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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

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Declaration of Authorship

I, Mick KÖRNER, declare that this thesis titled, "Implementation of a modular pipeline to evaluate different rigging and retargeting techniques for virtual humans using CrossForge" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
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Signed:

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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...

Acknowledgements

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parts starting with "-" need to be rewritten

Chapter 1

Introduction

1.1 Motivation

TODOm 1.1.1: Motiovation or Objectives and Scpoe?

Virtual Humans have been a major Part of Computer Graphics because of its wide range applications, spanning multiple research domains.
Creating a realistic Virtual Human is still a challenge today. Digital Reconstruction techniques like Strucute-from-Motion can create a very Detailed Surface replication of a Person. However, this Mesh is static. If it is desired to animate this Scan with Motion Capture Data, the Mesh does not contain any Information on how to apply these.
While Motion-Capture techniques like Shape-from-Silhouette exist, which are creating an Animation by storing a 4D Mesh. The use Cases for these Results are limited because the Motion and Virtual Character are coupled.

Simplifying the Virtual Human problem to decouple Motion- and Surface Data has naturally developed to be the standard today, not only for Realistic Virtual Humans, but also heavily stylized ones in Movies and Games.

TODOm 1.1.2: Motiovation or Objectives and Scpoe?

- Another important Motivation was to provide an easy to access and open source tool for motion retargeting, all widely used retargeting tools either require payment or an account login. Notibly there do no exist solid free motion retargeting Solutions.

- no basic tool for simple customizable motion retargeting

- while ik is already a common tool for animators to quickly get a desired pose, a well implemented and accessable motion retargeting can further improve an animators workflow by posing as a starting base for a desired pose using other motion editing tools

A deeper look into existing tools for these Problems reveals that many of them are sub-optimal or require some form of payment. Either in form of Currency or User Data.

1.2 Objectives and Scope

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. This is however not easy.

The primary Goal is a Tool which automates or streamlines the process of creating a Virtual Character just from a Scan. This includes the Implementation of Interfaces to easily add new methods for Autorigging and Motion Retargeting.

To further support Scalability for Future use. The proposed Tool should be interactive in order to test and compare algorithms more easily for correctness and potential drawbacks.

1.3 Summary of the Work

Firstly we will go over all Related Works in Chapter 2. This includes a Recap of how Computer Animation works and their basics. Then we go over Inverse Kinematics, Constraints up to Motion Retargeting and AutoRigging in Chapter 2.

In each Chapter, fundamentals are explained. Popular and recent novel techniques will be discussed and available tools will be evaluated, not primairly in performance but also in availability, open-ness and ease of use.

In Chapter 3 the Design and Implementation of the Automation Tool is explained. As well as details about specific Implementations of Motion Retargeting and Autorigging Methods or API interfaces.

Chapter 2

Related Work

2.1 3D Animation Fundamentals

Prior to examining the literature pertinent to this thesis, it is essential to define the fundamental principles of skeletal animation in computer graphics, establish consistent nomenclature, and establish a foundation to prevent confusion. In the field 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.

Furthermore, many papers adopt a clear and consistent naming convention prior review.

The most prevalent form of humanoid animation is skeletal animation. The majority of 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

- simillar to how a animals in the real world have a rigid bones connected to a skeleton and moved with muscles, a similar analogy developed in computer graphics in a bionics manner

TODOm 2.1.1: source? figure 2.1

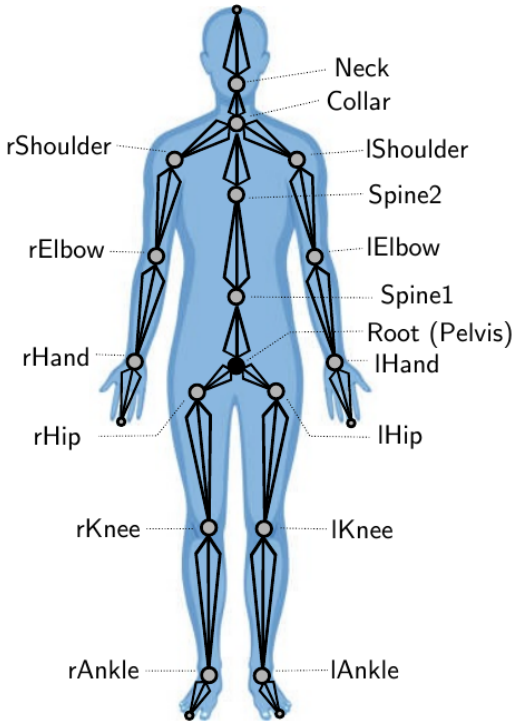

FIGURE 2.1: Example of human skeleton, note that bones and their parent joint are combined, this can cause confusion, in this example the root and collar joint have multiple bones. Image taken from [1]

Bones (sometimes called links) in Animation represent rigid objects inside virtual character - associated with a length attribute.

Joints represent the connection points between bones and are characterized by a rotational degree of freedom. - joint is the component concerned with motion;

In addition to joints connecting two bones, root and end effector joints are of particular interest.

A root joint has no parent. 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.

- endeffectors represent bones without children - depending on application sometimes it isnt clear if the endeffector is joint itself or a bone, having no joint at its tip, due to these discrepencies some systems having additional joints defined at it tips to ensure conversion between different formats happen seamlessly

- Bones are usually not explicitly defined in implementations and are implicitly included in their parent joint

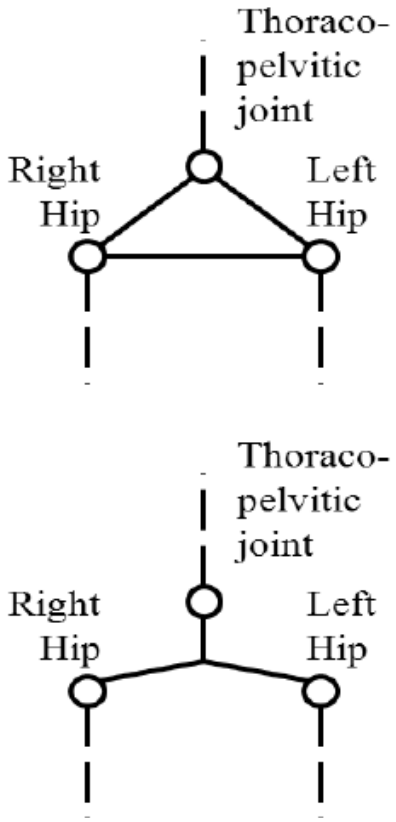

FIGURE 2.2: Visualization of an Armature with a loop, depending on implementation the tree becomes a Graph. Image taken from [2]

2.1.2 Skeletal Hierarchy

TODOm 2.1.2: tree-like?

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

explain chain

- a joint chain represents a link of multiple joints where each joint has at most 1 child

- branching happens when a joint has more than one child

TODOm 2.1.3: visualize? + position in TEX?

Closed loops - while tree structures are most often found, some systems allow for circular structures - using smartly placed bones, one can enforce constraits, for example ensuring 2 bones have always - harder to implement

chain loops, extend

- In implementations Bones and their parent joints are often combined. Since the parent joint describes the rotation of th

meaning

? - useful for centre of rotation correction - not allowed in some systems, e.g. blender

2.1.3 Pose Space vs. Work Space

Established common Spaces in the Graphics Pipeline include Window Mapping (NDC and Camera space), but more importantly for this work, World Space and Object Space. Object Space in regards to Skeletal Animation means the Space of the character in restpose.

later important expl

- In order to visualize a skeleton or parent other objects in worldspace to joints, for example a tool to simulate some kind of work. We need to know the position of a desired Joint in pose θ.

