Proceedings on Automation in Medical Engineering
Proc AUTOMED, Vol 2, No 1 (2023): Article Ref 763
www.journals.infinite-science.de/automed/article/view/763

Infinite Science Publishing

Do we still need magnetometers for inertial motion tracking?

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Abstract: A growing number of applications rely on inertial sensors for unobtrusive motion tracking, while readily adopting openly available magnetometer-dependent methods for the estimation of inertial sensor orientations. Magnetic fields are usually heavily disturbed, which lead to multiple recent and great innovations in accurate magnetometer-free alternatives. In this survey, we propose a generic framework for magnetometer-free inertial motion tracking. Together with the proposed workflow, a clear outlook on future research directions is provided to accelerate the intended application impact of magnetometer-free inertial motion tracking.

I. Introduction

A broad and growing range of applications heavily relies on inertial motion tracking (IMT) for unobtrusive analysis of biological and mechanical kinematic chains of connected segments. To estimate all relative segment poses from inertial sensors, most applications readily adopt openly available sensor fusion methods, e.g., [2], for out-of-the-box inertial orientation estimation (IOE). Such methods typically rely on magnetometer data (9D IOE) for absolute heading information. However, even in highly controlled indoor environments, magnetic fields are usually disturbed, which makes their usage debatable [1].

Recently, multiple joint-specific approaches have successfully applied constraints [3-9] to replace magnetometer measurements. Despite their high accuracy over long durations, a large impact can only be achieved by combining the most recent advances for magnetometer-free inertial motion tracking (MF-IMT).

In this work we summarize the most recent advances in MF-IMT, together with their main assumptions, singularities, and error ranges. To further boost the application potential of MF-IMT, we propose a generic workflow (Fig. 1) that is enabled by learning, state-estimation, and model-based sensor fusion. Additionally, we provide clear directions of future work in MF-IMT.

II. Magnetometer-free motion tracking

We consider kinematic chains (Fig. 2) of arbitrary length and joint types, and assume rigid segments, known alignments, and calibrated sensors. We aim to estimate all segment-attached relative orientations from specific forces $\mathbf{f}$, angular velocities $\boldsymbol{\omega}$, and prior linkage knowledge. Orientations are expressed as unit quaternions $\boldsymbol{q}$ or equivalent rotation matrices R, where ${}^{\mathcal{S}}_{\mathcal{E}}q = {}^{\mathcal{S}}_{\mathcal{E}}R$ describes the rotation of a sensor frame $\mathcal{S}$ with respect to an inertial reference frame $\mathcal{E}$. In the following, we review the latest advances in inclination estimation (Section II.I) and constraint-based heading tracking (Section II.II).

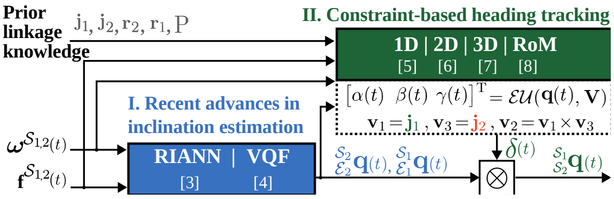

Figure 1: Proposed generic workflow. MF-IMT requires combining highly accurate and reliable inclination estimation and constraint-based heading tracking.

II.I Recent advances in inclination estimation

Although IOE has been studied for many decades, recent advances show remarkable improvements in inclination accuracy. With typical inclination (6D IOE) errors ranging from 2.4° to 6.3° [4], RIANN [3] obtained out-of-the-box average inclination errors of 1.3°, by implementing domain-specific advances, while showing generalization of its trained recuring neural network across unseen sensors and application contexts. Furthermore, with VQF [4], a novel inclination filtering approach was recently proposed that effectively compensates for instantaneous accelerations and decelerations, and further decreased average inclination errors to 0.9° on a challenging IOE benchmark datset [4].

II.II Constraint-based heading tracking

Given the recent advances in inclination estimation, the problem of tracking all relative sensor orientations in a kinematic chain is reduced to the tracking of the scalar relative heading offset δ (Fig. 1, Fig. 2). Recent methods show high tracking accuracies [5-8] by replacing missing heading information from magnetometer readings with prior linkage knowledge. Table 1 summarizes the joint-specific assumptions, singularities, and error ranges.

