Building Helper Bone Rigs from Examples

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Linear Blend Skinning (LBS)

\[ \mathbf{v}_i = \sum_{d=1}^{D} w_{i,d} \overline{\mathbf{v}}_i \mathbf{S}_d \]

Rest position

Skinning weight

Bone transformation
Helper Bone System

[Mohr et al., 2003, Parks 2005@GDC]

Maya expression

```
HelperBone.translateY = 0.02 * joint.rotateZ
```
Helper Bone Rigging

[ Mohr et al., 2003, Parks 2005@GDC ]

• No physical / anatomical meaning
  – How many?
  – Where to add?
  – Which primary bone does drive?

• Heuristic scripting
  – Polynomial?
  – IF-THEN rule?

Expression
HelperBone.transform = ???
Goal

Skin shape + skeleton pose
(crafted asset, physics simulation)

Real-time helper bone rig
Experiment - *DragonLeg*

- 663 vertices
- 5 DOFs of primary skeleton
- 11 virtual muscles
- 6,750 pairs of examples
  - Uniform sampling of joint DOFs
Input & Output

• **Input**
  – Bind mesh + primary skeleton
  – Example shape + skeleton pose
  – Number of helper bones

• **Output**
  – Skinning weight
  – Helper bone controller

• **Least-square approximation**
  – Reconstruction error of vertex position

Expression

\[
\text{HelperBone.transform} = ???
\]
Approach

Examples → Bone transformation → Bone controller → Procedural control

Skin weight and bind pose information

$\mathbf{f}(\mathbf{x}, \mathbf{y})$
Optimal Skinning Weights and Helper Bone Transformation

\[
\min \sum_{n=1}^{N} \sum_{j=1}^{J} \tilde{v}_{j,n} - \sum_{d=1}^{D} w_{j,d} \tilde{v}_j \tilde{s}_{d,n} - \sum_{h=1}^{H} \tilde{w}_{j,h} \tilde{v}_j \tilde{s}_{h,n}
\]

- Skinning weight
- Helper bone transformation
- Example shape and skeleton pose
Constrained Least Square Problem

\[
\min \sum_{n=1}^{N} \sum_{j=1}^{J} \left| \tilde{v}_{j,n} - \sum_{d=1}^{D} w_{j,d} \tilde{v}_{j} S_{d,n} - \sum_{h=1}^{H} \hat{w}_{j,h} \tilde{v}_{j} \hat{S}_{h,n} \right|^2 \\
\]

Subject to
\[\hat{S}_{h,n} : \text{Rigid transformation (rotation & translation)}\]
\[w_{j,d}, \hat{w}_{j,h} : \text{Non-negative}\]
\[w_{j,d}, \hat{w}_{j,h} : \text{Partition of unity for each vertex}\]
\[w_{j,d}, \hat{w}_{j,h} : \text{Maximum count of non-zeros for each vertex}\]
Previous Work

- **Smooth Skinning Decomposition with Rigid bones:** SSDR model [Le and Deng 2012, 2014]
Extension of SSDR Model

• SSDR model

\[
\min_{n=1}^{N} \sum_{j=1}^{J} \sum_{n=1}^{N} \left\| \tilde{v}_{j,n} - \sum_{d=1}^{D} w_{j,d} \tilde{v}_{j} \mathbf{S}_{d,n} \right\|^2
\]

• Helper bone rigging

\[
\min_{n=1}^{N} \sum_{j=1}^{J} \sum_{n=1}^{N} \left\| \tilde{v}_{j,n} - \sum_{d=1}^{D} w_{j,d} \tilde{v}_{j} \mathbf{S}_{d,n} \right\|^2
\]

Example

(Under same constraints)
Optimization Procedure

Bind mesh & primary skeleton pose, Example mesh & primary skeleton pose

Weight optimization

Insertion of a helper bone

Weight optimization

Transformation optimization

SSDR algorithm

Weight optimization

Transformation optimization

Converged?