As discussed previously joints describe rotation of their child bones. To determine Position of Joints relative to Object Space, all kinematic chains from the root bone have to be propagated.

TODOm 2.1.4: merge sec with Forward Kinematics?

2.1.4 Forward Kinematics

- forward kinematics describes the process of computing the working space from pose space parameters Let F be the forward Propagation of the kinematic chain and θ the current pose configuration, object space position and rotation t of the endeffector can be computed as:

$$t = F(\theta)$$

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

math formula example

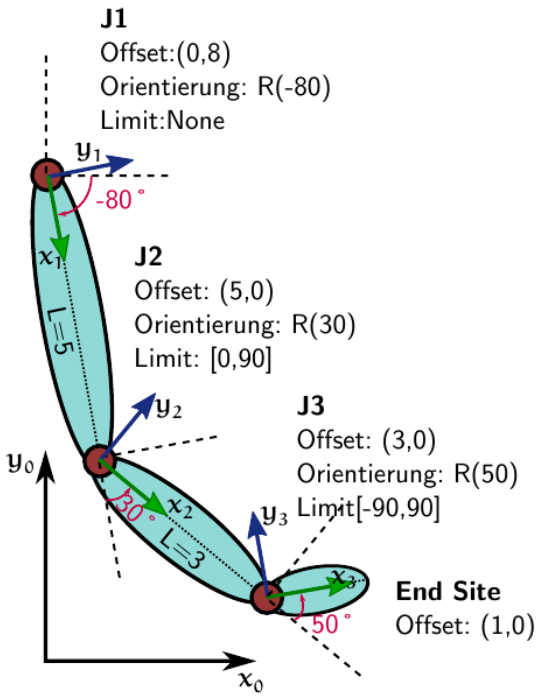

FIGURE 2.3: Example of a joint chain with respective local coordinate systems visualized, notice that the global transform of Joint J2 depends on J1, and J3 on J2 and J1. Image taken from [1]

explain affine matrix multiplication (rotation + translation)

- for affine transformation the propagating the chain results in object space relative rotation and translation

2.1.5 Restpose and Bind Pose Matrix

- Because Character Modellers or Scans have to define the surface of a Virtual Character in an existing pose, Bones have to be placed correctly in that Character. Joint rotations of a Motion are then applied relative to the restpose angle of that joint.

TODOm 2.1.5: later first?

This also suggest that motion transfer between skeletons poses already a challenge when restposes are different.

explain what term rig mean beforehand

The Bind Pose Matrices are assigned per Joint and describe the transformation from the Object Space Koordinate system of the rigged character to the corresponding Joint in Restpose.

TODOm 2.1.6: keywords cursive?

The Inverse Bind Pose Matrix, as the name implies, does the opposite of the bind pose matrix, in various paper and code sources this is also commonly referred to as Offset Matrix.

Both Bind Pose and Offset matrix are defined with the skeletal hierarchy and their restpose once for a character. The Offset Matrix is essential part for efficient Linear Blend Skinning.

2.1.6 Skeletal Skinning

- for now we have a skeletal definition, but what was initialy wanted was to animate a character mesh easily - the Idear of Skeletal Animation is to abstract parts of the body away into joints, this is to reduce the complexity by defining motion of every single surface vertex manually. For Skeletal Animation, Vertices of the character surface, also called Skin, is abstracted to a bone.

TODOm 2.1.7: skinning example?

This is done by assigning which vertex is affected by which bone. Furthermore, because Flesh is deformable and not rigid, there is a need to interpolate vertices near the joint of two bones, for a 2 bone example and a vertex inbetween them.

- depending on what kind of cloth a character is wearing, there is a need to define vertex weights. Vertex weights have been hand authored by weight painting or tools like

blender automatic weight computation, nearest bone name

TODOm 2.1.8: earlier?

- The most common used Skinning method is Linear Blend Skinning - there are many more skinning methods which try to fix artefacts of linear blend skinning, but this is not in the scope of this thesis

TODOm 2.1.9: in CForge?

- for linear blend skinning, the offsetmatrix moves the weighted vertices of a joint in object space to the center of the coordinate system, so that local rotations of a joint are applied correctly. Together the joint transformation chain with the offset matrix are combined into the skinning matrix, which then gets send to the vertex shader. There it is combined

explain math rotation and translation

- Box-Based or Spherical Skinning - Dual Quaternion Skinning (DQS) - Delta Mush

TODOm 2.1.10: unnecessary? or later?

2.1.7 Motion Data

For Motion Playback, Rotational, Translation and Scale values, per Joint. One pose configuration in an Animation is called Keyframe. A Motion consists of multiple keyframes played sequentially. Timepoints per Keyframe determine at which time of an Animation a given Pose should be displayed.

The Sampling rate determines how many Keyframes per second are contained in the animation.

explain bvh

- 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 - nearest neighbor interpolation between keyframes would result in choppy animation playback, to get a smooth playback at lower sampling rates linear interpolation is an quick, ease and sufficient enough for pleasing results

TODOm 2.1.11: F-Curves, shortly?

2.1.8 Other Animation Approaches

TODOm 2.1.12: unnecessary?

- Morph Targets - vertex animation textures (Vertex Shader Animations)
-> no one as flexible as skeletal animation due to abstraction of skeletal animation

2.2 Inverse Kinematics

check

- forward kinematics desribed 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

In the previous Section we learned that Forward Kinematics takes Input from the Configuration Space of a Rigged Model and gives us Working Space Coordinates we can use to Render a Skinned Mesh. But we could also do Collision test. or parent further objects a character could hold onto joints.

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

formulation

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

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.

formulation

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

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 themselfs as a helpful tool to model a desired pose more easily and quickly.

formulation

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

2.2.1 The IK Problem

reuse explaination of basics

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:

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

TODOm 2.2.1: explain chain transform multiple solutions here?

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

2.2.2 Reachability

- This is beacause the Inverse Kinematics Problem can not be solved unambiguously. - figure 2.4 shows that in 2D a chain of more than 2 joints yields an infinite amount of solutions for an reachable point

cases

- 3 cases - target is outsite of reach, no solution - depending on desired behavior, chain should be - target is at distance of of chain length ik is applied to - exactly one solution - easily identifyable, but rare occurance

TODOm 2.2.2: illustrate?

- 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 2.4. This already happens in 3d for chain length of two.

2D example infinite solution

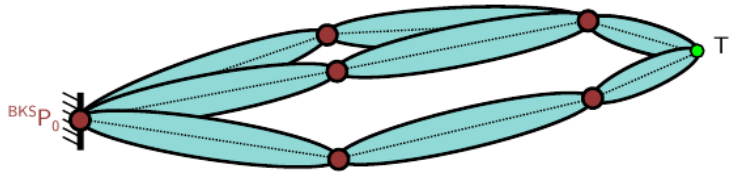

FIGURE 2.4: In 2D, for Chains with more than 2 Joints, there will be an infinite Amount of Configurations satisfying reaching the Target, when $|T - P_0| < |J1| + |J2| + |J3|$. Image taken From [1]

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

[3] has expl

2.2.3 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 [4] explained the analytical method simple for beginners.

main expl

- Figure 2.5 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.

