Quaternion estimation in rigid bodies motions using a triad of inertial and magnetic sensors with application in marine animals

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H. Fourati[1,2], N. Manamanni[1*], L. Afilal[1], Y. Handrich[2]

Abstract—**This paper addresses the problem of rigid body orientation tracking. A nonlinear filter with a complementary structure design is proposed for attitude estimation using inertial/magnetic sensors. The approach developed here is applied in Bio-logging, an interdisciplinary research area at the intersection of animal behavior and bioengineering.**

We propose a state estimation algorithm that combines three complementary data obtained from a 3-axis accelerometer, a 3-axis magnetometer and a 3-axis gyroscope in order to provide the best attitude. The proposed approach combines a quaternion based nonlinear filter with the Levenberg Marquardt Algorithm (LMA). The efficiency of the proposed approach is illustrated with a set of experiments performed on robot.

I. Introduction

Accurate tracking of rigid body attitude or orientation is a requirement for several applications such as mobile robots, Micro Air Vehicles (M.A.V), virtual reality, rehabilitation, and Bio-logging.

Bio-logging is at the intersection of animal behavior and bioengineering, and aims to obtain new information on the natural world and provides new insights into the hidden lives of animal species [1]. Bio-logging generally involves attaching a device to a free-ranging animal in order to record different aspects of the animal's biology (3D movement, behavior, physiology and energy expenditure) and of its environment. In this paper, the goal is to present an alternative method for body motion estimation (body attitude and orientation) which is suitable for use in marine mammals or birds. Marine animals are particularly difficult to study during their long foraging trips at sea. However, their need to return periodically to their breeding colony, gives us the opportunity to measure these different parameters with the use of bio-logger devices, fixed externally or internally [2], [3]. During the last 20 years, a considerable number of studies have been undertaken to describe the diving behavior of these predators, using a pressure sensor sampled at less than 2Hz [4]. The use of inertial or magnetic sensors is relatively recent, due to the difficulty of developing miniaturized technologies adapted to high rate record sampling (over 12-50 Hz [5]). The obvious advantage of this new approach is that we gain access to the third space dimension, which is the key to a good understanding of the diving strategies observed in these predators [6], [7]. The principle used to track the animal's posture estimates in the afore-mentioned studies consists of using a 3-axis accelerometer and a 3-axis magnetometer, with the reductive assumption that all the movements are static or quasi-static. This assumption made, we can consider that the accelerometer's readings correspond to the earth's gravity measurements in body coordinates, and it therefore becomes possible to estimate the attitude by the resolution of well known Wahba's problem [6]. However, the assumption made above is not valid in all the dynamic situations observed underwater in free-ranging animals, e.g. the phases of prey pursuit, and the performance of the attitude estimation is presumably significantly degraded. In [8], the authors assume that the running mean over a one second interval of total acceleration time is a good estimator of the gravity vector projection. However, this approximation is not valid over time and depends on other parameters such as the animal species and the type of movement it makes.

In this paper we propose the addition of a 3-axis gyroscope measurements to the sensors already used (accelerometer and magnetometer) [9], [10] in order to circumvent these problems. Indeed, the estimation of attitude and heading using fusion technologies with low-cost sensors such as gyroscopes, accelerometers and magnetometers has already been used in other fields. Micro Air Vehicles [11-13], rehabilitation [14] and walking robots [15] are examples using a linear complementary filter, an Extended Kalman Filter (E.K.F) or a nonlinear observer.

This paper proposes an alternative approach in the Bio-logging field; namely the estimation of attitude in free-ranging animals during movement. The main guideline is to use a complementary nonlinear filter based on measurements from a 3-axis gyroscope, 3-axis magnetometer and 3-axis accelerometer. The proposed approach combines a strap-down system, based on the time integral of the angular velocity, with a Levenberg Marquardt (LMA) that uses Earth's magnetic field and gravity vector to calculate attitude measurements. Moreover, we will show how the measurements provided by the sensors can be used in the filter design. The main advantage of this contribution is that only kinematic equation is required, meaning that no knowledge of the animal motion model is needed for the proposed algorithm.

