Feature-Based Locomotion Controllers

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Related Work: Linear Control

Raibert91
Hodgins9X
Faloutsos01
Yin07,08
Wang09,10
Related Work: MOCAP Tracking

Zordan02
Abe06
Sok07

daSilva08
Muico09
Tsai10
Feature-Based Control
Feature-Based Control

Describe control using a small set of goals
Describe control using a small set of goals
Goals describe high-level aspects of motion
Feature-Based Control

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Goals describe high-level aspects of motion

Directly map biomechanical observations
Feature-Based Control

Describe control using a small set of goals
Goals describe high-level aspects of motion
Directly map biomechanical observations
Simplifies reasoning about control
Feature-Based Control

Describe control using a small set of goals
Goals describe high-level aspects of motion
Directly map biomechanical observations
Simplifies reasoning about control
Speeds up controller development
Torques Simulation

State

Prioritized Optimization

Features Control

Simulation

$\mathbf{q}, \dot{\mathbf{q}}$ State

$\mathbf{T}$ Torques
Features \xrightarrow{E_i(x)} \text{Prioritized Optimization} \xrightarrow{\tau} \text{Simulation}

[q, \dot{q}] \rightarrow \text{State}

[\text{Todorov and Jordan, 2002}]
\[ x = \begin{bmatrix} \tau^T & \ddot{q}^T & \lambda^T \end{bmatrix}^T \]
Joint Torques

\[ \mathbf{x} = \begin{bmatrix} \mathbf{T}^T & \ddot{\mathbf{q}}^T & \mathbf{\lambda}^T \end{bmatrix}^T \]
Joint Accelerations

\[ \mathbf{x} = \begin{bmatrix} \tau^T & \ddot{\mathbf{q}}^T & \lambda^T \end{bmatrix}^T \]

Joint Torques
Joint Accelerations

\[ \mathbf{x} = \begin{bmatrix} \mathbf{\tau}^T & \mathbf{\ddot{q}}^T & \mathbf{\lambda}^T \end{bmatrix}^T \]

Joint Torques
Contact Forces
Joint Accelerations

\[ x = \begin{bmatrix} \tau^T & \ddot{q}^T & \lambda^T \end{bmatrix}^T \]

Joint Torques  
Contact Forces

Optimize \( x \) subject to

\[ C(x) = 0, \quad D(x) + f \geq 0 \]
Balancing

Features

Contact

COM

AM

Posture
Balancing

Features

- Contact
- COM
- AM
- Posture
Balancing

Contact

COM

AM

Posture
Balancing

Features

- Contact
- COM
- AM
- Posture
Balancing

Features

Contact
COM
AM
Posture
Balancing

Features

Contact

COM

AM

Posture
Features

Contact
COM
AM
Posture
Features

- Contact
- COM
- AM
- Posture

\[ y = f(q) \]
Features

\[ y = f(q) \]
$y = f(q)$
Features

\[ y = f(q) \]
Features

\[ y = f(q) \]
$y = f(q)$
\[ y = f(q) \]
\[ \ddot{y}_d = k_p(y_r - y) - k_v \dot{y} \]
\[ \mathbf{y} = f(\mathbf{q}) \]
\[ \ddot{\mathbf{y}}_d = k_p (\mathbf{y}_r - \mathbf{y}) - k_v \dot{\mathbf{y}} \]
\[ E(\mathbf{x}) = \| \ddot{\mathbf{y}}_d - \dot{\mathbf{y}} \|^2 \]
Setpoint Objective

\[ y = f(q) \]
\[ \ddot{y}_d = k_p(y_r - y) - k_v \dot{y} \]
\[ E(x) = ||\ddot{y}_d - \ddot{y}||^2 \]
Setpoint Objective

\[ y = f(q) \]

\[ \ddot{y}_d = k_p(y_r - y) - k_v \dot{y} \]

\[ E(x) = ||\ddot{y}_d - \dot{y}||^2 \]
Setpoint Objective

\[ y = f(q) \]

\[ \dot{y}_d = k_p (y_r - y) - k_v \dot{y} \]

