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A METHOD OF ARTIFACT COMPENSATION FOR DUAL QUATERNION SKINNING AND ITS APPLICATION IN DIGITAL TWIN MODELS

This paper is devoted to the task of realistic 3D model visualization. It presents a method which allows to avoid undesired deformations of 3D model. The proposed method allows to significantly reduce the bulging joint artifact which appears as a result of dual quaternion skinning. Dual quaternion skinning is a real-time skeletal animation technique, developed as an alternative to linear skinning. Unlike linear skinning, dual quaternion skinning does not suffer from loss of volume during deformations, but introduces a new type of artifact, namely, joints bulging outward during bending. The paper proposes a method of approximating the undesired deformation. The proposed method only takes into account the bulging, introduced by blending the poses of the first two bones (in order of decreasing weights) affecting the given vertex, and is designed to prevent discontinuities, which can arise from such approach, by smoothly decreasing the amount of bulging compensation around problematic zones, while improving the animation in areas, where bulging artifact is most noticeable. The developed method can be used for 3D model creation and visualization in digital twin technology. The paper presents an architecture of digital twin technology for medical information systems.

Keywords: skeletal animation, skinning, dual quaternions, digital twins

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МЕТОД КОМПЕНСАЦІЇ АРТЕФАКТІВ DUAL QUATERNION SKINNING ТА ЙОГО ЗАСТОСУВАННЯ ДО МОДЕЛЕЙ ЦИФРОВИХ ДВІЙНИКІВ

В статті вирішується проблема реалістичної візуалізації 3D моделей. Запропоновано метод, який дозволяє уникати небажаних деформацій 3D моделей, що виникають при застосуванні процедури Dual Quaternion Skinning. Процедура Dual Quaternion Skinning дозволяє перетворення у реальному часі скелету тривимірної моделі на реалістичну модель, зовнішній вигляд якої забезпечується полігональною сіткою, проте вона вносить небажані артефакти, такі як “роздування” суглоба моделі при згинанні. В даній статті пропонується метод апроксимації цього дефекту, що дозволяє значно зменшити небажану деформацію. Запропонований метод враховує дефект, спричинений інтерполяцією поз перших двох кісток (в порядку спадання коефіцієнтів ваги), що впливають на суглоб моделі, та запобігає створенню розривів шляхом плавного зменшення інтенсивності компенсації дефекту навколо проблемних зон, при цьому покращуючи якість анімації в зонах, де дефект найбільш помітний. Розроблений метод може бути застосований при створені та візуалізації моделей у технології цифрових двійників. В статті пропонується архітектура технології цифрових двійників для медичних інформаційних систем.

Ключові слова: скелетна анімація, скінінг, дуальні кватерніони, цифрові двійники.

Introduction

Realistic 3D animation is required for many applications where a certain object, subject, or process need to be visualized while changing in course of time. Skeletal animation is a technique of animation, in which the model is represented in two parts: polygonal mesh and a skeleton. The animator controls the motions of the skeleton, while the polygonal mesh is wrapped around it through the process of skinning. Skinning is the process of deforming a polygonal mesh, based on the current pose of the skeleton and the vertex weight coefficients, which determine the amount of influence each bone has on the given vertex.

Several techniques of real-time skinning are currently available [1-10]. Linear skinning and dual quaternion skinning are examples of such techniques. Each skinning technique introduces its own type of artifacts. For example, the linear skinning models suffer from loss of volume during deformations. At the same time, dual quaternion skinning, which was developed as an alternative to linear skinning, does not produce such artifact, but it introduces another one, namely, joints bulging outward during bending. Thus, the development of a method of artifact compensation for dual quaternion skinning is a topical task.

The method described in this paper is similar in principle to using corrective blend shapes to fix the bulging artifact of dual quaternion skinning, but instead of the animator manually creating the blend shapes, they are estimated in real-time, based on the data already available. A model of undesired deformation is created, and the inverse transformation is applied after the skinning, reducing the artifact.