This paper is organized as follows: Section II presents the

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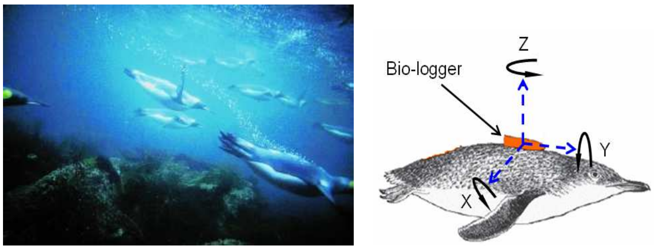
problem formulation. The bio-logging application is described, followed by details of the prototype design, the rigid body attitude parameterization, the frames used in the proposed approach, the rigid body kinematic model and finally, the sensor measurement models. Section III details the structure of the nonlinear attitude filter. Sections IV is devoted to experimental results performed on robot to illustrate the proposed filter's performances. Finally, section V summarizes the main conclusions of the paper.

II. Materials and Methods

A. General ideas on Bio-Logging application

The main theme of this study is the development of methods for movement pattern estimation in rigid bodies (attitude or orientation) for application in the bio-logging domain. This project stems from our biologist colleagues' need for a new generation of bio-logging devices (*logger*) which is able to estimate these movement patterns with an improved accuracy, or which can estimate these movement patterns with accuracy whether the activity deployed is phasic or quasi-static in their animal model. The one considered in this study is the king penguin (see Fig. 1(a)). This specie is studied in our laboratory for over 20 years. This particular need is motivated by the biologists' need to calculate body motion then remove the gravity component in order to calculate the Dynamic Body Acceleration (DBA). This DBA is apparently a good indicator of mechanical work in a moving animal, and is positively correlated with the animal's energy expenditure [8], [16], [17].



(a) (b)

Fig. 1. (a) King penguin during its dive – (b) Schematic diagram of how the bio-logger is attached to a penguin

To achieve this goal, an electronic device will be developed and equipped with a kinematic sensing unit (3-axis accelerometer, 3-axis magnetometer, and 3-axis gyroscope), temperature sensor, pressure sensor, data acquisition unit and power unit. In the case of a penguin model, the bird is caught in its breeding colony and the bio-logger is attached to the body as indicated in Fig. 1(b) (near to the gravity center). When the bird's return from a foraging trip at sea, the system is recovered and all the recorded measurements are downloaded. This bio-logger shall comprise: 1) kinematics sensing unit composed of a 3-axis accelerometer, a 3-axis magnetometer, and a 3-axis gyroscope; 2) pressure sensor; 3) temperature sensor; 4) data acquisition unit; 5) power unit; 6) flash memory. The first prototype of the bio-logger is under conception and still not ready to be deployed on penguin (see Fig. 2). Before deploying the new logger, the goal in this paper is to be able to convert the raw data (acceleration, angular rate and earth's magnetic field) into relevant information about the rigid body 3-D attitude. The algorithm that will exploit the measurements from this prototype is the main concerns of this work.

