Safe Physical Human-Robot Interaction

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Robots designed to work in human environments

Extreme light-weight arms and hands with 1:1 load-weight ratio
• mobile manipulation
• interaction with unknown environments
Serving Water
Placing of Pedicle Screws
Experimental Setup with LBR II

Robot

Linear guides with marker arrays

Registration of vertebra

Navigation system

Linear guides with marker arrays
~15 ms delay
Tele-Maintenance

Oberpfaffenhofen

Space

Force-Feedback: min. 6 DoF
"Affordable", remotely controlled operations in space with mobile (freeflying) robonauts for
• Servicing
  and
• Exploration
Virtual Product Design: Assembly Scenarios

DLR LWR as 6-DOF Haptic Interface
User Safety Concepts

- intrinsically safe robot design
- redundant, error detecting electronics
- redundant sensors
- "dead-man-switch", range check for measurements/commands,…
- robust, passivity based control algorithms
- collision detection/reaction with joint torque sensors
- direct control/limitation of exerted forces and torques
- soft robotics – compliance control
- collision avoidance with redundant kinematics
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
Vibration Damping

Light-weight $\iff$ higher joint compliance $\iff$ vibrations
Measurement $\iff$ torque sensor $\iff$ vibration damping
Joint Flexibility – a Feature, not a Drawback?

YES, for compliance control:

• Safe interaction with humans
• Manipulation in unknown environments
• Haptics

(Khatib Lab, Stanford Univ.)

(Bicchi Lab, Univ. of Pisa)
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
Design Overview
Mechatronic Joint Design

Additionally: force-torque sensor at the wrist
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Strategy

Starting Point:

Key Technology:

Control approach:

Goals:

Light-weight robot with elastic joints

Joint torque sensor

Position control with active vibration damping

Movement accuracy

Programmable stiffness („Soft Robotics“)

Safe human-robot interaction
Flexible Joint Robot

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

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

\[
B\dddot{\theta} + \tau + DK^{-1}\dot{\tau} = \tau_m
\]

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

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Light-weight robot with elastic joints

Joint torque sensor

Position control with active vibration damping

Programmable stiffness („Soft Robotics“)

Movement accuracy

Safe human-robot interaction
Position Control with Full State Feedback

- global asymptotically stable (Lyapunov-Analysis)
- passive => robust with respect to parameter uncertainties

Model error may cause performance degradation but not in instability
Passivity

The energy which can be extracted from the system is bounded
User Safety Concepts

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Planning

Control

Collision avoidance

Collision detection and reaction

Failure detection

Hardware
Quantization of Severity of Impact Injury

No standards for robotics

Some “borrowed” indices

Head
• **Head Injury Criterion** - HIC (car crash tests)
• Maximum Impact Power
• Maximum Mean Strain Criterion
• Vienna Institute Index, Effective Displacement Index, Revised Brain Model

\[
\text{HIC} = \max_{(t_2,v-t_1,v)} \left( (t_2,v - t_1,v) \cdot \left( \frac{1}{t_2,v-t_1,v} \int_{t_1,v}^{t_2,v} \ddot{x}_{Mav} \, dt \right)^{\frac{5}{2}} \right) \leq 1000
\]

mean acceleration
Collision Detection

measured signals: \( \theta, \tau \)

computed signals: \( q, \dot{q}, \ddot{q} \)

observable:

collision torque

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

\[
B \ddot{\theta} + \tau + DK^{-1} \dot{\tau} = \tau_m - \tau_F
\]

gearbox friction torque / actuator failure
Observer Implementation

(De Luca et. al., 2005)

\[
\hat{\tau}_{ext} = K_I \left[ p(t) - p(0) - \int_0^t \dot{p}(t) \, ds \right]
\]

\[p(t) = M(q) \dot{q}\] - generalized momentum

\[
\dot{p}(t) = \tau - C^T(q, \dot{q}) \dot{q} - g(q) - \hat{\tau}_{ext}
\]

Linear resulting observer dynamics:

\[
\hat{\tau}_{ext} + K_I \hat{\tau}_{ext} = K_I \tau_{ext}
\]

Ideal situation (no noise) \( K_I \rightarrow \infty \implies \hat{\tau}_{ext} \approx \tau_{ext} \)
Reaction Strategies

• **strategy 1**: stopping the trajectory

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

• **strategy 3**: impedance control mode using $T_{ext}$

• **strategy 4**: admittance control mode using $T_{ext}$
Impact Tests

Criteria And Control Structures For A Safe Human-Robot Interaction
Results on Balloon Impact

- residual & velocity on joint 4 for different reaction strategies

impact at 10°/s with coordinated joint motion
Results on Balloon Impact (cont’d)

- residual & velocity on joint 4 for different reaction strategies

Impact at 100°/s with coordinated joint motion
Results on Dummy Head Impact

- approaching at 30°/s with each joint
- residual gains $K_I = \text{diag}\{25\}$

HIC < 400

HIC approaches critical value at 70°/s

Joint torque

Observer

0/1 detection

Acceleration

2 ms
Strategy

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Joint torque sensor

Position control with active vibration damping

Programmable stiffness ("Soft Robotics")

Movement accuracy

Safe human-robot interaction
Cartesian Stiffness Control

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

Admittance control

- Force Controller
- Inverse kinematics for redundant robots

Stiffness control

- Projection of stiffness & damping: Cartesian to joints null-space to joints
- Variable gains for joint stiffness control & vibration damping

Impedance control

- Cartesian stiffness & damping matrices
- Operational space
- Robot dynamics
- Joint space
- Direct kinematics
- Desired Torque computation

1ms bus

Joint task

- Position control
- Impedance control
- Torque control

State vector:
\[ \theta, \dot{\theta}, \tau, \dot{\tau} \]
Application: Piston Insertion

Teaching by Demonstration
Cartesian Compliant Behavior

Admittance control

Force Controller

Inverse kinematics for redundant robots

Stiffness control

Projection of stiffness & damping: Cartesian to joints
null-space to joints

Impedance control

Cartesian stiffness & damping matrices

Joint space

Operational space

Robot dynamics

Direct kinematics

Desired Torque computation

1ms bus

Slow Cartesian Task (6ms)

Variable gains for joint stiffness control & vibration damping

Fast Cart. Task (1ms)

Joint task 0.33ms

Position control

k=max

Impedance control

k=0

Torque control

State vector: \( \theta, \dot{\theta}, \tau, \dot{\tau} \)
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)

=> Full state feedback
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
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 $U$

$$
\left| \frac{\partial^2 U(q, \theta)}{\partial q^2} \right| > \alpha
$$

Uniqueness of the solution

$$
\left| \frac{\partial^2 U(\theta, q)}{\partial \theta \partial q} \right| \neq 0
$$

Invertibility

Extendable to a broad class of noncollocated E-L systems
Unified approach for torque, position and impedance control on Cartesian and joint level
Torque Control
Impedance Control
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Inverse Kinematics for Redundant Robots

- Constrained optimization
  - Singularity avoidance
  - Multiple constraints
  - Nonlinear mobile systems

- Interactivity
- Reactivity
Collision Detection Using Redundancy
Collision Detection Using Redundancy