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Magnetometer-free motion tracking of one-dimensional joints by exploiting kinematic constraints

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Abstract: Inertial measurement units play an important role in human motion tracking since they provide a more flexible, low cost alternative to optical motion capture systems. However, in indoor environments the inhomogeneous magnetic field makes conventional sensor fusion approaches inapplicable. In connected multi-body systems, kinematic constraints between the individual segments can be exploited to enable a magnetometer-free, long-term stable and real-time capable orientation estimation. In this paper, we introduce a method for systems with one-dimensional joints that can be applied to different joints in the human body like the knee, the humeroradial joint or the proximal/distal interphalangeal joints of the hand.

I. Introduction

In rehabilitation, Inertial Measurement Units (IMUs) are often used to analyze the motion of the human body. They provide a more flexible, low-cost alternative to other approaches like optical motion capture.

In general, IMUs consist of a 3D gyroscope measuring the angular velocity, a 3D accelerometer measuring the acceleration as well as a 3D magnetometer measuring the magnetic field strength. Based on these measurements, a sensor fusion algorithm estimates the orientation of the IMU with respect to a fixed reference frame. This approach is commonly called 9D sensor fusion.

In connected multi-body systems like the leg or arm, knowing the orientation of each segment with respect to a common reference frame allows the calculation of the relative orientations as well as of joint angles and positional relationships. However, in indoor environments the magnetic field is heavily disturbed [1]. This makes common 9D sensor fusion inapplicable. Without the magnetometer, the heading component of the orientation is unknown [2]. One approach is to use a 6D sensor fusion algorithm based only on the gyroscope and accelerometer as well as an initial known pose during which the orientations of the segments are known [3]. However, due to drift, this approach only yields accurate results for short-term experiments. We proposed several methods exploiting the limited degrees of freedom of one- and two-dimensional joints [4], as well as the limited range of motion of arbitrary joints [2] for correction of the heading component of the relative orientation. These methods differ from existing methods [6] [7], as they are only based on orientational constraints and do not require knowledge of positional relationships of the sensors with respect to the joint center.

In this paper, we introduce the method for one-dimensional joints and verify it experimentally with mechanical and physiological joints.

II. Method

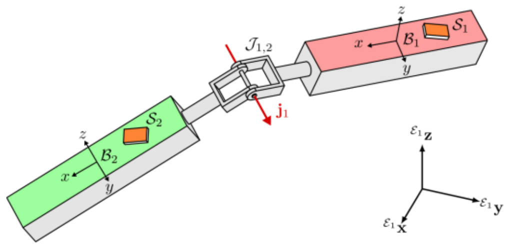

Figure 1: Mechanical model for a one-dimensional joint

Consider a system of two rigid bodies $\mathcal{B}_1$ and $\mathcal{B}_2$ connected by a one-dimensional joint with a known joint axis. On each body an IMU is attached, measuring the angular velocities $\boldsymbol{\omega}_1(t)$ and $\boldsymbol{\omega}_2(t)$ as well as the accelerations $\boldsymbol{a}_1(t)$, $\boldsymbol{a}_2(t)$. A 6D sensor fusion algorithm is used to estimate each body's orientation with respect to a reference frame. The orientations are represented by the quaternions ${}^{\mathcal{B}_1}_{\mathcal{E}_1}\mathbf{q}(t)$ and ${}^{\mathcal{B}_2}_{\mathcal{E}_2}\mathbf{q}(t)$ with the subscript denoting the frame of reference and the superscript denoting the frame of interest. Without magnetometers, the heading component of each orientation is unknown. This is modeled as if the orientations are estimated in the two reference frames $\mathcal{E}_1$ and $\mathcal{E}_2$. As only the heading is affected and the inclination can be correctly estimated by the accelerometer and gyroscope, the difference between $\mathcal{E}_1$ and $\mathcal{E}_2$ is only the rotation ${}^{\mathcal{E}_2}_{\mathcal{E}_1}\mathbf{q}(t,\delta)$ around the global vertical axis. The angle of this rotation is called *heading offset* and is denoted by $\delta(t)$ (see Fig. 2) [4]. Knowing this angle yields the relative orientation ${}^{\mathcal{B}_2}_{\mathcal{B}_1}\mathbf{q}(t)$ of the two bodies with

$$ {}^{\mathcal{B}_2}_{\mathcal{B}_1}\mathbf{q}(t) = {}^{\mathcal{B}_1}_{\mathcal{E}_1}\mathbf{q}(t)^{-1} \otimes {}^{\mathcal{E}_2}_{\mathcal{E}_1}\mathbf{q}(t,\delta) \otimes {}^{\mathcal{B}_2}_{\mathcal{E}_2}\mathbf{q}(t). \qquad (1) $$

