Medical Robotics

Medical robots design
Force control and teleoperation

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Robotic systems for medical interventions
- Medical robots in surgery and medicine
- Robotics basic concepts (definitions et models)

Autonomous control of robotic arms
- Position control, without control of the applied force
- Interaction control

Collaborative manipulation
- Principle
- Collaborative manipulation in robotics
- Collaborative manipulation in medicine

Telemanipulation
- Principle
- Unilateral teleoperation
- Force feedback teleoperation
Outline

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**Introduction**

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**Robot (Larousse dictionary definition)**

Automatic device able to manipulate objects or execute tasks according to a program.

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**Purpose of medical robotics (Taylor91, Poisson05)**

To allow the cooperation between a surgeon/physician and a robotic system in order to achieve tasks efficiently.

<table>
<thead>
<tr>
<th>Surgeon/physician</th>
<th>Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>- skills</td>
<td>- accuracy</td>
</tr>
<tr>
<td>- experiment</td>
<td>- repeatability</td>
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<tr>
<td>- anticipation</td>
<td>- velocity</td>
</tr>
<tr>
<td>- decision</td>
<td></td>
</tr>
</tbody>
</table>

* Cooperation for better perception, decision, action *
## Task oriented design

### Design considerations

Different points have to be taken into account:
- **Medical parameters**: medical purpose, gesture analysis, safety, sterility...
- **Human parameters**: patient diversity, difficult medical gesture, medical staff...
- **Robotic parameters**: workspace, possible architectures, actuation, sensors...

* Dedicated systems *

### Dedicated systems

The device has to:
- Respect norms
- Be certified by sanitation agencies (CE, FDA, etc.)
- Be useful for the achievement of the act (benefit)!
Task oriented design

1. Analysis of medical requirements
Task oriented design

1. Analysis of medical requirements
2. Gesture analysis: performed motions, critical steps
Task oriented design

1. Analysis of medical requirements
2. Gesture analysis: performed motions, critical steps
3. Specifications
Task oriented design

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2. Gesture analysis: performed motions, critical steps
3. Specifications
4. Robot architecture choice.
   Specifications: bulk, torques, velocities, accuracy.
   Mechatronics: choice of actuators and sensors.
   Software development.
Task oriented design

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5. Prototype validation: lab, phantom and in-vivo experiments.
   Clinical tests.
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Diagram:
- Medical requirements
  - Gesture analysis
    - Specify
      - Decide
        - Validate
          - Update
            - no
Task oriented design

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* Course about robot design and control *
Specifications

- Required degree of freedom of the tool
  - Workspace and type of motions
  - Required velocities and accelerations
  - Required forces and torques

- **Working principle**: autonomous, semi-autonomous or teleoperated

- Robot architecture
- Actuators
- Sensors
Medical robot design

Mobility: needle positioning task with a CT-scanner

The needle positioning and orientation (without the insertion) in interventional radiology correspond to 5 DOF:

- 3 translation to determine the entry point
- 2 rotations to rotate about this point
Mobility : laparscopic surgery

The trocar constraint imposes at least 8 mobilities.

- 4 extra-corporal DOF + 3 DOF for the rotation in the abdomen
- or 5 extra-corporal DOF + 2 DOF for the rotation in the abdomen if the tool self rotation is performed by the extra-corporal structure
### Robot specifications

**Workspace**
A few cm\(^2\) for eye surgery to the whole body for radiology

**Motions type**
Rotations, typically about an entry point; pure translations or combined with self-rotations, etc.

**Velocities and accelerations**
Usually not more than a few mm/s for safety reasons; high accelerations in some cases, e.g. for needle insertions with limited tissue deformations

**Forces and torques**
To interact with organs, pierce or cut, a few N are generally required except in bone surgery (hundreds of N to cut or drill a bone)
### Medical robot design

#### Serial architectures
- Anthropomorphic robots, spherical robots

#### Advantages
- Design simplicity
- Easy to control
- Large workspace

#### Drawbacks
- Limited rigidity
- Limited payload

---

Zeego robot, Siemens.
# Medical robot design

## Serial architectures

Anthropomorphic robots, spherical robots

## Advantages

- Design simplicity
- Easy to control
- Large workspace

## Drawbacks

- Limited rigidity
- Limited payload

DermaRob (SCALPP) LIRMM.
Medical robot design

Parallel architecture
Mechanism with closed kinematic chains.

Advantages
- High rigidity
- High payload
- Accurate and fast

Drawbacks
- Ratio volume/workspace
- More complex design and control

MARS Robot by Mazor Robotics.
Medical robot design

Parallel architecture
Mechanism with closed kinematic chains.

