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CHEMNITZ

BACHELOR THESIS

**Implementation of a modular pipeline to
evaluate different rigging and retargeting
techniques for virtual humans using
CrossForge**

Faculty of Computer Science
Professorship of Computer Graphics and Visualization

Author:
Mick KÖRNER

Examiner:
Prof. Dr. Guido BRUNNETT
Supervisor:
Dr.-Ing. Thomas KRONFELD

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for the degree of Bachelor of Science*

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UNIVERSITY OF TECHNOLOGY CHEMNITZ

Abstract

Professorship of Computer Graphics and Visualization

Bachelor of Science

**Implementation of a modular pipeline to evaluate different rigging and
retargeting techniques for virtual humans using CrossForge**

by Mick KÖRNER

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

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Chapter 1

Introduction

1.1 Motivation

Virtual humans have played a significant role in the field of computer graphics due to their extensive range of applications, which traverse multiple research domains. These applications have enabled the exploration of previously uncharted research territory, thereby contributing to the advancement in respective fields.

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The creation of a realistic virtual human remains a formidable challenge in the present day. Digital reconstruction techniques, such as Structure-from-Motion, have the capacity to produce a highly detailed surface replication of an individual, referred to as a human digital twin. However, the resulting mesh is static. Consequently, if the objective is to animate the scan with motion capture data, the mesh does not contain the necessary information how to apply this animation.

Despite the existence of techniques such as shape-from-silhouette, which utilizes motion capture to create animations by storing mesh sequences, the applications of these techniques remain limited due to the inherent coupling between motion and virtual characters.

The decoupling of motion from surface data into an underlying skeleton, termed "rig," has naturally emerged as the standard for both realistic and stylized virtual humans in contemporary media, including movies and video games.

Nonetheless, the process of creating a skeleton for a modeled or scanned character remains largely laborious. In order to obtain a skeleton of high quality, bones must be placed in a hierarchical structure and weights must be painted, both of which are still frequently done manually.

Specifically tailored skeletons necessitate specialized animations. Although standardized skeletal formats have emerged, they have a tendency to limit the expressiveness of characters. Furthermore, the capture of motion data and its corresponding formats can vary in terms of bone lengths and counts, depending on the subject's characteristics. This variation can lead to distortions and artifacts during playback, particularly when attempting to align data from different subjects. In addressing these challenges, motion retargeting approaches have been developed to transfer animations from one skeleton to another, taking into account variations in either bone lengths, structures, or both.

An investigation into the available methods and tools reveals that a significant number of implementations, if they are even available, are associated with specific skeletal hierarchies, utilize proprietary file formats, or are components of complex

commercial software. Consequently, these implementations frequently exhibit a lack of adaptability and extensibility.

Currently, there is an absence of open-source pipelines capable of automatically rigging and animating a character without necessitating the use of overly complex tools and workflows. Blender, the most widely used open-source 3D editor at present, lacks internal but even proper external solutions via plugins.

1.2 Objectives and Scope

The objective of this thesis is to implement a modular framework that facilitates the integration of diverse rigging and retargeting methodologies, thereby enabling a comparative analysis of their quality and performance. The primary goal is to create a tool that automates or streamlines the process of creating a virtual character just from a scan. The open-source 3D framework CrossForge, developed at the GDV professorship, will serve as the basis for this work.

The development of a modular processing pipeline, inclusive of a generic API, facilitates the combination and testing of various implementations and the pleasant creation of prototypes. CrossForge, which is based on C++, still requires a workflow to integrate tools utilizing foreign languages.

In addition to the implementation of selected procedures, the focus is on developing a sophisticated interface that will provide other students with the opportunity to easily integrate additional skinning and retargeting methods in the future. Thus, the proposed tool should be interactive to facilitate the testing, comparison, and combination of various algorithms, as well as to evaluate their correctness and potential advantages and drawbacks.

A Graphical User Interface (GUI) for the purpose of interactive control of the processing pipeline will also provide an open-source option to automatically rig and animate three-dimensional scans for scientists with less experience, for those from other domains, and for hobbyists.

1.3 Summary of the Work

A review of the relevant works in Chapter 2 will be conducted. This includes a recap of computer animation fundamentals, inverse kinematics, and animation constraints, as well as motion retargeting and auto-rigging. Popular and recent novel techniques will be explained and discussed.

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An evaluation of the available tools is provided in the appendix. This evaluation is not primarily concerned with performance; rather, it focuses on capabilities, availability, openness, and ease of use.

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In Chapter 3, the design and structure of the proposed editor and automation pipeline are described, along with the necessary implementations and API interfaces that facilitate an environment for evaluating automation methods. Due to the scope of this work and the evaluation of Chapter 2, an implementation of a motion retargeting solution is presented, while the integration of a autorigging tool is explained.

In addition to the aforementioned set requirements, the following elements are presented:

- An extensive graphical user interface for optional control of the environment and various processes
- The establishment of an animation workflow to test rigged characters and adapt animations
- Various tools required to facilitate constraint compliance of implemented and foreign-bound tools

The results of the proposed editor are concluded in Chapter 4. Potential bottlenecks are evaluated, and areas for improvement are investigated.

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Chapter 2

Related Work

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2.1 3D Animation Fundamentals

Prior to examining existing literature pertinent to this thesis, it is essential to review principles of skeletal animation in computer graphics, clear up various naming conventions used in literature to establish a foundation to prevent confusion.

In the domain of cross-paper naming, it is not uncommon for different designations to be used for the same concept or for separate concepts to be merged into a single term. Thus, it can be observed that many papers adopt a clear and consistent naming convention prior to review.

Skeletal animation is the most prevalent form of humanoid animation. All major graphics engines are capable of supporting this type of animation due to its inherent simplicity. This has led to its early adoption as a standard feature in hobby engines, with numerous motion editing tools in the industry also built around it.

2.1.1 Skeletal Animation

Analogous to the anatomical structure of real animals, which consists of rigid bones connected to a skeleton that is moved by muscles, a similar analogy has evolved naturally in the field of computer graphics in a biomechanical manner.

In order to simplify the process of animating the geometric surface of a character, referred to as a mesh, without the necessity of specifying all vertex positions individually, the use of skeletal bones is employed.

These *bones*, also known as links, serve to represent rigid objects within a virtual character. They are associated with a length attribute, and while their lengths can be altered with scaling factors in animation data, typically employed in stylized animation, they generally remain constant in realistic rendering.

Joints, representing the connection points between bones, are characterized by up to three by up to three rotational DoFs (Degree of Freedom). Joints are the components concerned with motion and may contain any affine Transformation, but primarily rotational.

In most cases, bones are not explicitly defined in implementations. Rather, they are implicitly included in their parent or child joint.

In order to establish a relationship between bones through the formation of a hierarchy, implementations utilize either pointers or indexing. Typically, a joint is assigned references to its parent joint in the hierarchy and potential child joints, however contingent on the implemented restrictions, this may differ.

It is advantageous to establish nomenclature for joints due to the unique characteristics they can acquire.

A *root joint* is distinguished by its absence of a parent joint, and any transformation applied to this joint is reflected in the actor's global movement. In animation, this joint is often translated in conjunction with a walking animation, ensuring that the actor does not remain stationary while walking. While this could be achieved through the use of a scenegraph, it facilitates the unification of motion playback across applications by circumventing the necessity for an additional abstraction.

end effectors represent bones without children. Depending on the application, endeffector may be a joint itself or a bone, sometimes having additional joint defined at its tips unused by animation data.

2.1.2 Skeletal Hierarchy

A *skeleton* is comprised of multiple bones arranged in a hierarchical structure, typically a tree-like configuration.

As illustrated in Figure 2.1, the skeletal structure of a virtual human is represented, with bones assigned unique names to facilitate their manipulation in various software applications. Various Formats between applications may treat Joints relative to bones differently, causing confusion, in this example it is not clear which bone belongs to the root joint, while there exist unnamed extra joints unused at the end effectors.

A joint chain, is defined as a link of multiple joints with no branches, indicating that each joint has at most one child. Within the specified chain definition, a start joint and an end joint emerge, analogous to the root and endeffector in the skeletal hierarchy. - Analogous to a kinematic chain, which is a subgraph of the skeleton, joint chains are

img pos

Tree structures are the most prevalent, but some systems permit circular structures known as closed loops (see Figure 2.2) or graphs, where multiple parent joints are allowed.

The employment of intelligently positioned bones enables the implicit enforcement of constraints, such as ensuring that the distance between two bones remains constant. This approach has been found to be particularly useful in the context of center of rotation correction. However, implementing this concept necessitates special consideration during various evaluation processes. Due to this reason, this is not permitted in all systems, as is the case with the Blender.

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An additional factor to consider is the potential for a Rigged character to comprise multiple roots. To illustrate, a character that incorporates a tool, such as a wrench for holding, could be rigged and transformed by a single bone or, alternatively, multiple bones in conjunction with other tools.

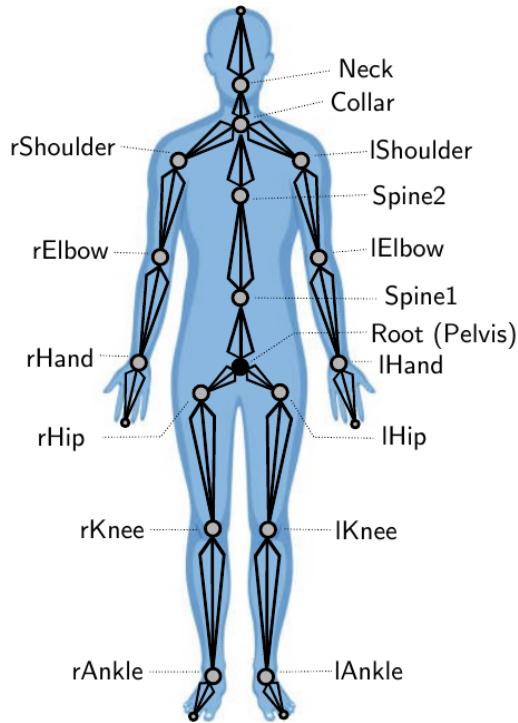


FIGURE 2.1: Example of human skeleton, note that bones and their parent joint are combined, this can cause confusion, in this example the root and collar joint have multiple bones. Image taken from [1]

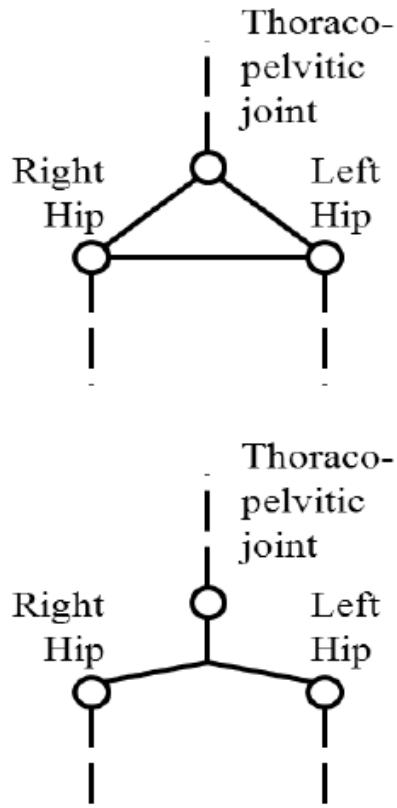


FIGURE 2.2: Visualization of an Armature with a loop, depending on implementation the tree becomes a Graph. Image taken from [2]

2.1.3 Pose Space vs. Work Space

Common spaces in the graphics pipeline that have been established include window mapping (NDC and camera space), but more importantly for this work, World Space and Object Space.

In the context of skeletal animation, the object space is defined as the spatial domain of the character in a state of rest.

In order to visualize a skeleton or parent other objects in world space to joints, or joints to other objects in world space, for example, a tool to simulate some kind of work, it is necessary to know the position of a desired joint in pose θ .

As previously discussed, joints influence the transformation of their respective child bones. To determine the position of joints relative to object space, it is necessary to propagate all kinematic chains from the root bone. Given that rotational transformations of a joint affect child joints in an arc, changing pose parameters (θ) results in a non-linear transformation of child joints.

Due to the discrepancy between pose parameters and the euclidian object space, pose parameters θ form the *pose space*. Conversely, the object space can be referred to as the *work space* relative to the subject and may be extended to world space coordinates.

2.1.4 Forward Kinematics

Forward kinematics is the process of computing the working space from pose space parameters. Let F be the forward propagation of the kinematic chain, and let θ be the current pose configuration, object space position, and rotation of the endeffector or any joint in between. It can be computed as follows:

$$T_i = F_i(\theta)$$

where i is the respective joint.

Figure 2.3 visualizes this process, translation, rotation (and sometimes scale) of each joint determines the transformation of all child joints.

The propagation of the chain using affine transformations results in object space relative coordinates. To illustrate this principle, consider the example depicted in Figure 2.3. The transformation of "End Site" is computed as the affine combination of Joint transformations up to the root bone.

Figure change Orientierung to Orientation

$$T_{EndSite} = M_{J3}M_{J2}M_{J1}M_{root}$$

where M denotes the affine transformation of each bone respectively relative to its parent bone. Consisting of scale rotation translation applied in that order.

2.1.5 Restpose and Bind Pose Matrix

Character modelers or scans are required to define the surface of a virtual character in an existing pose. Bones must be placed accordingly for that specific character. Joint rotations of a motion are then applied relative to the rest pose angle of the embedded joints. *Rig* is thereby defined as a character with a respective skeleton embedded, ready for animation. This suggests that motion transfer between skeletons poses a challenge when rest poses differ.

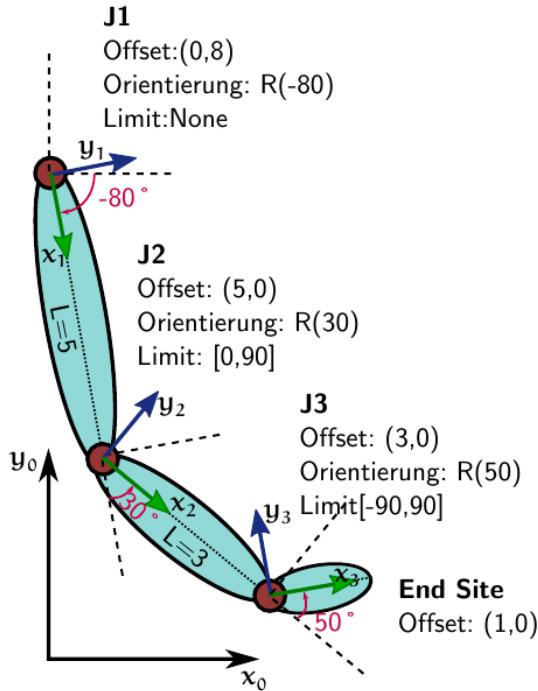


FIGURE 2.3: Example of a joint chain with respective local coordinate systems visualized. It is important to note that the global transform of Joint J2 depends on J1, and J3 depends on J2 and J1. Image taken from [1]

Bind Pose Matrices are assigned to each joint and describe the transformation from the object space coordinate system of the rigged character to the corresponding joint in rest pose. Since rest pose remains constant, precomputing bind pose matrices offers numerous advantages. For example, it facilitates skinning and provides a concise representation of the coordinate base system of a joint, making it useful for transferring between applications.

Inverse Bind Pose Matrix, as indicated by its name, performs the inverse transformation of the bind pose matrix. When applied to the respective joint, it transforms the joint to the object space center of the character, thereby representing its actual base coordinate system transformation. In various paper and code sources, this is also commonly referred to as the Offset Matrix.

The *Offset Matrix* is a critical component for efficient Linear Blend Skinning, a subject that will be addressed in the subsequent section.

2.1.6 Skeletal Skinning

A rudimentary definition of skeletons has been established. However, the original goal was to facilitate the animation of character mesh surfaces in an efficient manner. The concept of skeletal animation entails the abstraction of body parts into joints, thereby reducing complexity by manually defining the motion of every surface vertex. In the context of skeletal animation, the vertices of a character's surface, also referred to as *skin*, are abstracted to a bone.

This is achieved through the assignment of which vertex is affected by which bone. Additionally, given that Flesh is deformable and not rigid, there is a necessity to interpolate vertices in proximity to the joint of two bones, as observed in a 2-bone example and a vertex in between them, thus near a joint.

The determination of affection and interpolation, as well as the flexibility between two or more bones, can be achieved through the use of bone weights per vertex. The quantity of these weights is determined by the material defined on each vertex of a character. These weights can be authored manually through the use of weight painting or automated tools that utilize nearest neighbor or heat diffusion simulation.

Figure 2.4 shows an example of weights for the Humanoid Test model "Cesium-man" for the right elbow joint and its subsequent bone. The color blue is used to indicate a weight of zero, while red is used to indicate a weight of one.

