Robotics and Animatronics in Disney

Lecture 3: Physics-Based Character Animation

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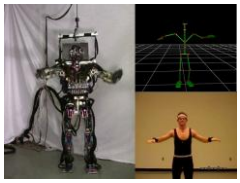
Goals

- Give overview of techniques for physics-based character animation in graphics
- Discuss why they are rarely used in production, and how to make them useful for production

Physics-Based Character Animation

Use physics (equation of motion) for animation
- Automatically obtain physically plausible animations
- Critical for physical characters (robots)
- Not always required for virtual characters (CG)



[Yamane, Anderson, Hodgins 2010]

The Incredibles (2004)

Use for Virtual Characters

Automatically synthesize new motions

Modify physical parameters

React to disturbances

Method Classification

- By source motion
  - With source motion (e.g., motion capture data)
  - Without source motion
- By approach
  - Optimization
  - Simulation

Use Source Motion?

- With source motion
  - Physically plausible and human-like
  - Noise and retargeting issues
- Without source motion
  - Design preferable motion pattern
  - Not guaranteed to be human-like

Optimization Approach

- Cost function with joint torques and/or contact forces
  - Joint torques: minimize power, energy
  - Contact forces: check feasibility
- Easier to control the result
  - Stop optimization somewhere reasonable
  - Results don't have to be strictly optimal
- Large optimization problem

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Simulation Approach

- Forward simulation of the motion resulting from a set of controllers
- Can generate responses to unscripted events
  - Environment change
  - Push
- More difficult to control
  - Characters may fall down (and they do)

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Methods

	Without source motion	With source motion
Simulation	[Isaacs and Cohen 1987] [Hodgins et al. 1995] [Zordan and Hodgins 1999, 2002] [Yin et al. 2007] [Macchietto et al. 2009] [Coros et al. 2010]	[Yamane and Nakamura 2003] [Treuille et al. 2007] [da Silva et al. 2008] [Muico et al. 2009] [Lee et al. 2010]
	[Jain et al. 2009] [Liu et al. 2010] [Wang et al. 2010] [Wang et al. 2012]	[Sok et al. 2007]
Optimization	[Witkin and Kass 1988] [Fang and Pollard 2003] + lots of work for humanoid robots	[Popovic and Witkin 1999] [Liu and Popovic 2002] [Safonova and Hodgins 2004]

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Simulation-Based

How to control simulated characters

Unstable

Contact forces are unilateral

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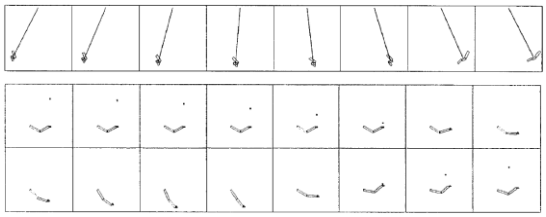
Early Simulation Work

[Isaacs and Cohen 1987]

Computed torque control with kinematic constraints



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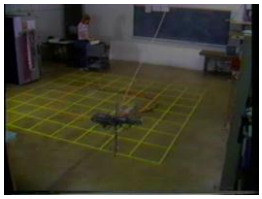
Simulating Complex Motions

[Hodgins et al. 1995]

Finite state machines and PD control

- Represent complex behaviors as state transitions
- Choose reference pose and PD gains for each state



[Hodgins, Koechling, Raibert]

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SIMBICON [Yin et al. 2007]

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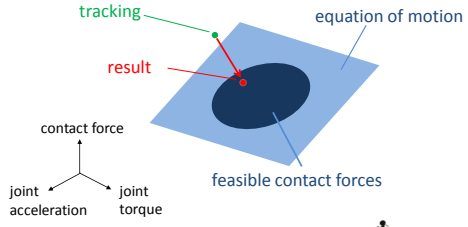
Simulation with Source Motion

[Yamane and Nakamura 2003]

Dynamics Filter



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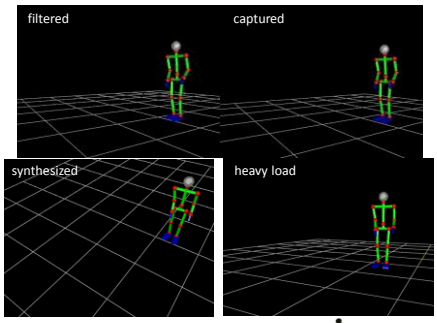
Simulation with Source Motion



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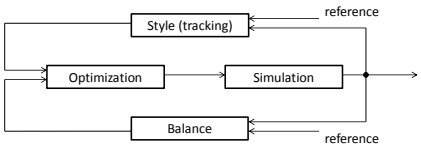
Tracking and Balancing

[da Silva et al. 2008]



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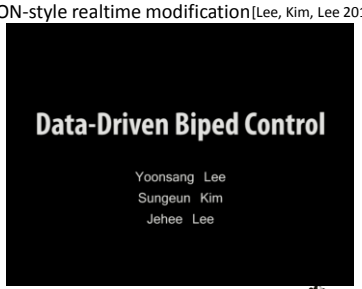
Simulation with Source Motion