The proposed method has a significant importance for creation of 3D models for digital twin technology. A digital twin is a virtual replica of its physical twin in terms of both behaviour and appearance. The technology of digital twins [11] has been introduced quite recently. It has been developed to help business in enhancing the processes of products and services development [12].

However, this technology can be also implemented in other areas where analysis, modelling, and prediction of an object (subject, process, phenomenon) future states, conditions, or behaviour is necessary. One of such new application areas are healthcare and medicine [13, 14]. For such applications, there are high requirements to visualization quality in order to ensure correspondence between a digital twin and its physical twin. Therefore, the developed method of artifact compensation for dual quaternion skinning can help to satisfy the requirements to the digital twin 3D model visualization.

Literature Review

One method of combating the bulging joint artifact of dual quaternion skinning was proposed by Kim and Han [1]. In order to prevent bulging, the distance between each vertex of the model and its nearest bone segment is calculated and stored. After performing the dual quaternion skinning, the vertices that moved away from respective bones are re-projected to maintain the stored distances. This approach effectively prevents joint bulging, but may create discontinuities in areas like knuckles, or crotch area (Fig. 1).

Another approach to reducing skinning artifacts is using different centres of rotations for different joints, as the bulging artifact arises from using the same centre of rotation for all vertices near a joint [2]. These centres of rotation can be pre-computed and stored, thus having little impact on real-time performance. However, for best results this method requires optimized set of skinning weights, while editing weights requires re-calculating optimized centres of rotation, which cannot be done in real-time.

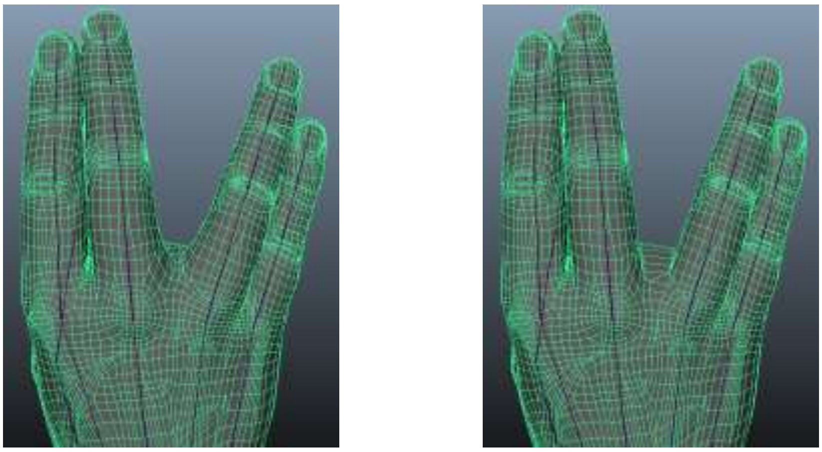


Fig. 1. Dual quaternion skinning (left) and bulging-free dual quaternion skinning (right) [1]

Apart from skinning techniques, bulging artifact can be reduced using corrective blend shapes. Corrective blend shapes are designed to improve the model's deformation in a particular problematic pose (e.g., raised arm). As the model approaches this target pose, the weight coefficient on respective blend shape is increased and vice versa. Corrective blend shapes allow for precise tweaking of animations and simulating effects, like skin contact, skin sliding and muscle bulging, but must be created manually, which significantly increases the amount of time spent on creating animations.

Multi-weight enveloping [6] and animation space skinning [7] avoid the artifacts of traditional linear skinning by utilizing multiple weights for every bone-vertex pair, but this makes manual painting of weights infeasible, requiring a set of example poses for parameter fitting, which takes additional time and effort to create.

Research Objective

The objective of this research is to develop a method of artifact compensation for dual quaternion skinning and to employ it to 3D model creation and processing within the digital twin information technology.