TODOm 2.2.3: example durchgehen 2.5

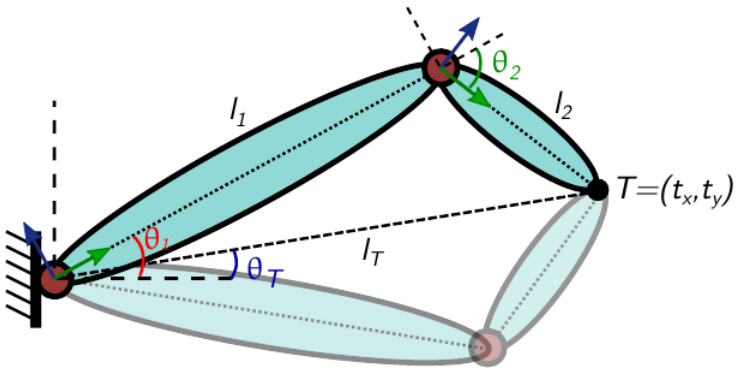

FIGURE 2.5: Visualization of relevant Variables for solving θ_1 and θ_2 analytically to reach point T using Trigonomic functions. A Second Solution is Visualized with less opacity below, Image taken from [5]

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.

TODOm 2.2.4: correct? any source?

- 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

2.2.4 Jacobian Methods

The Jacobian Inverse Method for solving Inverse Kinematics falls into the category of numerical solvers and represents the first Iterative Approach developed.

- also called inverse rate control

check

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: explain chain transform multiple solutions here?

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 2.6

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. 2.6 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:

fill

$$J = \begin{pmatrix} \frac{\partial F(\theta)_i}{\partial \theta_j} \end{pmatrix}$$

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

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

cite https://www.youtube.com/watch? and replace image with own

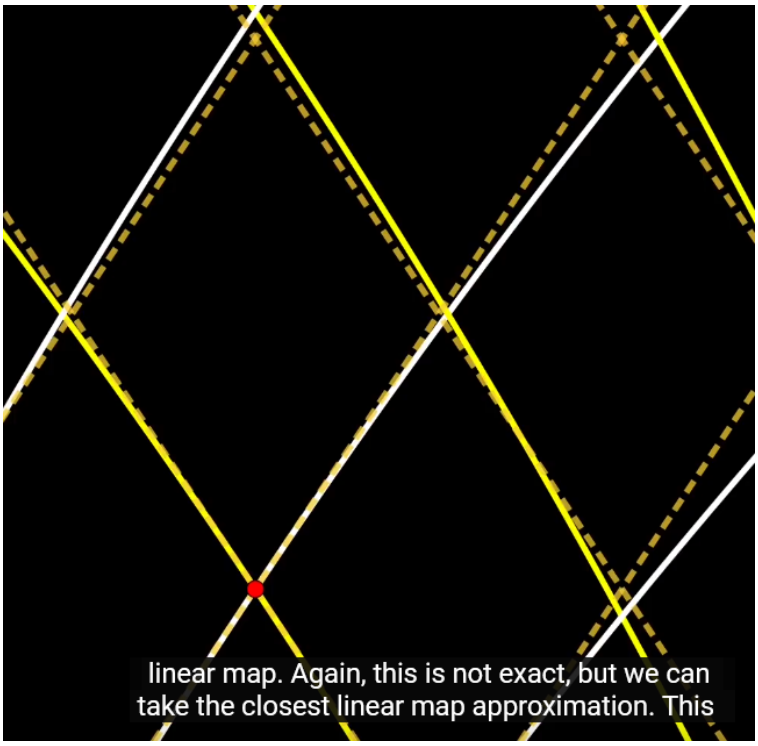

FIGURE 2.6

put rigid explaination of simplifying calculation into chapter 3

Buss [6] provides a more in-depth Introduction to the Jacobian Inverse Kinematics Method and how the Jacobian Inverse works.

- still lacking resources on how to implement Jacobian IK

2.2.5 Cyclic Coordinate Descent

Cyclic Coordinate Descent (CCD) were the first heuristic approaches to solving IK. Kenwright [7] 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 [8] are credited.

- 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?

TODOm 2.2.7: isnt this very inefficient?

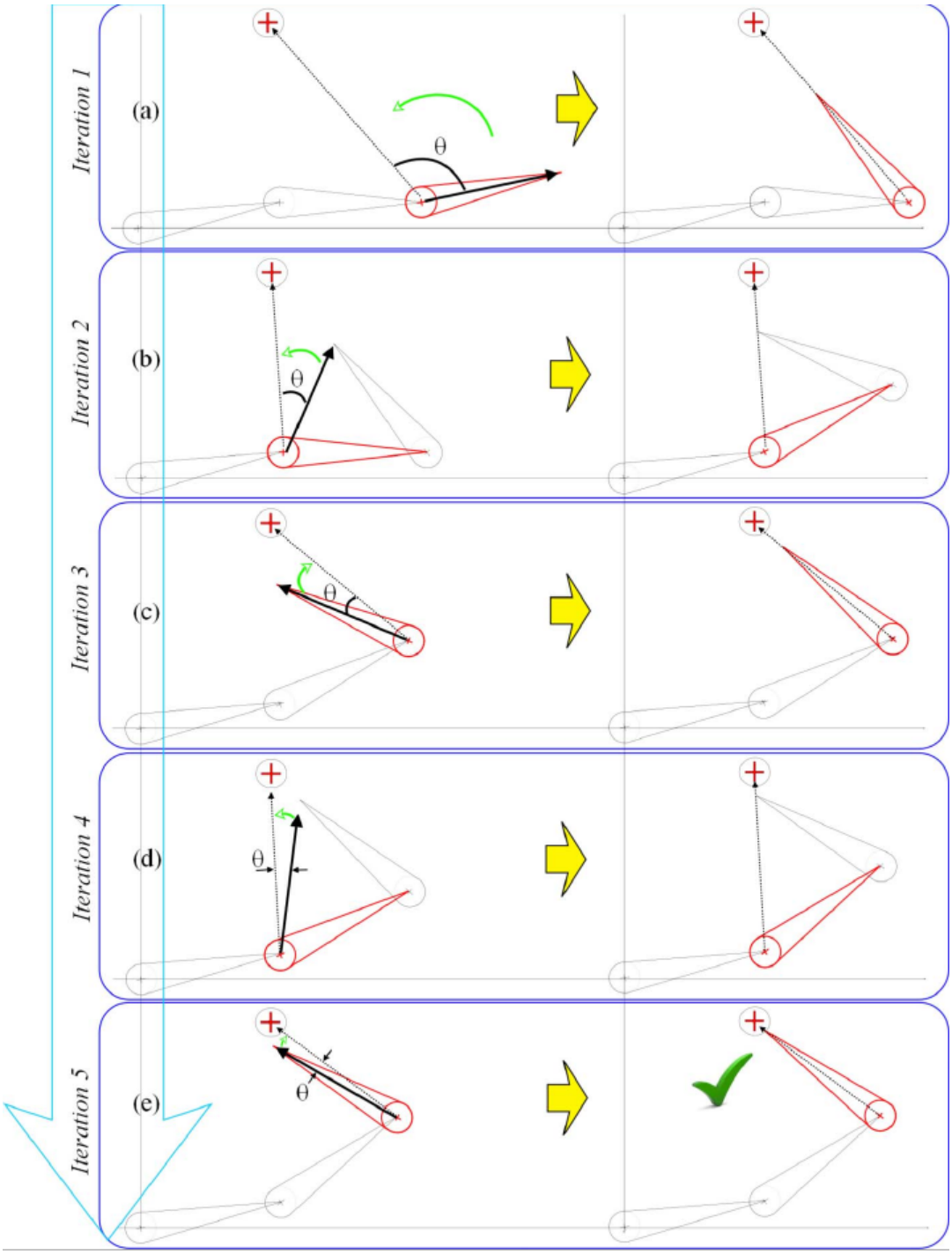

FIGURE 2.7: Three Joint Chain example of CCD, in each Iteration the Current Joint is rotated so that the Vector from current Joint to target and current Joint to endeffector align. Image taken from [7]

TODOm 2.2.8: list of algorithms after index?