SIMBICON-style realtime modification [Lee, Kim, Lee 2010]



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Optimization-Based

How to formulate a tractable optimization problem

Huge search space
Expressive motions

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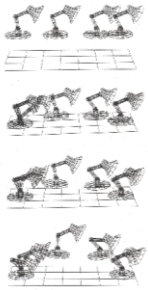
Spacetime Constraint

[Witkin and Kass 1988]

Minimize actuator power

Subject to

- Start and goal positions
- Contact constraints



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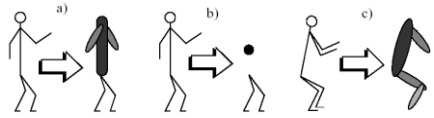
More Spacetime Constraints

[Popović and Witkin 1999]

Using simplified models



Objective function

- Difference from the original motion
- Smoothness of joint torques

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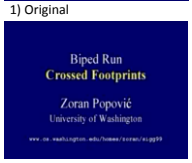
More Spacetime Constraints

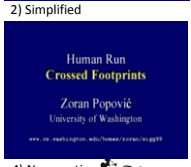
[Popovic and Witkin 1999]

1) Original

2) Simplified



3) New constraints



4) New motion

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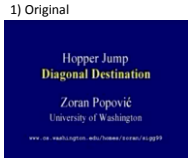
More Spacetime Constraints

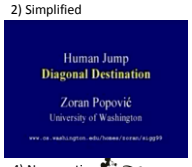
[Popovic and Witkin 1999]

1) Original

2) Simplified



3) New constraints



4) New motion

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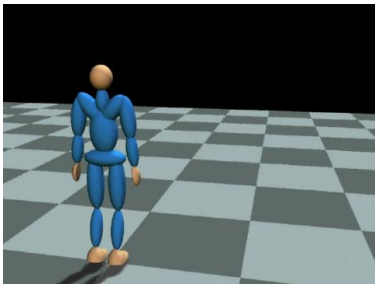
Optimize from Simple Animation

[Liu and Popovic 2002]



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Optimize from Simple Animation

[Liu and Popovic 2002]

Optimization setup

- unknowns: joint angles at all frames
- constraints
  - contacts
  - transition pose
  - momentum
- objective function
  - mass displacement
  - smooth joint angles
  - static balance

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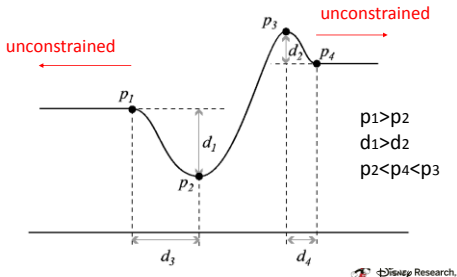
Optimize from Simple Animation

[Liu and Popovic 2002]

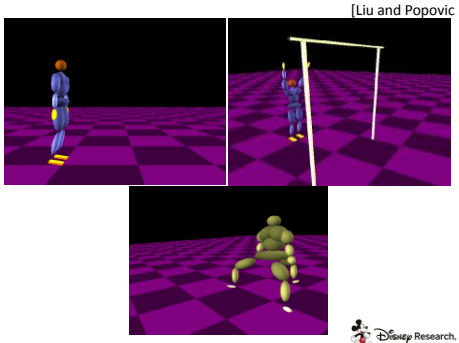
Angular momentum pattern from biomechanical data



$p_1 > p_2$
$d_1 > d_2$
$p_2 < p_4 < p_3$

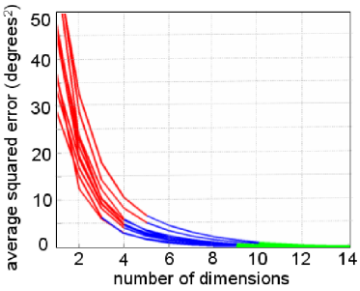
Optimize from Simple Animation

[Liu and Popovic 2002]



Optimize in Low-Dimensional Space

[Safonova, Hodgins, Pollard 2004]



Optimize in Low-Dimensional Space

[Safonova, Hodgins, Pollard 2004]

Optimization setup

- Unknowns: weights for the principal components
- Objective function: torque, acceleration, distribution
- Constraints: user-specified, physics

Optimize in Low-Dimensional Space

[Safonova, Hodgins, Pollard 2004]

Hybrid Methods

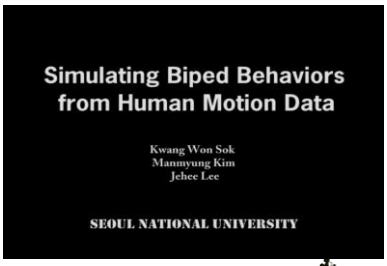
1) Optimization as pre-processing
2) Run simulation for reactions

Formulate an optimization problem that can be solved in real time

Optimization + Reaction

[Sok, Kim, Lee 2007]

Motion rectification and PD control



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Sampling-Based Optimization

[Liu et al. 2010]

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Fast Optimization

[Jain et al. 2009]

- Find the *joint angles* at next step (instead of joint torques)
- Discretized equation of motion: linear to the joint angles at next step
- Minimize joint torque change