Proposed Method

The idea behind the proposed method is to create an approximated model of undesired deformation (i.e., joint bulging) and apply an inverse transformation after the dual quaternion skinning is performed. In order to make such approximation possible, several assumptions are made about the target model:

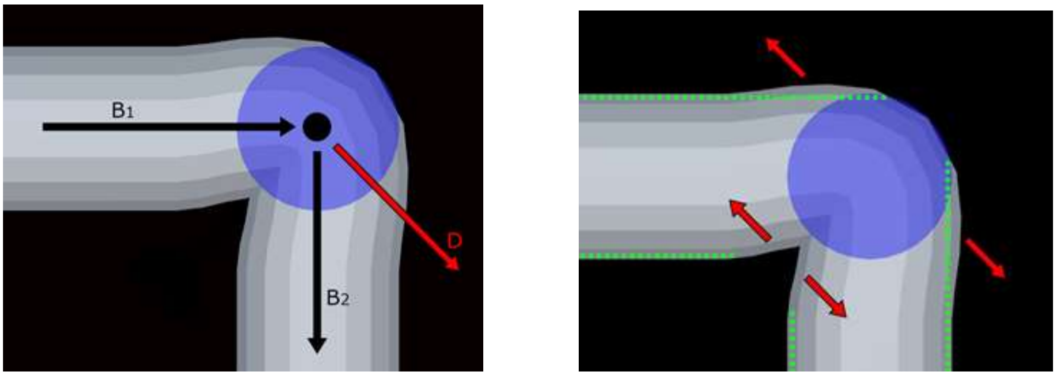
- Weights are smooth on the surface of the model;
- The bone that has the greatest skinning weight for any given vertex is the nearest bone to this vertex;
- The length of transition between areas affected by neighbouring bones is roughly proportional to the radius of the joint.

Current method only takes into account two bones with greatest weights that affect any given vertex. Considering that the sum of their weights cannot be less than 0.5 (in the worst-case scenario with 4 bones) and most vertices of the model are usually affected by less than four bones, such simplification can still provide satisfactory results.

The bulging artifact is approximated as a motion of vertices along the bisector of the angle, created by the two bones that have the greatest weights for the given vertex (Fig. 2a).

Bones of the skeleton must be sorted, so that in any given pair of bones, the bone, that is further away in hierarchy from the root bone, will have higher index. If the bone with greatest weight coefficient in the given pair has smaller index, then the direction of deformation is inverted. Without this inversion, all the vertices would move in the same direction, instead of compressing the bulged joint back into proper shape.

Notice that such inversion does not create a discontinuity, as in the middle of transition zone (where both bones of the pair have equal weights) there is no undesired deformation to compensate. So, while there is a discontinuity in direction, the length of the offset is zero (Fig. 2b).



(a) (b)

Fig. 2. Approximation of undesired deformation: (a) B1, B2 are bones, D is direction of undesired deformation; (b) Discontinuity in direction of deformation

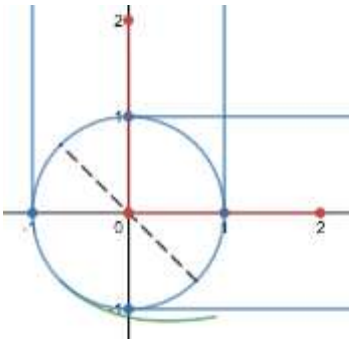


Fig. 3. The 2D model of a bent joint. Red lines represent bones, blue is surface of the model, green is bulging deformation introduced by dual quaternion skinning, dotted black is the direction of deformation

The length of the deformation vector is determined, based on the angle between current poses of the involved bones (relative to their bind poses) and the radius of the joint (which is calculated as the distance between the vertex and the nearest bone segment). In order to derive the length of the deformation vector, a 2-dimensional model of the bent joint was used (Fig. 3).

A unit step function convolved with Gaussian function was used for the weight transition falloff (Fig. 4):

$$H(x) = \frac{d}{dx}\max\{x,0\} \tag{1}$$

$$g(x) = \frac{e^{-\frac{x^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \tag{2}$$

$$w_1(x) = \int_{-\infty}^{\infty} g(t)H(t-x)dt \tag{3}$$

$$w_2(x) = \int_{-\infty}^{\infty} g(t)H(x-t)dt \tag{4}$$

$$w_1(x) + w_2(x) = 1 \tag{5}$$

where $H(x)$ is the unit step function; $g(x)$ is Gaussian function; $w_1(x)$ and $w_2(x)$ are bone weight coefficients for the vertex at horizontal position x.

