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SHAPE Algorithm for Approximate Computation of Angular Velocities in Humeral Motion

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Abstract—Estimating human motion is an area of emerging interest in instrumentation and measurement. Importantly, in such applications the physicality of the solution is paramount. Therefore, our paper proposes the SHAPE algorithm to estimate angular velocities of a moving segment from a cluster of passive markers used in a standard motion capture system known as stereophotogrammetry. We demonstrate the efficacy of our formulation with reference to the well known shape-matching algorithm in computer graphics. It is shown that our method is superior over the shape-matching algorithm.

I. INTRODUCTION

Current demands in automation is shifting drastically from industrial instrumentation and measurements towards domestic environments. With this change comes the challenge of monitoring human activity. In this regard, tracking human upper arm poses an estimation problem that is computationally daunting.

This computational complexity emerges from the inherent challenges in tracking the upper arm, mainly its complexity, variability, mathematical and practical aspects [1]. Although there is this need, finding a suitable framework is met with the high-reliability computational challenge [2]. Therefore, our paper proposes an algorithm to estimate the geometric parameters that underlies such movements in an everyday functional setting.

Presently, human movement is widely analysed based on stereophotogrammetry measurement system [3]. Note that, healthy human movement is inherently smooth, which can be parametrised by angular velocities [2]. Despite this possibility, to the best of our knowledge, there exists no known algorithms that can estimate the angular velocities from the marker cluster in stereophotogrammetry. Therefore, our paper presents an algorithm to estimate angular velocities from the marker cluster attached to the humeral segment. This is indeed challenging because of the soft tissue artefacts (STA) that accompany these measurements [1], [3].

This is a measurement problems that has received very little attention in the measurement society. There are

Figure 1: Figure illustrates the generalised motion of a continuum body which is an ensemble of particles. Note that, continuum motion allows the relative movement between particles.

some papers on how robots can use the method for multi-target tracking (see e.g. [4]), but these methods does not adress the STA problem directly. If the effects of the STA only is interpreted as a deformation of a non-rigid surface, there are image processing algorithms recover a 3D models of the deformation [5], [6]. However, these methods can not be used for reliable calculations of the angular velocity.

Mainly, the humeral segment is the positioned by the shoulder articulation – the joint with the largest number of unique movements in the human body. Let us explore the instantaneous kinematic problem.

II. GENERALISED INSTANTANEOUS KINEMATICS PROBLEM

A *continuum body* can be viewed as an ensemble of particles whose generalised instantaneous motion is known as the *Euler problem* (see Fig. 1). Theoretically, in order to reliably estimate or parametrize this motion of a continuum body, it is well known that infinite set of parameters are required. In order to make this higher dimensional problem tractable, the underlying movement can be approximated to rigid motion. Thereby, we assume that there is no relative motion between the particle

ensemble. In this case, the generalized velocity $\mathbf{v}_A$ of a particle on the body is given by,

$$\mathbf{v}_A = \mathbf{v}_O + \boldsymbol{\omega} \times \mathbf{r}_A. \quad (1)$$

Here, $\mathbf{v}_O$ refers to the instantaneous velocity of the origin of the body-fixed frame in the global frame, $\boldsymbol{\omega}$ denotes the angular velocity of the point A in the body-fixed frame and $\mathbf{r}_A$ denotes the position vector of this point in the body-fixed frame. Our paper adapts the SHAPE algorithm in molecular dynamics to the problem of estimating the angular velocity $\boldsymbol{\omega}$, which is presented below.

III. SHAPE ALGORITHM

As we have seen in (1), this formulation is only possible in the case of ideal rigid motion of particles. Recall that STA poses an important bottleneck in the case of parametrising humeral motion. This is problematic as existing algorithms to compute the angular velocity exactly such as in [2] are exact solutions, provided the rigidity constraints are taken care of. In reality, this rigidity constraint poses a hard computational problem.

In order to address this challenging problem, we use a well known technique in molecular dynamics known as SHAPE algorithm [7]. The choice of shape is motivated by two advantages inherent in the formulation. First, the angular velocity $\boldsymbol{\omega}$ is computed iteratively by relaxing the rigidity constraints. Second, the formulation is not based on Lagrangian approach which is computationally expensive [7]. When using Lagrangian-based approaches the like elastic models in [8]. After the optimization is performed the rigidity constraints have to be imposed explicitly and solved iteratively using algorithms like RATTLE [9].

Consider the position coordinate of the i th particle in the particle ensemble consisting of n particle cluster with respective fictitious mass m_i ; then, the center of mass (COM) of the cluster is

$$\mathbf{r}_{\text{COM}} = \frac{\sum_{i=1}^n \mathbf{r}_i m_i}{\sum_{i=1}^n m_i} \quad (2)$$

In order to choose m_i , we follow the recommendation in [6]. The angular velocity in (1) is computed using the coordinates of the i th particle with respect to the COM by

$$\mathbf{r}_i^b = \mathbf{r}_i - \mathbf{r}_{\text{COM}} \quad (3)$$

The fictitious angular momentum of the particle cluster computed at the COM is given by

$$\mathbf{L}^b = \sum_{i=1}^n \mathbf{r}_i^b \times m_i \mathbf{v}_i^b \quad (4)$$

