Maria SKUBLEWSKA-PASZKOWSKA, Jakub SMOŁKA

Institute of Computer Science, Electrical Engineering and Computer Science Faculty, Lublin University of Technology

Arms animation based on human hierarchical tree model

***Abstract**. The paper presents a human model based on hierarchical tree structure, which is used for creating various 3D animations of the human body. Two animations are presented as examples. The model uses quaternions for representing rotations. It is implemented in C++ language. Two integrated software libraries are used for manipulating quaternions and writing standard C3D files which can be further viewed and processed in various programs such as Mokka.*

***Streszczenie.** Artykuł przedstawia model człowieka oparty na hierarchicznej strukturze drzewa. Może on być wykorzystany do tworzenia animacji 3D ludzkiego ciała. Przedstawiono dwie przykładowe animacje. Do reprezentacji rotacji elementów modelu wykorzystywane są kwaterniony. Model został zaimplementowany jako program w języku C++. Do przekształcania kwaternionów i zapisywania plików C3D wykorzystano dwie zintegrowane biblioteki. Standardowe pliki C3D, można otworzyć i dalej przetwarzać w rozmaitych programach takich jak Mokka. (**Animacja kończyn górnych wykorzystująca hierarchiczny model człowieka)**.*

Keywords: arms animation, human hierarchical model, quaternions.
Słowa kluczowe: animacja kończyn górnych, hierarchiczny model struktury człowieka, kwaterniony.

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Introduction

3D animation is a common way of visualizing motion data. There are many techniques to creating and controlling specific movements. In order to create a movement model, a way of representing angular position is needed. There are four main ways of representing angular position in 3D space: (1) fixed axes, (2) Euler angles, (3) rotation and angle and (4) quaternions [1]. They can all be used to rotate the 3D objects.

This paper presents a hierarchical human model and a method of animating two human arms in 3D. The human body is represented as the simplified model consisting of 15 vertices (only arms are animated). Each vertex corresponds to one of the human body joints. Quaternions are used for representing the angular positions of limbs in space. The animation takes into account the physical properties and limitations of the human body. As a result the animation is realistic.

For the purposes of this paper, a computer program is implemented in C++. Two main libraries are utilized by the piece of software: the biomechanical toolkit (b-tk) [2] and Eigen [3]. B-tk is used to create and save an animation in C3D format [4]. Such a file can be opened in various programs meant for motion capture data viewing and editing. In our case animation is opened in Mokka [5] in order to visualise moving arms. The second library – Eigen – is used to manipulate quaternions describing the hierarchical model.

Representing rotations with quaternions

Quaternions are represented by four values $[s, x, y, z]$. They can be expressed as a pair $[s, v]$, where *s* stands for a scalar and *v* for a vector consisting of three coordinates *x,y* and *z* [1, 6]. They can be used for both representing rotations and for interpolating angular positions. They are also often used for combining various rotations into one transformation. All rotations can be represented by quaternions.

A point (*x,y,z*) – i.e. a point in space -- can be represented by a quaternion whose scalar part is 0 and the vector part consists of *x, y* and *z* (equation 1) [1].

$$v = [0, (x, y, z)], \quad (1)$$

Rotation of the point represented by *v* around the axis passing through the origin of the coordinate system can be performed by using quaternion multiplication as shown in equation 2 [1].

$$v' = qvq^{-1}, \quad (2)$$

where: *q*, *v*, *v'* stand for quaternion, point and rotated point correspondingly.

Compound rotations may be represented as a product of quaternions that represent consecutive rotations. A compound rotation of point *v* by two quaternions *q* and *p* is given by equation 3 [1].

$$\begin{aligned} v'' &= pv' p^{-1} = p(qvq^{-1})p^{-1} \\ &= (pq)v(q^{-1} p^{-1}) = (pq)v(pq)^{-1}, \end{aligned} \quad (3)$$

where *v"* stands for the point that was subject to compound rotation.