Algorithm 1 BackwardCCDIK Algorithm, Taken From [7]

```
1:  procedure BACKWARDCCDIK
2:      Input: e                                              ▷ threshold
3:      Input: k_max                                          ▷ max iterations
4:      Input: n                          ▷ link number (0 to numLinks-1 chain)
5:      k ← 0                                                 ▷ iteration count
6:      while k < k_max do
7:          for i = n − 1 to 0 do
8:              Compute u, v                  ▷ vector P_e − P_c, P_t − P_c
9:              Compute ang                                   ▷ using Equation 1
10:             Compute axis                                  ▷ 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                       ▷ reached target
14:                 return                                    ▷ done
15:             end if
16:         end for
17:         k ← k + 1
18:     end while
19: end procedure
```

2.2.6 FABRIK

address CCD problems in CCD sec

- In order to improve performance and the rolling and unrolling Problem of CCDs, Aristidou and Lasenby [9] came up with Forward And Backward Reaching Inverse Kinematics (FABRIK)

- 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

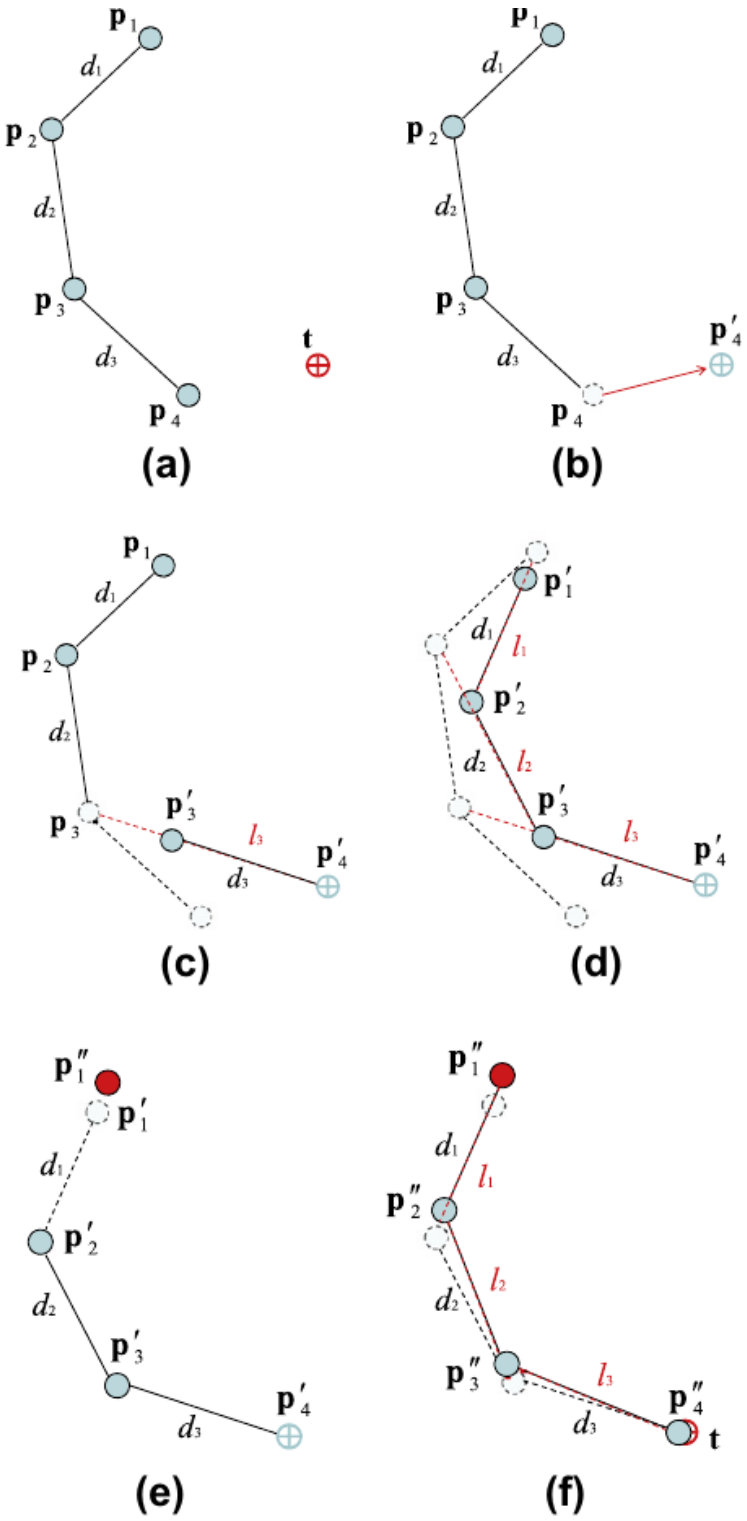

FIGURE 2.8: Image taken from [9]

Algorithm 2 A full iteration of the FABRIK algorithm, Taken from [9]

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

dist $\leftarrow \|p_1 - t\|$ ▷ The distance between root and target
▷ Check whether the target is within reach
if dist > $d_1 + d_2 + \ldots + d_{n-1}$ **then** ▷ The target is unreachable
  for i = 1 to n-1 **do** ▷ Find the distance r_i between the target t and the joint position p_i
    $r_i \leftarrow \|t - p_i\|$
    $k_i \leftarrow \frac{d_i}{r_i}$
    $p_{i+1} \leftarrow (1 - k_i)p_i + k_i t$ ▷ Find the new joint positions p_i.
  end for
else
  ▷ The target is reachable; thus, set as b the initial position of the joint p_1
  $b \leftarrow p_1$
  $dif_A \leftarrow \|p_n - t\|$
  ▷ Check whether the distance between the end effector p_n and the target t is greater than a tolerance.
  while $dif_A > tol$ **do**
    ▷ STAGE 1: FORWARD REACHING
    $p_n \leftarrow t$ ▷ Set the end effector p_n as target t
    for i = n-1 down to 1 **do**
    ▷ Find the distance ri between the new joint position p_{i+1} and the joint p
      $r_i \leftarrow \|p_{i+1} - p_i\|$
      $k_i \leftarrow \frac{d_i}{r_i}$
      $p_i \leftarrow (1 - k_i)p_{i+1} + k_i p_i$ ▷ Find the new joint positions p_i .
    end for
    ▷ STAGE 2: BACKWARD REACHING
    $p_1 \leftarrow b$ ▷ Set the root p_1 its initial position.
    for i = 1 to n-1 **do**
      ▷ Find the distance r_i between the new joint position p_i
      $r_i \leftarrow \|p_{i+1} - p_i\|$
      $k_i \leftarrow \frac{d_i}{r_i}$
      $p_{i+1} \leftarrow (1 - k_i)p_i + k_i p_{i+1}$ ▷ Find the new joint positions p_i.
    end for
    $dif_A = ||p_n - t||$
  end while
end if

2.2.7 Other Methods

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

TODOm 2.2.9: citation okay?, cite section in paper?, ref book in fabrik hard to understand

Newton Methods explained by [9] 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 [10]. 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

2.2.8 IK Surveys

Aristidou et al. [3] present various Inverse Kinematics techniques in depth for general applications.

