Soft Robotics – Design and Control Strategies for Robots Interacting with Humans

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Applications requiring mainly fast and precise positioning are covered in a high extent by industrial robots already.
Industrial robots get cheaper and cheaper → dead end?

Applications requiring mainly fast and precise positioning are covered in a high extent by industrial robots already.
Robotics orients towards new application fields, such as:

- Industrial assistant robots
- Space robotics
- Service robotics
- Medical robotics

For these applications, we need a type of safe and „soft“ robots, realized e.g. via high-fidelity torque control in the joints or with passive compliance.
Space Robotics

„Affordable“, operations in space with mobile/freeflying robonauts for
• Servicing
  and
• Exploration
ROKVIISS

- friction identification joint 2

- ROKVISS - friction identification point 2

- position

- force feedback

- Coulomb friction

- Load-dependent friction

- Viscous friction at 1°, 5°, 10°, 20°, 30° [deg/s]

- Force feedback

- Position
Experimental Humanoid Manipulator

**Arms:** 7 DoF DLR Light-weight robot III, modular concept enables symmetric construction of a right and left arm.
(2x7 DoF)

**Hands:** Modified 4-fingered DLR hand II, each Finger 3 DoF.
(2x(4x3) DoF)

**Head:**
DLR 3D Modeler (3DMo): Sensor head with stereo cameras, laser stripe sensor, laser range scanner mounted on a pan-tilt unit.
(2 DoF)

**Torso:**
Based on the DLR light-weight robot III joint technology realizing 3 active DOF and one passive Joint (3 DoF)

**Total:** 43 DoF
Service Robotics

Serving Water

Task: Open the container
Experimental – Surgical Robot
The DLR Medical Robot
Safety Requirements

- low inertia, high compliance
- redundant, error detecting electronics
- redundant sensors
- Control which is robust w.r.t. changes of the environment
  - direct control of the amount of energy introduced by the motors
- collision detection/reaction with joint torque sensors
- Self-collision avoidance control strategies
- Safety of the software: - safety of the algorithms
  - safety through processor and OS redundancy
- collision avoidance with redundant kinematics

planning
control

Hardware

safe, robust control, collision detection/reaction

safe design

collision avoidance
**User Safety Concepts**

- Safety measures for evaluating the effect of collisions on humans and robots
- Extensive experimental evaluation
Arm III: 7 joints, ~13.5 kg, weight/load ~1/1, power ~150 Watt, only three cables

Hand II: 13 joints, 3 kg fingertip-force
Light-Weight Design

DLR medical robot

- 7 Axes
- Weight < 10 kg
- Payload: 3 kg

DLR light-weight robot

- 7 Axes
- Weight: 13.5 kg
- Payload: 13.5 kg
Technology transfer

DLR-HIT-Hand

3dof-prothesis

KUKA Roboter GmbH

Schunk GmbH
Joint Flexibility – a Feature, not a Drawback

For compliance control:
- Safe interaction with humans
- Manipulation in unknown environments
- Haptics

(Khatib Lab, Stanford Univ.)

(Bicchi Lab, Univ. of Pisa)
DLR’s New Hand-Arm System

Will presumably be a highly complex robotic system

- Anthropomorphic design/kinematics
- 54 motors in one arm-hand
- Variable stiffness/antagonistic driven
- Size of average European male
- Two handed system planned (>110 Motors)

The antagonistic concept

Motor 1

Motor 2

Nonlinear spring

Output
Variable Stiffness Actuator Testbed

Testbed for VS-Joint prototypes

Load

VS-Unit

Angular Encoder

Motor Unit

Torque Sensor

Alternative VS-Unit with antagonistic actuation
Control components

Light-weight robot with elastic joints

Joint torque sensor

Movement accuracy

Safe human-robot-environment interaction

active vibration damping

compliance control

robust task execution

collision reaction

self-collision avoidance

collision reaction

self-collision avoidance

robust task execution

compliance control

active vibration damping

Movement accuracy

Safe human-robot-environment interaction

Light-weight robot with elastic joints

Joint torque sensor
Vibration Damping

Light-weight $\rightarrow$ higher joint compliance $\rightarrow$ vibrations
Measurement $\rightarrow$ torque sensor $\rightarrow$ vibration damping
Model of the flexible joint robot

possible state vector:

\[ x_1^T = \{\theta, \dot{\theta}, q, \dot{q}\} \]

used state vector:

\[ x^T = \{\theta, \dot{\theta}, \tau, \dot{\tau}\} \]

\[ \tau = K(\theta - q) \]

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau + DK^{-1}\dot{\tau} + \tau_{ext} \]

\[ B\ddot{\theta} + \tau + DK^{-1}\dot{\tau} = \tau_{\text{m}} \]
Joint Level Control

\[ \tau = \tau_m + \tau_{ext} \]

- **passive controlled actuators** - eq. (2),(4)
- **rigid robot dynamics** eq.(1)

4th order state feedback controller: \( \theta, \dot{\theta}, \tau, \dot{\tau} \)

same structure used for

- torque control
- position control
- impedance control

\[ \dot{\theta}, \dot{\dot{\theta}} \]
Control components

- Light-weight robot with elastic joints
- Joint torque sensor
- Movement accuracy
- Safe human-robot-environment interaction
  - Compliance control
  - Collision reaction
  - Self-collision avoidance
  - Robust task execution
- Active vibration damping
Cartesian Stiffness Control

\[ f = M \Delta \ddot{x} + D_k \Delta \dot{x} + K_k \Delta x \]
Cartesian Impedance Controller

Two step concept for noncollocated systems:

- **Shaping the potential energy - collocated feedback**
  - Asymptotic stabilization around $x_d$ ($\tau_{ext} = 0$)
  - Implementation of the desired compliance relationship ($\tau_{ext} \neq 0$)
  - Feedback of $\theta, \dot{\theta}$