The parameters were chosen empirically. Different values of standard deviation for Gaussian function were tested, as well as linear weight falloff. Best results were acquired with $\sigma = 0.63$.

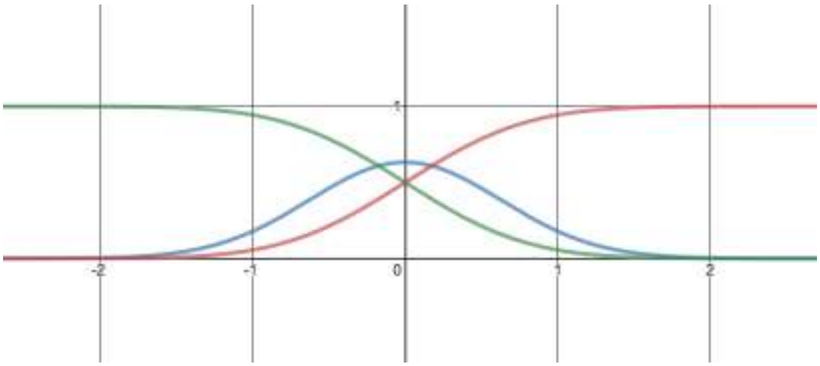


Fig. 4. Blue is Gaussian function (σ=0.63), red and green is weight coefficients for bones b_1 and b_2

The relationship between the length of translation along the deformation direction, required to make the bulging joint match the idealized circular shape during a 90° bend, and the weight coefficient of the second bone, was approximated with a cubic polynomial (Fig. 6), enforcing no deformation on the edges of transition area and in its centre: $f(0) = 0; f(0.5) = 0$. These restrictions meant that two of the four coefficients in the polynomial were fixed:

$$f(w_2) = c_0 + c_1x + c_2x^2 + c_3x^3 \tag{6}$$

$$\begin{cases} c_0 = 0 \\ c_3 = -4c_1 - 2c_2 \end{cases} \tag{7}$$

where $f(w_2)$ is an approximating polynomial; w_2 is weight coefficient of the second bone.

Second bone was chosen, because its weight lies in range [0; 0.5], thus the restriction of no deformation at the edges of transition can be enforced by simply equating c_0 to zero.

Having only two free coefficients allowed for manual adjustments and experimentation, which resulted in a slightly different polynomial and smoother deformations (Fig. 5).

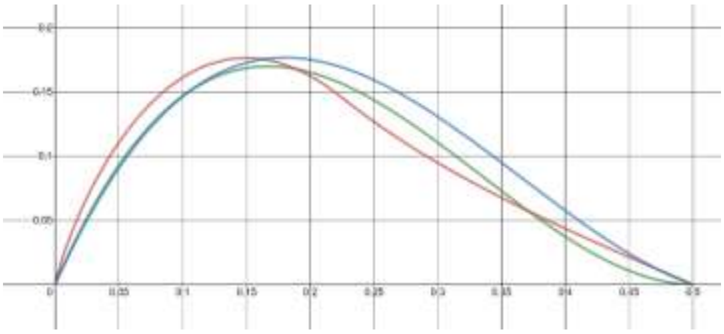


Fig. 5. Red is relationship between bulging deformation offset length (vertical) and weight coefficient of the second bone (horizontal), green is approximating polynomial, blue is manually adjusted polynomial

The polynomials are:

$$f_{orig}(w_2) = 2.29x - 9.14x^2 + 9.12x^3 \tag{8}$$

$$f_{manual}(w_2) = 2.2x - 8.1x^2 + 7.4x^3 \tag{9}$$

where f_{orig} is original approximating polynomial; f_{manual} is manually adjusted approximating polynomial.