TODOm 2.2.10: title? subsectionComparison of IK methods

Boulic et al. [11] survey different Inverse Kinematics techniques to correct noisy and incomplete motion capture data from vision Input.

TODOm 2.2.11: seem to be only using custom methods?, dont go more into detail?

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

complete

table to visualize comparison of ik methods like

2.2.9 Existing Tools

TODOm 2.2.12: into related or impl?

move to other section

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

TODOm 2.2.13: Exisiting Tools section in review or impl? would be more relevant for going over drawbacks, so Id say implementation?

- CCD Impl

TODO Tex

- Fabrik Impl

- a - Final IK ik collection for unity - http://www.root-motion.com/finalikdox/htm
- paid - no source code

formulate

formulate

comparison from FABRIK paper

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 themselfes 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 2.9.

- 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 relaxiation in form of joints are not connected anymore - done by projecting target onto joint plane bounds in algo

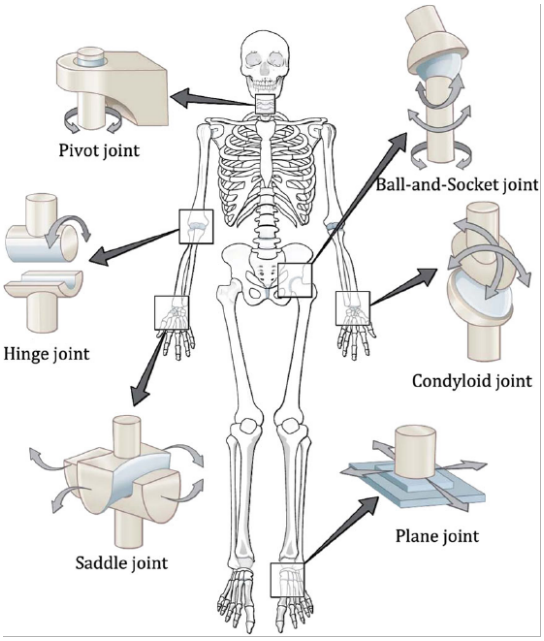

FIGURE 2.9: Various Constraint Types Visualized and where they could be used in a Virtual Human Skeleton. Image taken From [12]

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

TODOm 2.3.1: only in impl? (Motion Retarget Editor) eher nicht oder? (Jacobian, CCD, FABRIK)

hinge limits

swing twist limit

complete

2.3.4 Jacobian Inverse Constraints

[14]

2.3.5 CCD Constraints

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

- To ensure CCD doesnt run into a local minima under influence of constraints simulation annealing is used [7]. - Simulation annealing for CCD tries to jump out of a local minima by randomly rotating joints.

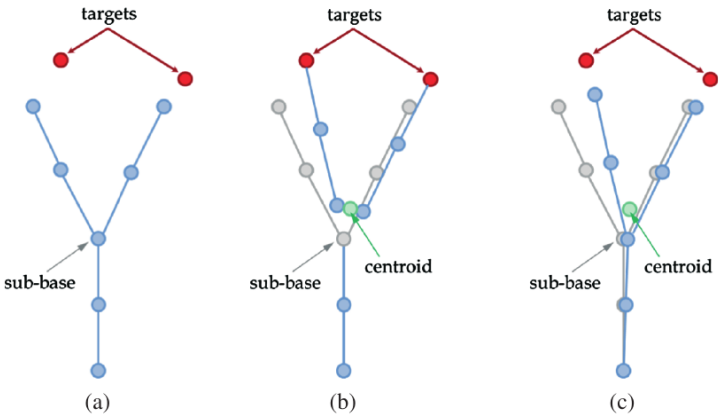

FIGURE 2.10: Image showing, Image Taken from [12]

2.3.6 FABRIK Constraints

- [12] mentioned multiple various constraint types, but lacks in detail on how to exactly implement these, referring to [9].

- While mentioned in [9], Aristidou et al. [12] explained more in detail how to solve a FABRIK armature for multiple endeffectors.

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

Multiple Endeffectors - 2 Stages
- first Normal (forward) - appliy 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 wich is the mean of all pos - - FABRIK iter contiued from new subbase pos (centroid) - second stage backward: - algo normal applied until sub-base - then applied seperately 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

caption

- 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

check source

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

iTASC blender pos

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

2.4 Motion Retargeting

- Motion Retargeting is the process of transfering motion data for a skeleton with a specific hierarchy and joint lenghts to another skeleton which either differs in one or both.

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, footsliding and more

TODOm 2.4.1: limb based MoRe, or better name?

2.4.2 Limb based Retargeting

TODOm 2.4.2: category?

[17] - describes the problem to be hard to solve mathematically because of how to define the quality of a motion - require basic features of motion identified as constraints

Limb based Motion Retargeting approaches abstract Joints into Joint Chains, where each Chain is retargeted individually.

[18]

2.4.3 Jacobian based

TODOm 2.4.3: is Limb based?

Choi and Ko use Inverse Rate Control, which is the Jacobian Inverse Method of Inverse Kinematics, and extend it to be applicaple to tree structures instead of chains without branches. [19]

- 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.

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

inverse rate control

2.4.4 Machine Learning Approaches

continue

- due to the complexity of the motion retargeting Problem, machine learning approches are a popular...

Aberman et al. [20] - using skeletal pooling, which reduces skeletons to a common primal skeleton by a sequence of edge merging, to archieve retargeting between different skeleton hierarchies

TODOm 2.4.4: list various more MoRe paper?

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

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

TODOm 2.4.5: correct?

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

- new features often require models to be retrained

2.4.5 Other approaches

2.4.6 Available Tools

2.5 Automated Rigging

2.5.1 Machine Learning Approaches

2.5.2 Thinning Approaches

TODOm 2.5.1: genauer anschauen für mögliche impl? (Future?)

2.5.3 Skin Matching Approaches

2.5.4 Re-Meshing

Chapter 3

Motion Retarget Editor

methodisches vorgehen hier

3.1 Chosen Tools

TODOm 3.1.1: goals from related work?

- 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

- Also having an open source foundation opens up community improvements and helps CrossForge mature by protyping 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 [21], developed by Tom Uhlmann at Chemnitz University of Technology, is a A C/C++ Cross-Platform 3D Visualization Framework using OpenGL. - design allows you to use the available CrossForge modules, modify them, or completely replace them with you own OpenGL based implementation and GLSL Shaders. - This flat design, simplicity and direct approach, CrossForge is well suited for educational purposes and computer graphics research.

formulation

- 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, notebly 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

3.2 Classes and Scene Management

smart pointer pos

- reoccuring 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

TODOm 3.2.1: picking in scene management, UI before scene management?, picking uses smart pointers, easy to explain reasoning, but scene uses also smart pointers

3.2.1 Character Entity

- The Character Entity Class represents a Single Virtual Character and manages various States related to it.

