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Minimization of the positional errors for an accurate determination of the kinematic parameters of a rigid-body system with miniature inertial sensors

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ABSTRACT

This paper presents an approach to minimize and control the error of the kinematic parameters of the space-constraint rigid-body system by using inertial micro-electro-mechanical sensors (MEMS). We analyze the error propagation when the kinematic joint constraints are observed for a sensor-fusion update in the kinematic model because of the uncertain position of the inertial sensors. The minimization of the errors of the kinematic parameters comes from applying multiple inertial units on every rigid body with the controlled input positional error between each inertial unit. The analytical approach proposes the inclusion of the position vectors from the inertial units to the kinematical joints into the state vector that consists of the observed kinematical and sensor parameters. A Kalman-filtering procedure is used to observe the state vector and, additionally, the adaptive estimation of the position vectors from the inertial units to the kinematic joints or constraints is presented in order to achieve the optimum performance of the filter. The analytical approach is experimentally validated on a pendulum mechanism, where the improved performance of the proposed approach is confirmed.

1. Introduction

Control over the kinematics of a rigid-body system, such as an industrial mechanism, is essential in engineering practice. On the one hand, the kinematic parameters of the observed system can be analytically defined, but this procedure might be time consuming because of the complexity of the system, and furthermore, obtaining information about the exact external forces over time is usually not straightforward if the system is not kinematically driven. On the other hand, the experimental observation and control of the kinematic parameters are strongly competitive approaches, especially if the parameters must be observed or controlled at a later stage. These experimental procedures are possible with inertial MEMS sensors, which in the past decade have begun to offer an alternative to traditional inertial sensors, or other appropriate devices, such as encoders and optical systems. The advantages of MEMS are a small weight and size and an attractive price, while their disadvantages relate to their long-term stability and accuracy, which become crucial during an integration procedure over time.

To control the long-term precision of experimentally defined kinematic parameters researchers have used aiding systems to update the inertial parameters. The fusion of different systems largely depends on the observed application. In the field of biomechanics Roetenberg [1,2] and Schepers [3,4] presented extensive research on combining the magnetic and inertial principles for an orientation determination of the human body. In industrial environments the use of the magnetic principle might be critical because of the interference with local magnetic fields or because of the ferromagnetic materials of the mechanisms, despite the proposed calibration

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procedures. Furthermore, the use of the magnetic and inertial principles shows reduced precision when the human body is exposed to increased translational and rotational accelerations because of the loosely-coupled constraints between the parts of the human body and the environment, as was shown by Brodie [5]. Therefore, other aiding systems were combined, such as a satellite signal [5,6], like in car navigation [7]. Also, in the field of biomechanics and entertainment the inertial principle is combined with an optical system [8,9], especially for an orientation determination, and with the UWB-RF system [10] for positioning purposes. However, the disadvantage of these aiding systems is more expensive hardware in comparison to the inertial MEMS sensors, the possibility of their installation in mechanisms in a robust industrial environment and the inaccessibility of the aiding signal. Therefore, the correction of the inertial principle in the case of a rigid-body mechanism should primarily rely on the constraints in the kinematic joints as much as possible.

A more specific approach to the observation of the kinematic parameters of the mechanisms was presented by Wagner [11]. He observed the independent degrees of freedom of the mechanism with the inertial principle and then corrected the calculated positions of the bodies and the inertial parameters with aiding radar units. However, his approach still requires more detailed knowledge of the observed kinematics and is therefore time consuming. Cheng [12] made a survey of the approaches to measuring the relative angles between coupled rigid bodies on a human body and a robotic mechanism using only inertial sensors. The observed methods differ in the type of inertial sensors used, in their number and in their layout on every body. Besides the lack of accuracy when using gyroscopes over a long period of time, Cheng highlighted the reduced angular accuracy due to the uncertain positioning of the accelerometers, which is problematic during fast rotations. He confirmed, on a simple mechanism, that the best solution is obtained when two accelerometers with a known distance and without any gyroscopes on each rigid body are used. However, in order to observe the position and velocity conditions the relations between the rigid bodies of the observed system must again be known in detail.

The observation of the kinematic parameters of the rigid-body system using inertial MEMS sensors is therefore challenged by the use of the appropriate aiding systems or kinematic constraints and by the precise positioning of the inertial units. The following research, in contrast to [1–11], focuses on the rigid-body mechanism problem, where only kinematic constraints are available for the long-term control of the kinematic and inertial parameters. Furthermore, in contrast to [11] and [12] we propose a general approach to the simultaneous characterization of the kinematic parameters with no need to inspect the independent and dependent degrees of freedom using a Kalman-filter formulation. Consequently, the expected uncertain estimation of the position vectors from the inertial units to the kinematic joints in everyday engineering practice might cause inaccuracy or the divergent behavior of the filter. Therefore, we present a solution by applying multiple inertial units on each rigid body with controlled positional errors between each other, which is based on the deduction of the error-propagation analysis in kinematic joints.

In the following Section 2 the inertial positioning is overviewed. The error propagation of the kinematic-constraints update is investigated and the conclusion for the use of the multiple inertial unit on each rigid body is presented. Section 3 presents a general formulation of the state and observation vector for a rigid-body system in a Kalman filter with the included adaptive estimation of the position vectors from the inertial units to the kinematic joints for optimum filter performance. Finally, in Section 4 the experimental validation is presented on a two-body pendulum mechanism to confirm the improved accuracy of the kinematic parameters.

2. Error-propagation analysis of the observation constraints in kinematic joints

2.1. Inertial positioning overview

The position $\boldsymbol{r}^i$, velocity $\boldsymbol{v}^i$ and the orientation $\boldsymbol{q}^i$ at an arbitrary point O^i on the ith-body, expressed in the reference frame $x^n y^n z^n$ as shown in Fig. 1, are, in discrete form, calculated from the raw acceleration $\bar{\boldsymbol{a}}^{s,i}$, the raw angular rate $\bar{\boldsymbol{\varpi}}^{s,i}$, the accelerometer bias $\boldsymbol{b}_a^i$ and the gyroscope bias $\boldsymbol{b}_\omega^i$, expressed in the ith-frame, as:

$$\boldsymbol{r}_{k+1}^i = \boldsymbol{r}_k^i + \boldsymbol{v}_k^i \Delta t, \tag{1}$$

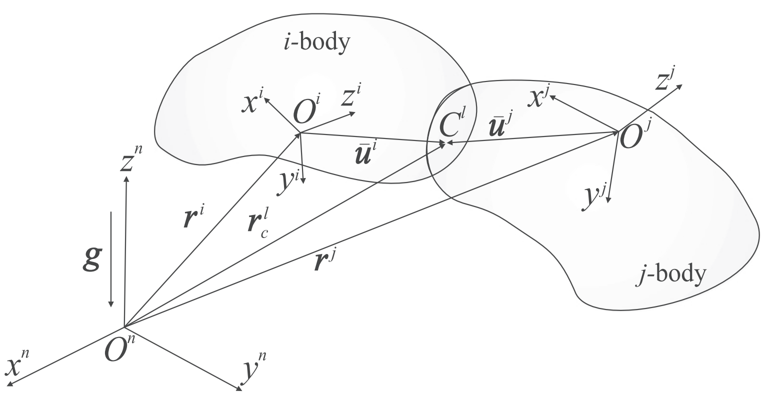

Fig. 1. Observation of the arbitrary kinematic constraint with one inertial unit on each rigid body.