The inverse of a quaternion represents rotation of a point around the same axis and by the same angle but in the opposite direction (equation 4) [1].

$$q^{-1}(qvq^{-1})q = (q^{-1}q)v(q^{-1}q) = v \quad (4)$$

Rotation by an angle *θ* around the axis determined by the vector $v = [x, y, z]$ can be represented by a unit quaternion *q* given by the equation 5 [1].

$$q = [\cos(\theta/2), \sin(\theta/2)(x, y, z)] \quad (5)$$

Rotation by an angle *θ* is equivalent to a rotation by an angle -*θ* around an axis whose orientation is the opposite. The quaternion $q = [s, v]$ and its negation $-q = [-s, -v]$ represent the same rotation [1].

As in the case of point rotation, in order to rotate a vector *w* a new quaternion has to be created $[0, w]$. It represents the vector being rotated. A second quaternion *q* describes the rotation. The rotated vector *w'* is given by the equation 6 [1].

$$[0, w'] = q[0, w]q^{-1} \quad (6)$$

Also with vectors compound rotations can be expressed by a product of several quaternions. For instance, two vector rotations described by two quaternions *p* and *q* can be compounded as shown in the equation 7 [1].

$$[0, w''] = q(p[0, w]p^{-1})q^{-1} = (qp)[0, w](qp)^{-1} \quad (7)$$

where: *w"* is the vector after the compound rotation.

As with points the inverse of the quaternion represents the rotation of a vector around the same axis by the same angle but in the opposite direction. The combination of two rotations represented by q and q^{-1} produces the identity transformation as shown in equation 8 [1].

$$q^{-1}\left(q[0,w]q^{-1}q\right)=[0,w] \quad (8)$$

Human hierarchical tree model

An artificial human model is a hierarchical data structure. A human is represented with the use of a tree consisting of linked nodes. The top node is the root. Its coordinates are given in the global coordinate system. Coordinates of other nodes are defined in relation to the root. Each node has a parent (except the root) and at least one child node (exceptions are the lowest nodes called leaves). Each node corresponds to a joint and a specific part of the body that starts in the parent node (a node higher in the hierarchy)

In fig. 1 a simplified human silhouette is presented. Joints/nodes are marked as red dots. Figure 2 shows the silhouette in a tree form. Nodes contain the names of the joints they correspond to. An arbitrary assumption is made as to which nodes represent the left and right side of the body.

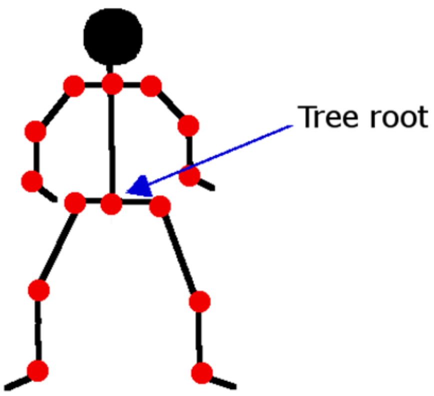


Fig.1. A simplified human silhouette

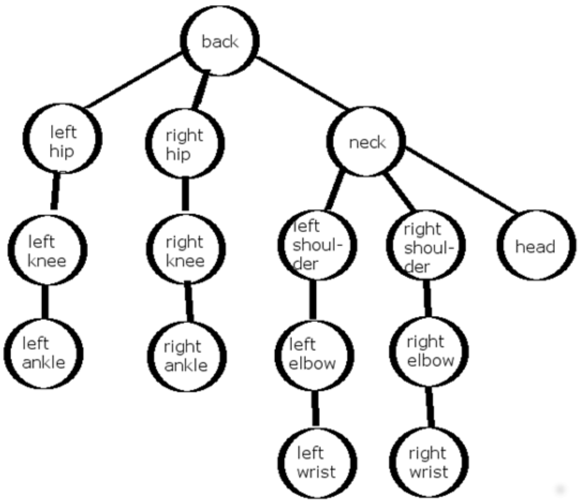


Fig.2. Human hierarchical tree model

The back of the human silhouette is the root of the hierarchical tree. It divides the model into two parts corresponding to the bottom and top part of the body. The root has three child nodes: left hip, right hip and neck. Each of the two hip nodes has one child a knee, which in turn also has one child an ankle, which are leaves of the tree. The neck node is the start of the top part of the body. It has three children: left shoulder, right shoulder and the head. Each shoulder has one child – the elbow which in turn also has one child – the wrist. The wrists and the head are leaves of the tree.

