prefer analytical ones
  - Reject wrist and shoulder singularity configurations out of the workspace as much as possible
... Many other issues in …

- Safety at “electrical level”
  - Intrinsically safe components
  - Redundancy
  - Wiring techniques
  - EMC … and so on
- Safety at software level
- Safety at system monitoring level

(see IEEE Magazine for more on that …)
• Design the controller as concurrent processes dedicated to specific tasks: security, Cartesian control, joint control, communication with peripheral units and sensors, HMI communication,…
• By tuning the process and variable priorities, an appropriate emergency procedure is switched on as soon as an error is detected. For instance, the dedicated security process may have the higher priority.
• ➞ Stable computation time ➞ closed-form solutions for models.
With safety in mind, you still have to select which arm to use…
A classic (means: serial)?
A not-so-classic?
A PKM?
PKM versus Serial

Passive Joints

Links

Actuated Joints
PKM & Serial in Motion
Historical Perspective

Machine-tool

N.C.

Robots

1900

1955

1965

1986

2000

Pioneers
(Gough, Stewart)

Delta
(Clavel, EPFL)

PKM

Variax
(Gidding & Lewis)
Classical Serial Arms

- Two important “families”:
  - Scara
  - Anthropomorphic

- Scara:
  - Comes from “pick-and-place” applications
  - 4 dof + possible 1~2 dof “wrist”
  - Workspace $\Rightarrow$ “flat” cylinder
Anthropomorphic Arm
- Comes from automotive industry applications (painting, welding)
- A carrier (3dof) + a “wrist” (2~3dof)
- Workspace $\Rightarrow$ a sphere

$$\begin{align*}
T_x, T_y, T_z \\
R_x, R_y, R_z
\end{align*}$$
Scara & Anthropomorphic in Surgery

Scara

ROBODOC

Anthropomorphic

CASPAR
Scara & Anthropomorphic in Surgery

ACROBOT

Anthropomorphic
Or
Anthropomorphic-like

Neuromate
Classical Arms Key Features

- Scara & A-R ⇔ the “foundation” of robotics (100% mastered)
- Transformation models are OK
  - F.K. is straightforward
  - I.K. just a bit more tricky
- Singular positions exist
• Scara presents less problem with Gravity effects
Scara vs Anthropomorphic

- Scara’s workspace is more likely to suit to the volume of a human body lying on a surgical table
It is possible to design an almost-singularity-free Scara arm
  - Most problems come from “wrist singularity”
  - Typical case: axis 4 and 6 aligned
  - One way out of this problem: non-spherical wrists
  - New problem: I.K. in closed form?
One offset is not enough

- Symmetric joint limits?
- Ranges of motion?

\[ \Theta_5 = 0 \]

\[ \Theta_5 = \pm \frac{\pi}{2} \]
Most non-spherical wrists aren’t OK

\[ \Theta_5 = 0 \]

\[ \Theta_2 = 0 \]

\[ \Theta_4 = \pm \frac{\pi}{2} \]

\[ \Theta_5 = \arctan \left( \tan(\Theta_2) \frac{D_5 \sin(\Theta_4) - D_3}{D_5 \cos^2(\Theta_4)} \right) \]
• 6-degree-of-freedom Scara Robot,
• No wrist-singularity,
• One classical singularity on the elbow,
• Inverse Kinematics Model,
• Non-spherical wrist,
• Large Workspace.
Easy singularity check + I.K. in closed form

\[ \text{det}(J) = D_3 D_4 \sin(\Theta_3) \cos(\Theta_5) \]

\[ U_0 = \begin{bmatrix}
    s_x & n_x & a_x & p_x \\
    s_y & n_y & a_y & p_y \\
    s_z & n_z & a_z & p_z \\
    0 & 0 & 0 & 1
\end{bmatrix} \]

\[ \theta_5 = \text{atan2}(a_z, \pm \sqrt{n_z^2 + s_z^2}) \]

\[ \theta_6 = \text{atan2}\left(\frac{-n_z}{C_5}, \frac{s_z}{C_5}\right) \]

\[ r_1 = p_z - R_4 - D_6 C_5 \]
Scalpp Kinematics
Scara vs Anthropomorphic: Two Examples
Not-so-classic Serial Arms