Number of helper bones?

no

yes
Insertion of Helper Bone

1. Find a vertex showing the largest error and its 1-ring neighbors

2. Estimate rigid transformation

3. Inserting a new helper bone using the rigid transformation
Bone transformation

Bone controller

Procedural control
Bone Controller Construction

Primary skeleton pose
Skin shape
Estimated helper bone

Helper bone transformation

Primary skeleton pose

Bone controller

$f$
Second Degree Polynomial as Controller

\[
\text{HelperBone.translateX} \quad f1 \times \text{joint1.rotateX} + f2 \times \text{joint1.rotateY} + f3 \times \text{joint1.rotateY} \\
+ f4 \times \text{joint1.rotateX}^2 + f5 \times \text{joint1.rotateY}^2 + \\
\quad \cdots + f53 \times \text{joint9.rotate}^2 + f54 \times \text{joint9.rotateZ}^2 + f55
\]

\[
\text{HelperBone.translateY} \\
\quad \vdots \\
\text{HelperBone.rotateZ}
\]
Second Degree Polynomial as Controller

\[ \text{HelperBone.translateX} = f_1 \ast \text{joint1.rotateX} + f_2 \ast \text{joint1.rotateY} + f_3 \ast \text{joint1.rotateY} + f_4 \ast \text{joint1.rotateX}^2 + f_5 \ast \text{joint1.rotateY}^2 + \ldots + f_{53} \ast \text{joint9.rotate}^2 + f_{54} \ast \text{joint9.rotateZ}^2 + f_{55} \]

\[ \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_{54} \\ f_{55} \end{bmatrix} T^{^2} 1 \]
Regression with Sparsity Constraint

\[ \text{HelperBone.translateX} \]
\[
  f_1 \cdot \text{joint1.rotateX} + 0 \cdot \text{joint1.rotateY} + f_3 \cdot \text{joint1.rotateY} \\
  + 0 \cdot \text{joint1.rotateX}^2 + f_5 \cdot \text{joint1.rotateY}^2 + \\
  \ldots + 0 \cdot \text{joint9.rotate}^2 + 0 \cdot \text{joint9.rotateZ}^2 + f_{55}
\]
Experimental Results

Examples  Bone transformation  Bone controller  Procedural control
Experiment - *Stylized DragonLeg*

- 8322 vertices
- 5 DoF of primary skeleton
- 11 exaggerated muscles
- Uniform sampling of joint DOF
- 6,750 pairs of examples
Experiment - *Miranda*

- 14,470 vertices
- Whole body skeleton
- A lot of muscles
- Rigging of only arm
  - Shoulder: 3 DOFs
  - Elbow: 1 DOF
  - Wrist: 1 DOF
- About 20,000 examples
Quantitative Evaluation

• DragonLeg (4 bones)
  – 32 sec for build (7k examples)
  – ~5 usec/bone for control
  – RMSE = 2.1 cm (height = 2 m)

• Stylized DragonLeg (4 bones)
  – 420 sec for build (7k examples)
  – ~5 usec/bone for control
  – RMSE = 2.9 cm (height = 2m)

• Miranda (4 bones)
  – 17 min for build (20k examples)
  – ~5 usec/bone for control
  – RMSE = 2.7 cm (height = 1.7m)

Dual Xeon E5-2687W 3.1GHz
(40 logical cores)
64 GB RAM
VC++2013, Intel TBB, MKL
Discussion

• Creating sufficient number of examples
  – Physically-based deformation [Li et al. 2010, Fang et al. 2014]
  – Shape capture [Neumann et al, 2013]

• Helper bone system
  – vs Scattered-data interpolation (PSD)
    ☐ Faster, more memory efficient
    ✗ Less accurate
Future Work

• Dynamic skin deformation
  – Velocity and acceleration

• High-res mesh, many joint DOFs
  – Minimal number of example data
  – Level-of-detail control
Building Helper Bone Rigs from Examples

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