LISTING 3.1: My Code Example

```
struct CharEntity {
    bool isStatic = false;
    std::unique_ptr<IKSkeletalActor> actor;
    std::unique_ptr<StaticActor> actorStatic;

    // animation
    std::unique_ptr<IKController> controller;
    Animation* pAnimCurr;

    // common
    std::string name;
    T3DMesh<float> mesh;
    SGNGeometry sgn;

    // Picking binding functions
    ...

    // various tool functions
    ...
};
```

- `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 initalization - 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-initlizing 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

```
class MotionRetargetScene : public ExampleSceneBase {
    ...
    void mainLoop() override;
    ...
    void renderUI();

    void loadCharPrim(std::string path, IOmeth ioM);
    void storeCharPrim(std::string path, IOmeth ioM);

    struct settings {
        ...
    } m_settings;

    std::vector<std::shared_ptr<CharEntity>> m_charEntities;
    std::weak_ptr<CharEntity> m_charEntityPrim; // currently
       ↪ selected char entity
    std::weak_ptr<CharEntity> m_charEntitySec; // secondary
       ↪ char entity for operations

    SGNTransformation m_sgnRoot;

    ...
};//MotionRetargetScene
```

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

3.2.3 Config

- No Configuration System to store Settings in Files for persistent usage accross sessions
- ability to store settings with string or overload with custom type
- to reduce overhead, an extra compile unit is used to define all serialization interfaces in order to seperate Config functionality from the corresponding core modules

- used to store camera position and other settings like paths or load behavior

3.3 User Interface

TODOm 3.3.1: Zenodo, to get DOI of github repo? upload others?

For the User Interface Cornut's ImGui [22] is used. 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 cleany place ui elements

3.3.1 Picking

TODOm 3.3.2: Picking sec position probably somewhere else better?

- 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

```
class IPickable {
    public:
    virtual void pckSelect() {};
    virtual void pckDeselect() {};
    virtual void pckMove(const Matrix4f& trans) = 0;

    virtual Matrix4f pckTransGuizmo() = 0; // used for guizmo
       ↪ update
    virtual Matrix4f pckTransPickin() = 0; // used for
       ↪ picking evaluation
    virtual const BoundingVolume& pckBV() = 0;
    virtual EigenMesh* pckEigenMesh() { return nullptr; };
};
```

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

LISTING 3.4: My Code Example

```
class Picker {
    void pick(std::vector<std::weak_ptr<IPickable>> objects);
    void forcePick(std::weak_ptr<IPickable> pick);
    void start();
    void resolve();
    void reset();
    void update(Matrix4f trans);
    std::weak_ptr<IPickable> getLastPick() {
        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 picked objects, most relevant methods are visualized in 3.4.

matrix seperation

- Matrix seperation

3.3.2 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 [23] 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 strenths in wireframe

3.3.3 Widgets

- Outliner
- visualizes Skeletal Hierarchy with collapsable 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

- Animation tab

- Popup - integrated ImGui Popup had artifacts due to

TODOm 3.3.3: term only render on update?

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

- TODO Matrix seperation

TODOm 3.3.4: position probably somewhere else better

TODOm 3.3.5: explain ui bindings / implementation in followin parts on the side?

- Popup
- used for

extend

3.4 Animation System

CrossForge already provided an implementation for skeletal animation playback using Linear-Blend-Skinning.

ref assimp

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 localy to the weighted vertices when doing linear blend skinning.

3.4.2 Sequencer

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

3.4.3 Joint Interaction

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

TODOm 3.4.1: this is hard to decide how to structure, since this is a problem connected with gizmo usage

- visualizing joints
- using good joint ...

- picking interaction

TODOm 3.4.2: this would be important, that picking is clarified beforehand

3.4.4 Editing Tools

In order to
- construct restpose

make algorithmic and shorten

LISTING 3.5: My Code Example

```
1 void IKController::initRestpose() {
```

```
    std::function<void(SkeletalAnimationController::
        ↪ SkeletalJoint* pJoint, Matrix4f offP)> initJoint;
    initJoint = [&](SkeletalAnimationController::
        ↪ SkeletalJoint* pJoint, Matrix4f offP) {
        Matrix4f iom = pJoint->OffsetMatrix.inverse();
        Matrix4f t = offP.inverse() * iom;

        // https://math.stackexchange.com/questions/237369/
            ↪ given-this-transformation-matrix-how-do-i-
            ↪ decompose-it-into-translation-rotati
        pJoint->LocalPosition = t.block<3,1>(0,3);
        pJoint->LocalScale = Vector3f(t.block<3,1>(0,0).norm
            ↪ (),
        t.block<3,1>(0,1).norm(),
        t.block<3,1>(0,2).norm());
        Matrix3f rotScale;
        rotScale.row(0) = pJoint->LocalScale;
        rotScale.row(1) = pJoint->LocalScale;
        rotScale.row(2) = pJoint->LocalScale;
        pJoint->LocalRotation = Quaternionf(t.block<3,3>(0,0)
            ↪ .cwiseQuotient(rotScale));
        pJoint->LocalRotation.normalize();

        for (uint32_t i = 0; i < pJoint->Children.size(); ++i
            ↪ )
        initJoint(getBone(pJoint->Children[i]),iom);
    };
    initJoint(m_pRoot,Matrix4f::Identity());
}
```

- update restpose

make algorithmic and shorten

LISTING 3.6: My Code Example

```
void CharEntity::updateRestpose(SGNTransformation* sgnRoot) {
    if(!actor)
    return;

    // apply current pose to mesh data
    for (uint32_t i=0;i<mesh.vertexCount();++i) {
        mesh.vertex(i) = actor->transformVertex(i);
    }

    // forwardKinematics to get updated global pos and rot in
        ↪ m_IKJoints
    controller->forwardKinematics(controller->getRoot());

    for (uint32_t i=0;i<mesh.boneCount();++i) {
        auto* b = mesh.getBone(i);

        //TODOff(skade) bad, assumes mesh idx == controller
            ↪ idx
```

```
17          IKJoint ikj = controller->m_IKJoints[controller->
                ↪ getBone(i)];
18
19          // get current global position and rotation
20          Vector3f pos = ikj.posGlobal;
21          Quaternionf rot = ikj.rotGlobal;
22
23          Matrix4f bindPose = Matrix4f::Identity();
24          bindPose.block<3,1>(0,3) = pos;
25          bindPose.block<3,3>(0,0) = rot.toRotationMatrix();
26          b->InvBindPoseMatrix = bindPose.inverse();
27      }
28
29      //TODOf(skade) update animations
30
31      init(sgnRoot);
32  }
```

- apply transform to Mesh

3.5 Inverse Kinematics Implementation

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.

list impl

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

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

- Interface for IKSolver `IIKSolver` 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 IIKSolver {
2      public:
3      virtual void solve(std::string segmentName, IKController*
           ↪ pController) {};
4
5      protected:
6      float m_thresholdDist = 1e-6f;
7      float m_thresholdPosChange = 1e-6f;
8
9      int32_t m_MaxIterations = 50;
10 };//IIKSolver
```

- 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

3.5.1 Jacobian Method

- Various Sources for Jacobian Inverse Kinematics lack in detail on what specific entries of each cell mean.

- this is due to what the input means

-

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

LISTING 3.8: My Code Example

```
enum Type {
    BACKWARD,
    FORWARD,
} m_type = BACKWARD;
```

- subsectionFABRIK - contains `std::vector< Vector3f > fbrkPoints` for visualization in framework

requirements for good IK

multiple endeffectors

survey table comparison

section Combined Constraint System (TODO eigenanteil in extra chapter)

3.6 Constraints Implementation

3.6.1 Target Weighting

(might be mentioned, check)

- 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.

- 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 endeffectors to potentially move

away from previously reached targets

or the other way around idk yet

- need simillar to fabrik 2 iterations, root to endeffectors, then endeffectors to root globally for the armature to get optimal position
- ik armature evaluated beginning from endeffectors until centoid

3.6.2 Angle Constraint Example

- 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)

3.7 Motion Retargeting

- Discussed Motion Retargeting Methods Section 2.4 vary significantly in adaptivity

formulation

- Motion Retargeting results still subjective depending on goal of application task

subsection Combined Retargeting Methodologies (TODO eigenanteil in extra chapter)

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

3.7.1 Armature

- `IKChain` defines a non-branching chain of joints to which a IK Solver is applied to
- Armature consits 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

TODOm 3.7.1: already explain here or later?