Offset matrices of each joint are essential for animating the attached surface. They move corresponding affected vertices to the center of the coordinate system in object space, causing following transformations applied being equivalent to transforming relative to the Base Coordinate System of each joint.

Skinning Matrices describe the transformation of each joint from rest pose to a set pose θ . This transformation ensures that local rotations of a joint are applied correctly. The joint transformation chain, in conjunction with the offset matrix, is combined into the skinning matrix, which is then applied in the vertex shader during rendering.

Skinning Matrix S_i of Joint i is computed as follows:

$$S_i = P_i \cdot J_i \cdot MO_i$$

where J_i is the Local Joint transformation, P_i are all parent transformations up to the root joint and MO_i is the Offset matrix of joint i .

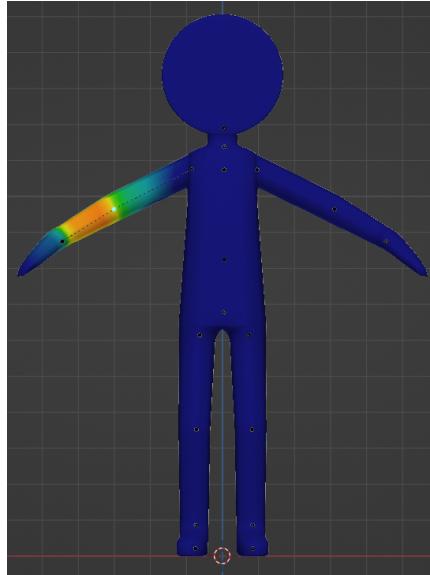


FIGURE 2.4: Simple Humanoid Test model Cesiumman visualized in Blender’s weight painting mode with the right Elbow Joint being selected. The gradient, ranging from blue to green to red, signifies an increase in weight for each vertex relative to the joint.

TODOM 2.1.2: caption Figure 2.4

Linear Blend Skinning (LBS) is the most common skinning method and demonstrates high processing speed due to its suitability for execution on GPUs via the utilization of vertex shaders. However, due to the approach of linear accumulating matrices, various artifacts can occur, such as volume loss and Candy-wrapping.

While various methods have been proposed to address these limitations, they fall beyond the scope of this thesis.

From a technical standpoint, the number of bones that can influence a vertex is not limited. However, to facilitate the incorporation of vertex shaders, it is common practice to impose a restriction of four bone weights per vertex.

2.1.7 Motion Data

During a specific time point of motion playback, rotational, translation, and scale values from pose θ are applied to the local transform of each joint.

One pose configuration in an Animation is usually called Keyframe. A Motion thus consists of multiple keyframes played sequentially. Timepoints per Keyframe determine at which time of an Animation a given Pose should be displayed.

Motion Data is stored either as a sequence of poses or a sequence of joint channels, resulting in slight differences in animation playback handling and performance, depending on the task.

The sampling rate dictates the number of keyframes displayed per unit time.

Between Keyframes, linear or other interpolation methods are often used to calculate Inbetweens to more smoothly display animations for variable playback speeds.

A common trick for gait motion is to use the sampling rate to create a variable amount of walking speeds from one animation, without having to create or capture gait motion for every desired speed.

However, these represent only a small part of the much broader field of motion processing and blending.

2.2 Inverse Kinematics

- forward kinematics described at we have joint angles and lengths, with which we can compute each subsequent joint starting point to get the endeffector position
- inverse kinematics describes the need to get joint angles with which rigid joint lengths and a target position, the endeffector matches the target position

check

In the preceding section, it was established that forward kinematics processes inputs from the configuration space of a rigged model, yielding working space coordinates that can be utilized for rendering a skinned mesh. Additionally, collision tests can be conducted, and further objects can be parented to joints.

For a dynamic grabbing motion a natural desire would be to know a Configuration to target any Point in Working Space.

- Definition IK - ik goal to find joint configuration where end effectors move to desired targets, while movement should be smooth fast and accurate

formulation

Inverse kinematics (IK) is the process of determining a joint configuration that satisfies various working space conditions, such as reaching a target or avoiding specific regions in space.

- Animators use Inverse Kinematics to intuitively animate characters without having to rotate each bone individually

formulation

Inverse Kinematics pose a fundamental tool for Motion Editing, its not only used for Automating Processes or real time interactive applications, but by 3D animators themselves as a helpful tool to model a desired pose more easily and quickly.

- very useful in animation such as movies and games as well as robotics - Inverse Kinematics widely used in Animation and Robotics industry

formulation

2.2.1 The IK Problem

The ideal approach would be to find a inverse mapping of the Forward Kinematics Mapping F so can get a pose configuration θ for a given target direction t :

$$\theta = F^{-1}t$$

- The primary challenge associated with inverse kinematics lies in the fact that pose space and working space are not linearly dependent.

reuse explanation of basics

2.2.2 IK Surveys

Aristidou et al. [3] present an extensive evaluation for various Inverse Kinematics techniques.

Boulic et al. [4] survey different Inverse Kinematics techniques to correct noisy and incomplete motion capture data from vision Input.

2.2.3 Reachability

- This is because the Inverse Kinematics Problem can not be solved unambiguously.
- figure 2.5 shows that in 2D a chain of more than 2 joints yields an infinite amount of solutions for a reachable point

- 3 cases - target is outside of reach, no solution - depending on desired behavior, chain should be - target is at distance of of chain length l_k is applied to - exactly one solution - easily identifiable, but rare occurrence

cases

- target is within bounds of chain length - still problem that depending on skeletal definition sometimes points inside chain length are not reachable (e.g. long and small joint)

In 2D, a chain of more than two joints yield an infinite amount of solutions for a reachable Point in space, illustrated in Figure 2.5. This already happens in 3d for chain length of two.

2D example infinite solution

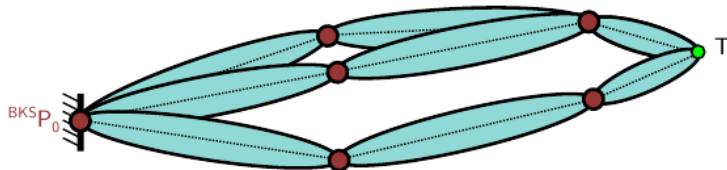


FIGURE 2.5: In 2D, for Chains with more than 2 Joints, there will be an infinite Amount of Configurations satisfying reaching the Target, when $|T - P_0| < \sum_i |j_i|$. Image taken From [1]

- multiple solution if chain length == target distance to chain root 1 sol - if target outside, no solutions

[3] has expl

2.2.4 Analytical Methods

- The analytical approach tries to solve the system of equations spanned by inverting the Forward Kinematics formula of the corresponding armature. Because they find solutions reliably, they are called Closed form solutions. Lander [5] explained the analytical method simple for beginners.

main expl

- Figure 2.6 illustrates relevant Variables for solving a 2 Joint chain. l_T , l_1 and l_2 span a triangle, because all lengths are given, trigonometric functions can be used to determine angles θ_1 and θ_2 .

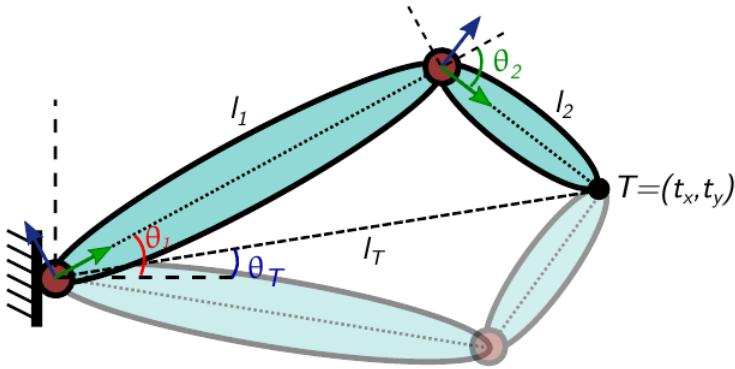


FIGURE 2.6: Visualization of relevant Variables for solving θ_1 and θ_2 analytically to reach point T using Trigonomic functions. A Second Solution is Visualized with less opacity below, Image taken from [6]

While this solution would be Ideal because it is very fast and numerically stable. Solving the system for more than two Joints becomes with each additional Joint more complex.

- but the computational increase with longer chains is not the only problem. providing either all Solutions or predetermined ones, finding solutions that produce plausible results related to temporal locality is even more difficult

2.2.5 Jacobian Methods

- Whitney's 1969 paper "Resolved Motion Rate Control of Manipulators and Human Prostheses" is often credited as one of the earliest works to introduce the use of Jacobian inverse for controlling robotic manipulators[1].

TODOM 2.2.1: rename section to Numerical Methods?

- Liegeois' 1977 paper "Automatic Supervisory Control of the Configuration and Behavior of Multibody Mechanisms" further developed the use of pseudoinverse for redundant manipulators[1].

TODOM 2.2.2: cite first IK paper?

The Jacobian Inverse Method, also called inverse rate control, for solving Inverse Kinematics falls into the category of numerical solvers and represents the first Iterative Approach developed.

- what is jacobian? - with non linear mappings there is a need to effectively handle transformations between different coordinate systems for example $f(x) = x^2$ - when focusing on a point, linear approximation error increases the further away we are from that point, near this point linear approximation is sufficient

- jacobian represents the best linear approximation of a non linear function near a specified region

TODOM 2.2.3: "specified region" near reference frame/point better?

- Main problem why Inverse Kinematics is hard is because pose space and working space are not linearly dependent - for one there multiple mapping of F^{-1} which would satisfy T , thus its already hard to determine which solution to use

TODOM 2.2.4: check and position

- moreover F is generally not directly invertible, thus F^{-1} is not always uniquely defined or may not exist for all points in the workspace. - meaning that when we rotate a joint the resulting endeffector moves in a circular motion, thus the forward kinematics function outputs a non linear space in which the endeffector moves - a

smart observation is that this non linear space can be approximated by a linear space for small amounts of movement

Previously 2.2.1 the Problem of multiple pose space configurations satisfying target position constraints. This implies that there exist multiple mappings of F^{-1} that could potentially satisfy t . Consequently, determining the optimal solution becomes a complex task.

TODOm 2.2.5: end check and position

TODOm 2.2.6: formulation

Furthermore, it is not uncommon for F to lack direct invertibility. This further complicates the determination of a unique and well-defined inverse function, or even the existence of such a function across the entire workspace.

go into detail with ??

When a joint is rotated, the resulting endeffector moves in a circular motion. This indicates that the forward kinematics function outputs a non-linear space in which the endeffector moves. ?? visualizes this difference for an endeffector.

However, it can be observed that this non-linear space can be approximated by a linear space for small amounts of movement:

Let J be a linear space mapping such that for a small movement of θ :

$$\Delta t \approx J(\theta)\Delta(\theta)$$

The Jacobian Matrix J is defined as the rate of change on Vector t when we turn angles of Joints in θ in each respective Dimension for a small amount Δ .

- Explicit values of J can then be evaluated by changing the corresponding angle of the armature by Δ and using the Forward Kinematics Function to determine the change of endeffector direction relative to its old position in object space.

For rate of change a common definition of the Jacobian Matrix is representing it using derivatives:

$$J = \left(\frac{\partial F(\theta)_i}{\partial \theta_j} \right)$$

fill

where i are respective Dimensions in which the target moves for each changeable angle θ_j .

$$\Delta\theta \approx J^{-1}(\theta)\Delta(t)$$

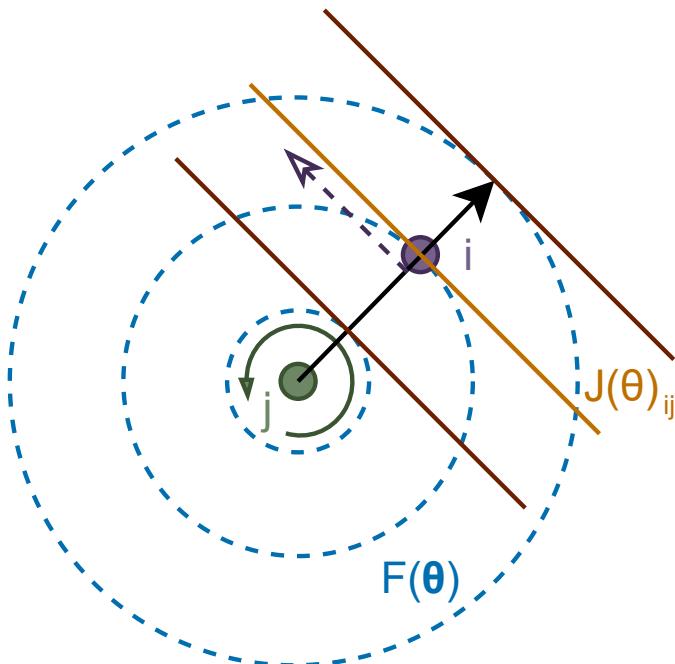


FIGURE 2.7

Buss [7] provides a more in-depth Introduction to the Jacobian Inverse Kinematics Method and how the Jacobian Inverse works.

put rigid explanation of simplifying calculation into chapter 3

- Open-Loop Implementation - Jacobian inverse is used to compute a single set of joint adjustments based solely on the initial conditions and the desired pose - no feedback loop; the system does not monitor or adjust its output based on the actual pose achieved - The control action is determined solely by the input (desired pose) without considering the actual output (current pose) of the system.

TODOm 2.2.7: explain open and closed loop jacobian ik

Closed-Loop Implementation - also called Closed-Loop Inverse Kinematics (CLIK), the system continuously monitors the current pose of the end effector and compares it to the desired pose - error between two poses is used to adjust the joint configurations iteratively until the desired pose is achieved or a specified threshold is met - This process involves feedback, where the output (current pose) is fed back into the system to correct and refine the pose at each iteration - Feedback helps in achieving better stability and accuracy by continuously correcting for any deviations from the desired state.

- Jacobian matrices sometimes ill-conditioned, having very small or very large singular values which can lead to Singularities and noise amplification

- Jacobian Transpose - straightforward method that involves directly multiplying the Jacobian transpose by the desired end-effector velocity - with transpose method, no costly matrix inversion is required - less accurate, especially for ill-conditioned problems

- Singular Value Decomposition (SVD) - Provides a robust solution by decomposing the Jacobian into singular values and vectors - can handle ill-conditioned problems

- least squares: Minimize $\|Jx - b\|^2$

least squares

- Damped Least Squares (DLS) - extension of least squares introducing regularization to the Jacobian to improve stability - Minimizes $\|Jx - b\|^2 + \lambda\|x\|^2$ - particularly useful when the Jacobian matrix is ill-conditioned or singular
- DLS uses damping factor λ is a positive scalar, controlling the trade-off between accuracy / performance, minimizing target error, and stability, avoid overly noisy and input sensitive solutions
- damping penalizes solutions with large values in the vector x (the solution vector) and discourages the solution from straying too far away from zero, especially when dealing with ill-conditioned matrices. Thus improving stability by preferring smaller solutions. - small damping factor less stability, large damping factor less performance
- Selectively Damped Least Squares (SDLS) - adaptive damping strategies adjust the damping factor based on jacobian properties or convergence rate
- Full Pivoting LU Decomposition (FullPivLU) can be used to check the invertibility of the Jacobian matrix and solve the resulting linear system. It's a reliable method for general matrix operations. - gives choice to adjust for performance or accuracy
- more hybrid approaches - Damped Least Squares with Singular Value Decomposition (SVD-DLS)
- jacobian approaches in general yield smooth postures but slow to compute

2.2.6 Cyclic Coordinate Descent

Cyclic Coordinate Descent (CCD) were the first heuristic approaches to solving IK. Kenwright [8] wrote a great article which summarizes the History Workings and Constraints. There he stated that, due to its simplicity, it is not certain who published, but Wang and Chen [9] are credited.

TODOm 2.2.8: combine with FABRIK section into heuristic?, but would be quite large

- in order to reach a target point with an endeffector, each joint will be rotated so that the current vector from current joint position to endeffector points to the target

expl more in depth + picture

- there are two variants of CCD, one which starts rotating joints from the endeffector joint back to the root, and one that starts from the root and rotates the endeffector last

break condition?