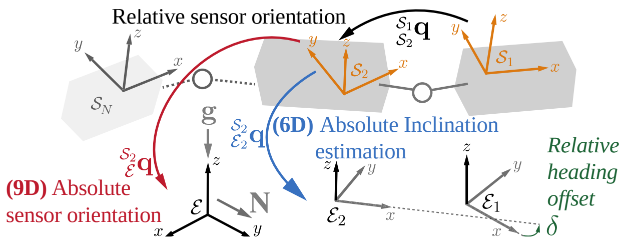

*Figure 2: Reference frames: Inertial reference frame $\mathcal{E}$: (**N**)North-bound (y) and upward (x) gravity $\boldsymbol{g}$.; almost inertial reference frame [4] $\mathcal{E}_{1,2}$, slowly drifting about the vertical.*

III. A generic MF-IMT workflow

In Fig 1., we present a generic MF-IMT workflow which combines the aforementioned advances (Section II.I) in inclination estimation, from measured specific forces **f**, and angular velocities $\boldsymbol{\omega}$ [3-4], with (Section II.II) constraint-based heading tracking, to generate observations of the relative heading offset δ, after Euler decomposition $\mathcal{EU}$ of the relative orientations (Fig. 2), about either:

- joint axes $\boldsymbol{j}_1/\boldsymbol{j}_2$ [5-6],
- by tracking a common connection point with position vectors $\boldsymbol{r}_1, \boldsymbol{r}_2$ [7],
- or by defining a set of permissible relative orientations P [8].

Note that if magnetometers cannot be avoided, we advise to make use of advanced magnetometer disturbance detection techniques [4], that are extensively validated on benchmark datasets for inertial orientation estimation.

IV. Conclusions and outlook

To conclude, if sufficient prior linkage knowledge can be acquired, constraint-based heading tracking should be considered and will generally outperform 9D-magnetometer aided IOE methods (Table 1). With the presented summary and generic workflow we propose to combine the most recent innovations to further accelerate the intended application potential of magnetometer-free motion tracking in diverse kinematic chains.

In practice, violations of the summarized assumptions and moments of unobservability due to singularities, may occur and sometimes reduce the tracking accuracy. To make MF-IMT wider applicable, and even in such edge case scenarios, we identified the following three promising directions of future work: (a) A *consolidation of existing constraints in MF-IMT* to complement strengths and overcome some of the presented singularities. (b) For *joints that do not completely satisfy mechanical joint setups* (Table 1. Assumptions), e.g., biological joints, we highly encourage the identification of novel kinematic constraints that better match true joint behavior by, e.g., incorporating coupling dynamics between joint axes that are typically defined to be static. (c) Investigate promising IOE approaches, e.g., [9] that aim *at propagating heading information in kinematic chains* from only sparse sources of heading information.

Author's statement

The authors state no conflict of interest.

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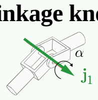
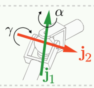
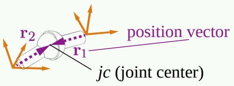
		RMSE:	6D IOE	9D IOE
II. Constraint-based heading tracking		Conventional **9D** IOE, e.g., [2]		**5.3°-16.7°** [4]
	I. Recent advances in inclination estimation	*VQF* **9D** IOE [4]	-	**2.4°** [4]
		RIANN **6D** IOE [3]	**1.3°** [4]	-
		VQF **6D** IOE [4]	**0.9°** [4]	-
Prior linkage knowledge	**Assumptions**	**Singularity**		
1D [5] 	$\lvert\beta(\delta)\rvert + \lvert\gamma(\delta)\rvert = 0$	$\mathrm{j}_1 \cdot \mathbf{g} = 1$	**1.7°** [5]	
2D [6] 	$\beta(\delta) - \beta_0 = 0$	$\mathrm{j}_1 \cdot \mathbf{g} = 1,$ $\mathrm{j}_2 \cdot \mathbf{g} = 1$	**<10.0°** [6]	
3D [7] 	$^{S_1}_{\mathcal{E}}R(t)\mathbf{f}^{S_1}_{jc}(t) - {}^{S_2}_{\mathcal{E}}R(t)\mathbf{f}^{S_2}_{jc}(t) = 0$ with $\mathbf{f}^{S_i}_{\mathrm{jc}}(t) = \mathbf{f}(t)^{S_i} - ([\boldsymbol{\omega}^{S_i}(t)\times]^2 + [\dot{\boldsymbol{\omega}}^{S_i}(t)\times])\mathbf{r}^{S_i}_i$	If the specific force of the joint centre and its derivative are linearly dependent [7]	**<2.6°** [7]	
RoM [8] 	$\begin{cases} 0, & \text{if } {}^{S_1}_{S_2}\mathbf{q}(\delta) \in \mathrm{P} \\ 1, & \text{otherwise,} \end{cases}$ $\alpha \in [\text{range}], \beta \in [\text{range}], \gamma \in [\text{range}],$	Model-reality RoM mismatch	**<4.0°** [8]	

Table 1: Combining recent advances in 6D IOE and constraint-based heading tracking promises the highest IOE accuracy.