The model imposes restrictions on the relative positions of objects it describes. When a specific joint is in motion, other related joints are also moved in a manner defined by the hierarchy. This means that all nodes located lower in the hierarchy will be moved according to a transformation defined for their parent. In other words, moving a joint is equivalent to moving a body part defined as a sub-tree consisting of all nodes (joints) taking part in this transformation.

The hierarchical model is implemented as a collection of classes in object oriented C++ language [7]. First is the `Node` class whose fragment is shown in figure 3.

```
class Node {
  Node(string jointName);
  btk::Point::Pointer mokkaPoint;
  Vector3d v;
  Transform3d initialTransformation,
              articulationOfTransformation;
  std::vector<Node*> children;
  string partOfBody ;
  Node* createNewNode(int numberOfChildren,
                      string jointName);
  void update(Transform3d parentTransform,
              int frameNumber);
}
```

Fig. 3. Selected fragment of Node class' implementation

The class consists of: (1) a constructor whose task is to prepare an object that represents joint named by the constructor's parameter, (2) a BTK library's point data structure (its value is written to C3D file), (3) current coordinates that represent the joint's current position in space, (4) a joint's initial transformation and its articulation, (5) a list of the node's children (nodes that are lower in the hierarchy), (6) a joint name (naming joints makes model manipulation easier), (7) two methods: `createNewNode()` and `update()` which will be described in more detail below. The former creates a node based on two pieces of information: the number of children and a joint's name. The latter method using two parameters (current node transformation and the frame number) computes a new node's position and also updates the positions of all its children as shown if figure 4. As one can see that the positions are updated recursively.

```
for(int i = 0; i <children.size(); i++){
 children[i]-> update(newTransform,
                      frameNumber);
}
```

Fig. 4. Updating positions of node's children

A new node position is obtained by computing a product of matrices representing: the current node transformation, the initial node transformation and its articulation. The result is saved in the `mokkaPoint` field. The node's updated position is needed not only for displaying purposes but also for com-puting the updated positions of all of the node's children.

Second class: `HierarchicalModel` is responsible for: (1) constructing the hierarchical model using node objects and (2) creating animations using the model. Class' definition is shown in figure 5.

```
class HierarchicalModel
{
  HierarchicalModel();
  Node *back, *leftHip,...
  void createHumanModel();
};
```

Fig. 5. Class' structure

The class's structure is simple – it consists of the constructor, pointers to 15 nodes that make up the model and the `createHumanModel()` method that builds the model and creates animations. Building the model consists of creating 15 node objects, defining relations between them and saving them in the pointer fields. The names are added for the more intuitive use.

The `createHumanModel()` method contains all the data necessary for building a model of a human silhouette and simulates its movement.

Arms animation based on hierarchical human model

With the use of the hierarchical model two example animations are created for the purpose of this paper.

Creating animation begins with setting up the model. It is constructed in the following manner: (1) the node objects are created for each joint represented by the model, (2) the nodes are organized into a hierarchical data structure whose root is the node representing the silhouette's back. An example of how the hierarchy is built is given in figure 6. (3) Each node is assigned its initial transformation (this way a human silhouette in its initial position is created), a new `Transform3D` object represents the initial transformation, (4) each node is assigned an object (saved in the `mokkaPoint` field), which is in turn associated with a point trajectory saved in C3D file, (5) When all the nodes are setup, their positions are updated by a call to the update() method.

```
back->children.push_back(leftHip);
back->children.push_back(rightHip);
back->children.push_back(necktHip);
```

Fig. 6. Assigning 3 child nodes to the root (the "back" node)

The model is positioned in such a way that the "back" node is placed in the origin of the coordinate system, and in its neutral position both arms are straight (fig. 7).