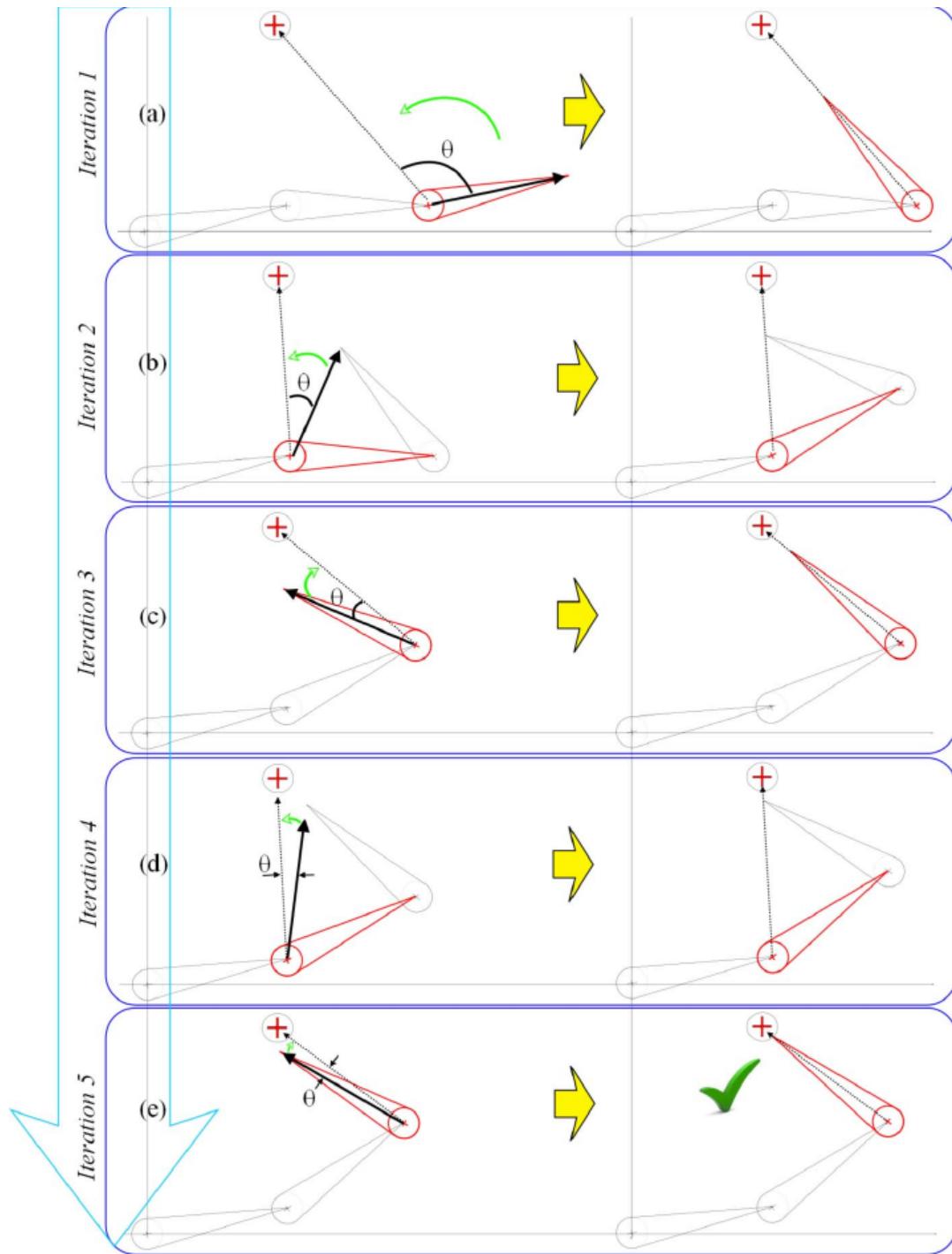


FIGURE 2.8: Three Joint Chain example of CCD, in each Iteration the Current Joint is rotated so that the Vector from current Joint to target and current Joint to endeffector align. Image taken from [8]

Algorithm 1 BackwardCCDIK Algorithm, Taken From [8]

```

1: procedure BACKWARDCCDIK
2:   Input:  $e$                                       $\triangleright$  threshold
3:   Input:  $k_{\max}$                                  $\triangleright$  max iterations
4:   Input:  $n$                                      $\triangleright$  link number (0 to numLinks-1 chain)
5:    $k \leftarrow 0$                                   $\triangleright$  iteration count
6:   while  $k < k_{\max}$  do
7:     for  $i = n - 1$  to 0 do
8:       Compute  $u, v$                                 $\triangleright$  vector  $P_e - P_c, P_t - P_c$ 
9:       Compute ang                                 $\triangleright$  using Equation 1
10:      Compute axis                              $\triangleright$  using Equation 1
11:      Perform axis-angle rotation (ang, axis) of link  $i$ 
12:      Compute new link positions
13:      if  $|P_e - P_t| < e$  then                   $\triangleright$  reached target
14:        return                                   $\triangleright$  done
15:      end if
16:    end for
17:     $k \leftarrow k + 1$ 
18:  end while
19: end procedure

```

2.2.7 FABRIK

- In order to improve performance and the rolling and unrolling Problem of CCDs, Aristidou and Lasenby [10] came up with Forward And Backward Reaching Inverse Kinematics (FABRIK)

address CCD problems in CCD sec

- builds and optimizes upon ccd - fabrik noted producing more natural results, avoiding rollung and unrolling of ccd and moving the whole chain like jacobian inverse

- fabrik simplifies the

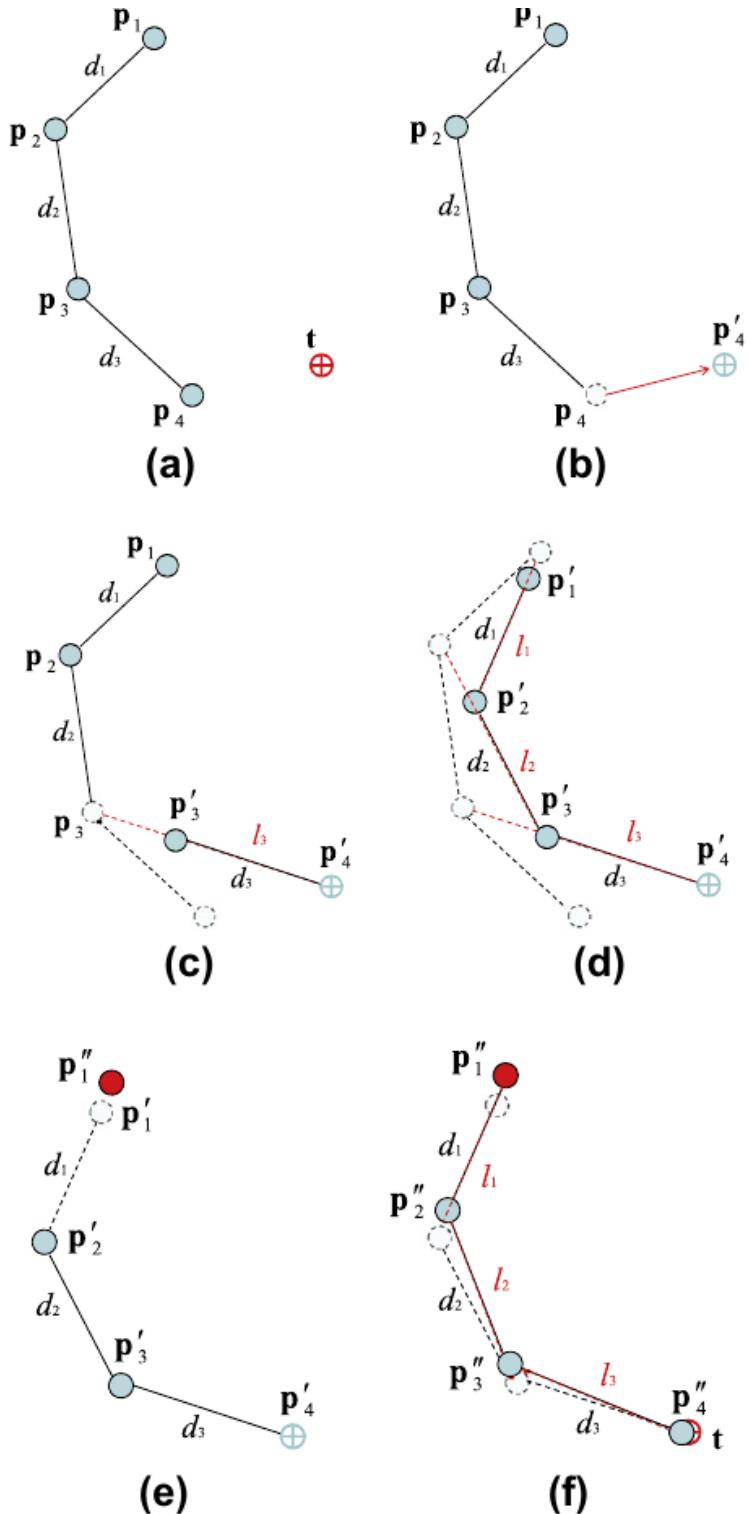


FIGURE 2.9: Image taken from [10]

Algorithm 2 A full iteration of the FABRIK algorithm, Taken from [10]

Require: The Joint positions p_i for $i = 1, \dots, n$,
Require: target position t ,
Require: distances $d_i = \|p_{i+1} - p_i\|$ for $i = 1, \dots, n - 1$
Output: New joint positions p_i for $i = 1, \dots, n$

```

1: dist  $\leftarrow \|p_1 - t\|$                                  $\triangleright$  The distance between root and target
    $\qquad\qquad\qquad$   $\triangleright$  Check whether the target is within reach
2: if dist  $> d_1 + d_2 + \dots + d_{n-1}$  then            $\triangleright$  The target is unreachable
3:   for i = 1 to n-1 do       $\triangleright$  Find the distance  $r_i$  between the target t and the joint
   position  $p_i$ 
4:      $r_i \leftarrow \|t - p_i\|$ 
5:      $k_i \leftarrow \frac{d_i}{r_i}$ 
6:      $p_{i+1} \leftarrow (1 - k_i)p_i + k_i t$            $\triangleright$  Find the new joint positions  $p_i$ .
7:   end for
8: else
    $\qquad\qquad\qquad$   $\triangleright$  The target is reachable; thus, set as b the initial position of the joint  $p_1$ 
9:   b  $\leftarrow p_1$ 
10:  difA  $\leftarrow \|p_n - t\|$                        $\triangleright$  Check whether the distance between the end effector  $p_n$  and the target t
    is greater than a tolerance.
11:  while difA  $> tol$  do
     $\qquad\qquad\qquad$   $\triangleright$  STAGE 1: FORWARD REACHING
12:     $p_n \leftarrow t$                                  $\triangleright$  Set the end effector  $p_n$  as target t
13:    for i = n-1 down to 1 do
     $\qquad\qquad\qquad$   $\triangleright$  Find the distance ri between the new joint position  $p_{i+1}$  and the joint p
14:       $r_i \leftarrow \|p_{i+1} - p_i\|$ 
15:       $k_i \leftarrow \frac{d_i}{r_i}$ 
16:       $p_i \leftarrow (1 - k_i)p_{i+1} + k_i p_i$            $\triangleright$  Find the new joint positions  $p_i$ .
17:    end for
     $\qquad\qquad\qquad$   $\triangleright$  STAGE 2: BACKWARD REACHING
18:     $p_1 \leftarrow b$                                  $\triangleright$  Set the root  $p_1$  its initial position.
19:    for i = 1 to n-1 do
     $\qquad\qquad\qquad$   $\triangleright$  Find the distance  $r_i$  between the new joint position  $p_i$ 
20:       $r_i \leftarrow \|p_{i+1} - p_i\|$ 
21:       $k_i \leftarrow \frac{d_i}{r_i}$ 
22:       $p_{i+1} \leftarrow (1 - k_i)p_i + k_i p_{i+1}$          $\triangleright$  Find the new joint positions  $p_i$ .
23:    end for
24:    difA  $= \|p_n - t\|$ 
25:  end while
26: end if

```

2.2.8 Other Methods

<https://zalo.github.io/blog/inverse-kinematics/#properties-of-various-ik-algorithms>

There exist many more Methods for solving Inverse Kinematics, but - fail due to high cost

Newton Methods explained by [10] treat IK as a minimization problem but are slow and hard to implement.

Mass Spring Models, is a IK method proposed by Sekiguchi and Takesue [11]. A numerical method which uses the virtual spring model and damping control. Suited for redundant robots, robots which have many DOF.

- DOF Degrees of Freedom explain in basics
- explain mass spring
- expl Particle IK

2.3 Constraints

- In the previous section we looked at Inverse Kinematics abstractly as a motion editing tool, because IK is dynamic in nature and only considers Skeletal strucutre

Compared to the real world, we have yet to model DOF limiting factors of our Skeleton Bones like neighboring tissue like muscles, organs, fat or Connective tissue, as well as physical limits related to the atanomy and structure of the bones themselves located at joints.

These are essential for Inverse Kinematics and its appliences in order to already avoid a set of self interpenetration Issues as well as non plausible poses to improve realism.

- many papers describe constraints specifically for an inverse kinematics method
- integration tied to a specific inverse kinematics method allows for optimization potential
- problematic is to incorporate constraints in a way that a global solution will still be found

2.3.1 Tree Structures

- in order for
- multiple inverse kinematic chains that share the same joint
- Jacobian Inverse Kinematics solves this naturally by incorporating not just one chain and a target, but all joints and targets into tha jacobian matrix.

2.3.2 Skeletal Constraints

- Aristidou et al. [12] have described six most common anthro- pometric Joint constraints, visualized in Figure 2.10.
- dependin on tpye various types of movements allowed
- ball-and-socket joint - ball moves within a socket - limits angular rotation in the direction of parent joint

- hinge joint - simplest type of joint; - elbows, knees - motion only in one plane / direction about a single axis

- pivot Joint - only rotation on one axis, used in neck - for a given target, the head orientates towards it, - the target point has to be projected on the axis, and the rotation constraint has to be enforced

condyloid - ovoid articular surface that is received into an elliptical cavity - permits biaxial movements, that is, forward-backward and side to side, but not rotation

saddle - convex-concave surface, treated same as condyloid, e.g. thumbs - different angle limits, allowable bounds - no axial rotation

plane joint - also gliding joint, only sideways/sliding movements - requires IK rule relaxation in form of joints are not connected anymore - done by projecting target onto joint plane bounds in algo

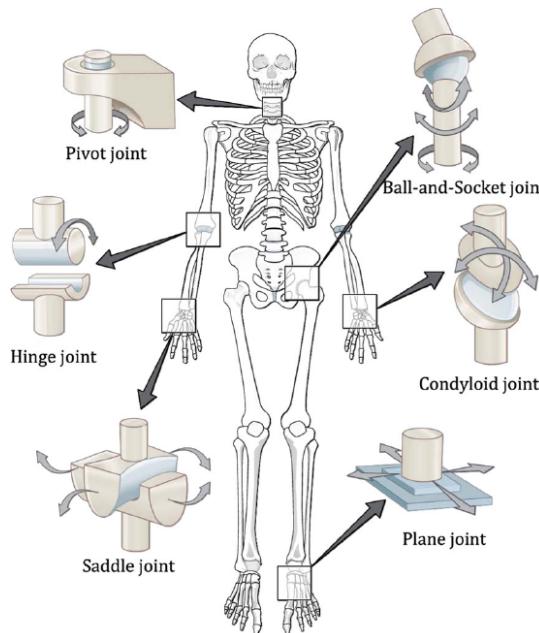


FIGURE 2.10: Various Constraint Types Visualized and where they could be used in a Virtual Human Skeleton. Image taken From [12]

2.3.3 Other Constraints

- Wilhelms and Gelder [13] proposed Reach cones, using spherical polygons to specifying a region for allowable joint movement.

- other constraints types that can be useful for motion editing
- distance constraints can ensure that either specific spaces are avoided or should be reached, for example elbow movement
- the same way a constraint could be incorporated that checks for self intersection

self intersection

- enforcing various constraints is difficult because it can affect an algorithms ability to converge

2.3.4 Jacobian Inverse Constraints

[14]

hinge limits

swing twist limit

complete

2.3.5 CCD Constraints

- While weighting CCD for multiple end effectors can be intuitive Hecker [15] explained how to utilize priorities by averageing desired angles at branches.

- To ensure CCD doesn't run into a local minima under influence of constraints simulation annealing is used [8]. - Simulation annealing for CCD tries to jump out of a local minima by randomly rotating joints.

2.3.6 FABRIK Constraints

- [12] mentioned multiple various constraint types, but lacks in detail on how to exactly implement these, referring to [10].

- While mentioned in [10], Aristidou et al. [12] explained more in detail how to solve a FABRIK armature for multiple end effectors.

- all chains of the armature are propagated from endeffector until the sub-base joint, which is equivalent term for branch.

