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Motion Analogies: Automatic Motion Transfer to Different Morphologies

Sumit Jain and C. Karen Liu

Georgia Institute of Technology

1. Introduction

Automatic synthesis of motion for articulated characters remains a challenging problem to date. Motion capture technology provides a partial solution as it largely simplifies the process of manual creation of expressive and natural human motion. In practice, however, it is rare that the recorded motion can be directly applied to the virtual character without modification. Existing authoring techniques allow the animator to retarget stylistic motion onto structurally similar characters, but fail to handle the situations when the characters have different numbers of degrees of freedom or dissimilar topologies.

In this paper, we describe an automatic method for motion transfer to different morphologies using an *analogy*, i.e. given two motions $\mathbf{Q}_A$ and $\mathbf{Q}_B$ of two completely different characters C_A and C_B (e.g. human and a dog) exhibiting similar behavior like walking, we automatically synthesize new motion $\mathbf{Q}_{B'}$ for C_B that *mimics* a new given motion $\mathbf{Q}_{A'}$ for C_A (e.g. marching) (see Figure 1). We aim for a completely generic algorithm that does not make any assumption about the morphologies of C_A and C_B or require authoring tools to define any correspondence between them. Our method can be used as a rapid prototyping tool that eases the effort in adapting the existing motion to new characters.

The key insight of our approach is derived from the analysis on the animal motion measured from the real world. We compared walking cycles of a human and a cat using eigen analysis on the motion. We found that the eigenmotion (low-dimensional motion in the space defined by eigenvectors), corresponding to the first few eigenvectors, is strikingly similar between the human and the cat, even though the eigenvectors are in completely different dimensions. Furthermore, when we combined the eigenmotion of the cat with the eigenvectors of the human, we obtain a human walk in a very cat-like manner. These observations inspired us to revisit the problem of motion retargetting from a completely different perspective: instead of solving for unknown motion

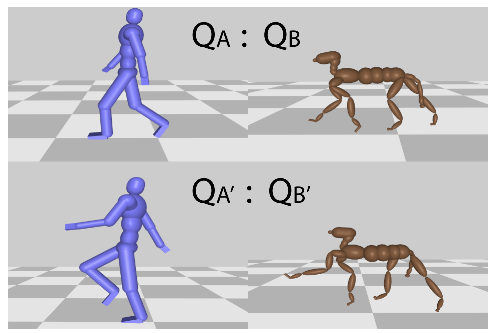

Figure 1: *Automatically synthesized marching motion for dog, $\mathbf{Q}_{B'}$, using an analogy of walking motions.*

on the new character based on the existing motion, our new approach transfers the existing eigenmotion to a new character with unknown eigenvectors.

Intuitively, the first few eigenvectors capture the main *coordinations* of a particular movement, and the eigenmotion indicates the execution of those coordinations over time. Based on our observation, we hypothesize that the same movement can be executed in a similar way (the same eigenmotion) by highly varied morphologies with inherently different coordinations (different eigenvectors).

The challenge in our approach is to compute the most important coordinations for synthesizing new motion automatically from the given input sequences. We analyze the two input motions $\mathbf{Q}_A$ and $\mathbf{Q}_B$ representing similar content and establish correspondence between the movement of the two characters. We perceive the similarity in the motion by the movement of the point cloud on each of the characters rather than their joint angles. We then use this correspondence to compute the coordinations for motion $\mathbf{Q}_{B'}$.

In this paper, we demonstrate transfer of motion in different styles from human character to other creatures e.g. a dog or a spider. These characters are markedly different in number of degrees of freedom (DOFs), body parts and skeleton structures. Our method automatically synthesizes motion for these characters by deriving correspondence from input motions and incorporating any user-specified constraints.

2. Algorithm

Our motion transfer algorithm synthesizes new motion for character C_B using the input motions. Our method comprises of two main steps:

1. **Correspondence Computation:** Establish correspondence between the two characters based on the movement of the point cloud on the characters in the respective example motions $\mathbf{Q}_A$ and $\mathbf{Q}_B$.
2. **Motion Optimization:** Given the character correspondence and a new motion $\mathbf{Q}_{A'}$, solve for $\mathbf{Q}_{B'}$ by finding the important coordinations for the character C_B performing the same behavior as $\mathbf{Q}_{A'}$. The correspondence can be obtained from step 1 or specified manually if motion $\mathbf{Q}_B$ is not available.

