A dynamic Whole-body Manipulation of Humanoid Robots: Robust and Adaptive Control Approach

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EUROPEAN PROJECT WALK-MAN

“Whole-body Adaptive Loco-Manipulation”

iit
italy

EPFL
swiss

KIT
Germany

UCL
Belgium

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Earthquakes in Italy

- L’Aquila April 6, 2009 (309) (Fukushima, 11 March 2011)
- Amatrice, Aug. 24, 2016 (247)

Source: Google image search
WALK-MAN Motivation

• Recent disasters have demonstrated that there was relatively little that current robots could do to assist.

• Unfortunately disasters of this or related types will occur again and it is essential that we work towards developing robots with the capacity to truly help.
European project WALK-MAN

• September 2013 – September 2017 (4 Years)

• aims to develop a humanoid robot that can operate in buildings that were damaged following natural and man-made disasters. The robot will demonstrate new skills:

  • dexterous, powerful manipulation skills - e.g. turning a heavy valve of lifting collapsed masonry,
  • robust balanced locomotion - walking, crawling over a debris pile, and
  • physical sturdiness - e.g. operating conventional hand tools such as pneumatic drills or cutters.

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WALK-MAN concept
Enabling technologies

- Soft Robotics
- Whole-Body Loco-Manipulation
- Loco-manipulation affordances
- Anytime planning and control for loco-manipulation and Motion Description Languages

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- 32 DOFs = 30 DOFs + 2DOF for hands
- **Actuation**
  - high power
  - *passive series compliance in all joints*
- **Sensing**
  - Joint torque sensing
  - 4 x 6 DOF custom F/T sensors
  - 2 x IMU
  - CMU Multisense (vision)

- **Power autonomy**
  - 2KWh Battery
  - Power management system
- **On board computation power**
  - 2 x COM Express
    (1 the back pack and one in the head)
- **Height:** 1.85m
- **Weight**
  - 118Kg without Power pack
  - 133Kg including the power pack
WALK-MAN in DRC

After 8 months from the scratch of the design...
WALK-MAN in DRC

WALK-MAN (185cm, 130kg) survived from serious impact during its falling over
Behind the scene of WALK-MAN in DRC

• Upper-body (manipulation) and lower-body (locomotion) separately operated.
  ➔ limits dexterity from abundant redundancy of whole-body kinematics

• kinematic-based control
  ➔ more dynamic motion interacting with environment is expected
Dynamic Whole-body Controller

• **Target:** Develop practical dynamic whole-body control for torque-controlled humanoids,
  • Agile, precise, robust performance
  • Easily implementable into real humanoids

• **Challenges**
  ➢ High kinematic redundancy
  ➢ Simultaneous Multiple tasks
  ➢ Control Accuracy
  ➢ Robustness to the uncertain disturbances
  ➢ Implementation effort
    (e.g., model identification, gain tuning…)
  ➢ Computational cost

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Main Approach

- High kinematic redundancy
- Simultaneous Multiple tasks

 ➔ Dynamics formulation
  Force-level operational space formulation + Task-priority

- Control Accuracy
- Robustness to the uncertain disturbances
- Implementation effort
  (e.g., model identification, gain tuning...)
- Computation cost

➔ Control
  Model-independent approach: online uncertainty compensation,
  called Time-delay estimation (TDE)
  Robust and Adaptive Controller: Adaptive sliding-mode

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Dynamic Whole-body Control Framework

• Force-level operational space formulation

Joint-space Robot dynamics

\[ \tau = M(q)\\dot{q} + c(q, \dot{q}) + g(q) + \nu(q, \dot{q}) + \tau_d + \tau_e \]

Task-space Robot dynamics

\[ f = A(q)\\ddot{x} + \eta(q, \dot{q}) \]

\[ \begin{cases} 
A(q) = (JM^{-1}J^T)^{-1} \\
\eta(q, \dot{q}) = A(q)JM^{-1}(c + g + \nu + \tau_d + \tau_e) - A(q)J\\dot{q} 
\end{cases} \]
Dynamic Whole-body Control Framework