Note that the velocity $\mathbf{v}_i^b$ is computed from (3) using a forward difference approximation. If $\mathbf{r}_i^b \in \{x_i, y_i, z_i\}$

are the body-fixed coordinates of the i th particle, then the moment of inertia of the marker cluster is given by

$$\mathbf{I}_b = \begin{bmatrix} \sum m_i(y_i^2 + z_i^2) & -\sum m_i x_i y_i & -\sum m_i x_i z_i \\ \sum -m_i y_i x_i & \sum m_i(x_i^2 + z_i^2) & -\sum m_i y_i z_i \\ \sum -m_i z_i x_i & \sum m_i z_i y_i & \sum m_i(x_i^2 + y_i^2) \end{bmatrix} \quad (5)$$

If δt is the data rate, by applying the law of conservation of angular momentum, the rigid angular velocity can be estimated by

$$\boldsymbol{\omega}_{\text{rigid}}^b(t + \delta t/2) = \mathbf{I}_b^{-1} \mathbf{L}_{\text{non}}(t + \delta t/2) \quad (6)$$

where $\mathbf{L}_{\text{non}}$ is computed using (4) and $\boldsymbol{\omega}_{\text{rigid}}^b$ is computed using (6) and The above equation is solved iteratively j times by computing the coordinates of the rigid body-fixed coordinates given by,

$$\mathbf{r}_{j,\text{rigid}}^b(t + \delta t) = \mathbf{R} \mathbf{r}_j^b \quad (7)$$

Here, the rotation matrix $\mathbf{R}$ is computed by the Rodrigues' formula

$$\mathbf{R} = \exp \boldsymbol{\omega}_{\text{rigid}}^b \delta t \quad (8)$$

Note that for very small values of $\boldsymbol{\omega}_{\text{rigid}}^b$, the above (8) is replaced by an equivalent Taylor series approximation [7]. The angular momentum in terms of rigid coordinates follows (4),

$$\mathbf{L}_{j,\text{rigid}}^b = \sum_{i=1}^n \mathbf{r}_{j,\text{rigid},i}^b \times m_i \mathbf{v}_{j,\text{rigid},i}^b \quad (9)$$

The convergence condition follows the weak form of the law of conservation of angular momentum of the particle cluster given by,

$$\|\mathbf{L}_{\text{non}}^b - \mathbf{L}_{j,\text{rigid}}^b\| < \epsilon \quad (10)$$

where, ϵ denotes a scalar positive tolerance. Note that, the approximation error of the angular velocity estimate is on the order of δt^2 . In this case this tolerance limit of ϵ can only be achieved by using eight humeral markers, and its convergence is dependent on the rate of deformation. The use of redundant marker points can boost the convergence and tolerance limit. Note that, in order to demonstrate the efficacy of our method we will compare the performance of our algorithm with shape-matching in computer graphics [6]. Shape-matching is a linear method to recompute rigid cartesian coordinates from deformable point cluster which is also non-lagrangian. Importantly, the simplicity of this algorithm is due to the linearity. From these recomputed rigid coordinates, the angular velocity is computed explicitly using the algorithm presented in [2].

Figure 2: Estimated angular velocity from SHAPE algorithm (solid) Shape-matching algorithm (dashed) during Vertical Abduction-Adduction task repeated six times by a male subject at a speed of 10 beats per minute (Age: 24, Weight: 69 kg, Height: 1.70 m).

Figure 3: Subject wearing the eight passive markers on the humeral segment (H1-H8).

IV. MEASUREMENTS AND EXPERIMENTS

Using a 17-camera OptiTrak Motive motion capture system and a metronome. A subject was wearing eight passive markers (see Fig. 3) and was asked to perform three sets of shoulder movements. These are 1) Vertical Abduction-Adduction, 2) Horizontal Abduction-Adduction and 3) Flexion-Extension-Hyperextension-Reverse hyperextension.

V. RESULTS

During the simplest of the humeral motion in Fig.2, it can be seen that, during the abduction motion the angular velocity is negative due to the left handedness of the angular velocity and reverses during adduction movement. Since, the effect of STA is known to be minimal in this case the performance of both the algorithms are comparable.

Similarly, when for the horizontal abduction-adduction movement in Fig. 4. Notably, the performance of the shape-matching algorithm deteriorates in comparison to SHAPE algorithm.

Contrastingly, as the movement becomes more complex as in the case of flexion-extension-hyperextension in Fig. 5 the shape-matching algorithm deteriorates. The superior performance of the SHAPE algorithm might be at the expense of redundant measurements due to use of eight humeral markers. Also, recall that the shape-matching algorithm compromises the physicality of the estimation by preserving the strict geometrical rigidity constraints. Importantly, the movement parameters can be interpreted based on the consistent features that constitute a movement of interest. As there will be unknown errors associated with movement kinematics and measurement [10]. The results presented here are preliminary. In fact, we have shown elsewhere that the SHAPE-algorithm performs consistently for different

Figure 4: Estimated angular velocity from SHAPE algorithm (solid) Shape-matching algorithm (dashed) during Horizontal Abduction-Adduction task repeated six times by a male subject at a speed of 10 beats per minute (Age: 24, Weight: 69 kg, Height: 1.70 m).

Figure 5: Estimated angular velocity from SHAPE algorithm (solid) Shape-matching algorithm (dashed) during Flexion-Extension-Hyperextension-Reverse Hyperextension task repeated six times by a male subject at a speed of 10 beats per minute (Age: 24, Weight: 69 kg , Height: 1.70 m).

class of movements at performed at different speeds [11]. The dataset evaluated here is at a very slow speed.

VI. CONCLUSION

In conclusion, we have demonstrated that, the SHAPE algorithm gives numerically stable estimates of the angular velocity over the shape-matching technique which deteriorates in the presence of large STA. Of course, this performance might be due to the redundant markers used in the first case.

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