Advantages
- High rigidity
- High payload
- Accurate and fast

Drawbacks
- Ratio volume/workspace
- More complex design and control

Surgiscope ISIS.
Medical robot design

RCM structure
Serial or parallel mechanisms with a remote center of motion (remote rotation center).

Advantages
- Actuators away from the operation field
- Passive or active joints

Drawbacks
- Complex design and control.

Passive RCM: DaVinci arm.
Medical robot design

**RCM structure**
Serial or parallel mechanisms with a remote center of motion (remote rotation center).

**Advantages**
- Actuators away from the operation field
- Passive or active joints

**Drawbacks**
- Complex design and control.

Active RCM: DLR MicroSurg
Medical robot design

Many other structures inherited from industrial robotics

- SCARA-like structures
- Spherical or cylindrical structures
- Hybrid serial-parallel structures
- Hyper-redundant structures: snake-like robots
- Patient-mounted structures
Medical robot design

Technological choices

Determine:
- Joint type: active or passive
- Stiffness or compliance
- Back-drivability and transparency
- Dynamic characteristics (friction, inertia, etc.)
- Bulk, weight, integration in the operating room
- Performance
Actuators

Parameters choice

- Is an actuator required?
- Backdrivability of the actuator and its transmission: a motor is often associated to a gear to increase torque and decrease nominal velocity (harmonic drive, epicycloidal gears), but it may affect backdrivability
- Compatibility with the environment (X rays, MRI, etc.)
- Performances and robustness

Actuators types

- DC, DC-brushless, induction, stepper motors
- Ultrasonic or piezoelectric motors
- Fluidic actuators: pneumatic or hydraulic
- ”Exotic” design like artificial muscles or specific design (with low velocity and high torque for instance)
Sensors

Parameters choice
- Interaction type
- Integration, robustness
- Performances
- Compatibility with the environment (X rays, MRI, etc.)

Sensor types
- Position sensor: optical encoder (incremental or absolute), Hall sensors, etc.
- Velocity sensors: tachymeter generator
- Vision sensors: imaging devices (CT, US, MRI), cameras (mono or stereo)
- Force sensors: constraint gauges associated to deformable structures
- Proximity sensors, switches

The choice depends on the application and the medical constraints.
Materials

Parameters choice
- Interaction with the patient, biocompatibility
- Possible sterilization
- Rigidity/Softness
- Density
- Fabrication process (machining, cost, etc.)

Material types
- Plastic parts: compatibility with most imaging devices, but flexibility and difficulty to obtain parts (rapid prototyping)
- Metal parts: more conventional, special metals depending on applications
## Software and electronics

### Parameters choice
- Type of control: autonomous, synergetic or telemanipulation
- Robot controllers, realtime software
- Fieldbus, acquisition cards
- Human-Machine Interface (ergonomy, utility, simplicity)

### Examples
- Robot controllers: Xenomai, RTAI, VxWorks, QNX, RTEMS, etc.
- Fieldbus: dedicated, EtherCAT, CANBus, serial
- Numerical velocity control, integrated axis control, etc.
- Tactile interface, graphical interface, joystick
Medical robot design

Some rules (Poisson05)

To maximize the safety of the patient and the medical staff it is required to:

- Block uncontrolled DOF
- Avoid to exert high forces to the tissues
- Keep the end effector in a predefined workspace
- Allow the surgeon to modify the robot motions
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Kinematic models

**Direct Kinematic Model**

MGD of a robotic manipulator: end effector pose as a function of the configuration:

\[ f: \mathcal{N} \rightarrow \mathcal{M} \]
\[ q \mapsto x = f(q) \]

Generally: \( x = (x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6)^T \), avec \((x_1 \ x_2 \ x_3)^T\) position coordinates in \( \mathcal{R}_0 \) et \((x_4 \ x_5 \ x_6)^T\) orientation coordinates

**Inverse Kinematic Model**

MGI: the configuration(s) corresponding to a given end effector pose:

\[ f^{-1}: \mathcal{M} \rightarrow \mathcal{N} \]
\[ x \mapsto q = f^{-1}(x) \]

Solvability: existence of a finite number of solutions

- Si \( n < m \): no solution
- Si \( n = m \): finite number of solutions
Differential kinematic models

**Direct differential kinematic model**

MCD : relation between the operational velocities $\dot{x}$ and the generalized velocities $\dot{q}$ : 

$$
\dot{x} = J \dot{q}
$$

with $J = J(q)$ the *Jacobian matrix* of $f$, with dimensions $m \times n$ :

$$
J : T_q\mathcal{N} \rightarrow T_x\mathcal{M}
$$

$$
\dot{q} \mapsto \dot{x} = J\dot{q}, \text{ where } J = \frac{\partial f}{\partial q}
$$