- Redundant Arms
  - Offer more dof than strictly needed
  - May help to avoid collisions
  - “Numerically tricky” (The I.K. is not solvable in closed form)
Solving I.K. for Redundant Arm

\[ V_{Tool} = J \cdot V_{Motors} \]

Not a SQUARE matrix!

\[ V_{Motors} = J^+ \cdot V_{Tool} \]

Pseudo-inverse

\[ P_{Tool} \]

\[ P_{Motors} \]
Not-so-classic Serial Arms

- Arms with kinematics constraint
  - The idea is to create a mechanical structure able to give the tool one SPECIFIC type of motion
  - Mostly applied to mini-invasive surgery
- M.I.S. ➔ a tool (shape ⇔ cylinder) passes through a trocar (shape ⇔ annulus ??)
- The tool axis always passes in one “fixed” point
- ➔ Two constraints (translation is constrained in two directions)
How many dof for respecting the constraints?

4 dof

? dof
How many dof for respecting the constraints?

- Gruebler formula: Mobility = (Total dof) – (6 x Nb of loops)

\[ \text{Mobility} \rightarrow T_x, T_y, T_z \rightarrow 3 \]

\[ 3 = (4 + ?) - (6 \times 1) \]
\[ \Rightarrow ? = 5 \]

\[ \text{Mobility} \rightarrow T_x, T_y, T_z, R_z \rightarrow 4 \]

\[ 4 = (4 + ?) - (6 \times 1) \]
\[ \Rightarrow ? = 6 \]
Option 1: passive joints

- Mobility $\rightarrow$ $T_x$, $T_y$, $T_z$ $\rightarrow$ 3
- $3 = (4 + 5) - (6 \times 1)$

Zeus

5 joints

- 3 motors

2 passive joints
Option 2: Remote Rotation Center

- A classical spherical wrist does not rotate at the “right” point

- A RRC system does and thus “cancel” the Constraint

\[ 3 = (6 + 3) - (6 \times 1) \]
RRC or “The Magical Parallelogram”

- RRC with spherical links requires complex parts

- … while a basic parallelogram may do the job as well
Implementation of RRC

[Diagram of a robotic arm with labels and arrows indicating movement]

Da Vinci
RRC in motion
RRC: other “unique” solutions…
RRC: other “unique” solutions...

From solid links to timing belts
Remark: the parallelogram must be a real one!
Option 3: force control

- Mobility $\Rightarrow$ $T_x, T_y, T_z \Rightarrow 3$
- $3 = (4 + 5) - (6 \times 1)$

5 joints
&
5 motors

2 dof controlled
with force
measurements

5 motors

3 data

2 data

position

force
Overview of arms with kinematics constraint

- **Option 1 (passive joints)**
  - Few motors
  - The trocar “forces” the passive joint to adapt “mechanically”
  - No accurate positioning is needed
- **Option 2 (RRC)**
  - Few joints and motors
  - The trocar has no influence on the arm motion
  - BUT, the arm MUST be precisely located (positioning device + procedure)
- **Option 3 (force control)**
  - The trocar “forces” the passive joint to adapt by means of measures + control software
  - A bit more complex
  - May open a path to “multi-purpose” systems
Overview of Serial Arms

ROBODOC

CASPAR

Zeus

Da Vinci

5 motors

3 data

2 data

position

force

5 motors

De Vinci
… Still half the way to go …

Passive Joints

Links

Actuated Joints
### Table 1. Symbols for Joint-and-Loop graphs.

<table>
<thead>
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<th></th>
<th>Revolute</th>
<th>Prismatic</th>
<th>Universal</th>
<th>Spherical</th>
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<td>Passive</td>
<td><img src="image" alt="R" /></td>
<td><img src="image" alt="P" /></td>
<td><img src="image" alt="U" /></td>
<td><img src="image" alt="S" /></td>
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<tr>
<td>Passive + measurement</td>
<td><img src="image" alt="R" /></td>
<td><img src="image" alt="P" /></td>
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<tr>
<td>Actuated</td>
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</tbody>
</table>

(not easy to implement)
An example (H4)
- The PKM Landscape -
Telescopic Legs or Fixed-Length Legs
- The PKM Landscape -

Telescopic Legs or Fixed-Length Legs
- The PKM Landscape -
Rotational or Linear Drives