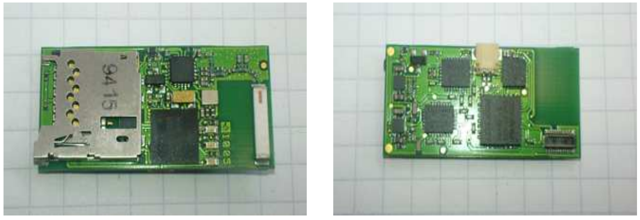


Fig. 2. Exploded view of the overall assembly

B. Attitude representation using unit quaternion

In the navigation field, the attitude estimation problem generally requires the transformation of measured and computed quantities between various frames. The attitude of a rigid body is based on measurements gained from sensors attached to it. Indeed, inertial sensors (accelerometer, gyroscope, etc…) are attached to the body-platform and provide inertial measurements expressed relative to the instrument axes. In most systems, the instrument axes are nominally aligned with the body-platform axes. Since the measurements are performed in the body frame, we describe in Fig. 3 the orientation of the body-fixed frame $B(X_B, Y_B, Z_B)$ with respect to the Earth-fixed frame $N(X_N, Y_N, Z_N)$ which is tangent to the Earth's surface (Local Tangent Plane, LTP). This local coordinate is particularly useful to express the attitude of a moving rigid body on the surface of the earth [18]. The X_N -axis points true north. The Z_N -axis points towards the interior of the Earth, perpendicular to the reference ellipsoid. The Y_N -axis completes the right-handed coordinate system, pointing east (NED: North, East, Down).

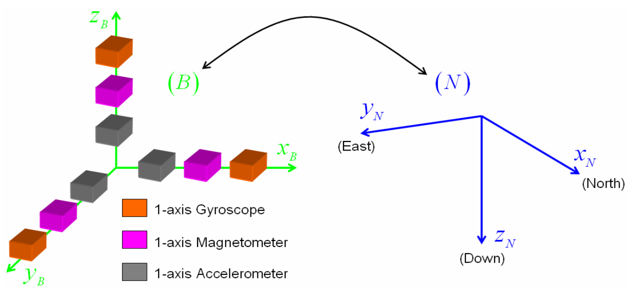


Fig. 3. The body frame (B), the Earth's fixed frame (N) and the configuration of the sensors

In this paper, we consider the unit quaternion as the mathematical representation of the rigid body attitude between the used frames. The unit quaternion, denoted by q, is a hyper-complex number of rank 4 such that:

$$q = q_0 + q_1 i + q_2 j + q_3 k = \begin{bmatrix} \cos\frac{\phi}{2} & \vec{u}\sin\frac{\phi}{2} \end{bmatrix}^T = \begin{bmatrix} q_0 \\ q_{vect} \end{bmatrix} \quad (1)$$

where q_0, q_1, q_2 and q_3 are real numbers, i, j, and k represent the components of the vector $\vec{u}$ (Euler axis), ϕ is the rotation angle and $q_{vect} = \begin{bmatrix} q_1 & q_2 & q_3 \end{bmatrix}^T \in \Re^3$ is the imaginary vector. A more detailed description of quaternion algebra can be found in [19].

C. Rigid body kinematic model

The kinematic equation, in terms of the unit quaternion describing the relation between the rigid body attitude variation and the angular velocity was given in [20] as follows:

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q}_{vect} \end{bmatrix} = \frac{1}{2} q \otimes \omega \quad (2)$$

where $\omega = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T$ denotes the angular velocity vector of the rigid body measured by the gyroscope in the Earth-fixed frame.

D. Sensor measurement models

The sensor configuration consists of a 3-axis gyroscope, 3-axis accelerometer and 3-axis magnetometer containing MEMS technologies. A detailed study of these sensors is given in [21].

1) Accelerometers: The 3-axis accelerometer measures the specific force f in the body frame B as follows:

$$f = \begin{bmatrix} f_x & f_y & f_z \end{bmatrix}^T = M_N^B(q) v + \delta_f \quad (3)$$

with $v = [a + g]$, $g = [0 \quad 0 \quad 9.81]^T$ and $a \in \Re^3$ represent the gravity vector and Dynamic Body Acceleration (DBA) respectively. a and g are expressed in the Earth-fixed frame N. $\delta_f \in \Re^3$ is assumed to be uncorrelated zero-mean white Gaussian noise. The rotation matrix $M_N^B(q)$ is expressed as:

$$M_N^B(q) = \begin{bmatrix} 2(q_0^2 + q_1^2) - 1 & 2(q_1 q_2 + q_0 q_3) & 2(q_1 q_3 - q_0 q_2) \\ 2(q_1 q_2 - q_0 q_3) & 2(q_0^2 + q_2^2) - 1 & 2(q_0 q_1 + q_2 q_3) \\ 2(q_0 q_2 + q_1 q_3) & 2(q_2 q_3 - q_0 q_1) & 2(q_0^2 + q_3^2) - 1 \end{bmatrix} \quad (4)$$