**Inverse differential kinematic model**

MCI given by $J^{-1}$
Direct dynamic model

Relation between the joint torques and the accelerations, velocities and generalized coordinates:

\[ D\ddot{q} + C\dot{q} + g + \tau_{ext} = \tau_m \]

with \( D = D(q) \) inertia matrix of the robot, \( C = C(q, \dot{q}) \) Coriolis and centrifugal forces matrix, \( g = g(q) \) the vector of the gravity effects and \( f \) the force applied on the end effector.

Static relation

With \( \ddot{q} = \dot{q} = 0 \), if gravity is compensated, it comes that:

\[ \tau_m = \tau_{ext} = J^T f_{ext} \]
Dynamic model: remarks

Direct dynamic model in the joint space

\[
D(q)^{-1} s_1 C(q, \dot{q}) \dot{\dot{q}} + g(q) + \tau_m - s_1 \tau_{ext} = 0
\]

Modeling and assumptions

- The robot structure is rigid
- The transmissions are rigid
- The actuators are torque controlled
- The model is highly nonlinear
Simplification

- Modelling around a configuration \((q_0)\), at low velocity
- Actuators dynamics neglected
- Gravity compensation
- Coriolis and centrifugal forces are neglected

Linearized model

\[
\begin{align*}
\tau_m & \rightarrow J^T F_{\text{ext}} \rightarrow D(q_0)^{-1} \rightarrow \frac{1}{s} \rightarrow \frac{1}{s} \rightarrow q
\end{align*}
\]
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Autonomous control of robotic arms

Position control

Two types of motions:
- in the configuration space (joint space)
- in the operationnal space

The goal is to move the robot to a specified position or to make it follow a prescribed trajectory.

Interaction control

The goal is to control the robot when it is in contact with its environment. Two types of problems:
- indirect force control (implicit force control)
- direct force control (explicit force control)

The choice will depend on the goal: react to the interaction or control the interaction force.
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Joint space control

Decentralized control with a local PID

Control law:

\[ \tau_m = K_p \left( q^d - q \right) + K_d \left( \dot{q}^d - \dot{q} \right) + K_i \int \left( q^d - q \right) dt \]

\( K_p, K_d \) and \( K_i \) are gain matrices. This control is applied to every joint independently.
Joint space control

Cascade control

PD control with a proportional loop for position and a tachymetric feedback:

\[ \tau_m = K_p \left( q^d - q \right) - K_d \dot{q} + \hat{g}(q) \]

Gravity compensation is generally required. Easier to determine, more robust.
**Joint space control**

<table>
<thead>
<tr>
<th>Advantages</th>
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</thead>
<tbody>
<tr>
<td>- Simple to use (implementation, synthesis, etc.)</td>
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<tr>
<td>- Works most of the time</td>
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</table>

<table>
<thead>
<tr>
<th>Drawbacks</th>
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<tbody>
<tr>
<td>- Not robust (depends on the robot dynamics and the configuration)</td>
</tr>
<tr>
<td>- The joint control is not adapted to solve problems that are expressed in the operational space (e.g. : friction, backlashes, etc.)</td>
</tr>
<tr>
<td>- References are generally given in the operational space</td>
</tr>
</tbody>
</table>
Operational space control

PID control - 2 control schemes

- Control in the operational space → Transpose in the joint space
- Control synthesis directly in the operational space

\[
D(q)^{-1} \left( K_p s^2 q + K_i s q + K_d \dot{q} \right) + C(q, \dot{q}) \dot{q} + g(q) = 0
\]

\[
x = MGD(q)
\]

... also with gravity compensation.
To improve the performances of position control, it is important to take into account the robot dynamics. The main difficulty is to determine and estimate the robot dynamic parameters!

