Animation, Motion Capture, & Inverse Kinematics
Velocities Interpolation

- In 2D: For each axis, find the 4 closest face velocity samples:
- (In 3D... Find 8 closest face velocities in each dimension)

\[ u_k = A_0 u_0 + A_1 u_1 + A_2 u_2 + A_3 u_3 \]
Bilinear Interpolation

- It might be simplest to think about one axis at a time
- It doesn’t matter which axis you start with!

- Calculate $u$, the fraction of the distance along the horizontal axis, \textit{e.g.}, $u=0.65$
- Then calculate the top & bottom averages:
  \[
  \text{orange} = (1-u) \cdot \text{red} + u \cdot \text{yellow} \\
  \text{bluegreen} = (1-u) \cdot \text{cyan} + u \cdot \text{green}
  \]

- Calculate $v$, the fraction of the distance along the vertical axis, \textit{e.g.}, $v=0.6$
- Then calculate the final average:
  \[
  \text{pukegreen} = (1-v) \cdot \text{bluegreen} + v \cdot \text{orange}
  \]

http://reedbeta.com/blog/quadrilateral-interpolation-part-2/

Last Time?

- Tetrahedral Meshing
- Haptics
- Anisotropic Materials
- Fracture
Today: How do we Animate?

• Readings for Today
• How do we Animate?
  – Keyframing
  – Procedural Animation
  – Physically-Based Animation
  – Motion Capture
  – Skeletal Animation
  – Forward and Inverse Kinematics
• Research Paper: Simple Artist Sketch + Motion Capture + Inverse Kinematics
• Figure Skating Lesson
• Readings for Next Time

Reading for Today

• “Real-Time Hand-Tracking with a Color Glove”
  SIGGRAPH 2009, Wang & Popović
Reading for Today

“Synthesis of Complex Dynamic Character Motion from Simple Animation”, Liu & Popović, 2002

- Rapid prototyping of realistic character motion from rough low-quality animations
- Obey the laws of physics & stay within space of naturally-occurring movements

Reading for Today

“Artist-Directed Dynamics for 2D Animation”, Bai, Kaufman, Liu, & Popović, SIGGRAPH 2016

Figure 6: Keyframes used in the articulated character walk example. The artist only specifies keyframes for a subset of handles (handles at hands and feet) which are shown as blue dots. Nine keyframes are used to create a walking cycle. Their timing is visualized by the black lines at the bottom. The artworks are adapted from Angryanimator.com (http://www.angryanimator.com/)
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Keyframing

- Use spline curves to automate the in betweening
  - Good control
  - Less tedious than drawing every frame
- Creating a good animation still requires considerable skill and talent and learning from observing the real world

ACM © 1987 “Principles of traditional animation applied to 3D computer animation”
### Disney’s 12 Principles of Animation

“The Illusion of Life: Disney Animation”,
*Ollie Johnston & Frank Thomas, 1981*

- **Squash & Stretch**
- **Slow In & Slow Out**

https://www.animdesk.com/the-principles-of-animation-squash-and-stretch

https://characteranimationlara.home.blog/2018/10/21/the-12-principles-of-animation

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### Procedural Animation

- Describes the motion algorithmically, as a function of small number of parameters
- Example: a clock with second, minute and hour hands
  - express the clock motions in terms of a “seconds” variable
  - the clock is animated by varying the seconds parameter
- Example: A bouncing ball
  - \( \text{Abs}(\sin(\omega t + \theta_0)) \cdot e^{-kt} \)
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Physically-Based Animation

• Assign physical properties to objects (masses, forces, inertial properties)
• Simulate physics by solving equations
• Realistic, but difficult to control
• Used for secondary motions (hair, cloth, scattering, splashes, breaking, smoke, etc.) that respond to primary user controlled animation

“Interactive Manipulation of Rigid Body Simulations” SIGGRAPH 2000, Popović, Seitz, Erdmann, Popović & Witkin
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Motion Capture

- Optical markers, high-speed cameras, triangulation → 3D position
- Captures style, subtle nuances and realism at high-resolution
- You must observe someone do something
- Difficult (or impossible?) to edit mo-cap data

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Articulated Models

- Articulated models:
  - rigid parts
  - connected by joints
- They can be animated by specifying the joint angles as functions of time.