\[ E(x) = \|\dot{y}_d - \ddot{y}\|^2 \]
AM Objective

Features
- Contact
- COM
- AM
- Posture
AM Objective

Features
- Contact
- COM
- AM Posture

Macchietto09

Kudoh02,06
AM Objective

$$E_{AM}(x) = \| \dot{L}_d - \dot{L} \|^2$$

$$\dot{L}_d = k_p (L_r - L)$$

$$\dot{L} = A_L \dot{q} + b_L$$
Torques

State

Simulation

Prioritized Optimization

Features

Prioritized Optimization

Simulation

Features

$E_i(x)$

Objectives

Torques

$\tau$
Weighted QP

\[ E(x) = \sum_i^{} \alpha_i E_i(x) \]
Weighted QP

\[ E(x) = \sum_{i} \alpha_i E_i(x) \]
$E_1(x)$
$E_1(x)$
Balancing

Features

- Contact
- COM
- AM
- Posture
WEIGHTED QP

Force: 200 N
Interval: 0.5 sec
Duration: 0.2 sec

PRIORITIZED
Layering Control
Layering Control

Normally hard to achieve many goals due to interference
Layering Control

Normally hard to achieve many goals due to interference

Prioritized Optimization allows control design and tuning in layers
Layering Control
Layering Control

Standing
Walking

Features

Contact

COM

Trunk

AM

Posture

Foot

Arms
Walking: COM
Walking: COM

Features
- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms
Walking: COM

Features
- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms
Walking: COM

Features
- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms
Walking: COM

Features
- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms

COM Trajectory
Walking: Swing Foot

$$E_{foot}(x) = ||\ddot{y}_d - \ddot{y}||^2$$

Features

- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms
Walking: Swing Foot

$$E_{foot}(x) = \| \ddot{y}_d - \ddot{y} \|^2$$
Walking: Swing Foot

$$E_{foot}(x) = ||\ddot{y}_d - \ddot{y}||^2$$
Walking: State-Machine

Features

Contact

COM
AM
Posture
Foot
Trunk
Arms

AM
Walking: State-Machine

Features
- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms

Diagram:
- L
  - HEELOFF
  - SWING
  - PLANT
  - SUPPORT
  - HEELOFF
- R
  - SUPPORT
  - HEELOFF
  - SWING
  - PLANT

Time intervals:
- $\Delta T$
- ≥ 1 Contacts
- 4 Contacts
- 60% of Swing
Walking: State-Machine

Features

- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms

Diagram showing a state-machine for walking with labels like 'L HEELOFF', 'SWING', 'PLANT', 'SUPPORT', 'R HEELOFF', 'SUPPORT', 'HEELOFF', 'SWING', and 'PLANT'. The diagram also highlights 

- \( \Delta T \)
- \( \geq 1 \) Contacts
- 4 Contacts
- 60% of Swing
Walking: AM Control

Features
- Contact
- COM
- Trunk
- AM
- Posture
- Foot
- Arms
Walking: AM Control

[Herr and Popović, 2004]
Basic "Relaxed" Style
Virtual Model Control

Previous Work

- Pratt et al. 1995-2001
- Coros, Beaudoin, van de Panne 2010
- Wu and Popović 2010
Virtual Model Control

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Pros

• Fast to evaluate
• No dynamics model required
Virtual Model Control

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Pros

• Fast to evaluate
• No dynamics model required

Cons

• Whole-body tasks are hard to express
• Doesn’t handle goal interference
Limitations/Future Work
Limitations/Future Work

Performance varies 50-100% realtime
Limitations/Future Work

Performance varies 50-100% realtime
Can’t generate motions such as flips/cartwheels
Limitations/Future Work

Performance varies 50-100% realtime
Can’t generate motions such as flips/cartwheels
Limited robustness to pushes
Force: 100 N
Duration: 0.1 sec
COM Height
Conclusions
Conclusions

Design control using high-level goals
Conclusions

Design control using high-level goals
New objectives for AM and distant targets
Conclusions

Design control using high-level goals
New objectives for AM and distant targets
New Prioritized Optimization algorithm
Conclusions

Design control using high-level goals
New objectives for AM and distant targets
New Prioritized Optimization algorithm
Walking controller with new capabilities
Until very recently, just making a character walk without falling over was incredibly hard.
Until very recently, just making a character walk without falling over was incredibly hard.

Now it is not.
Until very recently, just making a character walk without falling over was incredibly hard.

Now it is not.

Together with other exciting results from this year, the opportunities to create new control capabilities are wide open!