Summer School on Surgical Robotics
- The PKM Landscape -
Rotational or Linear Drives

Surgiscope
- The PKM Landscape -
With or Without a Passive Leg

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- The PKM Landscape -
Fully Parallel or Non-Independent Chains
- The PKM Landscape -
Fully Parallel or Non-Simple Chains
- The PKM Landscape -
Parallel or Hybrid P-S

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- The PKM Landscape -
Parallel or Hybrid S-P
- The PKM Landscape -
Parallel or Hybrid LH-RH

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- The PKM Landscape -
Kinematic Redundancy
- The PKM Landscape -

Actuation Redundancy

Guidelines for Design (70)
- The PKM Landscape -
Measurement Redundancy

Guidelines for Design (71)
- The PKM Landscape -
No Limit!
Common (Claimed) Advantages

- Stiffness, Accuracy, Speed, Acceleration (up to 40 g!)
- Good Weight/Load Ratio
- Lots of Common Parts
- Very good dynamic capabilities and ability to force control

Flexion

Traction / Compression
(Most) Commun Drawbacks

- Lots of Passive Joints
- Modeling / Singularities
- Not always supported by conventional NC
- Non classical calibration
- Too « advanced » for some markets
- Bad Foot-Print/Workspace Ratio
Application domains: simulators
Application domains: positioning systems
Application domains: handling

Delta

Tricept
Application domains: handling
Application domains: machine-tool
Application domains: surgery

Surgiscope
Application domains: surgery
Application domains: haptic devices
IKM (from \( x \) to \( q \))

\[
\begin{align*}
q_i &= s_i \cdot v(O_n) + (s_i \times C_i O_n) \cdot \omega \\
\dot{q}_i &= \dot{s}_i \cdot v(O_n) + (s_i \times C_i O_n) \cdot \omega \\
\dot{q}_i (B_i A_i \times r_i) \cdot B_i C_i &= B_i C_i \cdot v(O_n) + (B_i C_i \times C_i O_n) \cdot \omega \\
\dot{q}_i (l_i \cdot B_i A_i) \cdot B_i C_i &= B_i C_i \cdot v(O_n) + (B_i C_i \times C_i O_n) \cdot \omega
\end{align*}
\]
Singularities (1)

\[ \dot{q} = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \vdots \\ \dot{q}_k \end{bmatrix} \]

\[ J_q \cdot \dot{q} = J_x \cdot \dot{x} \]

\[ J_q = \begin{bmatrix} (B_1A_1 \times r_1) \cdot b_1 & 0 & 0 & 0 \\ 0 & (B_2A_2 \times r_2) \cdot b_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & (B_k A_k \times r_k) \cdot b_k \end{bmatrix} \]

\[ J_x = \begin{bmatrix} b'_1 \cdot (b_1 \times C_1 O_n) \\ b'_2 \cdot (b_2 \times C_2 O_n) \\ \vdots \\ b'_k \cdot (b_k \times C_k O_n) \end{bmatrix} \]

\[ \dot{x} = \begin{bmatrix} \nu(O_n) \\ \omega \end{bmatrix} \]
Singularities (2)

Under-mobility (serial):
motor moves $\Rightarrow$ no tool motion

Over-mobility (parallel):
High motor torque $\Rightarrow$ no force at tool
FKM (from $q$ to $x$) (1)

FKM:
- Few “nice” cases with closed form
- Often: numerical resolution (polynomial of 4th, 8th, 16th, ... order)
Two options for numerical solving:

- Solving the polynomial (😊 all solutions,énom computation cost)
- Looking for ONE solution (😊 fast,énom instability risk)

\[ \hat{x}_0 \rightarrow q_0 = mgi(\hat{x}_0) \]
\[ \hat{x}_0 \rightarrow (J_x, J_q)_0 \rightarrow J_0 = J_x^{-1} J_q \]
\[ e_0 = q_{mesurée} - q_0 \rightarrow \hat{x}_1 = \hat{x}_0 + J_0 \cdot e_0 \]

...stop if \( \| e_k \| < \text{accuracy threshold} \)
General remarks about control

- In Joint Space with IKM

\[ x \xrightarrow{IKM} q \xrightarrow{PID} \text{Machine} \]

- In Cartesian Space with Jacobian

\[ x \xrightarrow{PID} J^{-1} \xrightarrow{FKM} x_{\text{estimated}} \xrightarrow{q_{\text{measured}}} \]

\[ x \xrightarrow{FKM} q_{\text{measured}} \]
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Not enough?