- **Task Priority (Task Jacobian and Prioritized Jacobian)**

\[
J_i|P = J_i P_{i-1}, \quad P_i = P_{i-1} + J_i^\dagger P J_i|P, \quad \text{and} \quad P_0 = I
\]

\[
J_i^\dagger|P = M^{-1} J_i^T (J_i|P M^{-1} J_i^T P)^{-1}
\]

- **Prioritized Dynamics for Multiple Tasks** [O.Khatib and L. Sentis]

\[
f_i = A_i \ddot{x}_i + \eta_i
\]

\[
A_i = (J_i|P M^{-1} J_i^T P)^{-1}, \quad \eta_i = (J_i^\dagger|P)^T (c + g + \nu + \tau_d + \tau_e) - A_i J_i|P \dot{q}
\]

- Dynamic model parameters
- Uncertainties
- External disturbances

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Inverse dynamics based control

- Control law

\[ \tau = \sum_{i=1}^{k} J_{i|P}^T f_i^* \]

\[ f_i^* = A_i \ddot{x}_i^* + \eta_i \]

- Dynamic model parameters
- Uncertainties
- External disturbances

\[ A_i = (J_{i|P} M^{-1} J_{i|P}^T)^{-1}, \]

\[ \eta_i = (J_{i|P}^\dagger)^T (c + g + \nu + \tau_d + \tau_e) - A_i \dot{J}_{i|P} \dot{q} \]

To bring the humanoids into the real world,

Can we make this controller more robust and adaptive?

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Controller Derivation (1/3)

• idea 1: use of diagonal $\bar{M}$ instead of full $M$

\[
f_i = A_i \ddot{x}_i + \eta_i
\]

\[
A_i = (J_{i|P} M^{-1} J_{i|P}^T)^{-1},
\eta_i = (J_{i|P}^T (c + g + \nu + \tau_d + \tau_e) - A_i \dot{J}_{i|P} \dot{q}
\]

\[
f_i = \bar{A}_i \ddot{x}_i + \bar{\eta}_i,
\]

\[
\bar{J}_{i|P} = \bar{M}^{-1} J_{i|P}^T \bar{A}_i,
\bar{A}_i = (J_{i|P} \bar{M}^{-1} J_{i|P}^T)^{-1},
\bar{\eta}_i = (\bar{J}_{i|P}^T \zeta - \bar{A}_i \dot{J}_{i|P} \dot{q}
\]

\[
\zeta(q, \dot{q}, \ddot{q}) = [M(q) - \bar{M}] \ddot{q} + c + g + f + \tau_d + \tau_e
\]

Less identification effort
Less computation effort

(New terms to be compensated $\rightarrow$ see Idea 3)
Controller Derivation (2/3)

• idea 2: Adaptive Sliding-mode control

\[ s_i = \dot{e}_i + \lambda_i e_i, \]

\[ \dot{s}_i + \lambda_i s_i = 0 \]

\[ \ddot{e}_i + 2\lambda_i \dot{e}_i + \lambda_i^2 e_i = 0 \]

\[ f_i^* = \bar{A}_i \ddot{x}_i^* + \bar{\eta}_i, \]

\[ \ddot{x}_i^* = \ddot{x}_{id} + 2\lambda_i \dot{e}_i + \lambda_i^2 e_i \]

Auto-tuning by sliding-mode-based adaptive law

\[ \dot{m}_j = \begin{cases} \alpha_j |s_{q,j}| \text{sgn}(|s_{q,j}| - \delta_j) & \text{if } \gamma^- < \bar{m}_j < \gamma^+ \\ 0 & \text{if } \bar{m}_j \geq \gamma^+ \\ \gamma^- & \text{if } \bar{m}_j \leq \gamma^- \end{cases} \]

and

\[ s_q = \sum_{i=1}^{k} \mathbf{J}_{i}^\dagger \mathbf{P} (\dot{e}_i + \lambda_i e_i), \]
Controller Derivation (3/3)

