Force and Visual Control for Physical Human-Robot Interaction

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Physical human-robot interaction

Force control
- Impedance control
- Force control

Visual control
- Position-based visual servoing
- Pose estimation using vision

Interaction control using vision and force
- Position-based visual impedance control
- Pose estimation using vision and force

Experiments
Human-Robot Interaction

- Traditional industrial robotics
  - Segmented workspace for machines and humans

- Intelligent machines working in contact with humans
  - Haptic interfaces and teleoperators
  - Cooperative material handling
  - Power extenders
  - Rehabilitation and physical training
  - Entertainment

- Human-Robot Interaction (HRI)
  - Cognitive issues [cHRI]: perception, awareness, mental models
  - Physical issues [pHRI]: safety, dependability
  - Ethical issues: motivations and critics about HRI, acceptability
- **Risks for robots interacting with humans**
  - Heavy moving parts and objects transported
  - Sensory data reliability
  - Level of autonomy/unpredictable behaviours

- **Solutions for collaborative human-robot operation**
  - Design of non-conventional actuators (passive safety)
  - Interaction control (active safety)
  - Dependable algorithms for supervision and planning
  - Fault tolerance
  - Need for quantitative metrics
Motion control vs. force control

- Advanced industrial robotics and service robotics demand for control of interaction between robot manipulator and humans
- Use of purely motion control strategy is candidate to fail (task planning accuracy)
- Control of contact force (compliant behaviour)
- Use of force/torque sensor (interfaced with robot control unit)
Indirect vs. direct force control

- Indirect force control: force control via motion control (w/out explicit closure of force feedback loop)
- Direct force control: force controlled to desired value (w/ closure of force feedback loop)
- Impedance control with inner motion control loop
  - Force/torque measurements for linear and decoupled impedance
  - Compliant frame between desired and EE frame (disturbance rejection)
Set-up
- COMAU Smart 3-S robot
- Open control architecture
- ATI force/torque sensor
- 6-DOF spatial impedance

![surface contact](image)

- Low compliance, high damping
- High compliance, low damping
- High compliance, high damping

Experiments
Service Tasks

- Set-up @ ARTS Lab, SSSA Pisa
  - Assisting disabled people
  - DEXTER cable-actuated robot arm
  - Active vs. passive compliance

- microwave warming
- wiping table
- sheet removing
- Force control with inner motion control loop
  - Regulation of force and moment to desired values

\[
\begin{align*}
  f_d, \mu_d &\rightarrow \text{FORCE \& MOM} \\
  p_e, R_e &\rightarrow \text{POS \& ORIENT} \\
  a &\rightarrow \text{INVERSE} \\
  \tau &\rightarrow \text{MANIPULATOR} \\
  q &\rightarrow \text{DIRECT KINEMATICS}
\end{align*}
\]
- Force control
  - Regulation to zero force
  - Useful for manual guidance
Force/position control with full parallel composition

- Linear acceleration

\[
\mathbf{a}_p = \ddot{\mathbf{p}}_r + \mathbf{K}_{Dp}(\mathbf{p}_r - \dot{\mathbf{p}}_e) + \mathbf{K}_{Pp}(\mathbf{p}_r - \mathbf{p}_e)
\]

\[
\mathbf{p}_r = \mathbf{p}_c + \mathbf{p}_d
\]

\[
\dot{\mathbf{p}}_r = \dot{\mathbf{p}}_c + \dot{\mathbf{p}}_d
\]

\[
\ddot{\mathbf{p}}_r = \ddot{\mathbf{p}}_c + \ddot{\mathbf{p}}_d
\]
Experiments

- Parallel force/position control
  - Contact with unknown surface
  - Force regulation with position tracking
Extension to Cooperating Robots

- Dual-arm set-up
  - 6ax robot
  - 7ax robot

peg-in-hole assembly
6-DOF impedance
control of absolute motion
and internal forces

absolute & relative impedance
absolute impedance
human-object interaction

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Artificial intelligence vs. automatic control

- Vision capabilities bring the robots nearer to human skills
- The information that can be extracted from images is very rich and can be used at different levels of a hierarchical architecture

Visual servoing

Data complexity

Highest level (Artificial Intelligence)
Visual information used to understand the world and decide how to act
Bandwidth

Lowest level (Automatic Control)
Visual measurements used in the control law

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Distinguished Talk VIII
10-Oct-06, 10:30–11:10
- **Direct visual servoing**

  ![Direct visual servoing diagram]

  - Vision-based control
  - Robot
  - Camera
  - Visual feedback: $\geq 100$ Hz

- **Indirect visual servoing**

  ![Indirect visual servoing diagram]

  - Vision-based control
  - Motion control
  - Robot
  - Camera
  - Visual feedback: $\geq 20$ Hz
  - Joint feedback: $\geq 100$ Hz

  Dynamic look-and-move
Indirect Visual Servoing

Dynamic look-and-move

- Vision system
- 3D object
- Estimated pose
- Computer
- Control unit
- MOVE

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Position-based (3D) visual servoing scheme

- Calibration dependent
- Pose control and pose estimation

- Calibrated cameras
- Target objects of known geometry
Reconstruction of object pose from observed workspace

- Selection of image regions
- Image acquisition
- Image region segmentation
- Image features extraction
- Pose reconstruction

REAL TIME!
Pose estimation with dynamic image features selection

- Extended Kalman Filter (EKF) based on approximate object models
Extended Kalman Filter

- State-space model of the object motion
  \[ w_k = A w_{k-1} + \gamma_k \]
  \[ A = \begin{bmatrix} I_6 & T I_6 \\ 0_6 & I_6 \end{bmatrix} \]