Polynomials given above can be used in a manner, similar to blend shapes, without requiring additional work from the animator. The direction of deformation is determined using previously described algorithm, while the length of deformation vector is determined by the formula:

$$l = f(w_2) \cdot r \cdot \min\left\{1{,}2\sqrt{1 - \cos\left(\frac{\alpha}{2}\right)}\right\} \tag{10}$$

where l is length coefficient for deformation vector; f is polynomial, approximating the length of deformation offset, based on the second bone weight coefficient; r is radius of the joint (distance from vertex to the nearest bone segment); α is angle of rotation between current poses (relative to the bind pose) of the first and second bones (with greatest weights) that affect the given vertex.

The last term uses $\cos\left(\frac{\alpha}{2}\right)$, because this value can be extracted from the quaternion representation of the rotation, without additional calculations. This term is meant to act as a blend shape weight. Exact shape of the transition is not greatly important, above variant appears to have a good compromise between visually pleasing deformation and computational simplicity.

The proposed approximation has several limitations, which can be improved upon. The first limitation comes from expecting only two bones to affect the joint. In order to correctly determine the length of the deformation vector, the weights of first and second bone must be normalized (as if they are the only bones affecting given vertex). Thus, instead of directly using w_2 (weight coefficient of the second bone), following term must be used:

$$w_{2normalized} = \frac{w_2}{w_1 + w_2} \tag{11}$$

where w_1 is weight coefficient of the first bone; w_2 is weight coefficient of the second bone.

The second limitation is the artifact that arises when bending and twisting the joint simultaneously (Fig. 6a).

(a) (b)

Fig. 6. Left is an artifact, that arises, when bending and twisting same the joint simultaneously.

Right is reducing bulge-compensation, when twisting is introduced

A more advanced model of artifact approximation might solve this issue, but currently we propose using an additional term that determines the degree of twisting involved and decreases the amount of bulging compensation accordingly. These types of deformations are quite rare, and the bulging artifact is not as noticeable on them, so the overall visual quality of animation does not suffer much (Fig. 6b).

One possible approach is to multiply the deformation vector by the sine of the angle between the deformation vector and the axis of rotation between current poses of the first two bones affecting the given vertex (relative to their bind poses).

Alternatively, the vector representing mentioned axis can be multiplied by its dot product with the normalized deformation direction vector and the result subtracted from the normalized deformation direction vector, before multiplying it by further terms. Thus, yielding:

$$v_{deformation} = [\![(v]\!]_{bisector} - v_{axis}(v_{axis} \cdot v_{bisector})) \cdot l \qquad (12)$$

where $\mathbf{v_{deformation}}$ is deformation vector, $\mathbf{v_{bisector}}$ is normalized bisector of the angle between first two bones affecting the given vertex; $\mathbf{v_{axis}}$ is normalized vector, representing the axis of rotation between current poses of the first two bones affecting the given vertex (relative to their bind poses); l is length coefficient.

This way, when there is no twisting $[\![(v]\!]_{axis} \cdot v_{bisector} = \mathbf{0})$, $v_{deformation}$ will be equal to $v_{bisector}$. And when $v_{axis} \cdot v_{bisector} = \mathbf{1}$, the axis and bisector are two unit vectors with same direction, thus subtracting one from the other yields zero (no bulge-compensation).

Third limitation is the discontinuity, which is created, when the second and the third bones switch places in the area, affected by more than two bones (Fig. 7a):


(a) (b)

Fig. 7. Left is discontinuity, caused by the third and second bones switching places in order of greatest weights. Right is discontinuity removed by introducing additional coefficient to deformation vector length

This discontinuity can be removed by smoothly decreasing the bulging compensation strength around areas, where the weights of 2nd and 3rd bones are close to being equal:

$$k_{3rdbonefix} = 1 - \frac{w_3}{w_2} \qquad (13)$$

where $k_{3rdbonefix}$ is additional multiplier for deformation vector length, indented to fix the discontinuity; w_3 and w_2 is weight coefficients of the third and second bone, respectively.

Applying such multiplier to the deformation vector successfully removed the discontinuity (Fig. 7b).

