Exploiting contact for whole-body physical human-robot collaboration

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2 October 2015
IROS 2015
Exploiting Contacts in everyday activities
Exploiting contacts for dynamics compensation

2-DOF simulation shows 37% of forces are Centrifugal plus Coriolis Forces (in direction Normal to motion)
Valerio Ortenzi, Maxime Adjigble, Kuo Jeffrey, Rustam Stolkin, Michael Mistry, An Experimental Study of Robot Control During Environmental Contacts Based on Projected Operational Space Dynamics, Humanoids 2014
Optimizing trajectories with contacts

Projected Inverse Dynamics Control

Optimal Control on Projected Inverse Dynamics

Ortenzi, Stolkin, Kuo, Mistry, *Projected Inverse Dynamics Control and Optimal Control for Robots in Contact with the Environment: A Comparison*, IROS 2015
Contact is obviously a key ingredient in physical human-robot interaction:
For whole-body human-robot physical collaboration:

1. Can the robot understand the postural implications of its actions (to both itself and human partner)?

2. If so, can the robot actively influence the postural stability of its partner? And possibly make the task easier, safer, etc?
Understanding postural control:

Different body configurations, and contact points will result in different abilities to move your CoM

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Manipulability Ellipsoids:

Velocity Ellipsoids for 2-link arm

Siciliano et al., Robotics: Modelling, Planning, and Control, 2009
Manipulability: \[ \dot{q}^T \dot{q} = 1 \quad \ddot{x} = J \dot{q} \]

\[ \ddot{x}^T \left( J^+ J^+ \right) \ddot{x} = 1 \]

\[ \ddot{x}^T (J J^T)^{-1} J J^T (J J^T)^{-1} \ddot{x} = 1 \]

\[ \ddot{x}^T (J J^T)^{-1} \ddot{x} = 1 \]

Maps a unit hypersphere in joint space to an ellipsoid in task space:

Siciliano et al., Robotics: Modelling, Planning, and Control, 2009
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Manipulability of CoM

\[ J_c \dot{q} = 0 \quad \dot{c} = J \dot{q} \]

\( J \) constraint Jacobian

\( J_c \) CoM Jacobian

\[ P = I - J_c^\# J_c \]

projection into the null-space of the constraints

\[ \dot{q}^T \dot{q} = 1 \quad \Rightarrow \quad \dot{c} \left( J P J^T \right)^{-1} \dot{c} \]

\[ \tau^T \tau = 1 \quad \Rightarrow \quad ??? \]
Impulsive Dynamics of CoM

allows us to analyse the relationship between force and acceleration, in a particular configuration, without a dependancy on velocity terms

\[ H\Delta \dot{q} = B\tau' + J_c^T f_c' \]

\[ \Delta \dot{q} = H^{-1}B\tau' + H^{-1}J_c^T f_c' \] (solve for joint motion)

\[ J_c\Delta \dot{q} = J_cH^{-1}B\tau' + J_cH^{-1}J_c^T f_c' = 0 \] (consider constraints)

\[ f_c' = -\left( J_cH^{-1}J_c^T \right)^{-1} J_cH^{-1}B\tau' \] (solve for contact forces)

\[ \Delta \dot{q} = PHH^{-1}B\tau' \] (express joint motion without contact forces)

\[ \Delta \dot{c} = J\Delta \dot{q} = JP_HH^{-1}B\tau' \] (CoM motion)

\[ \tau^T\tau = 1 \quad \Delta \dot{c} \left( JP_HH^{-1}B \left( JP_HH^{-1}B \right)^T \right)^{-1} \Delta \dot{c} \]
Manipulability of Center of Mass (three metrics)

#1  Joint Velocity

\[
0 \leq \dot{\mathbf{c}}^T (\mathbf{J}_q \mathbf{P}_q^{-1} \mathbf{J}_q^T)^{-1} \dot{\mathbf{c}} \leq 1
\]

CoM Velocity

#2  \Delta Joint Velocity

\[
0 \leq \Delta \dot{\mathbf{c}}^T (\mathbf{J}_q \mathbf{P}_q^{-1} \mathbf{J}_q^T)^{-1} \Delta \dot{\mathbf{c}} \leq 1
\]

\Delta CoM Velocity

#3  Joint Impulse

\[
0 \leq \Delta \dot{\mathbf{c}}^T (\mathbf{J}_\tau \mathbf{M}_\tau^{-1} \mathbf{J}_\tau^T)^{-1} \Delta \dot{\mathbf{c}} \leq 1
\]

\Delta CoM Velocity

All three metrics take into account environmental constraints (e.g. at the feet or hands). Metrics #2 and #3 additionally account for underactuation (e.g. due to floating base.)
Which handle position is “best” for balance?

Hypothesis:
For the same CoM perturbation, a configuration with higher CoM manipulability implies that less torque is required to balance.
Manipulability ellipsoids (#3) for different handle positions measures the ability to accelerate the CoM given a unit vector of (actuated) joint impulses

Fig. 3. Schematic diagram of the planar humanoid robot model
\[
0 \leq \dot{\Delta \text{c}}^T (\text{JPM}_q^{-1} \text{J}^T)^{-1} \dot{\Delta \text{c}} \leq 1
\]

\[
0 \leq \Delta \text{c}_0^T (\text{JQM}_q^{-1} \text{J}^T)^{-1} \Delta \dot{\text{c}} \leq 1
\]

\[
0 \leq \Delta \dot{\text{c}}^T (\text{J}_\tau \text{M}_\tau^{-1} \text{J}_\tau^T)^{-1} \Delta \dot{\text{c}} \leq 1
\]

e.g. due to environmental disturbances, human contact, etc.

(whole-body) impedance relationship
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Cutaneous information aids balance

Touch as good as vision

Jeka, Physical Therapy, 1997
Moving objects drive sway

Lateral movement of touch plate evokes body motion at same frequency

Interpersonal touch for balance

Interpersonal contact reduces sway

More benefit when touching a more stable person

Interpersonal touch experiment

3 touch conditions:
- No contact (NC)
- Light touch (LT)
- Shoulder grasp (SG)

4 visual conditions:
- Both Eyes Closed
- Both Eyes Open
- Asymmetrical 1
- Asymmetrical 2

Outcome measures:
- Touch force (during LT condition)
- Centre of Pressure velocity
- Sway-Sway cross correlations

Postural sway

Contact reduces sway

Greatest effect with large baseline sway difference

Sway cross-correlations

Postural control model

All parameters except gains/delays fixed according to Peterka’s values.

Coupling the feedback loops

Designed to mimic light touch and vision
Physically coupling the pendulums

Designed to mimic shoulder grasp

Model (black) replicates data (grey)

Timing, shape and magnitude accurately replicated

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Thanks to:

Morteza Azad
Valerio Ortenzi
Rustam Stolkin
Raymond Reynolds
Jonathan Allsop
Jeff Kuo (NNL)
Jan Babic (JSI)
Luka Peternel (JSI)
Jerney Camernik (JSI)
Roy Featherstone (IIT)