Humanoid Robots

The Challenge: beyond mobility

.. not only walk, but also interact with the world!

a unified mobility & manipulation framework!

ASIMO

.. not only walk, but also interact with the world!

How much programming?
Mobile Manipulation
Human Guided Motion & Human-Robot Interaction
Romeo & Juliet (1993)

Human-Robot Interaction
Romeo & Juliet (1993-96)

Multi-contact Manipulation
Humanoid Robot Control
branching and under-actuated

- whole-body control
- constraints and obstacles
- multiple contacts
- internal forces & balance
- manipulation skills

Multi-Contact Whole Body Motion

Physical Interaction, Constraints, and Task Behaviors

Balanced Supporting Contacts
Internal Force Control – Virtual Linkage

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Physical Interaction, Constraints, and Task Behaviors

Posture
Task Behavior
Multiple Contacts
Internal Constraints
Self Collision
Local Obstacles
Balance
Unified Whole-Body Control Framework

posture consistent with {
  Task consistent with {
    contact consistent with {
      internal constraints self collision local obstacles consistent with {
        balance
    }
  }
}

interact with the world, cooperate, and manipulate

Constraint-Consistent Task-Space

\( \mathbf{\nu}_\otimes \in cc - space \)

interact with the world, cooperate, and manipulate

Unified Whole Body Control Framework

Task, Posture, Constraints, Multiple Contacts, and Balance

Dynamics

\[ \Lambda_\otimes \ddot{\mathbf{\theta}} + \mu_\otimes + \mathbf{p}_\otimes + F_j = F_\otimes \]

Control

\[ F_\otimes = \hat{\Lambda}_\otimes F^*_\otimes + \hat{\mu}_\otimes + \hat{\mathbf{p}}_\otimes \]

Whole-body Control

Task & Posture Decomposition

Task Dynamics and Control

Task Dynamics

\[ \Lambda \ddot{x} + \mu + p = F \]

Task Control

\[ IF = \hat{\Lambda} \left( -\nabla V_{\text{Task}} \right) + \hat{\mu} + \hat{p} \]

\[ \Gamma = J^T F \]

Task Dynamics – Branching Structures

\[ x = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix}, \quad \Lambda = \begin{pmatrix} \Lambda_1 & \Lambda_2 & \cdots & \Lambda_m \end{pmatrix} \]

\[ x \Rightarrow J \Rightarrow \Lambda \]

\[ \Lambda \ddot{x} + \mu + p = F \]
Posture Space Control

Joint-Space Dynamics

\[ \dot{\mathbf{x}} + \mu + p = F \]

Task Control: \( J^T \)

Posture Control: \( N^T \)

Posture Energy

Control Structure

\[ \Gamma = J^T F_{\text{task}} + N^T \Gamma_{\text{posture}} \]

Decomposition of torque vector

Dynamic Consistency \( \Rightarrow \dot{x}_{\text{task}} = 0 \)

Whole-Body Control: Dynamics

\[ \Gamma = \Gamma_{\text{Task}} + \Gamma_{\text{Posture}} \]

\[ \Gamma_{\text{Task}} = J^T F \]

\[ \Gamma_{\text{Task}} = J^T [\hat{\Lambda} (-\nabla_{\text{Task}} V) + \hat{\mu} + \hat{p}] \]

\[ \Gamma_{\text{Posture}} = N^T \Gamma_{\text{Desired-Posture}} \]

\[ \Gamma_{\text{Posture}} = N^T (-\nabla_{\text{Desired-Posture}}) \]

Dynamics in Posture Space
Posture Dynamics & Control

Posture sub-task: \( x_p \rightarrow J_p \)

Task-consistent posture Jacobian: \( \delta x_{p,t} = J_p (N, \delta q) \)

Dynamics:
\[
\Lambda_{pp} \ddot{x}_{pp} + \mu_{pp} + p_{pp} = F_{pp} 
\]

Control:
\[
\Gamma_{posture} = J_p ^{\top} (\ddot{\Lambda}_{pp} \nabla V_{posture} + \dot{\mu}_{pp} + \dot{p}_{pp}) 
\]

Constraints

Self Collision

Constraints and Priorities

\[
\Gamma = J_{next} ^{\top} F_{next} + N_{next} ^{\top} (F_{hand} + N_{hand} (\Gamma_{posture})) 
\]

Self Collision
Obstacles

Multi-Contact Whole-body Control
Integration of Whole-Body Control & Locomotion

Under-actuated Balance Reaction forces

Multi-Contact Whole-body Control
Integration of Whole-Body Control & Walking

Balanced Supporting Contacts
Internal Force Control – Virtual Linkage

Unified Whole Body Control Framework
Task, Posture, Constraints, Multiple Contacts, and Balance
Unified Framework
posture consistent with {
task consistent with {
contact consistent with {
internal constraints self collision local obstacles consistent with {
balance
}}
}}

interact with the world, cooperate, and manipulate

Constraint-Consistent Task-Space

\[ \mathbf{v}_{\otimes} \in \text{cc-space} \]

interact with the world, cooperate, and manipulate

Constraint-Consistent Task-Space

\[ \mathbf{v}_{\otimes} = \begin{pmatrix} \mathbf{v}_{c/s} \\ \mathbf{v}_{f/s} \\ \mathbf{v}_{m/s} \\ \mathbf{v}_{p/m/s} \end{pmatrix} \]

interact with the world, cooperate, and manipulate

Unified Whole Body Control Framework

Task, Posture, Constraints, Multiple Contacts, and Balance

Dynamics
\[ \Lambda_{\otimes} \ddot{\mathbf{q}}_{\otimes} + \mu_{\otimes} + \mathbf{p}_{\otimes} + \mathbf{F}_{f} = \mathbf{F}_{\otimes} \]

Control
\[ \mathbf{F}_{\otimes} = \hat{\Lambda}_{\otimes} \mathbf{F}_{\otimes}^* + \hat{\mu}_{\otimes} + \hat{\mathbf{p}}_{\otimes} \]

Actuated Torques
\[ \mathbf{\Gamma}_{\alpha} = (\mathbf{UN})^T \mathbf{J}^T \mathbf{F}_{\otimes} \]
Unified Whole Body Control Framework
Task, Posture, Constraints, Multiple Contacts, and Balance
Human Movement

Simulation 79 DOF and 136 Muscles
Biometric Data & Bone Geometry

Dynamic simulation
Motion capture

understanding human movement

Data from Subjects

Physiology-based Posture Field

A Task, $F$: $\Gamma = J^T F$
Muscle actuation: $\Gamma = L^T m$
Humans grow to learn the efficiency of the body’s physio-mechanical advantage.

In learned tasks, humans minimize muscular effort, under physical and “social” constraints.

Physio-Mechanical Advantage

Physiology-based Posture Field

Human posture is continuously adjusted to reduce muscular effort.

Muscular Energy minimization:

\[ E = c m^2 \]

Function of physiology, mechanical advantage, and task:

\[ E = F^T \left[ J \left( \bar{L} \bar{N}^{-2} L \right) J^T \right] F \quad E = F^T \Phi F \]

Validation - Arm Effort

\[ E = c m^2 \]
Validation - Arm Effort

$E = cm^2$

Validation – whole-body effort

$E = cm^2$

Physio-Mechanical Advantage

$E = cm^2$

ASIMO

SAI Neuromuscular Library
Human Motion Reconstruction
Injury prevention, Pathology Evaluation, and Athletics

Human Motion Reconstruction

Simulation 79 DOF and 136 Muscles
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Dynamic simulation
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