2) Gyroscopes: The 3-axis gyroscope measures the angular velocity ω_G in the body frame B as follows:

$$\omega_G = \begin{bmatrix} \omega_{Gx} & \omega_{Gy} & \omega_{Gz} \end{bmatrix}^T = \omega + \Delta_G \quad (5)$$

where $\Delta_G \in \Re^3$ is assumed to be a sum of bias and noise.

3) Magnetometers: The 3-axis magnetometer measures the direction of the earth's magnetic field in the body frame B as follows:

$$h = \begin{bmatrix} h_x & h_y & h_z \end{bmatrix}^T = M_N^B(q) m + \delta_h \quad (6)$$

where

$$m = \begin{bmatrix} m_x & 0 & m_z \end{bmatrix}^T = \begin{bmatrix} 0.5\cos(60°) & 0 & 0.5\sin(60°) \end{bmatrix}^T \quad (7)$$

represents the magnetic field measured in the fixed inertial coordinate system N. The theoretical model of the magnetic field nearest to reality considers a magnetic field vector with an inclination angle $\theta = 60°$ and norm vector $\|m\| = 0.5$ Gauss [22]. $\delta_h \in \Re^3$ is an uncorrelated zero-mean white Gaussian noise.

III. FILTER DESIGN FOR ATTITUDE ESTIMATION

In this paper, the objective is to design a rigid body attitude estimation algorithm based on inertial and magnetic MEMS sensors. The proposed approach will subsequently be used to track the orientation during several motions in free-ranging animals. This work is proposed in order to improve the attitude estimation approaches developed in [6]-[8] and limited to the static and quasi-static cases of animal's movements. We propose an approach based on a nonlinear filter to gain the most accurate attitude estimation using the advantages of accelerometers, magnetometers and gyroscopes. It is important to note that the resulting approach structure is complementary: high bandwidth rate gyro measurements are combined with low bandwidth vector observations to provide an accurate attitude estimate [23].

A. Attitude filter description

To achieve our goal, (2) is developed to form the nonlinear system $(\Im)$:

$$(\Im): \left\{ \dot{q} = \begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \otimes \begin{bmatrix} 0 \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -q_{vect}^T \\ I_{3\times3}\, q_0 + \left[q_{vect}^{\times}\right] \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \right. \quad (8)$$

where $q \in \Re^4$ is the state vector, $I_{3\times3}$ is the identity matrix and $\left[q_{vect}^{\times}\right]$ is defined as:

$$\left[q_{vect}^{\times}\right] = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}^{\times} = \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix} \quad (9)$$

The output $y \in \Re^6$ of the system $(\Im)$ is built by stacking the accelerometer and magnetometer measurements such as:

$$y = \begin{bmatrix} f_x & f_y & f_z & h_x & h_y & h_z \end{bmatrix}^T \tag{10}$$

In order to estimate the attitude, the following nonlinear filter is proposed (based on (3) and (6)):

$$\begin{bmatrix} \dot{\hat{q}}_0 \\ \dot{\hat{q}}_1 \\ \dot{\hat{q}}_2 \\ \dot{\hat{q}}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -\hat{q}_1\omega_x - \hat{q}_2\omega_y - \hat{q}_3\omega_z \\ \hat{q}_0\omega_x - \hat{q}_3\omega_y + \hat{q}_2\omega_z \\ \hat{q}_3\omega_x + \hat{q}_0\omega_y - \hat{q}_1\omega_z \\ \hat{q}_1\omega_y - \hat{q}_2\omega_x + \hat{q}_0\omega_z \end{bmatrix} \otimes \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & & & & & & \\ 0 & & & K & & & \\ 0 & & & & & & \end{bmatrix} \begin{bmatrix} 1 \\ \delta(\hat{q}) \end{bmatrix} \tag{11}$$

