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Posture and body acceleration tracking by inertial and magnetic sensing: Application in behavioral analysis of free-ranging animals

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ABSTRACT

This paper concerns body attitude (orientation) estimation for free ranging animal. The main idea of the proposed approach combines a quaternion-based nonlinear observer with an Iterated Least Squares Algorithm (ILSA) and exploits measurements from Micro-Electro-Mechanical-System (MEMS) sensors as 3-axis accelerometer, 3-axis magnetometer and 3-axis gyroscope to produce attitude estimates during the entire range of the observed animal's body movements. Moreover, the proposed observer allows estimating the bias in gyroscope which is used to correct the angular velocity measurements in the attitude estimation step. Since, biologists use an index of DBA for evaluating the energy consumption of the moving animal; the resulting estimations are then used to extract the Dynamic Body Acceleration (DBA) of the animal. Note that, this work is necessary in Bio-logging science and allows monitoring aspects of animal's biology (behavior, movement, and physiology) and environments. The performance of the algorithm is theoretically proven and illustrated by an attitude estimation example. Moreover, the efficiency of the proposed approach is shown with a set of experiments through sensor measurements provided by an Inertial Measurement Unit (IMU). We have also included some comparison results with another method already applied in Bio-logging field in order to point out the improvements issued from the proposed approach.

1. Introduction

The rigid-body attitude and orientation estimation problems are highly motivated from various applications. For example, in rehabilitation and biomedical engineering [1–4], the attitude is used in stroke rehabilitation exercises to record patient's movements in order to provide adequate feedback for the therapist. In human motion tracking and biomechanics [5,6], the attitude serves as a tool for physicians to perform long-term monitoring of the patients and to study human movements during everyday activities. Moreover, the attitude estimation is extensively used in tracking of handheld microsurgical instrument [7].

Recently, the problem of attitude and orientation tracking has been treated in another scientific field: the Bio-logging. This latter is at the intersection of animal behavior and bioengineering and aims at obtaining new information on the natural world and providing new insights into the hidden lives of animal's species [8,9]. Bio-logging generally involves a free-ranging animal-attached device that records aspects of the animal's biology (behavior, movement, and physiology) [10,11] and its environment. Thirty years ago, several tagging technologies such as satellite tracking (the Argos system) [12] and Time-Depth-Recorders (TDRs) [13] have been used to provide a basic knowledge on the function of free-ranging organisms. The recent advances in electronic miniaturization and digital information processing allowed researchers studying animal's biology with a high level of detail and across the full range of ecological scales.

The posture and orientation tracking of free-ranging animal represents one of the recent animal's biology aspects studied in Bio-logging. Indeed, some researches started to focus on this topic using low-cost sensors based on Micro-Electro-Mechanical-System (MEMS) technology as 3-axis accelerometer and 3-axis magnetometer. The main idea is how it is possible to extract the gravity components of the body animal. This information is exploited after to deduce the corresponding posture (attitude) and consequently the Dynamic Body Acceleration (DBA).

The authors assumed in [14] that the gravity measurements can be obtained from the running mean over a 1 s interval of the total acceleration, from accelerometer, during the motion of the animal.

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Then, the attitude is estimated using the obtained gravity components and magnetometer's measurements. In a second step, on the basis on the difference between accelerometer's measurements and gravity's components, the DBA is extracted. Nevertheless, in our opinion, this approximation is not valid over time since it depends on other parameters as the animal's species and their movement's types.

In [15], a low-pass filter is used to extract the gravity's components (the lowest frequencies of the natural panel of animal's movements) from the acceleration readings. Based on this information, the authors can deduce the attitude. Note that, the use of this type of filter introduces, in many cases, an error about the attitude information since the gravity measurements are not accurately extracted by the filter. After that, a high-pass filter is used to extract the DBA of the animal since it represents the highest frequencies movements. The main idea in [16,17] is based on the use of Iterated Least Squares Algorithm that combines measurements from accelerometer and magnetometer to estimate the attitude. In these works, the authors assume that the animal does not move at a large fraction of gravity (static and quasi-static situations of free-ranging animals) which leads to consider that accelerometer's readings measure only the earth's gravity. The DBA estimation is not addressed in this paper. Other works as [18] use simply some formulas existing in the navigation literature to deduce the attitude based on accelerometer and magnetometer measurements. The same assumptions of the work in [16,17], are considered also in [18].