Guidelines for Design (89)
A need for multi-purpose systems

• An industry sector is mature when standards exist

• This help to reach:
  – Lower costs
  – Better reliability
  – Portability of applications and tools
  – Creation of a “universal” knowledge
Multi-purpose systems?

- How many dof?
- What velocity, acceleration?
- What force?
- What kinematics?
- Above questions hold for both master and slave arms
• Nb of dof:
  – Brain ➔ 5 dof (a point & one direction)
  – Orthopedic ➔ 5 dof (drilling) or 6 dof (cutting)
  – M.I.S. ➔ 5 dof extra-body + 3 dof (intra-body rotations)
    ➔ 6 dof extra-body (if Rz is accounted for) + 2 dof (intra-body)
  – Skin grafting ➔ 6 dof

A multi-purpose slave arm may be composed of:
  – A “universal” carrier with 5 or 6 dof
  – A “specific” wrist with 1 to 3 dof
Multi-purpose slave arm: speed & force

- **Speed, acceleration**
  - Brain ➔ often works at rest
  - Skin grafting ➔ a few mm/s
  - M.I.S. ➔ several 100mm/s (large rotations of tool x tool length)
  - Orthopedic ➔ a few mm/s
  - Heart ➔ Acceleration probably > 1g (if “heart-beating surgery” is considered)

- **Forces:**
  - Brain ➔ ?
  - Skin grafting ➔ 40 N ~ 80 N
  - M.I.S. ➔ few N (+ disturbances due to the trocar)
  - Orthopedic ➔ up to 100 N (extremely dependent on cutting param.)
Remark: forces in machining bone

Drilling
Tool Diameter 2 mm
Speed 5.8 mm/s

Milling
Tool Diameter 12.5 mm
Depth of cut 2 mm
Speed 4.0 mm/s
Remark: DaVinci arm is not made for bone machining

- $k_x = 12 \, \text{N/mm}$
- $k_y = 2.4 \, \text{N/mm}$
- $k_z = 5.4 \, \text{N/mm}$

- Very low vibration frequency
A multi-purpose slave arm may be required to offer:
- Good behavior at speed as low as few mm/s
- The capability to move as fast as several 100mm/s
- A sensitivity good enough to guarantee low forces
- The capability to exert force up to 100N
- Good acceleration ability (for “heart-beating surgery”)
- Good stiffness

A multi-purpose slave arm could be based on Direct Drives (safety issues?)
• The carrier part of a multi-purpose slave arm may be based on Scara kinematics for the following reasons:
  - Convenient fit between robot workspace and human body volume
  - Models are straightforward, even with “fancy” wrists
    - Singularities are easily managed
  - Gravity effect may not be such a big problem
    - Scara fits well with DD technology
Multi-purpose slave arm: potential solutions
Selection of a master arm

- Dof: 6
- Range of motion
  - Translation $\Leftrightarrow [10 \text{ cm}]^3 \sim [20 \text{ cm}]^3$
  - Rotation $\Leftrightarrow > (140 \times 90 \times 120) \text{ degrees}$
- Force-feedback capable
  - Several N for rough force sensing (orthopedic)
  - $<$ N for M.I.S.
  - High dynamic, e.g. for heart surgery ("the touch of a finger on an atheromatous artery")

- High dynamics and extreme sensitivity makes it difficult for serial arms $\Rightarrow$ incredible costs!
- No "pure" PKM exists with such a large range of motion
A multi-purpose master arm may be based on advanced PKM concepts:

- Hybrid design
- Redundancy
- Both
Multi-purpose master arm: potential solutions

- Force/torque sensor
  1-DOF

- 2-DOF five bar spatial mechanism

- 3-DOF modified DELTA mechanism
Multi-purpose master arm: potential solutions
Multi-purpose systems: a general picture

- Standardized Scara-like DD arms
- Under force control
- Remotely operated by Hybrid PKM with Large tilting capabilities
- And Carrying Specific Wrists