- **Shaping of the kinetic energy - noncollocated feedback**
  - Damping of vibrations => increased performance
  - Feedback of $\tau, \dot{\tau}$ (torque controller)

$\Rightarrow$ Full state feedback
Main Idea for Energy Shaping

At equilibrium:
1 to 1 correspondence

\[ \tilde{q}(\theta) \]

Between \( \theta \) and \( q \)

A controller based on \( \tilde{q}(\theta) \) instead of \( q \)

- is collocated \( \Rightarrow \) passivity
- satisfies static requirements related to \( q \):
  - desired equilibrium point
  - desired stiffness
Unified approach for torque, position and impedance control on Cartesian and joint level
Impedance Control
Self-Collision Avoidance

Self collision avoidance based on repelling potentials fits within the passivity framework
developed together with Univ. Napoli
The skeleton algorithm for real-time collision avoidance of a humanoid manipulator

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Inverse Kinematics for Redundant Robots

- Constrained optimization
  - Singularity avoidance
  - Collision avoidance
  - Nonholonomic mobile systems

- Interactivity
- Reactivity
Collision Detection

\[ \tau_m \rightarrow \tau_F \rightarrow \tau \rightarrow \tau_{ext} \]

motor dynamics \hspace{2cm} rigid body dynamics

\[ \tau \rightarrow q \rightarrow \dot{q} \rightarrow \hat{\tau}_{ext} \approx \tau_{ext} \]

disturbance observer

developed together with Univ. Roma
Collision Detection

Motor dynamics

Rigid body dynamics

Disturbance observer

\[ \theta \rightarrow \hat{q} \]

\[ \hat{q}, \dot{q} \]

\[ \tau_m \]

\[ \tau_F \]

\[ \tau \]

\[ \tau_{ext} \approx \hat{\tau}_{ext} \]

developed together with Univ. Roma
Impact Experiments

- **strategy 1**: stopping the trajectory

- **strategy 2**: gravity compensated torque mode

investigated criteria for head, neck, chest
Safety aspects

How to define a safety standards for robots?

New standard for safety in Robotics: ISO 10218 says:

- \( v_{\text{max}} < 0.25 \text{m/s} \)  OR
- \( F_{\text{max}} < 150 \text{N} \)  OR
- \( P_{\text{max}} = 80 \text{W} \)
How dangerous is the robot really?

Safe Human-Robot Interaction

Impact Experiments

Head
Velocity: 2.0 m/s
Detection: None
Strategy: None
For all tested criteria the LWR was in the lower quarter of the green area.
For all tested criteria the LWR was in the lower quarter of the green area

**New safety indices** have to be defined for robotics
Collision detection

Collision Human-Robot

- 90°/Sec.
- Strategy 3
III. Impact Experiments LWRIII - Human
Cartesian Impedance Control:

vertical
  stiffness = 500 N/m
damping factor 0.001

horizontal
  stiffness = 500 N/m
damping factor 0.7
Safety Requirements

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Hardware

Planning

Control

Collision avoidance

Safe design
Conclusions

- Under assumption of joint elasticity, the torque becomes a state full state feedback
- Passivity based control is particularly suited for unknown environments
- Unified approach for position, torque and impedance control
- Impedance control needs adequate robust planning strategies
- Collision detection based on torque sensors is more accurate
- The DLR robot is safe (from automotive point of view) even at 2m/s
- We need new injury indices customized for robotics for protecting humans AND robots
Safe hardware design
- light-weight
- compliant

Redundant sensor systems

Control which is robust w.r.t. changes of the environment
- direct control of the amount of energy introduced by the motors

Collision avoidance strategies

Collision detection and reaction strategies

Safety of the software
- safety of the algorithms
- safety through processor and OS redundancy

Safety measures for evaluating the effect of collisions on humans and robots

EXPERIMENTAL EVALUATION
1 Title
1 Folie Industrial robots price
new applications DLR 4Folien
Measures for safety 1 folie
Hardware design 3 folien
New concept 2 folien
Sensor resolution 1
Robust control 6
Collision avoidance 1
Collision detection/reaction 3
Safety indices ADAC impact tests 6
1 Conclusions
Placing of Pedicle Screws
Experimental Setup with LBR II

Robot

Linear guides with marker arrays

Navigation system

Registration of vertebra

Linear guides with marker arrays
Conditions for Energy Shaping

In any equilibrium position $q = \bar{q}(\theta)$ if $k$ not too small

For very small $k$:

$q_1$ - first equilibrium

$q_2$ - second equilibrium

For a general potential energy $U$

\[
\begin{align*}
\left| \frac{\partial^2 U(q, \theta)}{\partial q^2} \right| & > \alpha \\
\left| \frac{\partial^2 U(\theta, q)}{\partial \theta \partial q} \right| & \neq 0
\end{align*}
\]

Uniqueness of the solution

Invertibility

Extendable to a broad class of noncollocated E-L systems

\[
\bar{q}(\theta)
\]

diffeomorphism
Antagonistic test joint setup

- Every motor used in bidirectional mode
- 4 progressive elastic elements per joint
- Direct drive to prevent gear side-effects
- Tendon-driven
- Motor unit miniaturisable to Ø 28mm
- At least 30N at fingertip
Passively yielding joints

- rubber balls have progressive spring properties with nearly exponential characteristics
- the force with which the balls are squeezed determines the stiffness of the box
- adaptable characteristics through number and diameter of balls
Robust Assembly Strategy

Object localization (Image Processing)

Geometrical Analysis

Automatical generation of optimal assembly trajectory

Impedance based execution of planed trajectory

Maximal robustness w.r.t. position and form errors