Multiple end effectors - 2 Stages

- first Normal (forward) - applying FABRIK starting from each endeffector moving inward - moving until sub-base: - (sub-base == joint with 2 or more child chains) - sub-base is joint that connects two or more joints -> so apply fabrik until sub-base is reached - on subbase joint, each position of joint on fabrik iter is stored -> centroid is calculated which is the mean of all pos -> FABRIK iter continued from new subbase pos (centroid) - second stage backward: - algo normal applied until sub-base - then applied separately for each chain

multi endeff cases: - neither reachable - just apply straight line - TODOf optimized version lowers to one iteration - one reachable - 2 solutions: - attain one target, leave other away - both away but closer - TODO option to interpolate with weights - both reachable - 2 cases: - both can reach target in configuration - only one can reach target, again interpolatable with weights

- option to smooth out noisy input data **4.4.2. Joint Control between Two True Joint Positions.**

- true root and end eff pos, noisy inter joints - if out of reach, straight line - if in reach fabrik applied from end eff (first forward) then backward

caption

- also possibility to run into deadlock - strict constraints cause not reaching config because of locality in algo (no parent, child consid) - solution - first check if reachable: - yes -> if dist not smaller each iter -> backward step first iter: bend by

check source

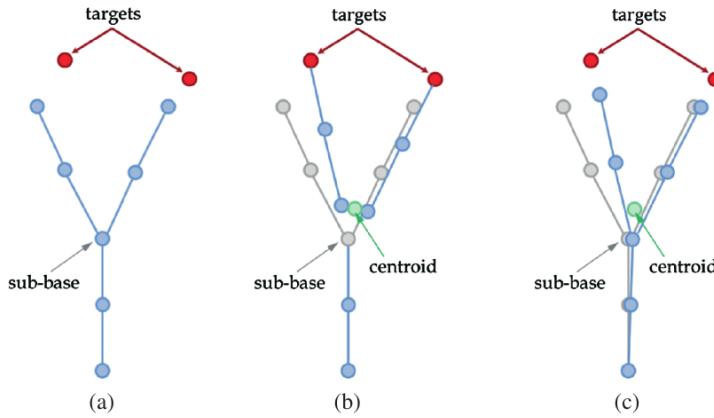


FIGURE 2.11: Image showing, Image Taken from [12]

increasing degrees away from target - allows joints to bend more - bending till 360 degrees, then no solution if not reached

- [12] also showed Self-collision Determination

2.3.7 iTASC

Instantaneous Task Specification and Control (iTASC) [16] - multiple constraints

- it Implemented as an optional Inverse Kinematics Solver in Blender but incomplete, having various issues, highlighting its implementation complexity.

iTASC blender pos

2.4 Motion Retargeting

- Motion Retargeting is the process of transferring motion data for a skeleton with a specific hierarchy and joint lengths to another skeleton which either differs in one or both. - In the following sections various Motion Retargeting approaches of the past years are inspected - There is no clear cut categorization of what type an approach exactly is - subject to many aspects, can be categorized differently, following a categorization sensible for this work

2.4.1 Naive Retargeting

- The naive retargeting approach is to simply transcribe motion applied to a joint from the source character to a target character by defining joint correspondences between source and target character

list problems

- this approach can cause various problems, including but not limited to ground penetration, self interpenetration, wrong directions due to restpose differences, foot-sliding and more

2.4.2 Motion Cleanup Approaches

- try to fix artifacts generated by naive approach

Tang et al. [17] presented a motion retargeting method to convert movements between characters with heterogeneous topologies.

- different topology (number of nodes), different coordinates systems, and different initial posture.
- manually set the joint correspondences between the two hierarchies
- ignore some useless leaf nodes and nodes cannot find a corresponding

- First, adjust the initial posture of source skeleton.
- but do not explain how to adjust in detail

- use adjustment matrix - Motion data from source skeleton needs to be adjusted to ensure the new skeleton has the same movement after the initial posture adjustment. The rotation of each joint is adjusted according to this initial posture adjustment.

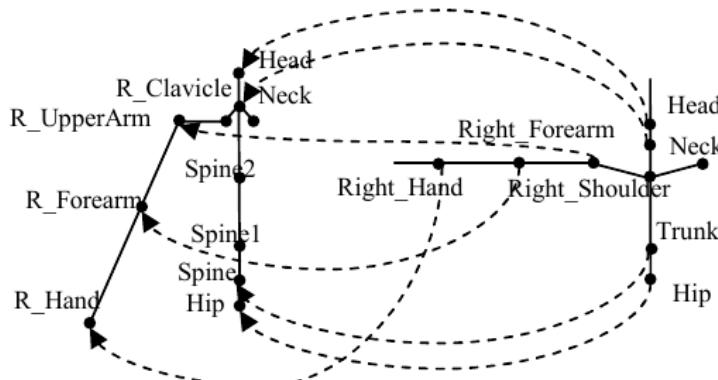


FIGURE 2.12: Image take from [17]

- Let A_j be the adjustment matrix of joint j , and R_j be the rotation matrix of joint j before adjustment, Adjusted rotation R' :

$$R'_{L_UpperArm} = A_{Hip} A_{Plevis} A_{Spine} A_{Spine1} A_{Spine2} A_{Neck} A_{L_Clavicle} R_{L_UpperArm} \\ (A_{Hip} A_{Plevis} A_{Spine} A_{Spine1} A_{Spine2} A_{Neck} A_{L_Clavicle} A_{L_UpperArm})^{-1} \quad (2.1)$$

- Scale Root Node: The global position of the root node is scaled based on the leg length ratio between the source and target skeletons
- skipping joints with no matches done with

$$R'_{\text{child}} = R_{\text{parent}} R_{\text{child}} \quad (2.2)$$

- processes on keyframes of a given animation
- correct the resulting motion and make it enforce Cartesian constraints by using Inverse Kinematics

- previous section problem of defining correspondences between joints

- Feng et al. [18] propose very similar method to Tang et al. for their Open Source Simulation Framework smartbody - Automated Skeleton Matching via similarly named joints and recognizing body part topology - use naming to determine left and right, but sometimes break at uncommon naming conventions, especially problematic because some motion capture systems only provide numeration as joint names - their offline Retargeting Process incorporates converting joint angles after aligning default poses and jacobian based inverse kinematics to enforce constraints, describing its property to maintain target pose as much as possible - original motion trajectory is warped according to the differences in leg lengths - framework also

[cite smartbody source code](#)

incorporates range of capabilities including: locomotion, object manipulation, gazing, head movements, speech synthesis, and lip-syncing - limited to humanoid or near-humanoid characters

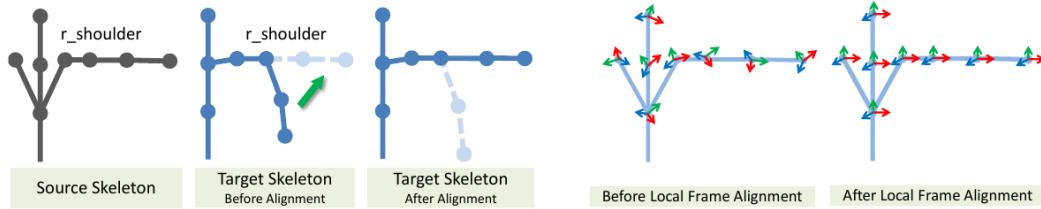


FIGURE 2.13: Image taken from [18]

Ming-Kai Hsieh et al. [19] tackle Retargeting across different articulated figures (e.g., humans, dogs, birds), focusing on transferring and concatenating motions, and generating smooth transitions

- correspondence between the bone structures of the source and target skeletons manually defined, describing automatic skeleton matching techniques as challenging - thus focusing on having a user interface for other aspects of their retargeting process - for joints between source and target mapping one-to-one, many-to-one, or no mapping can be defined
- initial poses are aligned by recursively computing the rotation angles between corresponding bones, from the root to the leaf.
- motion data transfer via converting rotation angles from local to global coordinates and then back to the local coordinates
- for interpolation between two source motions with different skeletal structure a meta-skeleton, combining both skeletons' bone structures, is constructed

2.4.3 Numerical approaches

- Numerical motion retargeting methods work by solving for the motion of the entire armature simultaneously. This is a departure from traditional techniques that might adjust the position or orientation of limbs independently. This is done by using numerical optimization methods, being able to take various aspects of the armature and motion data into consideration.

TODOM 2.4.1: was subsection Jacobian based

TODOM 2.4.2: see before naive?

expl

TODOM 2.4.3: category?

Gleicher [20] describes the challenge to solve Motion Retargeting mathematically because of how to define the quality of a motion, motivating a pragmatic approach.

- propose a numerical solver which utilizes the spacetime constraint approach for skeletons with identical structure but different segment lengths

- require basic features of motion identified as constraints

- spacetime constraints consider the entire motion simultaneously, not just individual frames. minimizes magnitude of the changes and restrict their frequency content To preserve the qualities of the transferred motion - constraints enforced Newton's laws, and the objective function minimized energy consumption

- explain that IK solvers consider each frame independently, adding undesirable high frequencies to a primarily smooth motion - key of preserving high frequencies

also feature of motion warpings popularity

- The system works by calculating a motion displacement curve, which represents the difference between an initial estimate of the motion and the final retargeted motion. This displacement is then used to generate the retargeted motion by adding it to the initial estimate. Utilizing motion-displacement maps as data representation and cubic B-splines to avoid encoding high frequencies into the generated motion.

Figure 2.14 shows an Example of motion displacement for an Animation retargeted to a smaller character, weighting the constraint to reach the box high.

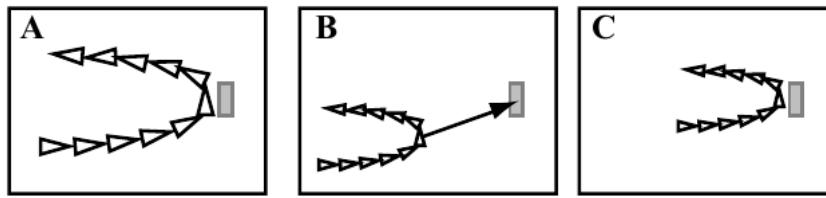


FIGURE 2.14: - A aerial view of a character walking up to, picking up, and carrying away an object. B scaling relative to origin, character does not reach box. C if reaching the box is the only constraint, the entire motion can be translated. Image taken from [20]

- similarities to Jacobian inverse kinematics, utilizing Damped least-squares to minimize constraint residuals across the entire motion
- each step, we construct linear approximation of constraint problem, solved iteratively using a damped pseudo-inverse
- also discuss Motion for Morphing to incorporate scaling of joints during animation
- constraints difficult to represent mathematically as well as hard to define because may not know all the properties required like physical laws, mass of the body and defining which constraints are important to consider to reduce complexity
- challenging to implement, Representation not clearly defined

- Choi and Ko use Inverse Rate Control, which is the Jacobian Inverse Method of Inverse Kinematics, and extend it to be applicable to tree structures instead of chains without branches. [21] - Their Proposed method, called Online-Motion Retargeting, achieves real-time performance for new characters with different anthropometric proportions. - utilizing jacobian inverse kinematics method fundamentally, Maintaining the characteristic features of the original motion during the retargetting process, avoiding loss of unique motion details.

- utilizes closed loop jacobian ik
- The OMR algorithm tracks multiple end-effector trajectories simultaneously from the source character. - Joint angle imitation through minimization of joint angle differences by intelligently using the kinematic redundancies - online: processing data as it comes in, without needing the entire sequence beforehand
- Choi and Ko have also showed a way to imitate joint angles of the source motion by incorporating them as a secondary goal. The primary task tracks given end-effector trajectories and the secondary task is to imitate the joint angle trajectory θ , as best as possible.

- jacobian IK method discussed in 2.2 gives a particular solution - the generalization, called null space, includes all possible solutions by adding a term from the null space:

$$\dot{\theta} = J_1^\dagger \dot{x}_1 + (I - J_1^\dagger J_1) y_2 \quad (2.3)$$

- where $(I - J_1^\dagger J_1)$ projects y onto null space - null space term corresponds to the redundant degrees of freedom

- for primary task x_1 and J_1 there can be a secondary task x_2 J_2 added:

$$\dot{\theta} = J_1^+ \dot{x}_1 + (I - J_1^\dagger J_1) J_2^+ \dot{x}_2 \quad (2.4)$$

- Input trajectories are a continuous input of constraints which applied to the target produce coherent motion.

inverse rate control

- integration of $J_1^+ \dot{x}_1$ should give $\theta(t)$ - open-loop integration can not eliminate initial tracking error - based on Jacobian pseudoinverse, Closed-loop Inverse Rate Control leads to zero steady state error which means that the error is exponentially convergent to zero for a fixed target position

- with usage of joint angles θ^{src} as a secondary target:

$$\dot{\theta}^{des} = J_1^+ \dot{x}_1 + (I - J_1^\dagger J_1) \dot{\theta}^{src}$$

TODOm 2.4.4: explaination more in detail unnecessary?

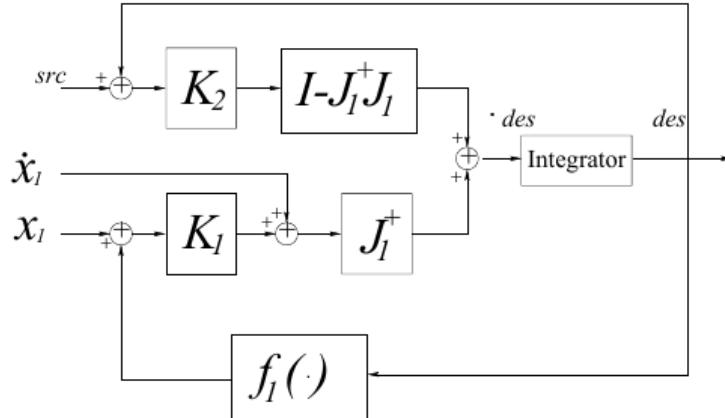


FIGURE 2.15: Image taken from [21]

- Jacobian matrix spans whole armature and contain zeroes where the joint angle and the end-effector have no relation observed different limbs - DOFs for each end-effector also includable, incorporating direction the end-effector has

- algorithm can be used to reduce measurement errors in restoring captured motion by using both measured end-effector data and joint angle data

Monzani et al. [22] introduce an "Intermediate Skeleton" as a bridge between the Performer and End User Skeletons using Inverse rate control to enforce spatial constraints. Developing a plugin for 3D Studio Max with a User Interface.

- Intermediate Skeleton solves this by reorienting its bones - same node structure and local axis system orientations as the End User Skeleton but the bones are oriented to match the Performer Skeleton's bone directions

- describe solution to smooth transitions between captured and corrected postures with multiples constraints, using easing functions to smoothly enable and disable constraints at defined key positions
- user has to indicate a one-to-one correspondence between joints

2.4.4 Limb based Retargeting

expl more

- abstract joint chains into limbs to allow for more complex task descriptions - in order to solve limbs independently of the whole armature - some tackle problem of automatically defining limbs and correspondences between skeletons

Du Sel et al. [23] tackled real-time motion retargeting for large crowds, developing a plugin for Autodesk Maya.

- use an intermediate skeleton representation called Golaem Skeleton for both source and target skeleton, motion are converted to the intermediate representation for playback on any targets.
- Golaem Skeleton consists of hierarchy of Bone Chains (limbs) defining beginning and end joints, visualized in Figure 2.16

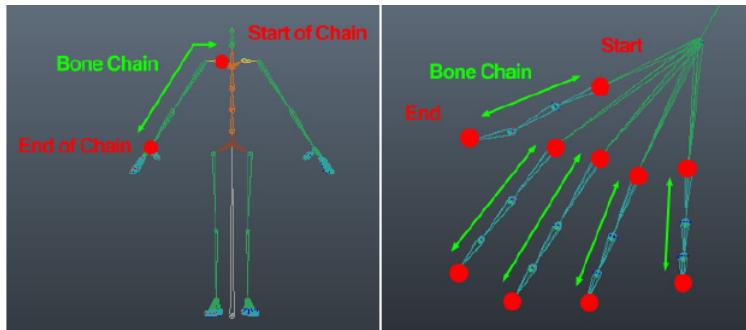


FIGURE 2.16: Example of Golaem Skeleton Bone Chains. Image taken from [23]

- assign different types for Bone chains: pelvis, spine, limb and effector to represent sufficient character morphologies
- automate generation of limb nodes, by searching the isomorphic branches and utilize tags generated from chain world position to determine legs or hands
- skeleton motion mapping maps limbs depending on type and tag and allows for surjective, injective and bijective mapping, for example mapping motion of a two-armed biped to a four-armed biped
- defining different movement modes, ability to take or take not restpose differences into consideration to allow for grasping targets or more natural motion playback
- focus on performance to allow for simulation of large crowds, proposing usage of a simplified version of the goalem skeleton, incorporating animation interpolation, mirroring of animation results, utilizing combined FABRIK and analytic IK and pre-computing and interpolating FABRIK results for differt chain lengths called IKCache
- Abdul-Massih et al. [24] retarget motion with focus on maintaining motion style to even non-humanoid characters.
- authors introduce the concept of "Groups of Body Parts" (GBPs), user-defined groupings of joints and motion features to carrying motion style - GBPs are defined

by multiple joints with a "base"- and "leading" joint, equivalent to root and end effector of a joint chain, but GBPs do not have to be a chain

- motion features are separated into positional and angular features
- positional features represent a path of representative vectors of each GBP - the representative vector points from base to leading joint, capturing basic aspects of the motion, later used in positional constraints in an Inverse Kinematics solver - representative vector can also be scaled depending on the ratio of itself with the matched source GBP vector
- angular amplitude features describe contraction or extension of body parts relative to the neutral input motion, capturing motion style - their angular amplitude constraints control the range of rotation
- Matched GBPs are then aligned semi-automatically based on their representative vectors direction and starting position - motion transfer is computed on a per GBP basis, being able to be used injectively or surjectively, similar to Du Sel et al.'s Bone Chains. Utilizing a space time approach enforcing constraints
- GBPs definitions for both the source and target are user defined via an interface
- extracted features are converted into constraints for a full body per frame optimization using space-time optimization

2.4.5 Machine Learning Approaches

- due to the complexity of the motion retargeting Problem, machine learning approaches have become popular in recent years providing high quality results - Traditional motion retargeting often requires hand-tuning, goal is to automate as much as possible
- Villegas et al. [25] introduce a novel neural network architecture to retarget motion different skeletal bone lengths and proportions without needing paired motion data.
- uses a recurrent neural networks (RNNs) with differentiable Forward Kinematics (FK) layer as its core component and cycle-consistent adversarial training to achieve unsupervised motion retargetting - network aims to solve the IK problem indirectly with cycle-consistent adversarial training, processing motion sequences on-the-fly, taking advantage of the temporal coherency in motion - for training Motion is retargeted also back to the source character with round trip penalty on difference and discriminator which evaluates its realism - but network limited to same skeleton topology

does mixamo dataset have same skel hierarchy?