Example in the joint space:

\[
\begin{align*}
\dot{q}^d 
\rightarrow & \quad q^d 
\rightarrow & \quad K_p 
\rightarrow & \quad K_i 
\rightarrow & \quad s 
\rightarrow & \quad \hat{D}(q) 
\rightarrow & \quad \hat{C}(q, \dot{q}) \dot{q} + \dot{\hat{g}}(q) 
\rightarrow & \quad \dot{q} 
\rightarrow & \quad q 
\rightarrow & \quad Robot
\end{align*}
\]
Neuromate, TIMC and ISS, Grenoble (1)

Neurosurgery

- Extreme accuracy
- Stereotactic surgery and planning
- Numerous applications: biopsy, radiotherapy, micro-probes
Brain Biopsy (1)
Brain Biopsy (2)
Advantages

- High mechanical accuracy
- Registration
- First clinical case in 1989

Drawbacks

- Industrial robotic arm
- Arm positioning
Characteristics of position servoing? Limitations?
Question

Characteristics of the medical tasks

Assumption: The preoperative data do not vary during the intervention.
- The interactions with the patient remain limited
- The task requires a very accurate positioning
- The task can be planned

Limitations

Without exteroceptive sensor the robot has nearly an open loop strategy. This type of control is not adapted to unstructured environments and to complex tasks.
Question

Solutions

- Add exteroceptive sensors: camera for visual feedback, force sensors for force feedback
- Adapt the robot structure to avoid any danger during interactions with the environment (passive approach)
- Develop a force control strategy (active control, implicit or explicit)
Future of positioning robots?

**Allura XPer Philips**

- System with 6 DOF + table motions (up to 6 DOF);
- Very accurate but very large workspace
- Allow to acquire an important volume (planar sensing surface 30x40cm);
- Table motions decoupled from robot motions
- Functionalities to assist percutaneous needle insertions (XPer Guide)
- Realtime acquisition (up to 30 images/s).
Future of positioning robots?
Zeego Siemens

- 8 DOF + table motions
- Very accurate but very large workspace
- Allow to acquire an important volume in a few seconds
- Table motions decoupled from robot motions
- Functionalities to assist percutaneous needle insertions (syngo iGuide).
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### Introduction

The robot/environment interaction imposes that the control or the robot structure takes this interaction into account:

- Active strategy with exteroceptive sensing
- Passive strategy with a compliant structure adapted to the interaction

### Goals

- React in case of unexpected loads or to high efforts applied to the environment
- Preserve the robot contact and possibly control the applied force
- Improve the constraints integration

### Force control strategies

- Implicit force control: no force reference (with or without sensor). Passive or active compliance.
- Explicit force control: force reference (with or without sensor). Hybrid parallel control, hybrid extern control.
Contact control: passive solutions (1)

Passive compliance

End effector with a compliant structure

Limitation of the system rigidity but position error compensation.

Advantages

- Simplicity
- Reliability
- Low cost

Drawbacks

- Task dependent
- No force control
Contact control: passive solutions (2)

Passive constraints

Dedicated kinematic chain: limitation of efforts in some directions

Advantage

- Passive safety

Drawback

- No force control
<table>
<thead>
<tr>
<th>Laparoscopy</th>
</tr>
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<tbody>
<tr>
<td>Minimally invasive surgery</td>
</tr>
<tr>
<td>Numerous applications (digestive surgery, gynecology)</td>
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</table>
Laparoscopy

Commercial success (5000) ?

<table>
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<tr>
<th>Discipline(s)</th>
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<tr>
<td>Epoque</td>
<td>1994</td>
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<tr>
<td>Lieu</td>
<td>USA</td>
</tr>
<tr>
<td>Inventeur(s)</td>
<td>Computer Motion.</td>
</tr>
</tbody>
</table>

**Invention:**
AESOP 1000 - world's first FDA-cleared surgical robot.

**Commentaires:**
Computer Motion a l'autorisation de mise sur le marché américain du robot porte-endoscope AESOP.
**Laparoscopy**
- Commercial success (5000) ?

**Advantages**
- Limited staff
- Intrinsic safety

**Drawbacks**
- Bulk
- Cost ?
Interaction control : active solutions (1)

Impedance control

Goal: impose the dynamic relation between the robot end effector position and the applied force, i.e. the impedance $= F(s)/X(s)$, generally chosen as a second order TF

Use of position and/or force sensor data

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**Figure 2-VIII-a**: commande d’impédance, basée sur la position.

**Figure 2-VIII-b**: commande d’impédance, basée sur l’effort.
Active stiffness

Particular case: control of the robot in order to obtain the behavior of a programmable spring:
- large gain in the position controlled directions
- small gain in the force controlled directions

Advantage
- Simple to implement

Drawback
- Gains tuning: depend on the environment knowledge
Hybrid position/force control

Some directions are position controlled and other are force controlled, using a selection matrix $S = \text{diag}(s_1, \ldots, s_{n_b})$, with $s_i = 1$ : pos and 0 : force.

