Computational Design of Mechanical Characters

6.S079 Computational Fabrication
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Last Time

- Computational Design of Articulated Characters
  - Bächer et al., Siggraph 2012
The Plan for Today

• So far we have seen static characters
• Today we will make them move

• Computational Design of Mechanical Characters
  Coros et al., Siggraph 2013
Automata: self-operating machines or robots

Sisyphus by D. Johnson
Mechanical Toys

http://www.flickr.com/photos/wandasowry/4547085963/
Mechanical Toys

Cabaret Mechanical Theatre Automata Exhibition
Mechanical Toys

http://itp.nyu.edu/~ejp291/eportfolio/clown.html
Traditional Design Process

Sketches → Research and plan → Fast prototype → Evaluation and tuning → Final production

Costly
Traditional Design Process

- Solution: digital fabrication
Goals

• Automate motion-to-form design
• Generate physically-realizable result
Mechanical Toy Design
Mechanical Toy Design

User Input
Mechanical Toy Design

Part Library
Mechanical Toy Design

Output
INTERACTIVE SESSION EXAMPLE
Interactive Session Example
User Input
- Character
- Motion Curves

Mechanism Design
- Database Retrieval
- Parameter Optimization
- Timing Control

Finishing
- Gear Connections
- Collision Resolution
- Support Structure
- Fabrication
Simulation Model

\[ s_i = \begin{bmatrix} x_i, y_i, z_i, \gamma_i, \beta_i, \alpha_i \end{bmatrix}^T \]

\[ T_i \]

\[ R_i \]
Simulation Model

Pin Connection           Point-on-Line Connection           Gear-to-Gear Connection
Constraints for Mechanisms: Review

- Constrain a point on one link to always be in the same place as a point on a different link
Constraints for Mechanisms: Review

- We know that:
  \[ x = w_1 \mathbf{R}_1 x + w \mathbf{p}_1 \]
  \[ y = w_2 \mathbf{R}_2 y + w \mathbf{p}_2 \]
Pin the two bodies using the following constraint:

\[
\begin{align*}
\mathbf{w}_1 R^1 \mathbf{x} + \mathbf{w}_1 \mathbf{p}_1 &= \mathbf{w}_2 R^2 \mathbf{y} + \mathbf{w}_2 \mathbf{p}_2 \\
\end{align*}
\]
Simulation Model

$$C = \begin{bmatrix}
C_{c_0} \\
C_{c_1} \\
\vdots \\
C_{c_n}
\end{bmatrix}$$
Inverse Kinematics Review

- Input: Configuration of driver and ground: \( q_{\text{driver}} \) and \( q_{\text{ground}} \)
- Output: Mechanism configuration variables \( q \)
- Minimize constraint violations using least squares

\[
q^* = \arg \min_q \frac{1}{2} \sum_{i=1}^{n} |c_i(q)|^2
\]

- Here \( c_i = w_1 R^1 x + w_2 p_1 - w_2 R^2 y + w_2 p_2 \)
- This is typically a nonlinear least squares problem
Assignment 3
Mechanism Design
Library of Mechanisms
Part Parameterization

Quick-return  Belt-pulley  Crank-slider
Snail cam  Ellipse cam  Double cam  Gears
Parameterized Mechanisms
Parameterized Mechanisms
Parameterized Mechanisms
Parameterized Mechanisms
Mechanism Design
Sparse Database of Representative Motions
Sparse Sampling of Parameter Space
Sparse Sampling of Parameter Space
Assembly Database
Curve Queries
Curve Matching (Frechet Distance)

Closest
Feature-Based Metric

Given two curves $c_i$ and $c_j$, compute difference in

- Total length, area, ellipticity
- Per-vertex curvature
- Number of intersections
- ...

\[ d(c_i, c_j) = \|f_{ij}\|_A = \sqrt{f_{ij}^T A f_{ij}} \]
Metric Learning

\[
\min_{A} \sum_{(i,j) \in S} \| f_i - f_j \|^2_A \\
\text{s.t.} \quad \| f_k - f_l \|_A \geq \gamma, \quad \forall (k,l) \in D \quad \text{and} \quad A_{ij} \geq 0
\]
Example

Frechet distance

User-trained
Example

Frechet distance

User-trained
User Input
- Character
- Motion Curves

Mechanism Design
- Database Retrieval
- Parameter Optimization
- Timing Control

Finishing
- Gear Connections
- Collision Resolution
- Support Structure
- Fabrication
Continuous Optimization
Continuous Optimization
Timing Control

- Phase Offset
Timing Control

- Phase Offset
- Velocity Profile
Gearing Up

1. Gear Layout

2. Gear Optimization
   - Equality constraints model connections
   - Inequality constraints prevent intersections
Gear Layout Generation

Sequential

Paralell

Combined
Overview

User Input
- Character
- Motion Curves

Mechanism Design
- Database Retrieval
- Parameter Optimization
- Timing Control

Finishing
- Gear Connections
- Collision Resolution
- Support Structure
- Fabrication
Collisions & Layering

\[(A < B) \, || \, (B < A)\]

\[(C < A) \, || \, (C > B)\]
Support Structure
Overview

User Input
- Character
- Motion Curves

Mechanism Design
- Database Retrieval
- Parameter Optimization
- Timing Control

Finishing
- Gear Connections
- Collision Resolution
- Support Structure
- Fabrication
Fabrication
Pushing Man
EMA Dog

EMA Walk

EMA Galop

30 sec.
DrillR

20 sec.
Method Summary

An interactive, non-expert design system for creating animated mechanical characters

Limitations

– Kinematic design
Method Summary

An interactive, non-expert design system for creating animated mechanical characters

Limitations
- Kinematic design
- Cyclic motion
- Limited 3D motion
Similar Systems

Motion-Guided Mechanical Toy Modeling
Zhu et al. (Siggraph Asia 2012)
New Year Toy
Lazy Drawer: Motion Editing
Construction Site
Clock: Long Kinematic Chain
Another Similar System

Designing and Fabricating Mechanical Automata from Mocap Sequences

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Actuated Deformable Characters

Computational Design of Actuated Deformable Characters

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That’s All for Today

http://www.disneyresearch.com/project/mechanical-characters/