Aberman et al. [26] tackle skeletons that differ in number of joints but have topologically equivalent graphs - Deep Motion Representation considers dynamic (joint rotations) and static (joint offsets) components - using skeletal pooling, different skeletons are reduced to a common primal skeleton by a sequence of edge merging operations on degree two joints - the resulting skeleton is also called latent space, visualized in Figure 2.17, on which motion retargeting is learned and performed

- Retargeting is performed on the dynamic part of the latent space, encoder transforms motions into the shared latent space, while a decoder reconstructs motion on other skeleton, also called skeletal unpooling

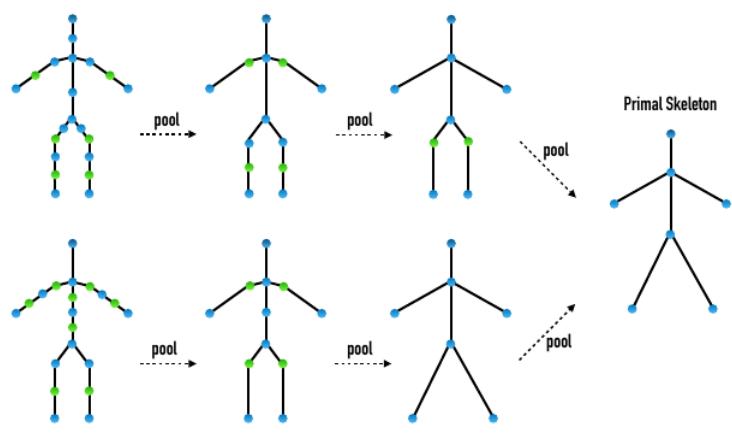


FIGURE 2.17: Image taken from [26]

- encoders learns on Deep Motion Representation, which decouples dynamic (time dependent, rotational) and static (time independent, offsets) aspects of motion
- convolution kernels consider the skeleton structure in both dynamic and static branches separately during retargeting
- model uses a combination of losses for training, notably encoded-decoded motion should matches input, motion should retain dynamic features, adversarial loss to check for plausibility of retargeted motion, since no ground truth exists and End-Effectors to have similar velocity
- Inverse Kinematics is used to refine foot contact with ground
- limitations include Challenges retargeting between skeletons with very different T-poses, and difficulty retargeting complex tasks that were not seen in the training set

- Skinned Motion Retargeting with Residual Perception of Motion Semantics & Geometry

expand

- Unsupervised Motion Retargeting for Human-Robot Imitation

- <https://arxiv.org/pdf/2402.05115v1>

- HMC: Hierarchical Mesh Coarsening for Skeleton-free Motion Retargeting

- <https://arxiv.org/pdf/2303.10941v1>

- ==Correspondence-Free Online Human Motion Retargeting==

- <https://arxiv.org/pdf/2302.00556v3>

- OKR: Joint Keypoint Representation for Unsupervised Cross-Domain Motion Retargeting

- <https://arxiv.org/pdf/2106.09679v1>

- Skinned Motion Retargeting with Dense Geometric Interaction Perception

- <https://arxiv.org/pdf/2410.20986v1>

- Self-Supervised Motion Retargeting with Safety Guarantee

- <https://arxiv.org/pdf/2103.06447v1>

- Flow Guided Transformable Bottleneck Networks for Motion Retargeting

- <https://arxiv.org/pdf/2106.07771v1>

- MoCaNet: Motion Retargeting in-the-wild via Canonicalization Networks

- <https://arxiv.org/pdf/2112.10082v2.pdf>
- Hierarchical Neural Implicit Pose Network for Animation and Motion Retargeting
- <https://arxiv.org/pdf/2112.00958v1.pdf>

- new features often require models to be retrained

2.4.6 Other approaches

- there are many other novel approaches that can't be categorized clearly or have a special approach separating it from previously discussed ones
 - Hecker et al. [27] tackle the motion retargeting issue during the animation authoring stage
 - in a Semantic Approach, animation definition is decomposed into Specialized (character-relative) and Generalized (character-independent) Space
 - because animators have to recreate animations in their proposed system, various tools are introduced to help authoring animation, like converting between Specialized and Generalized space
 - further specification of body parts are categorized into Body capabilities (grasper, mouth, spine, root etc.), narrowed down with Spatial and Extent (FrontMost, Back-Most, RightMost, etc.) Queries
 - Movement Modes introduced similar to other papers applying motion either on the Identity or Rest Relative, Scaling targets, enforcing ground constraints (picking up objects from floor), Secondary Relative Movement (e.g. reaching mouth with hand) or Lookat
 - proposed system incorporated in an interactive editor simultaneously previewing animation while editing, tweaking specialized and generalized parts to ensure motion quality
 - to enforce defined constraints a novel IK Solver, Particle IK, is proposed - Particle IK is a two-phase solver; the first phase solves for the spine pose, and the second phase solves for the limb poses, treating the spine as fixed
 - the proposed system was used for animating user-created characters in the game Spore

[cite others](#)

[particle ik in rel 2 IK](#)

[complete](#)

2.5 Automated Rigging

-

2.5.1 manual approaches

Avril et al. [28] reuse existing rigged characters, transferring their skeleton and skinning weights with distinct mesh topologies, maintaining subtle artistic variations.

[TODOm 2.5.1: section name](#)

- present methods to adjust joint orientation based on vertex weights and retarget skinning weights across different mesh resolutions
- they compute a vertex-to-vertex between source and target meshes, by deforming

the source mesh using a set of user defined markers to reduce overhead of defining per vertex correspondences

- joints are placed relative to corresponding vertex joint distances and further refined with Energy minimization techniques while skinning weights are transferred using barycentric coordinates

- streamlines character creation process, allowing refinement of character geometry, skeleton or weights on existing rigged characters - but heavily relies on time-consuming user input to define marker correspondences to achieve good results, requires source and target meshes to be in similar poses and is limited to clean manifold watertight meshes

2.5.2 Machine Learning Approaches

- Baran and Popovic [29] introduce a fully automatic rigging method adapting a predefined skeleton to an unrigged character, providing an implementation called Pinocchio

- medial surface is approximated by examining C1-discontinuities in computed signed distance field of the mesh - then spheres are packed based on medial surface position reaching towards the isosurface, placing largest spheres first - essential sphere centers are then connected in a graph on which the predefined skeleton is embedded depending on penalty functions - weights for various hand constructed penalty functions are determined with maximum-margin supervised learning, inspired by support vector machines - finally continuous optimization refines the location of joints and heat-diffusion simulates weights

TODOm 2.5.2: is machine learning?

- pre-existing animations for the predefined skeleton will play more nicely on the rigged character, reducing potential problems of retargeting approaches - drawback character needs to be a closed volume

Xu et al. [30] proposed RigNet, an end-to-end deep learning method to automate character rigging. - Only using 3D character mesh as input, they generate specifically tailored skeletons for a variety of Humanoid and non-humanoid creatures, also automatically computing Surface skin weights

- learns directly from the mesh representation, imitating the joint placement intuition of animators, e.g. spine created closer to the back rather than the medial surface

- present designed a deep modular architecture consisting of Skeletal Joint Prediction, Skeleton connectivity prediction and Skinning prediction.

- Skeletal Joint Prediction, predicts location and number of joints for relevant areas using differentiable clustering scheme "The network learns to displace mesh vertices towards joint locations. A differentiable clustering scheme identifies joint locations using a neural mesh attention mechanism." - some ambiguity even among animators regarding the number and placement of joints - optional parameter that can control the level-of-detail of the output skeleton (override the learned bandwidth used to determine cluster density, Lowering the bandwidth results in denser joint placement, while increasing it results in sparser skeletons., zero bandwidth value will cause each displaced vertex to become a joint) - learns to displace mesh geometry towards candidate joint locations - graph neural network extracts topology-and geometry-aware features, a differentiable clustering scheme is then used to extract joints - (incorporates global and local information) - Symmetrization according to the global bilateral symmetry plane before performing clustering improved results

- Skeleton Connectivity Prediction, learns which joints pairs from skeletal joint prediction step should connect to bones using learned shape- and skeleton representation, giving probabilities for each pair, Minimum Spanning Tree algorithm is then used to form a tree starting most likely bones

network learns which joint pairs to connect with bones, forming a hierarchical skeleton tree structure, uses both shape features and joint positions "BoneNet: Predicts the probability of connection between all pairs of joints. A Minimum Spanning Tree (MST) algorithm then generates the final skeleton tree." better - predict a hierarchical tree structure - connecting the joints. The output bone structure is a function of joints predicted from the first stage and shape features - utilizing Euclidean distance and proportion are useful indicators of joint connectivity - considers root as special case having extra network simillar to bone prediction to determine good root bone

- Skinning Prediction - graph neural network predicts skin weights based on intrinsic distances from the mesh vertices to the bones better - also based on a graph neural network operating on shape features and intrinsic distances from mesh vertices to the predicted bones better - use of volumetric geodesic distances from vertices to bones better - using mesh representation capturing spacial relationship of mesh vertices to skeletal bones with volumetric geodecic distances (mesh interior) - inverse of distances used to determine bone priorities, choosing closest bones first - another module is used to compute final skinning weights with learned parameters and a softmax function to get normalized weights

- use a cobination of manually authored loss functions during training simillar to Baran and Popovic - Unlike "Pinocchio", RigNet doesn't rely on pre-defined skeletal templates - direct mesh input avoids pre-processing or lossy conversions - like voxelization Xu et al., 2019 - full solution for both skeleton prediction and skinning, rather than a partial - better captures the anatomical intuition compared to geometric methods.

- not completely invariant to mesh resolution and connectivity - Limited representation of small parts like fingers - control over the level-of-detail of generated skeleton using single bandwith parameter, limited control could be expanded to more parameters

TODOm 2.5.3: if ref old paper

highlight in rignet integration
necessesry to cleanup mesh

2.5.3 4D approaches

2.5.4 Thinning Approaches

list more papers

2.5.5 Re-Meshing

Chapter 3

Motion Retarget Editor

methodisches vorgehen hier

3.1 Processing pipeline

- current research focuses on machine learning - despite ik / limb based methods existing for a long time, there exist no standalone free open source tools or plugins for blender

TODOm 3.1.1: goals from related work?

- Also having an open source foundation opens up community improvements and helps CrossForge mature by prototyping features and incorporating them if deemed useful - for a fully automated pipeline, there is a need to keep various parts interactive for interactive testing to verify correct implementation of algorithms

- Noteably, there is a lack of Open Source Implementations of more complex Motion retargeting algorithms and especially frameworks in order to compare and improve motion retargeting.

- Furthermore the process of creating a usable virtual human for various applications remains tedious - goal creating for creating an autonomous virtual human

user interface section?

3.1.1 CrossForge

CrossForge [31], developed by Tom Uhlmann at Chemnitz University of Technology, is a A C/C++ Cross-Platform 3D Visualization Framework using OpenGL. - design allows to use the available CrossForge modules, modify them, or completely replace them with new OpenGL based implementation and GLSL Shaders. - This flat design, simplicity and direct approach, CrossForge is well suited for educational purposes and computer graphics research.

- CrossForge allowes for quick implementation of various visualization approaches without beeing restricted the integrated SceneGraph, allowing for quick Prototyping

- while CrossForge already has LinearBlend Skinning and an simple Animation Controller Implemented, it is lacking in many Features, notably a User Interface for Keyframe Control, Joint Visualization, a Picking System, which had yet to be implemented and will be discussed in the following sections

- because CrossForge is a relatively small Framework compared to Unity or Unreal Engine, many tools like Scene management, User Interfaces or Picking had yet to be implemented - CrossForge lacks User Interface for dynamic loading and unloading of Actors

3.1.2 Prototyping approach

- hard to decide beforehand how the class structure might look like - use smart pointers to better structure classes - todo explain smart pointers

- reoccurring pattern weak pointer to smart pointer in order to seperate logic to corresponding classes more easily and reduce overhead - weak pointer make it easy to invalidate reference, corresponding class which wants to process another object first has to lock it, checking for its validity, when the referenced object is accessed but invalid by beeing deleted, the corresponding module can act accordingly - reduces state management sagnificantly

- steps should be interactive in order allow the potential for user correction interaktive steps (wie accurig) um optional rigging anzupassen - joint positionen korregieren Automatisierte pipeline welche eingabemodelle automatisch riggt auf beliebige skelette und bindings/convertierung für motion retargeting anbietet

- due to shere amount of features that are yet to be implemented, this approach allows for various advantages, - testing the correctness of implementations interactivly, thus keeping the system realtime - keeping concepts as modular as possible, thus making it easy to reuse and combine parts

3.1.3 class hierarchy overview

- Figure 3.1 shows the class hierarchy of the Motion Retargeting Editor, including most important classes

- TODOm 3.1.2: secton name "class structure" or something better?, also keep it here or move it to sectionClasses and Scene Management
- TODOm 3.1.3: explain class structure, following chapters
- scene
- TODOM 3.1.4: I like it, but question was, split? + position?

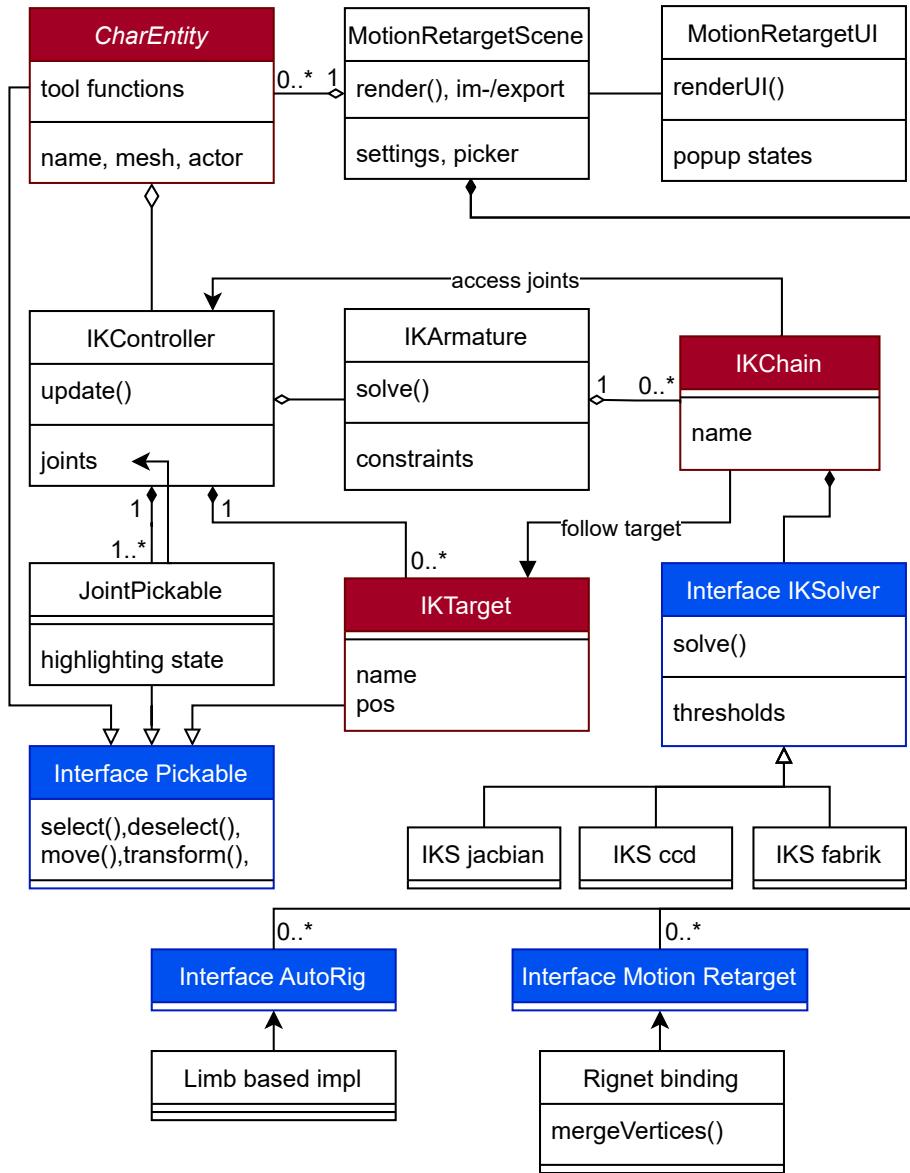


FIGURE 3.1: UML class diagram visualizing essential classes and their relationships, blue indicates interfaces and red are dynamically instantiable objects during runtime. AutoRigger and Motion Retargeting solutions can access various listed classes over the CharEntity class without restriction.