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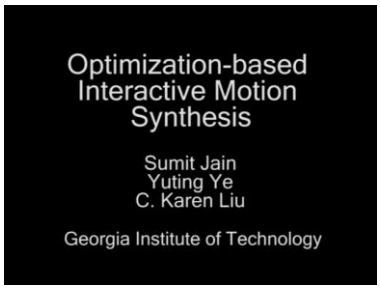
Fast Optimization

[Jain et al. 2009]



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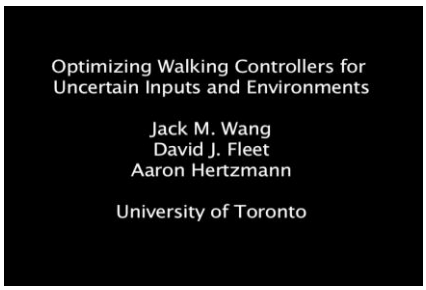
Optimize Robustness

[Wang, Fleet, Hertzmann 2010]



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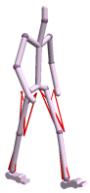
Physiology-Based Optimization

[Wang et al. 2012]

- 8 muscles for each leg
- Controllers and cost function inspired by physiology
- Produce muscle force patterns close to humans



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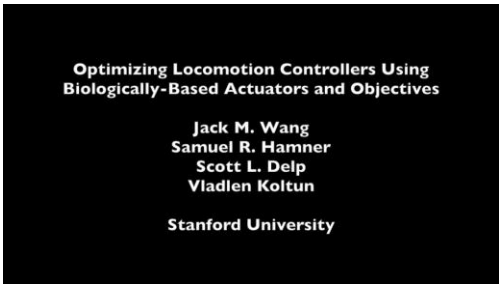
Biomechanical Model

[Wang et al. 2012]



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Use in Production

- Not quite yet…
  - Animators want full control of motion
  - Characters don't always have to be physically correct
  - Still too much computation for games
- Production-friendly methods?
  - Art-directable
  - Only simulate the parts that are difficult to animate
  - Allow exaggeration

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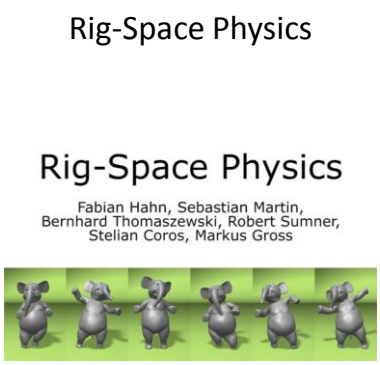
Rig-Space Physics



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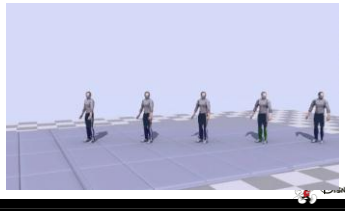
Exaggerated Physics

Edit human motions

- In momentum/force space
- Obey basic physics
- Intuitive



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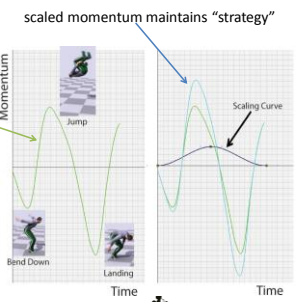
Editing Momentum

original momentum in back flip



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Editing Momentum

- Problem: cannot keep
  - Final position
  - Gravity acceleration
- Normalized dynamics by time scaling [Hollerbach 1984]

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Normalized Dynamics

Equation of motion

$$f = \frac{d}{dt}P + mg$$

$$P = m\frac{d}{dt}x$$

Linear momentum

time scale

$$c = \frac{dt}{d\tau}$$

τ : phase

Normalized equation of motion

$$\phi = \frac{d}{d\tau}P + \mu\gamma$$

$$P = \mu\frac{d}{d\tau}x$$

$\phi = cf$ normalized force

$\mu = m/c$ normalized mass

$\gamma = c^2 g$ normalized gravity

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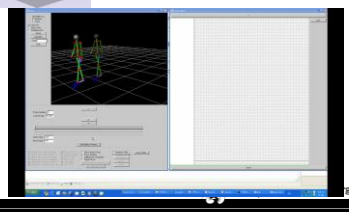
Example: Double Kick

original



editing process

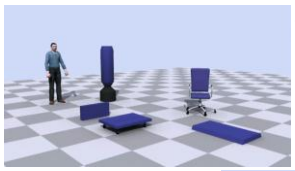
Example: Double Kick

original

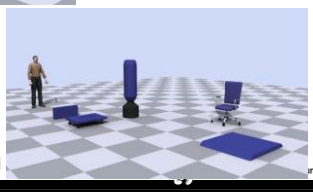
more dynamic

less dynamic

Propagating Edits



original



edited

Discussion

- Physics is rarely used in production for character animation
- However, simulation is used for different purposes:
  - Dynamics simulation for very complex systems such as cloth, hair, and fluid
  - Light simulation for rendering
- Recent trend
  - Art-directable: artists can intuitively control the results

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