- auto create armature

make algorithmic and shorten

LISTING 3.9: My Code Example

```
void CharEntity::autoCreateArmature() {
    if (auto ctrl = controller.get()) {

    std::map<std::string,std::vector<
        ↪ SkeletalAnimationController::SkeletalJoint*>> ikc;

    std::function<void(SkeletalAnimationController::
        ↪ SkeletalJoint* pJoint, std::string name)> propagate
        ↪ ;
    propagate = [&](SkeletalAnimationController::
        ↪ SkeletalJoint* pJoint, std::string name) {
        // end current chain and add all childs as new chains
        int cc = pJoint->Children.size();
        // add joint to chain
        if (name != "")
        ikc[name].insert(ikc[name].begin(),pJoint);
        if (cc > 1) {
```

```
14          for (uint32_t i = 0; i < cc; ++i) {
15              auto c =ctrl->getBone(pJoint->Children[i]);
16              propagate(c,c->Name);
17          }
18          } else if (cc == 1) { // add to current chain
19              auto c =ctrl->getBone(pJoint->Children[0]);
20              propagate(c,name);
21          } //else //(cc == 0)  // end effector nothing to do
22      };
23      propagate(ctrl->getRoot(),"");
24
25      ctrl->m_ikArmature.m_jointChains.clear();
26      for (auto& [k,v] : ikc) {
27          IKChain nc;
28          nc.name = k;
29          nc.joints = v;
30          ctrl->m_ikArmature.m_jointChains.emplace_back(std::
                ↪ move(nc));
31      }
32      }
33  }
```

TODOm 3.7.2: better name?

3.7.2 Joint angle Imitation

- Joint angle Imitation
- many papers dont explain how how to transfer motion of

- despite having similar rest pose position, non-redundant parts of skinning matrix still have influence on how motion data is applied to a rig - thus cant simply apply motion data from one rig to another

- recreate restpose, not always feasable, 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

make algorithmic and shorten + expl

LISTING 3.10: My Code Example

```
1       std::function<void(SkeletalAnimationController::
            ↪ SkeletalJoint* j, Matrix4f parentT)> imitate;
2
3       imitate = [&](SkeletalAnimationController::SkeletalJoint*
            ↪  jt, Matrix4f parentT) {
4       IKChain* ct = nullptr;
5       if (jointToChain[jt].size() > 0)
6       ct = jointToChain[jt][0]; //TODOff(skade) multiple chains
            ↪ ?
7       bool noMatch = true;
```

```
8       if (ct) {
9           //TODO(skade) find corresponding retarget chain
10          int is = 0;
11          for (int it = 0; it < m_ikcorr.size();++it)
12          if (&tCtrl->m_ikArmature.m_jointChains[it] == ct)
13          is = m_ikcorr[it];
14          IKChain& cs = sCtrl->m_ikArmature.m_jointChains[is];
15
16          int i = std::distance(ct->joints.begin(),std::find(ct
                ↪ ->joints.begin(),ct->joints.end(),jt));
17          int matchIdx = jointIndexingFunc(i,cs,*ct);
18
19          if (matchIdx != -1) {
20              SkeletalAnimationController::SkeletalJoint* js =
                    ↪ cs.joints[matchIdx];
21              Eigen::Matrix4f jsT = CForgeMath::
                    ↪ translationMatrix(js->LocalPosition)
22              * CForgeMath::rotationMatrix(js->LocalRotation)
23              * CForgeMath::scaleMatrix(js->LocalScale);
24
25              Eigen::Matrix4f parentS = Matrix4f::Identity();
26              {
27                  auto* jsc = js;
28                  Matrix4f adjS = Matrix4f::Identity();
29                  while (jsc->Parent != -1) {
30                      jsc = sCtrl->getBone(jsc->Parent);
31                      Eigen::Matrix4f jscT = CForgeMath::
                            ↪ translationMatrix(jsc->
                            ↪ LocalPosition)
32                      * CForgeMath::rotationMatrix(jsc->
                            ↪ LocalRotation)
33                      * CForgeMath::scaleMatrix(jsc->LocalScale
                            ↪ );
34                      parentS = jscT * parentS;
35
36                      ////TODO(skade) adj
37                      //// with adjustment
38                      //parentS = jscT * adjS * parentS;
39                      //Matrix4f adjS = js->OffsetMatrix.
                            ↪ inverse() * adjS;
40                  }
41              }
42
43              //Matrix4f t = jt->OffsetMatrix * parentT.inverse
                    ↪ () * parentS * js->OffsetMatrix.inverse() *
                    ↪  jsT;
44              //Matrix4f t = jt->OffsetMatrix * parentT.inverse
                    ↪ () * parentS * js->OffsetMatrix.inverse() *
                    ↪  jsT;
45
46              // new local transform
```

```
47              Matrix4f t = Matrix4f::Identity();
48
49              // parent target
50              if (jt->Parent != -1 && js->Parent != -1) {
51                  auto* jtp = tCtrl->getBone(jt->Parent);
52                  auto* jsp = sCtrl->getBone(js->Parent);
53
54                  // current global transform of retargeted
                        ↪ parent
55                  //Matrix4f parentGlobal =  parentT * jtp->
                        ↪ OffsetMatrix;
56                  //Matrix4f parentGlobalS = parentS * jsp->
                        ↪ OffsetMatrix;
57
58                  // allign next transform so global transform
                        ↪ of target and source are identical
59                  //t = jsT;
60
61                  ////TODO(skade) adj
62                  //// get parent relative joint change of
                        ↪ restpose
63                  //Matrix4f adjS = js->OffsetMatrix.inverse()
                        ↪ * jsp->OffsetMatrix;
64                  //Matrix4f adjT = jt->OffsetMatrix.inverse()
                        ↪ * jtp->OffsetMatrix;
65                  //adjS.block<3,1>(0,3) = Vector3f::Zero();
66                  //adjT.block<3,1>(0,3) = Vector3f::Zero();
67                  //t = adjT.inverse() * parentT.inverse() *
                        ↪ parentS * adjS
68                  //   * jsT * js->OffsetMatrix * jt->
                        ↪ OffsetMatrix.inverse();
69
70                  // correct but doesnt account for rest pose
                        ↪ differences
71                  //t = parentT.inverse() * js->SkinningMatrix
                        ↪ * jt->OffsetMatrix.inverse();
72                  //t = parentT.inverse() * parentS * jsT * js
                        ↪ ->OffsetMatrix * jt->OffsetMatrix.
                        ↪ inverse();
73
74                  t = parentT.inverse() * parentS
75                  * jsT * js->OffsetMatrix * jt->OffsetMatrix.
                        ↪ inverse();
76
77                  //parentS = parentS * js->OffsetMatrix * jsT;
78
79                  // correct
80                  parentT = parentT * t;
81                  // but also means:
82                  //parentT = parentS
```

```
83                  //  * jsT * js->OffsetMatrix * jt->
                        ↪ OffsetMatrix.inverse();
84
85                  ////TODO(skade) adj
86                  //parentT = parentS * adjS
87                  //  * jsT * js->OffsetMatrix * jt->
                        ↪ OffsetMatrix.inverse();
88              }
89
90              { // set local rotation of joint
91                  Vector3f p,s; Quaternionf r;
92                  MRMutil::deconstructMatrix(t,&p,&r,&s);
93                  //jt->LocalPosition = p;
94                  jt->LocalRotation = r;
95                  //jt->LocalScale = s;
96              }
97              noMatch = false;
98          }
99      }
100     if (noMatch) {
101         Eigen::Matrix4f jtT = CForgeMath::translationMatrix(
                ↪ jt->LocalPosition)
102         * CForgeMath::rotationMatrix(jt->LocalRotation)
103         * CForgeMath::scaleMatrix(jt->LocalScale);
104
105         ////TODO(skade) adj
106         //Matrix4f adjT = Matrix4f::Identity();
107         //if (jt->Parent != -1) {
108             //  auto* jtp = tCtrl->getBone(jt->Parent);
109             //  Matrix4f adjT = jt->OffsetMatrix.inverse() *
                    ↪ jtp->OffsetMatrix;
110             //}
111         //parentT = parentT * jtT * adjT;
112
113         parentT = parentT * jtT;
114     }
115
116     for (auto child : jt->Children) {
117         imitate(tCtrl->getBone(child), parentT);
118     }
119 };
120 //TODO(skade) make toggable
121 imitate(tCtrl->getRoot(), Eigen::Matrix4f::Identity());
```