- in order to archive usable results with the developed prototype, Rignet was chosen as an example for a foreign tool integrated into CrossForge - due to a lack of more sophisticated Open Source Motion Retargeting solutions, Limb based solution will be presented

[cite rignet](#)

3.2 Classes and Scene Management

- all classes related to the prototype are managed in its own subdirectory, being able to inherit CrossForge modules and replace only required parts keeps classes concise and reduces error potential by avoiding duplicated code

3.2.1 Character Entity

- The Character Entity Class represents a Single Virtual Character and manages various States related to it.
- represents central data unit for editor, various modules utilize a char entity, being able to change its state for example when giving a rig, the char entity changes from a static actor to a skeletal actor

LISTING 3.1: My Code Example

```

1 struct CharEntity {
2     bool isStatic = false;
3     std::unique_ptr<IKSkeletalActor> actor;
4     std::unique_ptr<StaticActor> actorStatic;
5
6     // animation
7     std::unique_ptr<IKController> controller;
8     Animation* pAnimCurr;
9
10    // common
11    std::string name;
12    T3DMesh<float> mesh;
13    SGNGeometry sgn;
14
15    // Picking binding functions
16    ...
17
18    // various tool functions
19    ...
20 };

```

- `IKSkeletalActor` and `StaticActor` are renderable objects created from the intermediate Format `T3DMesh` - in order to adapt the underlying mesh data contained in `T3DMesh`

- when a Model is created using an importer, a corresponding CharEntity is created and the geometry node is added to the Scenegraph - in order to differentiate between already rigged Characters and Characters without a Skeleton, unique pointers are used, which can be checked easily for initialization - during initialization `T3DMesh` is loaded by the actor in order to be visualized using OpenGL - during runtime we need to apply animation changes and mesh operations on the `T3DMesh`

- re-initializing the renderable actor with the updated `T3DMesh` checks again which features `T3DMesh` has and chooses corresponding actor accordingly

- in order to identify a Char, their name is derived from the filename of the imported asset, if an asset has already the same name, a number will be added

3.2.2 Main Scene

- want to dynamically load various models to test quickly without having to restart or delete existing CharEntities during runtime
- since Motion Retargeting requires definition which characters, need to define them

- done using intuitive selection, last click will always define primary charEntity, secondary charEntity is assigned upon selecting a new charEntity that is different from the current one
- operations which require two charEntities can check if both are present beforehand to avoid errors

LISTING 3.2: My Code Example

```

1  class MotionRetargetScene : public ExampleSceneBase {
2
3    ...
4    void mainLoop() override;
5    ...
6    void renderUI();
7
8    void loadCharPrim(std::string path, IOmeth ioM);
9    void storeCharPrim(std::string path, IOmeth ioM);
10
11   struct settings {
12     ...
13   } m_settings;
14
15   std::vector<std::shared_ptr<CharEntity>> m_charEntities;
16   std::weak_ptr<CharEntity> m_charEntityPrim; // currently
17   ↪ selected char entity
18   std::weak_ptr<CharEntity> m_charEntitySec; // secondary char
19   ↪ entity for operations
20
21   SGNTransformation m_sgnRoot;
22
23   ...
24 };//MotionRetargetScene

```

- in order to inspect model from various angles for comparison, the camera has been extended to rotate to world space axes and toggling between orthographic and perspective projection, controlled with the numpad similar to blender

3.2.3 Config

- crossforge has No abstraction for a Configuration System to store Settings in Files for persistent usage across sessions - while simple ini configuration file loader isn't hard to implement, an abstraction would benefit from ease of use

- ability to store settings with string or overload with custom type
- to reduce code overhead, an extra compile unit is used to define all serialization interfaces in order to separate Config functionality from the corresponding core modules
- used to store camera position and other settings like paths or load behavior

TODOm 3.2.1: more details?

3.3 User Interface

- while various user interface libraries exist, ImGui [32] provides the most mature and extensible experience.

It provides a:

- large and flexible set of Widgets
- very easy integration
- many plugins written for it

- immediate mode, imgui is redrawn every frame
- no separation of states, clean code - imgui docking used to more cleanly place ui elements
- followup sections will detail specific user interface interaction for proposed methods and functionalities

3.3.1 Widgets

Outliner

- visualizes Skeletal Hierarchy with collapsible tree nodes containing joint names
- also lists targets
- visibility options only for character settable
- clicking on element in list fetches the corresponding object, when pickable, the picker state gets forced on that object, enabling feedback with highlight visualization

Animation tab - select animation for playback, set animation speed etc

Popup - integrated ImGui Popup had various artifacts due to the on-demand rendering

Grid

- helps with orientation in 3d space,
- main axis intuitively marked with corresponding color red x, green y, blue z in order to avoid confusion during usage

TODOm 3.3.1: explain ui bindings / implementation in following parts on the side?

3.3.2 Picking

- in order to interact with objects in the 3D scene, a picking system is needed

- picking objects implemented using ray shooting, transforming mouse click position from screen space back to world space and checking for intersections
- CrossForge already implemented `BoundingVolume` type including AABB and Sphere, checking intersections firstly before checking for intersection with mesh data

cite libigl

- in order to quickly check for intersection libigl is used for important parts like joints, needing conversion from `T3DMesh` to a list of Vectors in a Matrix

- Picker is a class which evaluates a Set of IPickable objects and stores the last and previous clicked Object as a weak pointer reference.

LISTING 3.3: My Code Example

```

1 class IPickable {
2     public:
3         virtual void pckSelect() {};
4         virtual void pckDeselect() {};
5         virtual void pckMove(const Matrix4f& trans) = 0;
6
7         virtual Matrix4f pckTransGuizmo() = 0; // used for guizmo
8             ↪ update
9         virtual Matrix4f pckTransPickin() = 0; // used for picking
10            ↪ evaluation
11         virtual const BoundingVolume& pckBV() = 0;
12         virtual EigenMesh* pckEigenMesh() { return nullptr; };
13 }

```

- any class can derive from this interface making it easier adding new types of pickable objects

LISTING 3.4: My Code Example

```

1 class Picker {
2     void pick(std::vector<std::weak_ptr<IPickable>> objects);
3     void forcePick(std::weak_ptr<IPickable> pick);
4     void start();
5     void resolve();
6     void reset();
7     void update(Matrix4f trans);
8     std::weak_ptr<IPickable> getLastPick() {
9         return m_pLastPick;
10    };
11    std::weak_ptr<IPickable> getCurrPick() {
12        return m_pCurrPick;
13    };
14    Matrix4f m_guizmoMat = Matrix4f::Identity();
15
16    void rayCast(Vector3f* ro, Vector3f* rd);
17    std::weak_ptr<IPickable> m_pLastPick; // picked object
18    std::weak_ptr<IPickable> m_pCurrPick; // last clicked object
19    std::weak_ptr<IPickable> m_pPick; // last clicked object
20 }

```

- with the `Picker` class the application can store references to various types of picked objects, most relevant methods are visualized in 3.4.

Matrix separation

matrix seperation

expl

3.3.3 Scene Control

In Order to apply transformations to picked objects, a gizmo is needed. The term "gizmo" is typically used to refer to a small device or gadget that has been designed for a specific purpose. It often signifies a tool that is capable of performing a particular task in an innovative or efficient manner. The term is informal and can apply to various types of devices.

In the context of graphics programming, gizmos facilitate the manipulation of objects within 3D space. They are widely used in graphics editors to visually represent and control object transformations, most commonly position, rotation, and scale. However, they also cover various other types, such as camera manipulation

or mesh editing. They provide intuitive controls that enhance user interaction with the 3D space.

ext

ImGuizmo [33] is a easy to integrate Gizmo Plugin for ImGui.

- ImGuizmo works by taking a reference to an array of floating point number, to stay independent from linear algebra libraries
- a

- LineBox `CForge::LineBox` used to visualize picked object with different highlight strengths in wireframe

3.4 Animation System

CrossForge already provided an implementation for skeletal animation playback using Linear-Blend-Skinning. - however there is currently no way to interact with an animation, be it selecting specific keyframes of the animation or changing joints of a keyframe

3.4.1 CrossForge format

For this feature CrossForge implements a direct approach. Assimp, the C++ library used for importing and exporting to various 3D formats. Provides the Inverse Bind Pose matrix. The purpose of this matrix is to transform the joint from global to local space so that local transformation of that joint are applied locally to the weighted vertices when doing linear blend skinning.

ref assimp

3.4.2 Sequencer

- A sequencer is a powerful tool in game engines and animation software used for creating and editing cinematic sequences, for

explain animation state, queing an animation
extend

3.4.3 Joint Interaction

- todo explain requirement of separating matrix for gizmo in order or global space transformations to be visualized correctly

extend

- visualizing joints - `JointPickable` derives from `IPickable` and handles joint picking interaction and visualization - since imguizmo only uses one affine matrix for interaction and rendering but we want to apply transformations of the joint relative to the actor in world space, we need to book keep and extract the world space transformation of the characters scene graph node - Listing 3.5 shows an excerpt of the `JointPickable` class

LISTING 3.5: My Code Example

```

1 class JointPickable : public IPickable {
2     public:
3         void init() {
4             // initialize private actor
5         };
6         void update(Matrix4f sgnT);
7         void render(RenderDevice* pRD);
8

```

```

9   // RAII constructor
10
11  void pckMove( const Matrix4f& trans );
12
13  // IPickable bindings, setting private Matrix transforms and
14  // → handling highlighting
15
16  JointPickableMesh* m_pJPMesh;
17
18  Vector4f colorSelect;
19
20  SkeletalAnimationController::SkeletalJoint* m_pJoint;
21  private:
22    Matrix4f m_transform; // global space transform of joint
23    Matrix4f m_transformGuizmo; // global space transform of joint
24    Matrix4f m_fromPar; // parent joint transform
25    Matrix4f m_sgnT; // parent sgn transform of SkeletalActor
26    IKController* m_pIKC;
27
28  StaticActor actor; // visualizer actor used for rendering
};
```

- in order to visualize the joint we would just need to use the Skinning Matrix of the joint, but since we want to apply the gizmos transformation relative to the local frame of the joint we need to separate and keep track of both transformations separately

- the global transformation of a joint can be separated into:

$$M_{glob} = M_{sgn} \cdot M_{parent} \cdot M_{local}$$

where M_{parent} can be computed as:

$$M_{parent} = I \mid \text{when joint } i \text{ has no parent}$$

$$M_{parent} = SM_{parent} \cdot OM_{parent} \mid \text{when joint } i \text{ has a parent}$$

SM and OM denote corresponding Skinning and Offset Matrices.

- in order to decompose the global matrix used by imguizmo to extract the local transformation change we can apply M_{parent} accordingly:

$$M_{local} = M_{parent}^{-1} \cdot M_{sgn}^{-1} \cdot M_{global}$$

- For visualization, using M_{glob} would result in Joints pointing towards their Base Coordinate Systems direction either in one of the 3 base vectors, depending in which direction the picking mesh points to, this however does not align with the intuitive visualization of a joint pointing to its next child in the hierarchy, causing joints to point in seemingly random directions

- in order to make bones of joints point to their child joint, rotating the Joint visualizer according to the local child joint position yields correct results:

$$M_{globVis} = M_{sgn} \cdot M_{parent} \cdot M_{local} \cdot R_{childDir} \cdot S_{childLength}$$

where $R_{childDir}$ is a rotation matrix which aligning the Joint visualizer towards child joint position and $S_{childLength}$ is a scale matrix scaling the joint accordingly.

- of course there is some ambiguity which child joints gets chosen if bones correspond to their parent joints

TODOm 3.4.1: make image of error?

- picked joints are highlighted using a larger joint with inverted normals, causing backface culling to draw an aura around the joint mesh

[add image of picked joint highlighting](#)

3.4.4 Editing Tools

- for animation keyframes can be written by simply reading and writing current pose θ use in the Skeletal Controller back into the current set of keyframes

[split section editing tools for armature and tools for animating?](#)

- this can be done in sequence during the creation of a new animation

[TODOm 3.4.2: anim seq belongs to MoRe process, move there?](#)

- In order to visualize an armature in restpose, for alignment process and restpose correction, but still being able to use as a starting point for posing a new animation, desire to set current pose to restpose - in order to construct the restpose Skinning Matrices of each joint need to evaluate to the Identity, this is not trivial to construct - Listing 3 shows the process of reconstructing local joint parameters in order to model the restpose, and is called from the root joint and Identity matrix for the OM_{parent} parameter

[for what else?](#)

Algorithm 3 Compute Restpose

```

1: procedure COMPUTERESTPOSE
2:   Input: joint                                 $\triangleright$  current joint
3:   Input:  $OM_{parent}$                            $\triangleright$  offset matrix of parent joint
4:    $M_{local} := OM_{parent}^{-1} \cdot joint.OM^{-1}$      $\triangleright$  iteration count
5:    $joint.M_{local} := M_{local}$ 
6:   for child in joint.children do
7:     ComputeRestpose(child,joint. $OM^{-1}$ )
8:   end for
9: end procedure

```

- some motion retargeting methods describe updating restposes in order to align 2 skeletons - in order to update restpose vertex data of the mesh has to be updated, this can be done using cpu vertex skinning - Listing 3.6, describes this process, firstly all vertices are transformed using vertex skinning indicated with the `transformVertex` function - Offset Matrices, here called Inverse Bind Pose, have to be updated by computing global rotation and position of the bone, combining it to the bind pose matrix, and inverting it

[cite corresponding papers](#)

- while this is a straight forward approach, the same deformation issues of linear blend skinning occur in the updated mesh, and are thus visible on any other poses
- note that existing animation data will have the difference between new and old restpose applied as well

[TODOm 3.4.3: make algorithmic and shorten?](#)

LISTING 3.6: My Code Example

```

1 void CharEntity :: updateRestpose(SGNTransformation* sgnRoot) {
2   if (!actor)
3     return;
4
5   // apply current pose to mesh data
6   for (uint32_t i=0;i<mesh.vertexCount();++i) {
7     mesh.vertex(i) = actor->transformVertex(i);
8   }
9

```

```
10 // forwardKinematics to get updated global pos and rot in
11 //→ m_IKJoints
12 controller->forwardKinematics(controller->getRoot());
13
14 for (uint32_t i=0;i<mesh.boneCount();++i) {
15     auto* b = mesh.getBone(i);
16
17     //TODOOff(skade) bad, assumes mesh idx == controller idx
18     IKJoint ikj = controller->m_IKJoints[controller->getBone(i)
19     //→ ];
20
21     // get current global position and rotation
22     Vector3f pos = ikj.posGlobal;
23     Quaternionf rot = ikj.rotGlobal;
24
25     Matrix4f bindPose = Matrix4f::Identity();
26     bindPose.block<3,1>(0,3) = pos;
27     bindPose.block<3,3>(0,0) = rot.toRotationMatrix();
28     b->InvBindPoseMatrix = bindPose.inverse();
29 }
30
31     init(sgnRoot);
32 }
```

- also important is the feature to transform a mesh and its animation for alignment as well, many tools use a different direction as the frontfacing one, Algorithm 4 shows the process of updating a rigged characters transformation in object space

Algorithm 4 apply transform to Mesh

```

1: procedure TRANSFORMMESH
2:   Input:  $T$                                       $\triangleright$  transform matrix
3:   Input:  $mesh$                                  $\triangleright$  input mesh
4:   for vertex  $v$  in  $mesh$  do
5:      $v := T \cdot v$ 
6:   end for
7:   deconstruct  $T$  into rotation  $R$ , position  $P$  and scale  $S$             $\triangleright$  update restpose
8:   for bone  $b$  in  $mesh$  do
9:      $b.OM := b.OM \cdot R$ 
10:    scale translational component  $b.OM$  according  $S$ 
11:   end for                                          $\triangleright$  update animations
12:   for animation  $a$  in  $mesh$  do
13:     only rotate root bone
14:     get root bone  $b_r$ 
15:     for rotation  $r$  in  $a[b_r]$  do
16:        $r := R \cdot r$ 
17:     end for                                          $\triangleright$  scale all translation offsets with  $S$ 
18:     for position  $p$  in  $a$  do
19:        $p := S \cdot p$ 
20:     end for
21:     for position  $p$  in  $a[b_r]$  do
22:        $p := P + R \cdot p$ 
23:     end for
24:   end for
25:   reinitialize actor
26: end procedure

```

3.5 Inverse Kinematics Implementation

- ik takes subchain, joint chain, without branches of the skeleton - subchains can be defined and changed interactively using a popup window

- ik implementation useful, since many motion retargeting approaches rely on them - since performance is crucial and proper ik libraries are sparse, ik methods are reimplemented using crossforge Skeletal Controller - thus can also be adapted and extended in the future

- furthermore while some ik methods might outperform others, fundamental approaches reviewed in Section 2.2 remain relevant due to their behavioural differences - also explained in Survey of Aristidou et al. [3]

While various Inverse Kinematics Implementations exist, they are usually implemented across various Programming Languages or use different 3D Engines, resulting in vastly different and complex APIs.