Once the model is set up, an animation can be created. As stated above, two animations are created. The duration of both animations is set to 5 seconds. The total number of frames is 125. Each frame contains coordinates of all 15 points that make up the hierarchical model. The first depicts a person who is moving his/her arm (as if he/she were lifting weights). In order to describe the initial and final positions of both wrists, the quaternions are used. Two quaternions represent the initial and final position of right hand and two quaternions represent the initial and final position of left hand. The initial position of the left hand (q0Left in figure 8) and the final position of the right hand (q1Right) is the same as their position in the initial setup of the model. This orientation is represented by the identity quaternion (a zero angle rotation). The left hand in its final position (q1Left) and the right hand in its initial position (q0Right) are rotated by 135 degrees around the X axis. Appropriate quaternion is generated using AngleAxis class [3].

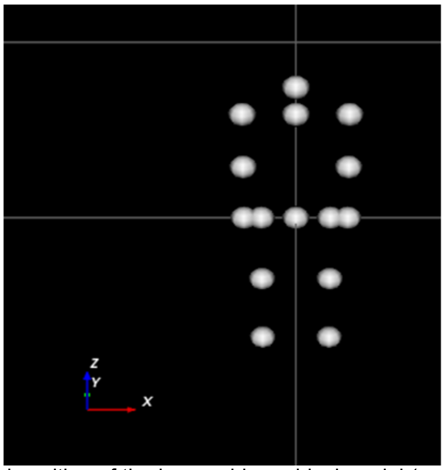


Fig.7. Initial position of the human hierarchical model (as presented in the Mokka software)

The animation is created by iterating through all the frames to be created. For each frame the wrist's relative position *p* in the range of [0;1] is computed. Then the quaternions describing the intermediate (between initial and final) positions are obtained using the SLERP interpolation method [8,9]. New articulation is assigned to the left and right elbow nodes and the nodes' positions are updated.

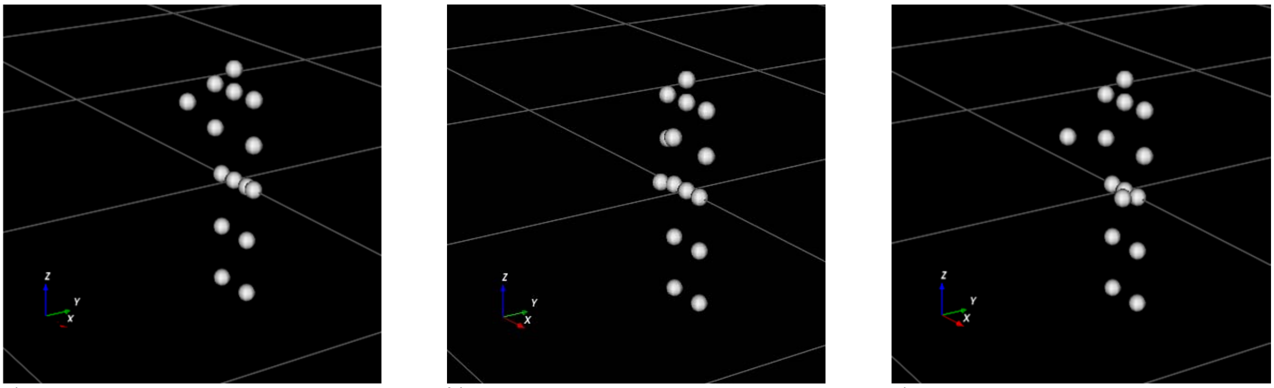
```
for (int i =1; i <frameCount;  i++)
{
  //compute relative position p in the range of
[0;1]
  //compute new position of the right arm
  qRight = q0Right.slerp(p, q1Right);
  // compute new position of the left arm
  qLeft = q0Left.slerp(p, q1left);
  rightElbow->articulationOfTransformation =
    qRight; //new articulation of right elbow
  elbowleftElbow->articulationOfTransformation =
    qLeft; //new articulation of left elbow
  //recursively update positions of the nodes
  back->update(ident, k);
}
```

Fig. 8. Arm animation

As the animation progresses, the left hand bends while the right straightens and then the situation reverses. The bending angle varies from 0 (straight arm) to 135 degrees. Two joints are animated: the wrist and the elbow. Selected animation frames are presented in fig. 9.