where $\hat{q} = \begin{bmatrix} \hat{q}_0 & \hat{q}_1 & \hat{q}_2 & \hat{q}_3 \end{bmatrix}^T \in \Re^4$ and $K \in \Re^{3\times 6}$ denote the estimated states (attitude) and the filter gain, respectively. Note that, $\delta(\hat{q}) = (y - \hat{y})$ is the modelling error which represents the difference between real measurements y, as defined in (10), and estimated values $\hat{y}$ given by:

$$\hat{y} = \begin{bmatrix} \hat{f}_x & \hat{f}_y & \hat{f}_z & \hat{h}_x & \hat{h}_y & \hat{h}_z \end{bmatrix}^T \tag{12}$$

The components of $\hat{y}$ are calculated by:

$$\hat{f} = \begin{bmatrix} 0 & \hat{f}_x & \hat{f}_y & \hat{f}_z \end{bmatrix}^T = \hat{q}^{-1} \otimes g_q \otimes \hat{q} \tag{13}$$

$$\hat{h} = \begin{bmatrix} 0 & \hat{h}_x & \hat{h}_y & \hat{h}_z \end{bmatrix}^T = \hat{q}^{-1} \otimes m_q \otimes \hat{q} \tag{14}$$

where

$g_q = \begin{bmatrix} 0 & 0 & 0 & 9.8 \end{bmatrix}^T$ is the quaternion representation of the gravity vector.

$m_q = \begin{bmatrix} 0 & 0.5\cos(60°) & 0 & 0.5\sin(60°) \end{bmatrix}^T$ is the quaternion representation of the earth's magnetic field.

The filter gain K in (11) is used to correct the modelling error $\delta(\hat{q})$. This can be done if we are able to locate the minimum of the scalar squared error criterion function defined such as:

$$\xi(\hat{q}) = \delta(\hat{q})^T \delta(\hat{q}) \tag{15}$$

In this paper, the Levenberg Marquardt Algorithm is used to minimize the non-linear function $\xi(\hat{q})$ [24]. Then the unique minimum can be written in the following form [10], [25]:

$$\eta(\hat{q}) = K\delta(\hat{q}) = k\left[X^T X + \lambda I_{3\times 3}\right]^{-1} X^T \delta(\hat{q}) \tag{16}$$

where $\lambda \in \Re$ guarantees that the inverted term will be non-singular. $X \in \Re^{6\times 3}$ is the Jacobian matrix defined as in [26]:

$$X = -2\begin{bmatrix} 0 & -\hat{f}_z & \hat{f}_y & 0 & -\hat{h}_z & \hat{h}_y \\ \hat{f}_z & 0 & -\hat{f}_x & \hat{h}_z & 0 & -\hat{h}_x \\ -\hat{f}_y & \hat{f}_x & 0 & -\hat{h}_y & \hat{h}_x & 0 \end{bmatrix} \tag{17}$$

B. Nonlinear filter performance analysis

The scheme of the attitude estimation algorithm is summarized in Fig. 4. A frequency analysis of accelerometer signals shows that gravity components (g) tend to lie towards the low end of the frequency spectrum while the DBA (a) has higher frequencies components [23]. The frequency analysis of magnetometer measurements shows also that the magnetic field tends to lie towards the low end of the frequency spectrum [23]. The gyroscope signals analysis shows that the bias Δ_G, being a slow moving process, tends to lie towards the low end of the spectrum, and the angular velocity ω tends to have higher frequency components [23]. Therefore, signals coming from the accelerometer-magnetometer pair and signals from the gyroscope have a complementary frequency spectrum [23]. The resulting structure of the nonlinear filter is complementary: it blends the low frequency region (low bandwidth) of the accelerometer and magnetometer data, where the attitude is typically more accurate, with the high frequency region (high bandwidth) of the gyroscope data, where the integration of the angular velocity yields better attitude estimates. Indeed, the filtering approach can perform a low-pass filtering on the signals from the accelerometer-magnetometer pair and a high-pass filtering on the signals from the rate gyroscope [27]. By filtering the high frequency components of the signals from the accelerometer (DBA) and the low-frequency components of the gyroscope signal (slow moving drift), the nonlinear filter produces an accurate estimate of the attitude.