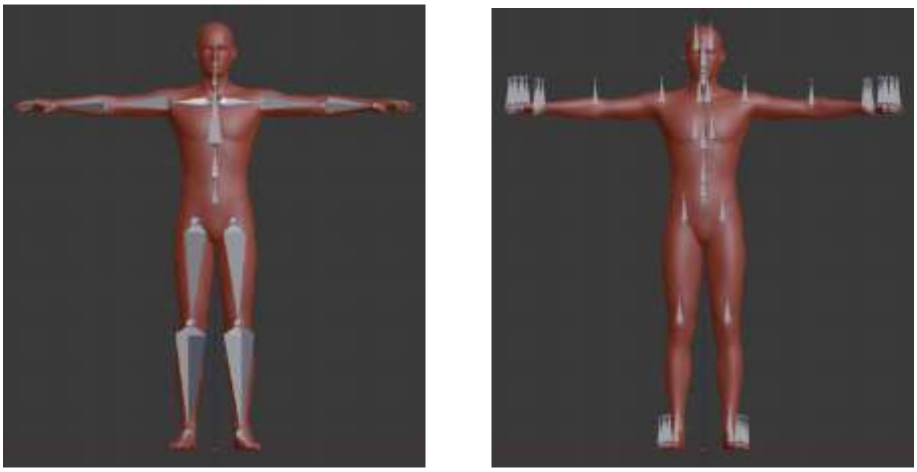


Fig. 8. Skeletons with bones aligned (left) and not aligned (right) along the limbs

Method Implementation

The proposed method can be implemented as an additional step after applying dual quaternion skinning to every vertex (Algorithm 1). However, several additional requirements are introduced:

- The bones of the skeleton must be sorted in such a way, so that for every given pair of bones, the bone, that is further away from the root bone, has greater index;
- The bones of the skeleton must be aligned with one local axis (consistent across the skeleton) running along the limbs (Fig. 8);
- World-space directional vectors of the bones must be provided to the skinning algorithm.

Algorithm 1. Applying bulging compensation to a vertex after dual quaternion skinning

Input:

rotation quaternions $\mathbf{RQ_1}$ and $\mathbf{RQ_2}$, representing world space rotations of first and second bone, respectively;

unit vectors $\mathbf{V_{bone1}}$ and $\mathbf{V_{bone2}}$, representing world-space directions of the first and second bone, respectively;

$\mathbf{I_1}$ and $\mathbf{I_2}$ are indices of the first and second bone, respectively

$\mathbf{w_1}$, $\mathbf{w_2}$, $\mathbf{w_3}$ are weight coefficients for first, second and third bone, respectively;

is a coefficient for manual adjustment of bulging compensation strength;

$\mathbf{V_{orig}}$ is an original position of the vertex V after dual-quaternion skinning.