- root special bone - root handling — impl rotation, make optional

LISTING 3.11: My Code Example

```
1     // copy root position
2 for (int i=0;i< tCtrl->boneCount();++i) {
3     auto jt = tCtrl->getBone(i);
4     if (jt->Parent == -1) {
```

```
5           auto jt = tCtrl->getBone(i);
6           for (int j=0;j< sCtrl->boneCount();++j) {
7               auto js = sCtrl->getBone(j);
8               if (js->Parent == -1) {
9                   jt->LocalPosition = js->LocalPosition;
10                  break;
11              }
12          }
13          break;
14      }
15  }
```

- 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 alligned with another joint in the longer chain, beeing then used during correction in ik
- surjective more complex, one joint should imitate the the transformation of 2 or more joints, which need to be computed using offset matrix to correctly take restpose orentation into account

3.7.3 limb scaling

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

- 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 unforseen 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

formula

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

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

- 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

TODOm 3.7.3: section name?

3.7.4 Editor Main Loop

TODOm 3.7.4: flowchart ideal here?

-
- algo that gets applied every frame

edit mode other name

Algorithm 3 main loop editor

```
1:  procedure MAIN LOOP EDITOR, EXECUTED EACH FRAME
2:      while Editor not terminated do
3:          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
```

class hierarchy overview

scene

TODOm 3.7.5: how ideally split? + position?

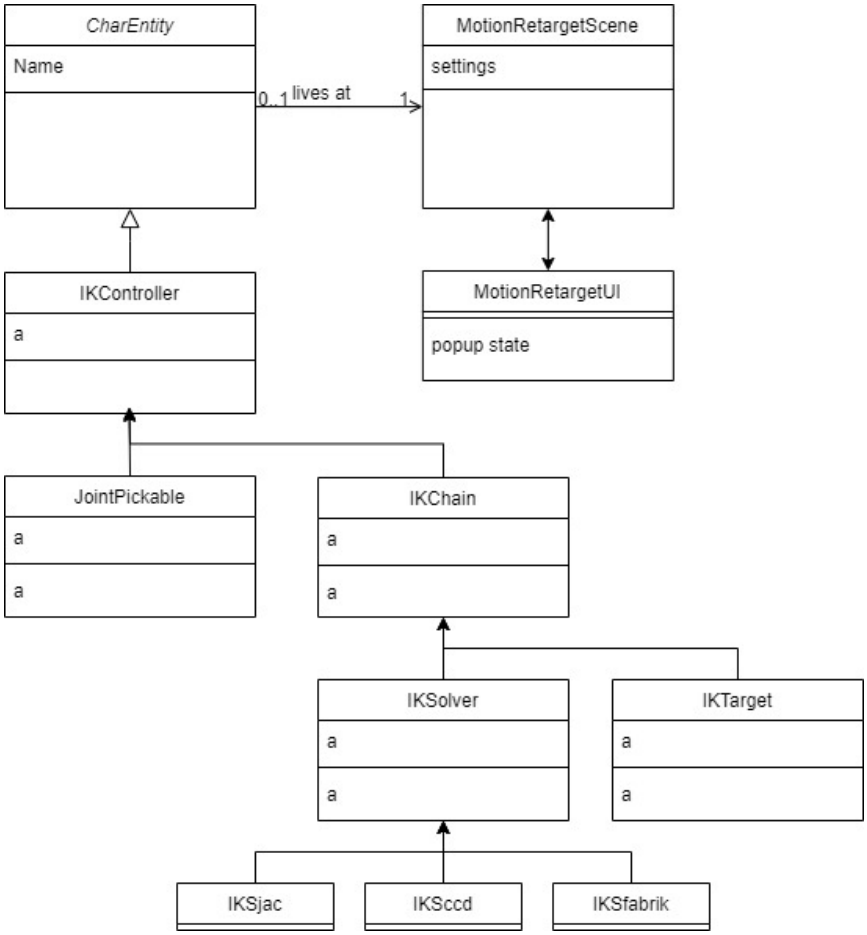

FIGURE 3.1

3.7.5 Comparison of IK Methods

- 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 runing or pushing motions. jacobian inverse has the ability to more naturaly correct these due to its way of distributing change and thus work across all bones instead of ones closes to the endeffector

image of comparison without joint angle imitation

3.7.6 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 differering skeletons
- todo

3.8 Skeleton Matching

- durin import - can use ICP for algining characters using limb chain positions - prone to error, manual alignmend as option better

- motion retareting 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

TODOm 3.8.1: Skel Match before or after MoRe?

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

3.9.1 assimp

- 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 cant 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 - assimps intermediate format focuses on providing an easy to use integration, beeing 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 models topology slightly in some cases to ensure most compatability across multiple formats, meaning that a round trip, import export without changing anything, produces a different file - which can be undireable when the goal is to produce a clean model

3.9.2 gltfio

- 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 fromat 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 propietary 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 redundencies - because blender is foss, there is no need to implement various file format interfaces for CrossForge - with crossforges direct gltf export interface, correct export is assured, optionally assimp can be used as well but might have problems exporting correctly

TODOm 3.9.1: better? subsectionModel Data subsectionAnimation Data

- bvh, which most commonly motion capture databases use, is supported by assimp

future

- implement native bvh

3.9.3 Armature

- import / export armature, limb chain definitions and constraints for Motion Retargeting

3.10 foreign tool Integration

TODOm 3.10.1: section name

- 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 environemnt wrapper for python libraries - starting such an environment from an embedded pyhton 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 preferablyfiles can be

TODOm 3.10.2: subsection? not related to foreign tool integration

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

LISTING 3.12: My Code Example

```
template<typename AROptions>
class IAutoRigger {
    virtual void rig(T3DMesh<float>* mesh, AROptions options)
        ↪ = 0;
};
```

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

TODOm 3.10.3: manifold?

- 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)

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, - rignet plugin for blender already exists - implement motion retargeting

4.3 SMPL fitting

explain smpl

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

CrossForge already has an 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 integreted into the propsed editor

Furthermore transferring geometric surface propertices 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

TODOm 4.3.1: sec better name

4.4 Other Ideas

- Utilizing Skinning Alternatives (direct delta mush, 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

in appendix

- 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

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