Figure 2-VI : scheme de commande hybride dynamique.
LCP : Loi de Commande en Position,
LCF : Loi de Commande en Effort,
MGD : Modèle Géométrique Direct,
$F_{\text{act}}$ : torseur des efforts et couples des actionneurs.
Interaction control: active solutions (4)

Hybrid position/force control

Some directions are position controlled and other are force controlled, using a selection matrix $S = \text{diag}(s_1, \ldots, s_{n_b})$, with $s_i = 1 : \text{pos}$ and $0 : \text{force}$

Advantage

- Simultaneous action on the two outputs: position and force, thanks to two control laws

Drawbacks

- Position perturbation in a force controlled direction not compensated
- Contact has to be maintained in force controlled directions and no contact is required in position controlled directions: perfect knowledge of the environment
Interaction control: active solutions (6)

External hybrid position/force control

Same principle, but with a cascade structure

Figure 2-VII: schéma de commande hybride externe, avec asservissement articulaire de la position.
LCP : Loi de Commande en Position,
LCF : Loi de Commande en Effort,
MGI : Modèle Géométrique Inverse,
U : consignes moteurs,
q : variables articulaires.
**External hybrid position/force control**

Same principle, but with a cascade structure

**Advantages**

- Force reference is dominant/position reference
- No environment knowledge required

**Drawback**

- Potentially less stable
Skin harvesting

- Skin samples of less than a mm thick and 5 to 10 cm large
- Regular contact and high applied force (environ 100 N)
Skin harvesting

Automated skin samples cutting
Scalpp, LIRMM, Montpellier (4)

**Avantages**
- Accuracy
- Repetability
- Simple to use

**Drawbacks**
- Clinical use

[Video Scalpp]
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Collaborative manipulation

Definition
Collaborative manipulation: direct use of one or several robots by an operator. Robot hold by the user, and controlled to guide the operator gestures.

Advantages
- Task constraints or virtual fixtures: forbidden zones, motion filtering, tool gravity compensation
- Safety
History of collaborative manipulation

Origins

Cobots, Hands-on robot...

**Discipline(s):** Robotique & médecine

**Époque:** 2001

**Lieu:** Londres, UK.

**Inventeur(s):** J. Cobb, B. Davies et Acrobot Ltd.

**Invention:**
Première procédure clinique assistée par ACROBOT en chirurgie du genou (Prothèse totale de genou).

**Commentaires:**
Premier robot synergique mis en œuvre en clinique.


...with industrial robots

**Properties**

- Non backdrivable systems
- Force sensor

**Drawback**

- No intrinsic safety

[Video Austin University]
Motivation: orthopedic surgery

Bone drilling for knee surgery, knee prosthesis
in medicine: Acrobot, Imperial College (2)

Acrobot kinematic architecture

4 DOFs (1 position controlled DOF, 3 force controlled DOFs)

Backdrivable actuators
Steady-Hand, JHU

Motivation: eye microsurgery

Positioning precision (tremor, drift), tactile feedback

Augmented reality, microscopic vision

[Image of Steady-Hand device]

Video Steady Hand
Plan

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Telemanipulation

Definition

Telemanipulation: manipulation with a remote robot

Basic telemanipulation system

Master robot manipulated by an operator and slave robot achieving the task at a distance
History of telemanipulation

Origins

Need to manipulate dangerous material

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<td>Inventeur(s)</td>
<td>R. Goertz</td>
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Invention:
Premier système robotique "maître-esclave" avec motorisation électrique.  

Commentaires:
Applications dans le nucléaire.
Background

Laparoscopy: several tools, complex medical acts, tiredness
Commercial products

- Aesop: moves endoscopes with voice-teleoperation
- da Vinci telemanipulation system for surgery
Principle

- Trocart constraint achieved by passive joints
- Numerous tools with extra-DOF
Principle

- Trocart constraint achieved by passive joints
- Numerous tools with extra-DOF
Example

Mitral valve repair

Video da Vinci
### Advantages

- Ergonomics
- Augmented reality
- Tools
- Clinical practice

### Drawbacks

- Investment (daVinci 1.3 M$ + maintenance)
- No force feedback
- Long term feedback?
Force feedback teleoperation

History

First *haptic* system in 1967

First commercial system: Phantom (end of the 1990’s)

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</tr>
</thead>
<tbody>
<tr>
<td><strong>Epoque</strong></td>
<td>1967</td>
</tr>
<tr>
<td><strong>Lieu</strong></td>
<td>USA</td>
</tr>
<tr>
<td><strong>Inventeur(s)</strong></td>
<td>UNC</td>
</tr>
</tbody>
</table>

**Invention:**
Premier système de retour haptique (retour d’effort).

**Commentaires:**
Forces générées par un champ de particules modélisées.
Force feedback teleoperation

CT-Bot !