To reduce complications, various inverse kinematics algorithms proposed in section 2.2 are re-implemented using CrossForges Animation Controller interface.

- IK play an important role for implementing limb based methods various - IK methods presented in 2.2 while trying to achieve a common task, show significant differences during motion and thus pose when a target is reached

- Interface for IKSolver `IISolver` defines termination settings implementations of solvers need to provide - furthermore additional settings can be added and checked in the Userinterface using `std::dynamic_pointer_cast`

LISTING 3.7: My Code Example

```

1 class IISolver {
2     public:
3         virtual void solve(std::string segmentName, IKController*
4                           → pController) {};
5
6     protected:
7         float m_thresholdDist = 1e-6f;
8         float m_thresholdPosChange = 1e-6f;
9
10    int32_t m_MaxIterations = 50;
11 } //IISolver

```

- subtypes
- `IKController` inherits `SkeletalAnimationController` already defined in CrossForge to reduce overhead and code duplication, only replacing function that need changes
- to stay compatible with `SkeletalAnimationController` functions, types that could need improved structuring or functionality can be extended by using a `std::map<Type*, Extension>` to comfortably extend
- used to assign `SkeletalJoint` not only a local but global component to avoid having to recompute each time on usage
- followup methods are abstracted into the IKSolver class and assigned per IKChain which defines a subchain of a skeleton

TODOM 3.5.1: abstraction into subsectionHeuristic Methods end of this section?

3.5.1 Jacobian Method

- lack of existing jacobian ik implementations make it hard to implement because jacobian ik specifications in paper are rather difficult to understand

TODOM 3.5.2: explaining problem of missing jacobian ik okay?

- Various Sources for Jacobian Inverse Kinematics lack in detail on what specific entries of each cell mean. - depending on how input vectors that get multiplied with the jacobian inverse, population remains open to interpretation

- Figure 3.2 shows an example of how to populate the jacobian matrix, each row represents the influence of all joints and their angles on the endeffector change in corresponding dimensions.

- the transposed variant of the matrix, rows and columns swapping means when multiplied with a desired direction vector on the right side, the matrix returns - thus for a jacobian matrix with one end effector, the vector should be 3x1 for two 6x1 and so on. - when multiplied with the transpose, the returned vector is of dimension $m \times 1$, where m is the sum of all joints and their respective dimensions - joint angles are read out in the same spacing vertically as they were fed into the matrix horizontally

$$\begin{array}{l}
 \text{eef1 x} \\
 \text{eef1 y} \\
 \text{eef1 z} \\
 \text{eef2 x} \\
 \vdots
 \end{array}
 \left(\begin{array}{ccccc}
 \text{joint1} & & & & \\
 \frac{\partial \text{eef1 x}}{\partial \text{joint1 x}} & \frac{\partial \text{eef1 x}}{\partial \text{joint1 y}} & \frac{\partial \text{eef1 x}}{\partial \text{joint1 z}} & \frac{\partial \text{eef1 x}}{\partial \text{joint2 x}} & \dots \\
 \frac{\partial \text{eef1 y}}{\partial \text{joint1 x}} & \frac{\partial \text{eef1 y}}{\partial \text{joint1 y}} & \frac{\partial \text{eef1 y}}{\partial \text{joint1 z}} & \frac{\partial \text{eef1 y}}{\partial \text{joint2 x}} & \dots \\
 \frac{\partial \text{eef1 z}}{\partial \text{joint1 x}} & \frac{\partial \text{eef1 z}}{\partial \text{joint1 y}} & \frac{\partial \text{eef1 z}}{\partial \text{joint1 z}} & \frac{\partial \text{eef1 z}}{\partial \text{joint2 x}} & \dots \\
 \frac{\partial \text{eef2 x}}{\partial \text{joint1 x}} & \frac{\partial \text{eef2 x}}{\partial \text{joint1 y}} & \frac{\partial \text{eef2 x}}{\partial \text{joint1 z}} & \frac{\partial \text{eef2 x}}{\partial \text{joint2 x}} & \dots \\
 \vdots & \vdots & \vdots & \vdots & \ddots
 \end{array} \right)$$

FIGURE 3.2: Population example of the Jacobian matrix for Inverse Kinematics. eef designates end effector position change, and joint denotes joint angles. Each row is populated with every joint angle change and its influence on the end effector in the corresponding dimensions.

- implementation is currently limited to solving joint chains, but can be expanded to support trees in the future

3.5.2 Heuristic Methods

- explain combined as there shouldnt be as much content?
- subsectionCCD - contains m_type accessable through dynamic pointer cast for ui

extend

LISTING 3.8: My Code Example

```

1 enum Type {
2     BACKWARD,
3     FORWARD,
4 } m_type = BACKWARD;

```

- for FABRIK solver contains fabrik points the framework can access for visualization

- requirements for good IK
- multiple end effectors
- survey table comparison

3.6 Constraints Implementation

- todo introduction constraints - constraints more essential for retargeting the more source and target skeleton differ in structure and proportions

- section Combined Constraint System (TODO eigenanteil in extra chapter)

3.6.1 Joint Constraints

- implementing various types of constraints time consuming and challenging - for this example simple Ball-Socket Constraint implemented - Interface for constraint, each inverse kinematics solver can choose a corresponding implementation, best fit for each solver

yet to implement

- cone and sphere

todoff describe visualizer

- rendered via forward pass (primitive factory)

3.6.2 Target Weighting

- as of now, ik chains are evaluated in order, causing chains processed later potentially overwriting results, for example evaluating the right arm before the spine

TODOm 3.6.1: section name Target Weighting or Multiple target evaluation?

causes the the right arm to get replaced by the endeffector change of the spine chain
 - while this is not noticeable in real time interaction, due to temporal coherency, it can be problematic if angle are set artificially

- currently there is not a way to prioritize reach, for example if both targets for the left and right arm are out of reach, but would be in reach if the spine bends accordingly, it is desired to set a priority evaluating which target is more important, furthermore it should be interpolatable

- while not mentioned by Aristidou et al. [12], Target priorities can be archived by lineary interpolating centoids between optimal sub-base position depending on their Weight.

(might be mentioned, check)

- in cases where certain position in space cant be reached, chain can optionally be propagated to parent chain and weighted accordingly to avoid problem of stretched limbs

- problem spine is defined as limb, when ideally evaluate?
- evaluate at beginning? (from root to eef / spine first then limbs) - cannot account for centoid / multichain weighting
- evaluate at end? (from eef to root, limbs first then spine) - do not yet know where chain begins, spine evaluated afterwards causes end effectors to potentially move away from previously reached targets

look ref

- need simillar to fabrik 2 iterations, root to end effectors, then end effectors to root globally for the armature to get optimal position

- ik armature evaluated beginning from end effectors until centoid

3.7 Skeleton Matching

- simplifying problem of matching joints to matching limbs
 - during import - can use ICP for algining characters using limb chain positions
 - prone to error, manual alignmend as option better

- motion retargeting initialization sets targets of all chains of primary CharEntity to the selected chains of the secondary CharEntity

- retargeting happens implicitly, during animation playback of the seconday CharEntity, its target points are updated

- because targets are defined in local space, world space transformation is not taken into consideration, in order to view both models clearly, world space transformation can be applied beforehand

- simillar to other editors when manipulating mesh structure, a mode to view objects in local space for aligning is added called edit mode (note that mesh editing is not implemented)

- while testing the new motion retargeting implementation, limbs were matched manually with a popup user interface - could define matching by limb names, but want to autogenerate armature

- only inital guess, user will be able to check matched joints - TODO visualize joint chains with JointPickable

3.7.1 Armature

- IKChain defines a non-branching chain of joints to which a IK Solver is applied to
- Armature consists of a set of joint chains, which are able to intersect, solving an armature solves each individual chain including constraints

- todo order of evaluation of chains problem

already referenced in 3 constraints section

3.7.2 Autocreate Armature

- todo explain autoCreateArmature

- auto create armature

make algorithmic and shorten

LISTING 3.9: My Code Example

```

1 void CharEntity :: autoCreateArmature() {
2     if (auto ctrl = controller.get()) {
3
4         std :: map<std :: string , std :: vector<
5             ↪ SkeletalAnimationController :: SkeletalJoint*>> ikc
6             ↪ ;
7
8         std :: function<void(SkeletalAnimationController ::  

9             ↪ SkeletalJoint* pJoint , std :: string name)>  

10            ↪ propagate;
11         propagate = [&](SkeletalAnimationController ::  

12             ↪ SkeletalJoint* pJoint , std :: string name) {
13             // end current chain and add all childs as new
14             ↪ chains
15             int cc = pJoint->Children.size();
16             // add joint to chain
17             if (name != "")  

18                 ikc[name].insert(ikc[name].begin(), pJoint);
19             if (cc > 1) {
20                 for (uint32_t i = 0; i < cc; ++i) {
21                     auto c = ctrl->getBone(pJoint->Children[i]);
22                     propagate(c, c->Name);
23                 }
24             } else if (cc == 1) { // add to current chain
25                 auto c = ctrl->getBone(pJoint->Children[0]);
26                 propagate(c, name);
27             } //else //(cc == 0) // end effector nothing to do
28         };
29         propagate(ctrl->getRoot(), "");
30
31         ctrl->m_ikArmature.m_jointChains.clear();
32         for (auto& [k,v] : ikc) {
33             IKChain nc;
34             nc.name = k;
35             nc.joints = v;
36             ctrl->m_ikArmature.m_jointChains.emplace_back(std ::  

37                 ↪ move(nc));
38         }
39     }
40 }
```

3.8 Motion Retargeting

- while machine learning approaches can offer good quality retargeting, there is a lack of interactively changing retargeted motion

To facilitate the option to use a large set of Motion Data with Rigged Characters popular Tools like Mixamo use standardized Human like Skeleton to simplify the Process by moving the Motion Retargeting Problem to a Auto-Rigging Problem. Thus for a scalable system, the underlying Skeleton should be abstractable and independent of Motion Data. However, this is not easy.

Skeleton-Aware Networks for Deep Motion Retargeting [26] fig:deep-more1 2.17, shows similarities with limb based approaches

- Discussed Motion Retargeting Methods Section 2.4 vary significantly in adaptivity
- Motion Retargeting results still subjective depending on goal of application task

- because ik methods vary in results - propose novel limb based method, which is able to utilize different IK methods for different limbs

furthermore, while ik is already a common tool for animators to quickly get a desired pose, a well implemented and accessible motion retargeting method can further improve an animators workflow by posing as a starting point for a desired sequence, further refining using other motion editing tools - Motion Retargeting as a tool should be easily adaptable and extensible

3.8.1 Joint angle Imitation

- Joint angle Imitation
- many papers don't explain how to transfer motion of

- despite having similar rest poses between two characters, non-redundant parts of skinning matrix still have influence on how motion data is applied to a rig - thus can't simply apply motion data from one rig to another

- recreate restpose, not always feasible, as some limbs may not exist in the other rig, or restpose adaptation causes unpleasing deformations
- we expect that simply applying motion data causes problems described in Section 2.4.1
- still imitating Joints still provides good initial guesses, in which the task of IK is to cleanup artifacts

- While Tang et al. [17] explain the usage of adjustment matrices to transfer motion data, they leave reader to guess how to correctly implement them.

- follow up there will be an intuitive derivation on how to imitate joint angles / adjustment

- during motion transfer using global rotations for joints is not feasible for limb based approach since orientations have to be re-evaluated

The Skinning Matrix of each joint consists of the following Components:

$$SM = M_{parent} \cdot M_{local} \cdot OM$$

Let overset s be the source and overset t be target components, we want the Rotational component of $\overset{t}{SM}$ to be equal of $\overset{s}{SM}$ in object space, but independently of parent joints.

Since the Skinning Matrix encodes global transformation In order to compute the adjusted local transformation:

$$\overset{s}{SM} = \overset{s}{M_{parent}} \cdot \overset{s}{M_{local}} \cdot \overset{s}{OM}$$

$$\overset{t}{M_{newLocal}} = \overset{t}{M_{parent}}^{-1} \cdot \overset{s}{M_{parent}} \cdot \overset{s}{M_{local}} \cdot \overset{s}{OM} \cdot \overset{t}{OM}^{-1}$$

$$\overset{t}{M_{newLocal}} = \overset{t}{M_{parent}}^{-1} \cdot \overset{s}{SM} \cdot \overset{t}{OM}^{-1}$$

- equals rest pose relative mode
 - novel way to retarget motion data adaptively between defined limb matches -
- Algorithm 5 shows process

- avoids unnecessary recomputation of global joint positions with forwardkinematics when using the approach suggested by ..., staying efficient

ref which paper

TODOm 3.8.1: no global mode yet

who suggested?

TODOm 3.8.2: Statements too long in alg limb based joint angle imitation?

Algorithm 5 limb based joint angle imitation

```

1: procedure IMITATE
2:   Input:  $J$                                       $\triangleright$  current joint
3:   Input:  $M_{parent}$                             $\triangleright$  parent joint transform
4:   Input:  $corr$                                  $\triangleright$  chain correspondences between CS and CT
5:   Find target limb  $CT$  which contains  $J$ .
6:   if  $CT$  exists then
7:      $\triangleright$  Use defined limb correspondence to find matched limb  $CS$  from source
      chains.
8:      $CS := corr(CT)$ 
       $\triangleright$  Run customizable joint Indexing Function to retrieve matched source
      joint  $idx_{js}$ 
9:      $idx_{js} := jointIndexingFunc(idx_{jt}, CS, CT)$ 
9:     if  $idx_{js}$  is a valid joint then
10:    Construct source joint local transform matrix  $M_{local}^s$ 
11:    Construct source parent joint transform  $M_{parent}^s$ 
       $\triangleright$  use angle imitation function to transfer motion.
12:     $M_{newLocal}^t := M_{parent}^{s-1} \cdot SM \cdot OM^{t-1}$ 
13:     $M_{parent}^t := M_{parent}^s \cdot M_{newLocal}^t$                                 $\triangleright$  update  $M_{parent}$ 
14:    Deconstruct  $M_{newLocal}^t$  and set local joint transform
15:  end if
16: end if
17: if no joint was matched then
       $\triangleright$  keep current posture
18:   Construct target joint local transform matrix  $M_{local}^t$ 
19:    $M_{parent}^t := M_{parent}^s \cdot M_{local}^t$                                 $\triangleright$  update  $M_{parent}$ 
20: end if
21: for child in  $J.\text{children}$  do
22:    $\text{imitate}(child, M_{parent})$ 
23: end for
24: end procedure

```

- root special bone and requires speical handling, is not included in any limb -
 - joint indexing function choses which joint inside a limb gets selected, adaptable,
examples, chose by closest distance, chose by index or chose by distribution

ref paper combination of angular
information of 2 or more joints

- compute when one joint of target covers multiple source joints and combine
 their rotational information, and take discrepancy of joint amount between source
and target chain into account, simillar to ...