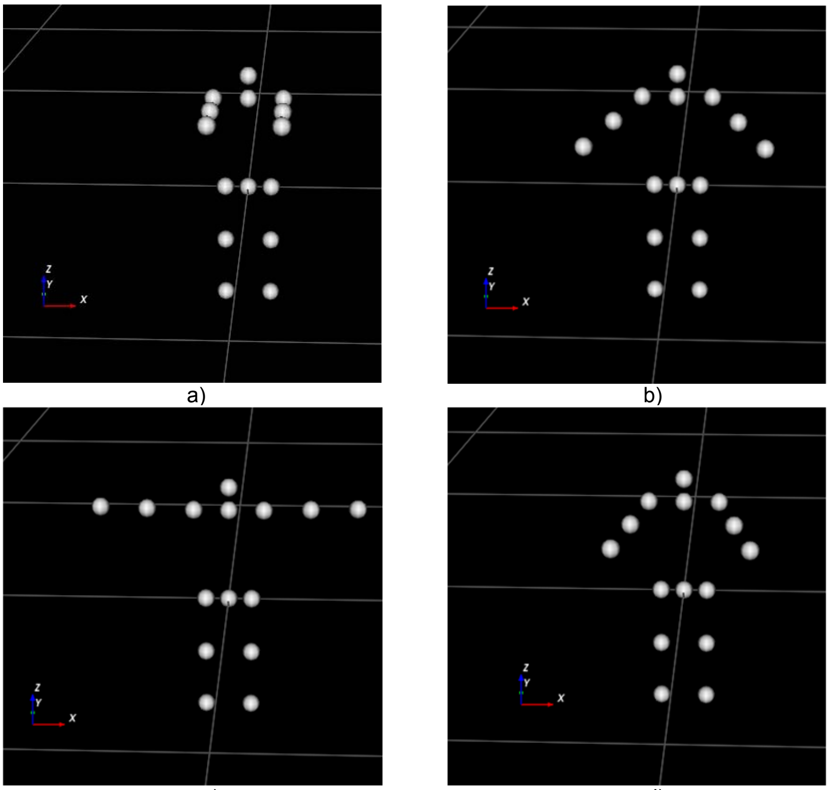
The second animation is created similarly. It depicts straight arms being lifted. The difference is that the positions of both writs and elbows change in this animation. Initial and final positions of the animated nodes are given by four quaternions, two for each arm. The initial rotation of both arms is identical and set to -90 degrees around the X axis. The final position of the right arm is -90 degrees and +90 degrees for the left arm. They are both rotated around the Y axis. Appropriate quaternions were created again with the AngleAxis class.

Selected frames from the animation are presented in fig. 10.



a) b) c)

Fig. 9. Selected frames from the created animation (arm bending and straightening): a) initial position (first frame), b) in the middle movement (67th frame); c) at the end of movement (108th frame).



a) b) c) d)

Fig.10. Selected frames from arm animation (lifting): a) initial set- first frame; b) 26th frame; c) 63rd frame; d) 108th frame.

Conclusions

This paper presents a hierarchical human model which is a base for creating animations of selected parts of the human body. The animations are saved to C3D files which is one of the standard formats. Quaternions are used for describing limb movements. The advantage that use of quaternions offers is that it eliminates side effects such as gimbal lock [1]. The animation is smooth and resembles actual human movement.

The hierarchical model is a tool that can be used for creating animation of the whole human body and also for comparison with real motion capture data.

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Authors:

dr inż. Maria Skublewska-Paszkowska, Politechnika Lubelska, Instytut Informatyki, ul. Nadbystrzycka 36B, 20-618 Lublin, Email: maria.paszkowska@pollub.pl,

dr inż. Jakub Smołka, Politechnika Lubelska, Instytut Informatyki, ul. Nadbystrzycka 36B, 20-618 Lublin, Email: jakub.smolka@pollub.pl,

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