• idea 3: Online dynamics estimation

\[ \ddot{\eta}_i = (\mathbf{J}^T_{i|P})^T \zeta - \tilde{A}_i \mathbf{J}_{i|P} \ddot{q} \]

\[ \zeta(q, \dot{q}, \ddot{q}) = [\mathbf{M}(q) - \tilde{\mathbf{M}}] \ddot{q} + c + g + f + \tau_d + \tau_e \]

\[ \ddot{\eta}_i = \lim_{L \to \epsilon} \ddot{\eta}_i(t-L) \]

\[ = f_i(t-L) - \tilde{A}_i \ddot{x}_i(t-L) \]

Lumped dynamics term to be known

“Time-delay Estimation Technique”

One-step delayed information of input-output signals (e.g. \( L = 1\text{ms} \))

Final torque-level Controller Equation:

\[ \tau = \sum_{i=1}^{k} \mathbf{J}_{i|P}^T \left[ \tilde{A}_i (\ddot{x}_{id} + 2\lambda_i \dot{e}_i + \lambda^2_i e_i) + f_i(t-L) - \tilde{A}_i \ddot{x}_i(t-L) \right] \]

Adaptive sliding-mode control

Adaptive dynamics estimation
Proposed dynamic Whole-body Control

Online compensation of dynamics & uncertainty (Robustness):
Time-delay Estimation

Less computational effort:
Use of diagonal $\bar{M}$

Control accuracy:
Sliding-mode based adaptive control

Easy implementation:

$$\tau = \sum_{i=1}^{k} J_{i/P}^T \left[ \bar{A}_i (\ddot{x}_{id} + 2\lambda_i \dot{e}_i + \lambda_i^2 e_i) + f_i(t-L) - \bar{A}_i \ddot{x}_{i(t-L)} \right]$$

Adaptive sliding-mode control
Adaptive dynamics estimation

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Dynamic Simulation

Task 1: end-effectors position
Task 2: CoM position

OSF control based on full inverse dynamics
proposed control

- While OSF control (left) uses full inverse dynamics with perfect model information, the proposed controller (right) need no inverse dynamics calculation.

- Nevertheless, the responses of the proposed controller is almost identical to that of OSF controller.

(*By Robotran WALK-MAN dynamic simulator)

Jinoh Lee, ADVR, IIT @15-07-2015
Dynamic Simulation 2

T1: COM XY-Pos

T2: Feet pos/ori

T3: Right hand XYZ-Pos

Speed x3

Speed x2

Speed x1

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Experiments

- 3 multiple tasks
- 1ms sampling period
- Monitored computation time < 0.4ms (Intel 1.5Ghz dual-core CPU)

Experiment Setup

> CoMan: 23-DoFs Humanoids

> Hard Realtime Control System
  (sampling frequency = 1kHz)

> Torque controlled

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Experiments

- 3 multiple tasks
- 1ms sampling period
- Monitored computation time < 0.4ms (Intel 1.5GHz dual-core CPU)

(Play speed X2)

Experiment 2 Scenario

Hierarchical tasks

> Task 1: Regulation of CoM X-Y position for balance (2 DoFs)
> Task 2: Regulation of two feet position and orientation (6DoF x 2)
> Task 3: Drawing circle with right end-effector (3 DoFs)

6 DoFs natural null-space motion
Under uncertain disturbances
> ground reaction forces and torques
> sudden impacts (t=30~40s)
Limitations and future works

• Hardware:
  – WALK-MAN needs torque-controlled SEAs.

• Control:
  – Floating base, Contact model…

“BRING THE ROBOT INTO THE REALITY”
Thank you for your attention!
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“Whole-body Adaptive Loco-Manipulation”