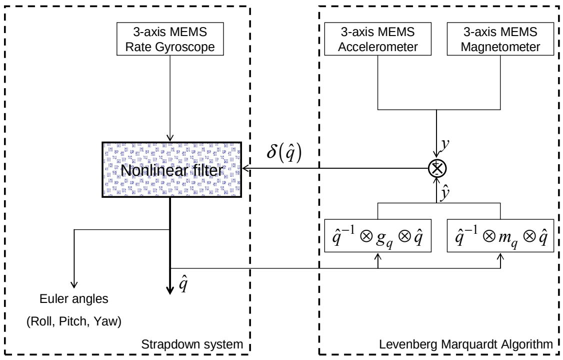


Fig. 4. Block diagram for the attitude estimation algorithm

IV. EXPERIMENTAL RESULTS

In order to evaluate the efficiency of the proposed approach in real world applications, an experimental setup was developed using an inertial and magnetic sensor module. In this study, an Inertial Measurement Unit (IMU) was used, namely the MTi from Xsens Technologies [28], which outputs data at a rate of 100Hz. This device is a miniature, light-weight, 3D digital output sensor (output of 3D acceleration from the accelerometer, 3D angular rate from the gyroscope, and 3D magnetic field data from magnetometer) with built-in bias, sensitivity and temperature compensation. The Xsens MT device can track the attitude in Euler angles, quaternion, and rotation matrix representations. The attitude from MTi is computed using an internal algorithm based on Xsens Kalman Filter (XKF) [28]. In the set of experiments, the calibrated data from MTi are all used as input to the proposed nonlinear filter. Note that MTi serves as a tool for the evaluation of proposed attitude estimation algorithm efficiency, and cannot be used on free-ranging animals due to its dependence on an energy source as well as its heavy weight, makes it unsuitable for use.

A. *Experiment*

In this section, the experiment is achieved at the robotic laboratory of PSA industrial base (Metz, France) under a popular industrial robot manipulator IRB 2400 from ABB Group (ABB Group, 2010) [29]. It offers an excellent motion control around six axes and gives a high performance in the material handling with a position repeatability of 0.06mm. Before starting the experiment, the MTi was attached to a wooden board and joined to the last axis of the robot. A lot of attention is given during the assembly to obtain two aligned frames *TooL0* and *T_st_iner* corresponding to the MTi and the last axis of the robot, respectively (see Fig. 5). The reason is to get a ground truth orientation reference from the robot and to test the behavior of the inertial tracking approach. Notice that the length of the board is fixed to 20cm to place the unit far from magnetic disturbance.

The ABB robot axes are programmed to rotate in such way of performing a trajectory like a straight line by the last axis in the space and without changing its orientation. Since the two frames are aligned, the MTi describe also the same trajectory as done by the robot axis. This motion is repeated many times by the robot to investigate the accuracy of the proposed filtering approach. During the experiment, we choose to increase the robot velocity at each test. The recorded data (angular rates, accelerations, Earth's magnetic fields) by the MTi are transmitted to a computer via USB port. Note that the robot gives the orientation of the frame *TooL0* in quaternion form. In the last step, we feed the nonlinear filter proposed in the section III with the recorded data by MTi to obtain an estimation of the orientation and to compare it with the one given by the robot.

B. *Results and analysis*

Figures 6 and 7 show two series of the estimated quaternion components by the proposed filtering algorithm. These same figures contain the evolution of the orientation given by the robot. Note that each figure corresponds to an experiment done with a different robot velocity. The goal is to verify if the filter is disturbed by the change of this velocity. We can see that the nonlinear filter estimates the truth attitude stably and smoothly. We plotted also in these figures the corresponding residue, i.e., error between the estimator and the reference (robot) for the quaternion components during the motion. This error is computed as the difference between the quaternion estimate produced by the complementary nonlinear filter and the robot. Notice that this error is very small for the four quaternion components which proves the efficiency of the developed approach in the paper.