TODOm 3.8.3: position, follow-
ing point

- motion retargeting routine stores temporary references to source and target
 character, intializing source and target limb lenghts, automatically creating tempo-
 rary targets which the target characters limbs reference during the procedure until
 motion retargeting gets disabled

- for a given limb pair we need to determine which joint pairs which should
 transfer the motion

- for this an adaptable index function can be used

- bijective ideal case, mapping corresponding joints, disregarding of length to the other joint, will produce wrong endeffector positions in case matched joints differ in length strongly

- in case the mapping is not bijective, we need to find a good indexing function
- injective will cause redundant joints to be aligned with another joint in the longer chain, being then used during correction in ik
- surjective more complex, one joint should imitate the transformation of 2 or more joints, which need to be computed using offset matrix to correctly take restpose orientation into account
- initialization, creating copy of targets

3.8.2 kinematic chain scaling

- after joint angles have been transferred, the resulting posture will show artifacts as discussed, to clean these artifacts up using a desired solver

already included

- a natural desire for Motion Retargeting would be to support animation transfer between not only vastly different skeletal structures but also sizes and heights

position bad

- it is hard to define how a good retargeting should look like, depending on the desired task:

- e.g. retarget animation of virtual character holding a box, with different arm lengths
- should the box keep its position in space? can its size change? if not motion can cause
- same for gait motion, walk speed or root height

- while machine learning approaches find good looking results, they fail in this regard because they often cannot be adapted or extended for specific needs or unforeseen requirements

- need user defined adaptivity, in order to satisfy various desired tasks
- compare matched limb lengths and scale target position relative to limb scale root

let T be target position and R the root position of the inspected chain C :

$$T_{new} = \frac{|T - R| \cdot |C_{tar}|}{|C_{src}|} + R$$

formula

- depending on task specification, this term can be extended using linear interpolation term d :

$$T_{new} = \frac{|T - R| \cdot (d(|C_{tar}| - |C_{src}|) + |C_{src}|)}{|C_{src}|} + R$$

- for $d = 0$ source target position is used, while for $d = 1$ rescaled target position is used

- of course more heuristics can be used in order to keep a certain target height fix

- target positions for armature solver are rescaled in the MotionRetargeting routine update function - Algorithm 6 shows process - if input is 0, source offsets are used, input 1, target offsets are used - linear interpolates root position and target

kinematic chain scaling not explained yet, explained in next chapter, potentially move this to next section

length, adaptable in order to reach grasping targets or preserve motion style better
- in future parameters should be adaptable using the sequencer, smoothly interpolating scale values between keyframes

TODOm 3.8.4: in future section?

Algorithm 6 target rescaling

```

1: procedure TARGETRESCALE
2:   Input: SLL                                 $\triangleright$  array of source limb lengths
3:   Input: TLL                                 $\triangleright$  array of target limb lengths
4:   Input: corr                                $\triangleright$  chain correspondences between CS and CT
5:   Input: limbScale                          $\triangleright$  array of interpolation values for limbs
6:   Input: rootScale                           $\triangleright$  array of interpolation values for roots
7:   for CS and CT in corr do
8:     scale := lerp(1., TLL[CT] / SLL[CS], limbScale[CT])
9:     pos_root := lerp(CS.pos_root, CT.pos_root, rootScale[CT])
10:    dir := CS.pos_target - CS.pos_root       $\triangleright$  direction vector from of source limb
11:    CT.pos_target := pos + dir · scale
12:   end for
13: end procedure

```

3.8.3 Retargeting Routine

- flowchart depicting process of editor

make flowchart

the pipeline process has been depicted in Figure 3.3

make colors for flowchart to signal parts that are not automated, or parts that can be refined, dont color automated parts

describe in detail

- import source and target characters and character with motion
- align characters using applymeshtransform and editmode to compare object space alignment
- use rignet to autocreate skeleton for target
- automatically create armature and targets
- match limbs automatically using proposed weighting function
- init motion retargeting, setting up targets, scaling parameters

during motion retargeting routine

- potentially adapt retargeting parameters with adapting scaling offsets and incorporating constraints to improve motion quality
- bake realtime simulation into new animation
- change inverse kinematics solver of a limb to accommodate a specific task

after animation baking

- export character with newly created skeleton and animation in desired format for use in other applications like blender for further improvements and motion cleanup or into engines like godot unity or unreal for direct use

TODOm 3.8.5: somehow id like to incorporate the process of retargeting itself, so 1. imitate joint angles, 2. ik for cleanup and so on, but they are minor, should I include them in Figure 3.3

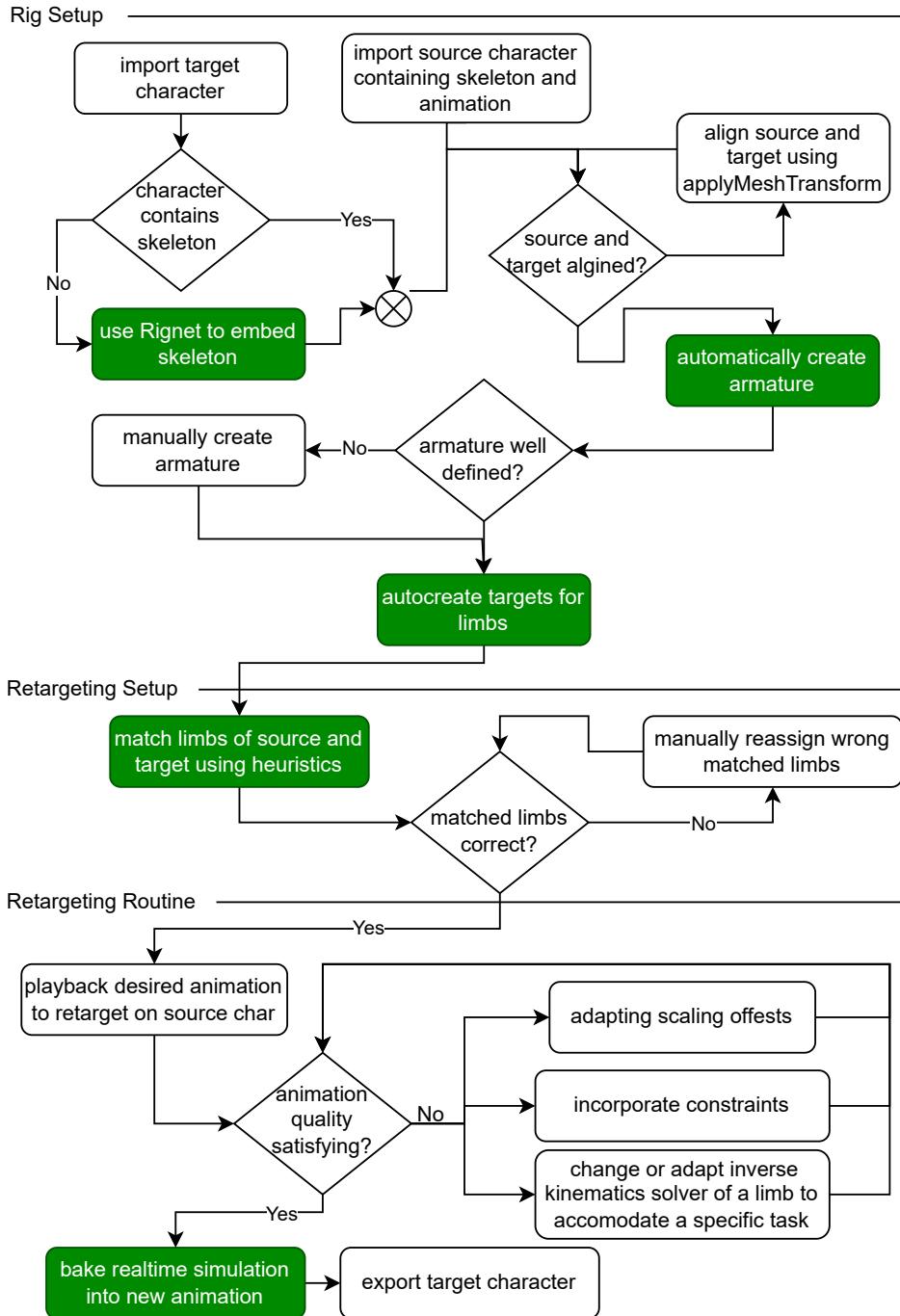


FIGURE 3.3: User workflow of using the Editor for realtime Motion Retargeting. Green indicates automated processes, while not many, most of the manual tasks are minor or checks to assure motion quality.

- following Algorithm 7 depicts the Editor's main loop, specifically, of the `MotionRetargetScene` class - Motion Retargeting routine gets applied every frame
- uses on-demand rendering, only rendering on scene graph update or on user input, saving energy when the application is idling

TODOM 3.8.6: from here was subsectionEditor Main Loop

TODOM 3.8.7: doesn't really fit in this section, should be in 3 classes and scene management section?

TODOM 3.8.8: "event-driven rendering" or "on-demand rendering.?"

TODOM 3.8.9: prefix dash in alg editor main loop?

edit mode other name

Algorithm 7 editor main loop

```

1: procedure MAIN LOOP EDITOR, EXECUTED EACH FRAME
2:   while Editor not terminated do
3:     label START
4:     if no input or action flag set then
5:       wait for input events
6:       goto START
7:     end if
8:     apply joint imitation (or other Motion Retargeting properties)
9:     apply IK to reach targets of each limb
10:    for all Character do
11:      if Character has active animation then
12:        apply animation
13:      else
14:        solve armature for ik targets
15:      end if
16:    end for
17:    Edit Mode
18:    if no ImGui element hovered then
19:      handle Object deletion
20:      handle Picking for all pickables
21:      update Camera
22:    else
23:      handle view manipulate widget
24:    end if                                ▷ Render Scene
25:    Shadow Pass
26:    Geometry Pass
27:    Lighting Pass                         ▷ Render GUI
28:    Forward Pass
29:    render visualizers
30:    render ImGui interfaces
31:    Swap Buffers
32:  end while
33: end procedure

```

3.8.4 Comparison of IK Methods

- more tests have shown that jacobian inverse better keeps motion style intact because it can distribute change across all joints well compared to ccd or fabrik, where most change is concentrated at the end effector or root, depending either forward or backward ccd or fabrik

- while fabrik author x stated that fabrik produces more natural results this is not necessarily true for all kinds of motions.

For example, while it may be true that fabrik produces more plausible results for grasping or low energy reaching motions.

Motions that require more force or result as a measure of lowering energy consumption like running or pushing motions. jacobian inverse has the ability to move naturally

correct these due to its way of distributing change and thus work across all bones instead of ones closer to the end effector

image of comparison without joint angle imitation

3.8.5 Comparison with other existing MotionRetargeting Methods

- todo other methods yet to be implemented
 - possibility to use error metric to compare quality of
- by comparing joint position and angle or surface properties in case of differing skeletons
 - todo

3.9 Import and Export

- CrossForge already used Assimp as an interface - Assimp supports various Formats including simple ones like obj, ply, stl, bvh but also more complex ones e.g. fbx, gltf - assimp uses a unified intermediate format which is then used to transfer data between T3DMesh

- during import meshes are auto-scaled to fit into the predefined scaling using the AABB, can be disabled

- assimp has various issues regarding round trip export and import, not preserving bone structure, namings or graphs in some cases, but more importantly - assimp is not suited for editing meshes, intended workflow of the MotionRetarget Editor would be to export the Character in blender, rig and retarget motion in the proposed editor, and export back to import into blender - assimp can't ensure that the imported mesh preserves structure, as different formats might not support the same representable surface properties of each format, assimp tries to cover as many formats - assimp's intermediate format focuses on providing an easy to use integration, being close to how Graphics APIs expect it, for example ensuring seams are handled by splitting the mesh up at corresponding positions

assimp is prone to change the underlying model's topology slightly in some cases to ensure compatibility across multiple formats, meaning that a round trip, import/export without changing anything, produces a different file - which can be undesirable when the goal is to produce a clean model

- in order to improve round trip import and export CrossForge had a native gltf interface prototype, but incomplete and various issues

- with gltf 2.0, gltf has become a good format rivaling fbx, in comparison to its predecessor version 1.0 pbr materials, binary representation of data with glb or morphtargets are great additions to form a good open source alternative to the proprietary industry standard from Autodesk - while assimp is a popular tool for importing assets for prototyping engines, its intermediate format and wide support of formats limit the correctness of bidirectional export and import, depending on file format certain kinds of data get changed, for example triangle count or order - because Blender focuses 3D creation, its internal format and exporting tools support a wide range of options for export and thus avoiding redundancies - because Blender is FLOSS, there is no need to implement various file format interfaces for CrossForge - with CrossForge's direct gltf export interface, correct export is assured, optionally assimp can be used as well but might have problems exporting correctly

TODO on 3.9.1: better? subsectionModel Data subsectionAnimation Data

- bvh, which most commonly motion capture databases use, is supported by assimp
- implement native bvh
- import / export armature, limb chain definitions and constraints for Motion Retargeting

future

3.10 Additional Library Integration

- not every existing tool is written in C++ - while bindings other languages exist - in order to integrate other tools there needs - many - Rignet recommends using Anaconda, a environment wrapper for python libraries - starting such an environment from an embedded python in C++ is challenging - with each additional tool there would be effort required to find or develop binding

what is std::system exactly

- solution, simply use std::system, creating a subprocess to run a command, either executing an executable or script - in order to transfer data, either command line arguments or preferably files can be

- Interface for binding Auto-Rigging solutions
- AROptions is template type, used to define struct containing options
- ImGui interfaces uses these structs to compactly define a set of options

LISTING 3.10: My Code Example

```

1 template<typename> AROptions>
2 class IAutoRigger {
3     virtual void rig(T3DMesh<float>*> mesh, AROptions options) = 0;
4 };

```

title

3.10.1 Rignet

- T3DMesh format not abstracted, close to visualization, causes vertices to be doubled at texture seams or other parts, furthermore - no detailed instructions from the provided python implementation on how to use correctly

explain bandwidth and threshold

- threshold - bandwidth

- start corresponding conda environment, and using the enclosed quick start script with minor changes to specify model and parameter input, as well as processing folder - option to use previous computed cache

- Rignet expects - vertices need to be merged in order to provide optimal results
- rignet provides the resulted rig in a custom format that needs to be parsed

- because there are no standardized formats for describing a skeleton including skinning weights, Rignet outputs a custom format

explain format parsing

Chapter 4

Conclusion and Future Work)

- a dynamic prototype Editor and Pipeline for scalable Auto-Rigging and Motion Retargeting was presented - a fundamental framework to evaluate motion retargeting and autorigging methods has been established

- while a goal is to compare autorigging and motion retargeting approaches, only one tool for each has been integrated yet, but scalable API bindings have been provided for future integration - incorporate error functions, comparing joint and end effector positional and rotational divergence, for example to compare heuristic Motion Retargeting with Data driven ones to deduce improvements.

4.1 Editor Improvements

- CrossForge problem `T3DMesh` representation not suited for mesh editing - need seamless internal format - extending editor animation tools

4.2 Blender Addon

- while blender would have been an alternative suspect to implement the pipeline, highly abstract source code and potentially limiting python API as well as debugging possibilities made it unattractive for prototyping - still blender one of the most used animation and modelling editors, many users would benefit from an improved Motion Retargeting solution - rignet plugin for blender already exists - that no proper motion retargeting solution exists for blender highlights challenge of implementation - Addon for popular open source game engine godot also useful

cite blender

4.3 SMPL fitting

- option to fit the learned human model smpl to a 3d scan and then transfer surface properties via projection

explain smpl

CrossForge already has a working test of transferring textures by projecting triangle vertices of a scan to the nearest SMPL vertex using normals, but has yet to be properly implemented in order to be integrated into the proposed editor

Furthermore transferring geometric surface properties could be done using neighbor evaluation with laplacian difference.

more in depth

- Compared to Rignet, SMPL already has rigged hands and face, despite its limitation to humans it would provide a great alternative

4.4 More Ideas

- thinning approaches, implementation als future work

- Utilizing Skinning Alternatives (direct delta mesh, goes into autorigging simplifications) - Clothing (clothing simulation integration)

- Motion Blending, combine motion data of multiple motions during retargeting

was already proposed in other paper ref

- TODO MetaHuman (UE5) provides an excellent quality with facial and hand rig - but creation restricted to existing toolset provided by environment - clothing has to be recreated - cant use scan

in appendix

Appendix A

Existing IK Tools

- Jacobian Methods Impl Because of the Mathematical complexity of Jacobian Methods, implementations are hard to find.

- CCD Impl

TODO Tex

- Fabrik Impl

- a - Final IK ik collection for unity - <http://www.root-motion.com/finalikdcox/html/index.html>
- paid - no source code

formulate

formulate

comparison from FABRIK paper

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