Humanoid Robots

The Challenge:
beauty 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

Unified Whole-Body Control Framework

Posture
Task
Multiple Contacts
Internal Constraints
Self Collision
Local Obstacles
Balance

consistent with {
interact with the world,
cooperate, and manipulate}
**Constraint-Consistent Task-Space**

\[ \nu_{\circ} \in \text{cc-space} \]

interact with the world, cooperate, and manipulate

**Unified Whole Body Control Framework**

Task, Posture, Constraints, Multiple Contacts, and Balance

**Dynamics**

\[ \Lambda_{\otimes} \dot{\theta}_{\otimes} + \mu_{\otimes} + p_{\otimes} + F_f = F_{\otimes} \]

**Control**

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

**Whole-body Control**

Task & Posture Decomposition

**Task Dynamics and Control**

**Task Dynamics**

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

**Task Control**

\[ BF = \dot{\Lambda} ( - \nabla V_{\text{task}} ) + \hat{\mu} + \hat{p} \]

\[ \Gamma = J^T F \]

**Task Dynamics – Branching Structures**

\[ x = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix} \Rightarrow J \Rightarrow \Lambda \]

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

**Posture Space Control**

Joint-Space Dynamics

\[ N^T \]

**Posture Control**

\[ J^T \]

Task Control: \[ J^T \]

Posture Control: \[ N^T \]
Control Structure

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

Decomposition of torque vector

Dynamic Consistency \[ \Rightarrow \dot{x}_{\text{task}} = 0 \]

Posture Energy

Whole-Body Control: Dynamics

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

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

\[ \Gamma_{\text{Task}} = J^T [\dot{A} (\nabla V_{\text{Task}}) + \dot{\mu} + \dot{\rho}] \]

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

Dynamics in Posture Space

Posture Dynamics & Control

Posture sub-task: \[ x_p \rightarrow J_p \]

Task-consistent posture Jacobian: \[ \delta x_{\text{post}} = J_p (N_i \delta q) \]

Dynamics: \[ \Lambda \dot{x}_{\text{post}} + \mu_{\text{post}} + p_{\text{post}} = F_{\text{post}} \]

Control: \[ \Gamma_{\text{posture}} = J^T_{\text{post}} [\dot{A} (\nabla V_{\text{posture}}) + \dot{\mu}_{\text{post}} + \dot{\rho}_{\text{post}}] \]
Constraints and Priorities

\[ \Gamma = J^T F + N^{\text{const}} F^T + N^{\text{task}} (F^T + \Gamma) \]

Self Collision

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

Under-actuated Balance Reaction forces

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

Constraint-Consistent Task-Space

\( u \in cc \text{ -- space} \)

interact with the world, cooperate, and manipulate
Constraint-Consistent Task-Space

\[ \mathbf{v}_c = \begin{pmatrix} v_{c|x} \\ v_{c|y} \\ v_{c|z} \\ v_{c|\theta_x} \\ v_{c|\theta_y} \end{pmatrix} \]

interact with the world, cooperate, and manipulate

Unified Whole Body Control Framework

**Dynamics**

\[ \Lambda \dot{\theta} + \mu + p_f + F_f = F_\theta \]

**Control**

\[ F_\theta = \dot{\Lambda} F_\theta^* + \dot{\mu} + \dot{p}_f \]

**Actuated Torques**

\[ \Gamma_a = (UN)^T J^T F_\theta \]
understanding human movement

Simulation 79 DOF and 136 Muscles
Biometric Data & Bone Geometry

Dynamic simulation
Motion capture

Data from Subjects

Physiology-based Posture Field

A Task, $F$: $\Gamma = J^T F$

Muscle actuation: $\Gamma = L^T m$

Data from Subjects

Learning from the Human

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:

\[ E = cm^2 \]

Function of physiology, mechanical advantage, and task

\[ E = F^T \left( \frac{\Omega}{L} \right)^{-1} \frac{\Omega}{L} F \]

Validation - Arm Effort

\[ E = cm^2 \]

Validation - whole-body effort

\[ E = cm^2 \]
Physio-Mechanical Advantage

\[ E = cm^2 \]

Upper body

Lower body

SAI Neuromuscular Library

ASIMO

Human Motion Atlas
Human Motion Reconstruction
Injury prevention, Pathology Evaluation, and Athletics

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