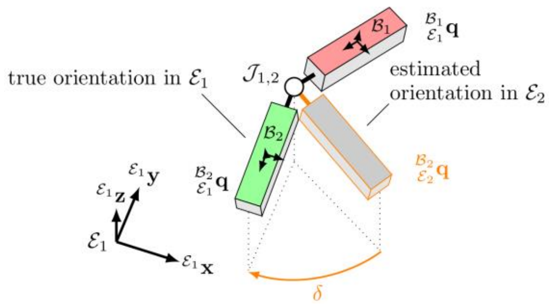

Figure 2: Heading offset of the orientation estimation of two connected bodies when using no magnetometer

The basic idea to estimate the value of $\delta(t)$ is that the relative orientation ${}^{\mathcal{B}_2}_{\mathcal{B}_1}\mathbf{q}(t)$ of a one-dimensional joint is limited to rotations around one well-defined joint axis. Following (1), the relative orientation can be formulated as a function of $\delta(t)$ with ${}^{\mathcal{B}_2}_{\mathcal{B}_1}\mathbf{q} = f(t,\delta)$. It is then possible to find an Euler angles decomposition of ${}^{\mathcal{B}_2}_{\mathcal{B}_1}\mathbf{q}(t,\delta)$ such that the first angle corresponds to the joint angle [4]. The angles of the decomposition are denoted by α, β and γ. Then the following constraint must hold true for all times:

$$ |\beta(t,\delta)| + |\gamma(t,\delta)| = 0 \quad \forall t \qquad (2) $$

The heading offset $\delta(t)$ is a slowly changing scalar value that can be estimated using a sliding window optimization method based on the constraint (2) [4] with the cost function

$$ e(\delta) = \sum_{k=1}^{N} \beta(t_k,\delta)^2 + \gamma(t_k,\delta)^2 , \qquad (3) $$

with t_k being the time instances in a window with N samples. Using this repeatedly for overlapping time windows yields an estimate $\hat{\delta}(t)$ for the heading offset.

III. Experimental validation

To validate the method experimentally, we employed two different experimental setups. We used a mechanical test object [2] with a perfect one-dimensional joint (see Fig. 3). For validation an optical motion capture system was used. At the beginning of each experiment, the orientation of each segment was unknown. In total, 7 experiments were performed with durations between 60 s and 600 s.

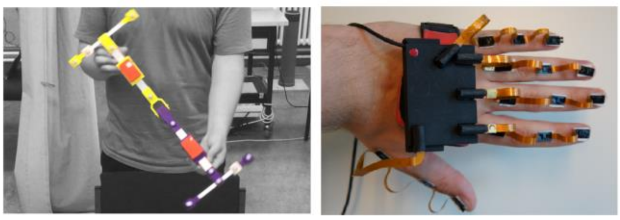

Figure 3: Experimental setups. Left: Mechanical test object. Right: Hand sensor system

To test the method on less-rigid biological joints, we used the hand sensor system from [3] (see Fig. 3) and estimated the relative orientations of the segments connected by the proximal (PIP) and distal interphalangeal joint (DIP). To test the long-term stability of the method, the experiments are longer than 400 s.

IV. Results

To benchmark the proposed method (KC), it is compared to the 9D sensor fusion method with magnetometers (9D) as well as the 6D sensor fusion method with initial heading correction (6D) [3]. The mean and maximum total angular errors between the true and estimated relative orientation are shown in Tab. 1. For both the mechanical and biological joints, the proposed method performs best. The maximum error is below 3° for mechanical and 6° for biological joints.

Table 1: Mean / Max errors for all experiments

	KC	6D	9D
Mechanical	**1.7° / 2.9°**	6.0° / 45.0°	3.5° / 9.1°
Biological	**2.0° / 5.9°**	18.6° / 60.2°	6.8° / 21.1°

V. Conclusions

The proposed constraint-based method can estimate the relative orientation of one-dimensional joints accurately without magnetometers and known initial orientations. It yields a long-term stable result and is independent of excitation or knowledge of positional relationships. In addition to precise mechanical joints, it has been shown that the method also works for approximate joints like the PIP and DIP joint of the human hand and can therefore overcome previous limitations in hand motion tracking for rehabilitation purposes. Future work will aim at a universal framework for magnetometer-free motion tracking in connected multi-body systems.

Acknowledgments

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