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

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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
User Safety Concepts

- Safety measures for evaluating the effect of collisions on humans and robots
- Extensive experimental evaluation

- Collision avoidance
- Safe, robust control, collision detection/reaction
- Safe design

Hardware

Planning
Control
Hand II: 13 joints, 3kg fingertip-force

Arm III: 7 joints, ~13.5 kg, weight/load ~1/1, power ~150 Watt, only three cables
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

Schunk GmbH

KUKA Roboterer GmbH

AUTOMATICA 2006
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
Mechatronic Joint Design

- Link Position Sensor
- Cross Roller Bearing
- Power Converter Unit
- Joint- and Motorcontroller Board
- Power Supply
- Torque Sensor with digital interface (redundant)
- Harmonic Drive Gear Unit
- DLR RoboDrive with Safety Brake and Position Sensor
- Carbon Fibre robot link
Control components

- Light-weight robot with elastic joints
- Joint torque sensor
- Movement accuracy
  - active vibration damping
- Safe human-robot-environment interaction
  - compliance control
  - collision reaction
  - self-collision avoidance
  - robust task execution
  - collision reaction
  - self-collision avoidance
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:

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

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

\[
M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau + DK^{-1}\ddot{\tau} + \tau_{ext} \\
B\ddot{\theta} + \tau + DK^{-1}\ddot{\tau} = \tau_m
\]
Joint Level Control

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

same structure used for

- torque control
- position control
- impedance control
Control components

Light-weight robot with elastic joints

Joint torque sensor

Movement accuracy

active vibration damping

Safe human-robot-environment interaction

compliance control

robust task execution

collision reaction

self-collision avoidance

collision reaction

self-collision avoidance
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
Unified approach for torque, position and impedance control on Cartesian and joint level
Impedance Control
Impedance Behavior for Two-handed Manipulation
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

developed together
with Univ. Roma
Collision Detection

\[ \tau_m \rightarrow \tau \rightarrow \tau_F \rightarrow \text{robot} \]

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

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

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

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

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
Main Idea for Energy Shaping

At equilibrium:
- 1 to 1 correspondence

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

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

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

- is collocated \( \rightarrow \) passivity
- satisfies static requirements related to \( q \):
  - desired equilibrium point
  - desired stiffness