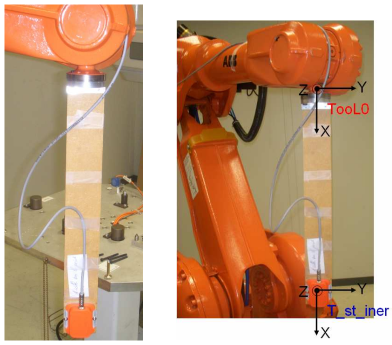


Fig. 5. Experimental setup: MTi is mounted on the robot for orientation tracking

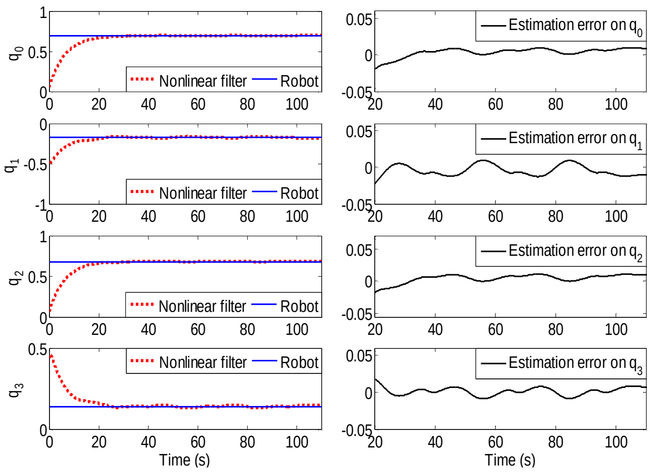


Fig. 6. Comparison of quaternion components estimated from the nonlinear filter and those given by the robot and the corresponding estimation errors

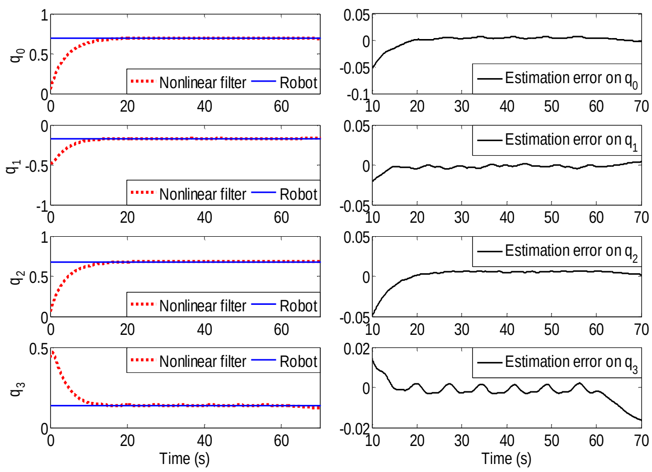


Fig. 7. Comparison of quaternion components estimated from the nonlinear filter and those given by the robot and the corresponding estimation errors

V. CONCLUSION

This paper proposes an alternative approach to solve the attitude estimation in rigid bodies' motion. This work is dedicated to the Bio-logging domain and aims to attain animal posture tracking over wide motion range. We have proposed a state estimation algorithm that combines three complementary data from a 3-axis accelerometer, 3-axis magnetometer and 3-axis gyroscope to estimate motion expressed in quaternion terms. A complementary nonlinear filter was designed and the preliminary experimental results prove that the algorithm is able to track orientation over several motions. Our future works will focus on the experimental evaluation of the algorithm using our first prototype. This logger will be attached to the king penguin and deployed in the Crozet island. This step will give us the opportunity to know the spatial orientation of the king penguin during its dives which helps the biologist to study some aspects of its behaviour. Also, we will interest in other research to estimate the 3D position of the animal using a fusion between inertial sensors and GPS measurements.

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