Output: bulge-compensated vertex position V

```
$RQ = RQ_1 \cdot RQ_2^{-1}$
$V_{axis} = normalize(RQ.xyz)$
$V_{bisector} = normalize(V_{bone1} + V_{bone2})$
$if\ (I_2 > I_1)\ then:$
    $V_{bisector} = -V_{bisector}$
$end\ if$
$V_{offset} = V_{bisector} - V_{axis} \cdot (V_{axis} \cdot V_{bisector})$
$w = \frac{w_2}{w_1 + w_2}$
$l = (2.2w - 8.1w^2 + 7.4w^3) \cdot \min\left(1, 2\sqrt{1 - RQ.W}\right) \cdot (w_1 + w_2) \cdot \left(1 - \frac{w_3}{w_2}\right) \cdot s$
$V = V_{orig} + [(V]_{offset} \cdot l)$
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The comparison of dual quaternion skinning with and without applying the proposed method of bulging compensation is demonstrated in Fig. 9.

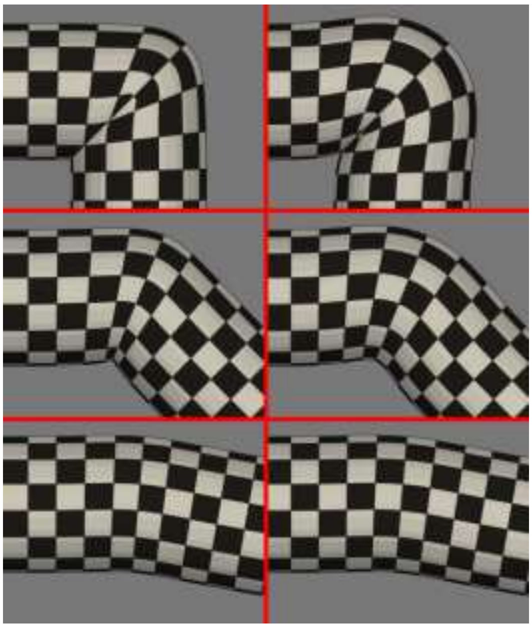

Fig. 9. Dual quaternion skinning with (left) and without (right) applying the proposed method of bulging compensation

The proposed method significantly decreases unwanted joint bulging from dual quaternion skinning without introducing new artifacts.

Method Application for Digital Twin Technology

The digital twin technology enables analysis, modelling, and prediction of a physical twin's possible states and behaviour by experimenting on its digital twin. In this way, the technology helps to avoid critical situations for the twinned physical object (subject, process, phenomenon). It makes this technology a promising solution for medical and healthcare applications. It can create a special value in many areas of medicine including orthopaedics, cardiology, surgery, orthodontics, etc.

Since the physical twin can be characterized by both behaviour and appearance, its digital twin needs to represent them both. The source of the physical twin data includes different general-purpose and special-purpose (medical) devices. The data, which is obtained as a result of measuring or estimation and describing the physical twin, needs to be processed according to the general scheme of the digital twin technology architecture (Fig. 10). This data can be of two types: behavioural data and appearance data. The former is necessary for creation of a mathematical model of the digital twin behaviour and the latter is used for visual modelling of the physical twin.

To simplify the visual modelling, a template model can be used. For example, a human body model or its parts (e.g. a leg, an arm, a heart, etc.) can be such a template. Based on real measurements and medical investigations carried out on a certain patient, this template needs to be individualized by changing sizes and proportions. One of the modelling process stages is the skinning. It is highly important to ensure that the individualize model is accurate and corresponds to the specific patient. Thus, the proposed method of artifact compensation for dual quaternion skinning can be employed.

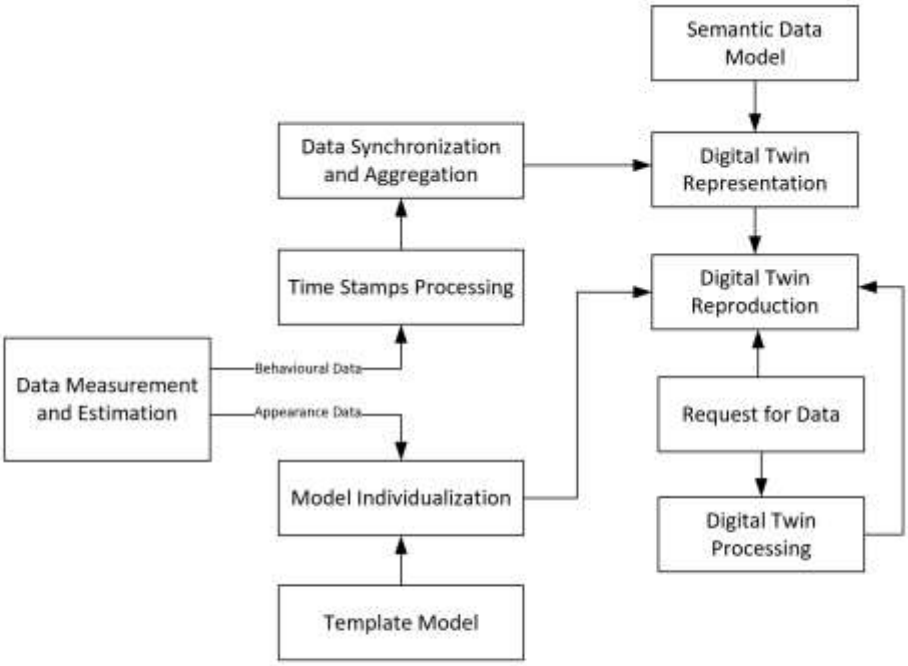

Fig. 10. An architecture of the digital twin technology for medicine and healthcare applications

Behavioural data includes multimodal parameters of the physical twin. This data can be obtained by means of a wide range of devices and tools. It is important that this data needs to be accompanied with temporal data (time stamps). These temporal data can be obtained either from the device used for measuring the data of a certain modality, or they can be added manually. The time stamps indicate moments when data of a certain modality is measured. These stamps enable data synchronization. When data is synchronized, it needs to be aggregated to represent the multi-image of the physical twin. Both the visual model and the multi-image represent the digital twin which is a subject of further processing depending on the requests for data retrieval and analysis.