2.1. Correspondence between motions

We compute the motion, $\mathbf{X}_A$ and $\mathbf{X}_B$, of some points or *markers* spread across on the respective skeletons. We do an eigen analysis and separate the coordinations of the movement (eigenvectors) and their execution over time (eigenmotion). Eigenvectors capture the important *directions* of movement of the markers and eigenmotion capture *how much* and *when* the markers are moved along these directions. Therefore to establish correspondence between the motions, we compare the eigenvectors of the two motions.

Since we have decoupled coordinations and their execution in the given motions, we analyze how these coordinations of the two motions are related. l^{th} eigenvectors, $\mathbf{e}_A^l$ and $\mathbf{e}_B^l$, represent the "direction" of the movement of markers of C_A and C_B projected on their respective l^{th} eigenvectors.

Therefore, for each marker $p_{j,A}$ of C_A, we compare its three components $\mathbf{e}_{A,p_j}^l$ in the eigenvector $\mathbf{e}_A^l$ with those of each marker $p_{i,B}$ of C_B. If the cosine of the angle between $\mathbf{e}_{A,p_j}^l$ and $\mathbf{e}_{B,p_i}^l$ is close to 1 (or -1), the markers are said to match since they always move in same (or opposite) direction with any eigenmotion.

2.2. Optimization problem for motion transfer

Given a new motion $\mathbf{Q}_{A'}$ for character C_A, we want to compute the new motion for C_B, $\mathbf{Q}_{B'}$, using the correspondence established in the previous section. Rather than directly solving for the joint DOFs $\mathbf{q}_{B'}^k$ at each frame k, we solve for the basis vectors $\mathbf{F}_{B'}$ representing coordinations for C_B and the mean pose $\boldsymbol{\nu}_{B'}$ while using the eigenmotion $\mathbf{N}_{A'}$ of $\mathbf{Q}_{A'}$.

We formulate a space-time optimization problem to solve for the unknowns, $\mathbf{F}_{B'}$ and $\boldsymbol{\nu}_{B'}$. The DOFs at time sample k, $\mathbf{q}_{B'}^k$ (k^{th} column of motion matrix $\mathbf{Q}_{B'}$), are then reconstructed as:

$$\mathbf{q}_{B'}^k = \boldsymbol{\nu}_{B'} + \mathbf{F}_{B'}\mathbf{n}_{A'}^k \tag{1}$$

The objective of the optimization is to compute the coordinations $\mathbf{F}_{B'}$ such that the movement of the markers in the new motion $\mathbf{Q}_{B'}$ *matches* the movement of markers in the input motion $\mathbf{Q}_{B'}$ in accordance with the correspondence established using the matching criterion used in Section 2.1. The columns of $\mathbf{F}_{B'}$ have to satisfy orthogonality constraints. The user can also add pose constraints to direct the optimization, since the problem being under-constrained and non-convex makes the solution sensitive to constraints and initialization.

3. Results

We now briefly describe our results of automatic motion transfer using the techniques described in Section 2.1 and Section 2.2. In all the following examples, we use a human adult walking motion as the input $\mathbf{Q}_A$. Adult human skeleton comprises of 18 limbs and 42 DOFs.

- **Child march.** We choose human adult marching motion as the input $\mathbf{Q}_{A'}$ and a child walking motion as the input $\mathbf{Q}_B$. The child skeleton with similar morphology but has 35 DOFs and different bone lengths as compared to that of adult human.
- **Dog march.** We choose human adult marching motion as the input $\mathbf{Q}_{A'}$ and a dog walking sequence as $\mathbf{Q}_B$. This example illustrates our method on a very different morphology with 30 limbs and 81 DOFs.
- **Dog march with pose.** To synthesize marching motion using only two feet, we added pose constraint at a particular frame. The motions with and without a pose constraint are noticeably different, yet demonstrate similar marching behavior.
- **Dog sneaky walk.** To demonstrate variability of our method, we choose a sneaky walking motion as the new input $\mathbf{Q}_{A'}$ for the adult human skeleton. Motions $\mathbf{Q}_A$ and $\mathbf{Q}_B$ are same as the previous example. We create a crouching pose for the dog skeleton and add a pose constraint at the first frame capturing the characteristic sneaky behavior of the input motion.
- **Spider walk.** We create a skeleton for a spider that has 26 limbs and 48 DOFs. We do not have any given motion for the spider. Therefore, we manually specify a sparse correspondence of markers of the spider and the human adult.
- **Spider march.** We use the spider's walking motion synthesized in the previous example as our input motion $\mathbf{Q}_B$ to synthesize its marching motion $\mathbf{Q}_{B'}$.