- Output equation
  \[ f_k = g_f(w_k) + \nu_k \]

- Jacobian of the output equation
  \[ J_f = \frac{\partial g_f(w)}{\partial x_o} \sim \text{image Jacobian} \]
- **Occlusion detection**
  - Representation of polyedral objects based on Binary Space Partitioning (BSP) trees
  - Built through a recursive and hierarchical partition of the set of object surfaces with respect to suitable partition planes
  - A recursive $O(N)$ visit of the tree allows recognizing all the occluded features with respect to a camera
Dynamic mode (interposing parts)

- A single BSP tree is generated on-line, describing all the objects with respect to a common reference frame.
- For each camera, the visit algorithm is applied to the BSP tree.
- A Kalman filter is used for each object.
The preselection algorithm estimates the position of the projections of the object visible corners on the image planes of each camera.
A selection algorithm based on suitable quality indexes is employed to find the (sub)optimal set of (6 to 8) feature points.

Some quality indexes for the cost function:
- Spatial distribution (⇒ avoiding points concentration)
- Angular distribution (⇒ avoiding alignments)
- Camera distribution (⇒ triangulation)
- Anti-chattering (⇒ estimate noise reduction)
- Extraction reliability (⇒ robustness)
Features Extraction

Visual Control > PBVS > Pose Estimation

Out of sight

extracted corners
Visual Servoing Architecture

COMAU - C3G 9000 open

Robot CPU
Servo CPU
Power amplifiers

User interface modules

Board BIT 3

BUS VME

Robot COMAU SMART–3S
FOLLOWER

Robot COMAU SMART–3S
LEADER

Vision - PC (VESPRO)

Vision PC

Board BIT 3
Control PC

Control - PC (RePLiCS)

SONY XC 8500 CE

MATROX GENESIS

BUS AT

RS232

MATROX GENESIS

SONY XC 8500 CE

(PDL2)
Extension to Grasping

- Visually guided grasping
  - Object in unstructured environment
  - Visual servoing
  - Tracking of object motion
  - Good reaction to uncertainties
- Occlusion detection in a multi-arm robotic cell
  - BSP-tree representation of the whole robotic cell updated online
Hybrid eye-in-hand/eye-to-hand camera system
- Good accuracy and ability to explore the workspace with a limited sight (eye-in-hand)
- Panoramic sight of the workspace with a limited accuracy (eye-to-hand)
- Higher flexibility in the presence of a dynamic scenario (hybrid)
Interaction control using vision and force

- Vision provides global information on surrounding environment to be used for motion planning and obstacle avoidance.
- Force allows adjusting robot motion so that local constraints imposed by environment are satisfied.
- Set-up @ DLR, Germany
  - KUKA robot with force sensor and camera embedded in the gripper

- Integration of vision and force
  - Visual feedback in gross motion
  - Force feedback in fine motion
Control Strategy

Problem

- Control interaction of a robot manipulator with a rigid object of known geometry but unknown position and orientation

\[ \varphi(p) = 0 \]

\[ \{o_o, R_o\} \rightarrow x_o \]

Solution

- When robot is far from object
  - Position-based visual servoing is adopted
  - The relative pose of the robot with respect to the object is estimated recursively using only vision

- When robot is in contact with object
  - Any kind of interaction control strategy can be adopted (impedance control, parallel force/position control)
  - The relative pose of the robot with respect to the object is estimated recursively using vision, force and joint position measurements
Position-based visual impedance
Pose estimation algorithm same as before for the visual part

Input measurements set enlarged

- Image features = \( f \)
  \[
  f = g_f(x_o) \rightarrow J_f = \frac{\partial g_f(w)}{\partial x_o}
  \]

- Force = \( h \) (Hp: point contact)
  \[
  n_h = \frac{h}{\|h\|} = g_h(x_o) \rightarrow J_h = \frac{\partial g_h(w)}{\partial x_o}
  \]

- Joint positions = \( q \)
  \[
  \delta_{hq} = n_h^T p(q) = g_{hq}(x_o) \rightarrow J_{hq} = \frac{\partial g_{hq}(w)}{\partial x_o}
  \]
Modified EKF

- State-space model unchanged
- Modified output equation (when $h \neq 0$)

\[
\begin{bmatrix}
    f_k \\
h_k \\
\delta_{h,q,k}
\end{bmatrix}
= 
\begin{bmatrix}
g_f(w_k) \\
g_h(w_k) \\
g_{h,q}(w_k)
\end{bmatrix}
+ \nu_k
\]

- Modified Jacobian

\[
J = 
\begin{bmatrix}
    J_f \\
    J_h \\
    J_{h,q}
\end{bmatrix}
\]
• Pose estimation errors

Experiments

Interaction Control Using Vision and Force

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References

References

- V. Lippiello, B. Siciliano, L. Villani, "3-D objects motion estimation based on Kalman filter and BSP tree models for robot stereo vision", *Archives of Control Sciences*, 12, 2002
- V. Lippiello, B. Siciliano, L. Villani, "Robot interaction control using force and vision", *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2006
Interaction control of robot manipulators in partially structured environments

- Position-based visual servoing of multi-robot cells using hybrid eye-in-hand/eye-to-hand cameras configuration
- Position-based visual impedance control

Future work

- Hybrid force/visual control and parallel force/visual control
- Interaction control in unstructured environments (presence of humans)
- Uncalibrated cameras
- Integration of new sensors (proximity sensors, joint torque sensors, …)
- ...

Conclusion
Happy 70th Birthday, Suguru 😊