Skeleton Hierarchy

- Each bone transformation described relative to the parent in the hierarchy:

Skeletal Animation Challenges

• Skinning
  – Complex deformable skin, muscle, skin motion

• Hierarchical controls
  – Smile control, eye blinking, etc.
  – Keyframes for these higher-level controls

• A huge amount of time is spent building the 3D models, its skeleton, and its controls

Forward Kinematics

• Given skeleton parameters $p$, and the position of the effector in local coordinates $V_l$, what is the position of the effector in the world coordinates $V_w$?

$$
V_w = T(x_h, y_h, z_h)R(q_h, f_h, s_h)T_hR(q_t, f_t, s_t)T_tR(q_c)T_cR(q_f, f_f)V_l
$$

$$
V_w = S(p)V_l
$$

*S(p) is “just” a 4x4 affine transformation matrix!*
Inverse Kinematics (IK)

- Given the position of the effector in local coordinates $V_l$ and the desired position $V_w$ in world coordinates, what are the skeleton parameters $p$?
- Much harder requires solving the inverse of the non-linear function:

  $$\text{find } p \text{ such that } S(p) V_l = V_w$$

*Why is this hard? Why is it non-linear?*

Under-/Over- Constrained IK

- Application: Robot Motion Planning

“The good-looking textured light-sourced bouncy fun smart and stretchy page”
Hugo Elias, [http://freespace.virgin.net/hugo.elias/models/m_ik.htm](http://freespace.virgin.net/hugo.elias/models/m_ik.htm)
Searching Configuration Space

- Use gradient descent to walk from starting configuration to target
- Angle restrictions & collisions can introduce local minima

"The good-looking textured light-sourced bouncy fun smart and stretchy page"
Hugo Elias, http://freespace.virgin.net/hugo.elias/models/m_ik2.htm

IK Challenge

- Find a “natural” skeleton configuration for a given collection of pose constraints
- A vector constraint function \( C(p) = 0 \) collects all pose constraints
- A scalar objective function \( g(p) \) measures the quality of a pose, \( g(p) \) is minimum for most natural poses.
  Example \( g(p) \):
  - deviation from natural pose
  - joint stiffness
  - power consumption

Force: Newton (N) = kg * m / s^2
Work: Joule (J) = N*m = kg * m^2 / s^2
Power: Watt (W) = J/s = kg * m^2 / s^3
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What’s a Natural Pose?

- Training database of ~50 “natural poses”
- For each, compute center of mass of:
  - Upper body
  - Arms
  - Lower body
- The relative COM of each generated pose is matched to most the most similar database example

Liu & Popović
Linear and Angular Momentum

• In unconstrained animation (no contacts), both linear & angular momentum should be conserved
• The center of mass should follow a parabolic trajectory according to gravity
• The joints should move such that the angular momentum of the whole body remains constant

During Constrained Motion

• During constrained motion (when in contact with the ground), the angular momentum follows a spline curve modeled after biomechanics data
System Features

- Automatically detect point/line/plane constraints
- Divide animation into constrained portions (e.g., feet in contact with ground) and unconstrained portions (e.g., free flight)
- Linear and angular momentum constraints without having to compute muscle forces
- Minimize:
  - Mass displacement
  - Velocity of the degrees of freedom (DOF)
  - “Unbalance” (distance the COM is outside of ground constraints)

“Synthesis of Complex Dynamic Character Motion from Simple Animation”, Liu & Popović, 2002
“Synthesis of Complex Dynamic Character Motion from Simple Animation”, Liu & Popović, 2002

Coach Mary Figure Skating

https://www.youtube.com/channel/UCUqodbdTE3hIjfloPDn6amw
https://www.youtube.com/watch?v=eVP8r-ubbp8
Coach Mary Figure Skating

https://www.youtube.com/channel/UCUqodbdTE3hljfloPDn6amw
https://www.youtube.com/watch?v=eVP8r-ubbp8

Figure Skating Motion Capture, Richards Biomechanics Lab, University of Delaware, 2017

https://www.udel.edu/udaily/2017/december/figure-skating-biomechanics-olympics/
**Figure 8:** A five-link eel swims in a 2D fluid environment. In contrast to the simulation in 3D, an eel swimming in 2D fluid sheds only one single vortex street. Red traces show the counter-clockwise vortices while blue traces show the clockwise vortices.

http://www.cc.gatech.edu/~jtan34/project/articulatedSwimmingCreatures.html
“Flexible Muscle-Based Locomotion for Bipedal Creatures”, Geijtenbeek, van de Panne, van der Stappen, SIGGRAPH Asia 2013

Figure 1: Physics-based simulation of locomotion for a variety of creatures driven by 3D muscle-based control. The synthesized controllers can locomote in real time at a range of speeds, be steered to a target heading, and can traverse variable terrain.

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Reading for Tuesday


Optional Makeup/Extra Credit Reading

Also pick any paper you didn’t read originally and read & post about it before Tuesday’s class