Conclusions

The proposed method smoothly decreases the amount of bulging compensation in potentially problematic areas, to avoid creating artifacts due to its limited ability to model undesired deformations. These problematic areas include those affected by more than two bones, and joints, which are being bent and twisted simultaneously. A more advanced model of undesired deformation would allow to further reduce bulging in such areas. The proposed method was not designed to work with joint scaling, as dual quaternion skinning is not capable of handling non-rigid deformations. Additional research is needed to ensure the compatibility with the approach, proposed in [8] for handling non-rigid deformations.

The method presented in this paper can be used in many applications. The promising application area is 3D model creation and visualization for digital twin technology in medicine and healthcare. The architecture of such specific digital twin technology is proposed and discussed in this paper, as well.

References

1. Kim Y, Han J. Bulging ‐ free dual quaternion skinning, in Computer Animation and Virtual Worlds, 2014, Vol. 25 (No 3-4), pp. 323–331.

2. Binh Huy Le, Jessica K. Hodgins. Real-time skeletal skinning with optimized centers of rotation, in ACM Transactions on Graphics, 2016, Vol. 35(4), pp. 1–10.

3. Kavan L., Collins S., Žára J., O'Sullivan C. Geometric skinning with approximate dual quaternion blending, in ACM Transactions on Graphics, 2008, Vol. 27(4), pp. 1–23.

4. Kavan L., Collins S., Žára J., O'Sullivan C. Skinning with dual quaternions, in proceedings of the symposium on Interactive 3D graphics and games, 2007, pp. 39–46.

5. Kavan L., Collins S., O'Sullivan C., Zara J. Dual quaternions for rigid transformation blending, in Tech. Rep. TCD-CS-2006–46Trinity, College Dublin, 2006.

6. Wang X. C., Phillips C. Multi-weight enveloping: least-squares approximation techniques for skin animation, in proceedings of the ACM SIGGRAPH / Eurographics symposium on Computer animation, 2002, pp. 129–138.

7. Merry B., Marais P., Gain J. Animation space: A truly linear framework for character animation, in ACM Transactions on Graphics, 2006, Vol. 25(4), pp. 1400–1423.

8. Lee G. S., Lin A., Schiller M., Peters S., Mc Laughlin M., Hanner F., Studios WD. Enhanced dual quaternion skinning for production use, in SIGGRAPH Talks, 2013, pp. 1–9.

9. Kenwright B. A beginners guide to dual-quaternions, in Winter School of Computer Graphics 2012, Vol. 2.

10. Aidan Fuller, Zhong Fan, Charles Day, Digital Twin: Enabling Technology, Challenges and Open Research, in Computers and Society, 2016, arXiv: 1911.01276.

11. Michael Grieves, John Vickers. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems, in book Transdisciplinary Perspectives on Complex Systems, Springer, 2017, pp. 85–113.

12. Elisa Negria, Luca Fumagalli, Marco Macchi. A review of the roles of Digital Twin in CPS-based production systems, in Procedia Manufacturing, Vol. 11, 2017, pp. 939–948.

13. Digital twin for personalized therapies, Swiss Federal Laboratories for Materials Science and Technology, 2019.

14. Ivan Dychka, Yevgeniya Sulema, Iurii Bukhtiiarov. Digital Twin Information Technology for Biomedical Data Complex Representation and Processing. Visnyk of Kherson National Technical University, Vol. 3(70), 2019, pp. 112–119.

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