To circumvent these problems, we propose in this paper the addition of 3-axis gyroscope measurements to the sensors already used. The use of gyroscope measurements in Bio-logging has never been done before in our knowledge. In fact, the previous works in this area are based only on 3-axis accelerometer and 3-axis magnetometer. Moreover, regarding other applications as aerial and marine vehicles, one can note that the application considered here (Bio-logging) is constrained by the lack of GPS data. The main guideline in this paper is to use a nonlinear observer that exploits MEMS sensors readings from the nine sensor channels cited above. The orientation reconstruction is based on an iterative procedure where the raw sensor data are combined with a previous estimate of the orientation to compute an update for the estimated orientation [19]. The proposed approach combines a strap-down system, based on the integral of the angular velocity, with an Iterated Least Squares Algorithm (ILSA) that uses Earth's magnetic field and gravity vector to calculate attitude measurements. These latter are then used to compensate those predicted by the gyroscope. Thanks to the knowledge of the estimated attitude, it is possible to reconstitute the DBA of the animal in order to evaluate its locomotor activities and daily diary [14] (sleeping, walking/flying, running, and hunting). Such information on the DBA is a major objective in a Bio-logging approach and provides important insights into some of the stresses faced by free-ranging animals especially the one studied in this work: the king penguin.

The paper is organized as follows: Section 2 presents the problem statement related the Bio-logging concept. Section 3 describes the rigid body attitude and its kinematical model. Section 4 gives some details about the used sensors in this paper. The attitude nonlinear observer design and its stability conditions are depicted in Section 5. Section 6 is devoted to simulation results that illustrate the efficiency of the observer. Section 7 is dedicated to a set of experiments and finally some conclusions are given in Section 8.

2. Problem statement

The concept of Bio-logging refers to the use of autonomous electronic devices to monitor something related to free-ranging animal itself and then to study its behavior, physiology and ecology. The king penguin is one of the major model of diving birds studied in Strasbourg University thanks to the Bio-logging technology [10,11]. Then, knowing in details its foraging activities and understanding its energetic strategy need the development of new Bio-loggers. This generation of logger mainly contains 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer. The king penguin will be equipped with this kinematical logger (see Fig. 1). The prototype will then collect and store the sensor's data until the animal (king penguin) returns to a place where the tag can be recovered. After that all calculations are performed offline by extracting the measurements recorded on the memory card using a computer. Before deploying this new logger, the goal in this paper is to be able to convert this complex set of row data in relevant information: attitude and energy expenditure (DBA). The algorithms that will exploit the measurements from 3-axis accelerometer, 3-axis magnetometer and 3-axis gyroscope are the main concerns of this work.

3. Rigid body attitude description

There is one major question to be considered when designing an algorithm for rigid-body rotations that is what representation to use? In this study we will use quaternion representation due to its simplicity.

3.1. Coordinate systems of a rigid body

The attitude estimation problem of rigid-body requires the transformation of measured and computed quantities between various frames. The attitude of a rigid-body is based on measurements from sensors attached to a rigid-body (the animal in our case (see Fig. 1(a))). Since the measurements are performed in the body frame, we describe in Fig. 1(b) the orientation of the body frame F_B (x_B,y_B,z_B) with respect to the navigation frame F_I (x_I,y_I,z_I) (attached to the earth: North, East, Down).

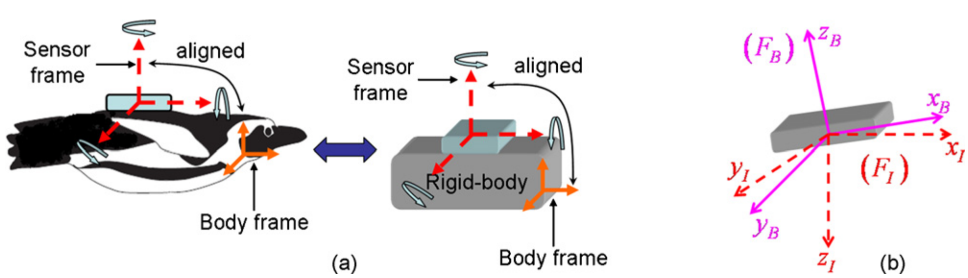

Fig. 1. (a) The schematic diagram of an electronic device (logger) attached to a king penguin. (b) The coordinate systems of a rigid body.