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Medical Robotics

A Teleoperation System for Research in MIRS

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the DLR teleoperation system

- three versatile robots MIRO
  - light-weight: weight < 10 Kg, payload 30N
  - compact and redundant: 7 DOF, coupled joints
  - torque sensors in all joints
  - safe interaction: reduced mass, compliant control
  - adaptable and flexible: magnetic instrument interface, redundant, position, impedance, torque control
- a stereo endoscope carried by the transparent robot
- bimanual force feedback
  - haptic device Omega.7
  - forces and grasping displayed
- vision
  - auto stereoscopic display (glasses-free 3D vision)
  - eye-tracking
  - augmented reality
  - image stream via ethernet
- control by optically tracked forceps
surgical tools

- versatile instrument interface

- two surgical instruments with force/torque sensing attached to the white robots
optimized setup of robots relative to the patient in the OR obtained by taking into account robot kinematics and optimization criteria to avoid collisions, singularities and workspace boundaries throughout the operation ⇒ setup times and error sources are reduced
preoperative planning

- on VR and patient data (CT/MRI . . .)
- the user defines the operating field inside the patient (in VR, CT slices, . . .)
- an optimization algorithm (currently, genetic algorithms combined with a gradient-based method) finds several setup sufficiently satisfying the optimization criteria
output of preoperative planning

\[ S_{\text{pre}} = \{ \text{world}_i T_i, \text{base}_i T_i, \text{work}_i T_i, \text{q}_{\text{work},i}, \text{base}_i T_i, \text{q}_{\text{app},i}, \text{world}_i \text{trocar}_i P_i, \text{base}_i P_i \} \]

(where \( b^a T_i \) defines the frame \( a \) in frame \( b \), relative to robot \( i \))
intraoperative setup

- markerless, contact-free registration based on the ICP algorithm to align the preoperative image data with the actual patient position
- table referencing, i.e., measurement of the table position relative to the patient
- mounting of the robots
- recalculation the optimal OR setup taking into consideration the registration and table referencing results (takes about 20 sec since good initial solutions are known from the preoperative planning)
- robots positioning and trocars setting through the Autopointer

if the user decides on short notice to arrange robots or trocars differently from the planned configuration, the updated trocar positions or robot base poses are measured using an optically tracked probe and fed back to the planning software
• signal based control software organized in different hierarchical layers

• a layer is composed of different function based components; all layers communicate only with their neighboring layers or with the user being above the top layer, or the hardware below the lowest one

• the components are structured according to the demand of execution time (3 kHz for joint control)

• the layer structure creates abstraction levels for developers and researchers
operating modes

1. *autonomous positioning*: the slaves move automatically to the approach pose and back (position controller)
2. *manual motion*: the user moves the slave arms through the trocars with his hands on the robot (a cartesian impedance controller allows only translational motions)
3. *teleoperation*: the user teleoperates the slaves from the master station (position controller)
1. hand-eye-coordination matrix: \[
baseM R_v^{baseS} = tcpE R^{display} R_v^{display} baseM R
\]
(alignment of the haptic channel with the visual channel)

2. desired tcp in the slave base frame: \[
tcpS T_d(t) = tcpS T(0) + \int_0^t g(tcpS, tcpS v(t), s, c(t))
\]

3. force/torque commanded to the master: \[
tcpM w_d(t) = h(tcpS, tcpS w(t), p, c(t))
\]

- \( c(t) \in 0, 1 \) couples master to slave if the user presses the foot pedal and the slave is in within the admissible workspace
- \( s/p \in \mathbb{R}^6 \) velocity/force scaling
inverse kinematics

In the context of robotic surgery, inverse kinematics is a critical aspect for ensuring precise and safe interactions. The process involves solving for the joint configurations that achieve desired poses and conditions. Specifically:

1. **Cartesian condition** $c_1$: To reach the TCP (Tool Center Point) pose $\mathbf{T}_{\text{TCP}}$.

2. **Trocar condition** $c_2$: To intersect the instrument with the trocar $\mathbf{p}_{\text{trocar}}$.

3. **9 DOF - (6 + 2) constraints**: 9 degrees of freedom minus the 8 degrees of freedom already constrained by the 6 joint positions and 2 fixed joints, resulting in a 1-dimensional null space available for optimization.

The process involves:

- **Closed form calculation of trocar condition** $c_2$: Determination of $q_6, q_9$.
- **Choice of redundant joint** $q_{\text{fix}}$.
- **Optimization of** $q_{\text{fix}}$: Updating $q_{\text{fix}}$, evaluating optimization criteria, and calculating the closed-form solution for condition $c_1$.

These steps ensure that the robotic system can accurately and safely interact with the patient during surgical procedures.
\[ q_8 = -\arctan2(-8t_y, -8t_x) \quad q_9 = -\arctan2(-9t_y, -9t_x) \]
all possible configurations of the robot to reach a certain tool tip position and orientation through a given trocar with $q_7 = -3.92^\circ$
