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Development of the Wireless Ultra-miniaturized Inertial Measurement Unit WB-4: Preliminary Performance Evaluation

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***Abstract*— This paper presents the preliminary performance evaluation of our new wireless ultra-miniaturized inertial measurement unit (IMU) WB-4 by compared with the Vicon motion capture system. The WB-4 IMU primarily contains a mother board for motion sensing, a Bluetooth module for wireless data transmission with PC, and a Li-Polymer battery for power supply. The mother board is provided with a microcontroller and 9-axis inertial sensors (miniaturized MEMS accelerometer, gyroscope and magnetometer) to measure orientation. A quaternion-based extended Kalman filter (EKF) integrated with an R-Adaptive algorithm for automatic estimation of the measurement covariance matrix is implemented for the sensor fusion to retrieve the attitude. The experimental results showed that the wireless ultra-miniaturized WB-4 IMU could provide high accuracy performance at the angles of roll and pitch. The yaw angle which has reasonable performance needs to be further evaluated.**

I. INTRODUCTION

IN recent years there has been an ever increasing amount of research and development of robotics technologies and methods to improve the quality and the performance of medicine [1]. A fundamental task for the development of these robotics technologies is a better prior understanding of the performance of human being in various medical applications, such as minimally invasive surgery (MIS), gait analysis and rehabilitation, and to clarify not simply what a skilled (or healthy) person does better than a novice (or patient), but also how.

Among different methods currently available, motion capture usually provides an effective solution for analyzing human movements and performance. The most currently used motion tracking technologies in medical applications are optical-based systems and electromagnetic-based systems. Optical-based motion capture systems could offer reliable and accurate ways to record performer's motion; however, they are expensive and poor in portability. The markers used for motion tracking should always be seen by several cameras, which cannot be satisfied at all times. Moreover, these systems normally can track the positions of the objects. If we want to calculate the orientations, at least 3 markers are needed, which might be a problem for measuring some small objects' orientations due to the relative big size of multiple markers. Electromagnetic-based motion capture systems can provide reasonable accuracies with no serious obstruction problems. However, they can only offer limited measurement volumes. This limitation makes it nearly impossible to track the movements of more performers in wide working space.

A very promising frontier on the wearable and reliable motion capture technology for medical applications is based on inertial sensors. Inertial tracking is appealing due to the lack of dependence on an artificially generated source. It thus does not suffer from range limitations and interference problems of sourced technologies. The inertial-based motion tracking systems basically consist of a set of inertial measurement units (IMUs), which are attached to the objects for tracking orientations. Each IMU normally is composed of a 3-axial accelerometer, a 3-axial gyroscope and a 3-axis magnetometer, approximately mounted in one unit. There are currently some commercial products of IMUs available on the market, such as MTx (Xsens Inc.) and InertiaCube3 (InterSense Inc.). These commercial IMUs with high performance have been implemented to various scenarios of robotics and human performance research. However, the sizes and weights of those commercial IMUs are still relative too big to be attached on some small objects for motion tracking, such as the bipolar forceps (header size 94 x 10 x 10mm and weight 34g) used in neurosurgery [2].

This study, therefore, presents the development of our new wireless ultra-miniaturized inertial measurement unit WB-4 for human motion capture and its performance evaluation compared with Vicon system (VICON Company). The light weight, compact size and wireless communication make the WB-4 IMU possible to realize a better wearable and portable motion tracking system, which could extend the prospect of the system applications to more various medical scenarios.

II. MATERIALS AND METHODS

A. System Requirements

Since the hand and arm motions represent the quickest

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motions of human body, it can be assumed that a system capable of tracking the hands and arms will be able to track the rest of the body [3]. Especially in surgical trainings and operations, the operative performance is strongly related to the movements of surgeons' upper limbs. For the wrist or elbow, a change of approximately 2 deg can be perceptible by human [4]. Therefore, the system should be capable of achieving accuracy within 2 deg in the dynamic conditions, which will not be in conflict with the kinaesthetic nervous system of the users.

B. *WB-4 Wireless IMU*

Our group recently developed a new wireless IMU named WB-4, which primarily contains a mother board, a Bluetooth module (ADC Technology Inc.) and a Li-Polymer battery (Kayo Battery Co., Ltd.). A picture of the new IMU is showed in Fig. 1. The WB-4 is very compact and lightweight (size 37x23x12mm and weight 7.0g) – at present the smallest, lightest in the world.

WB-4 uses two-layer configuration for the connection between the mother board and Bluetooth module (Fig. 2). The mother board is primarily composed of a 32-bit microcontroller STM32F103CBT6, a DC regulator ST1S12 and the following sensors: 3-axis accelerometer LIS331DLH; 3-axis gyroscope LYPR540AH; and 3-axis magnetometer HMC5843 (Fig. 3). More detail information about the hardware description of WB-4 could be referred to [5].

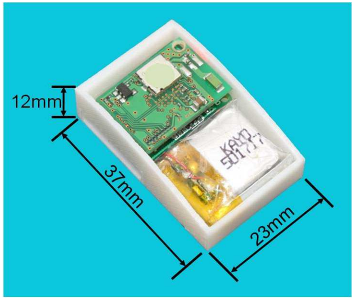

Fig. 1. WB-4 wireless IMU.

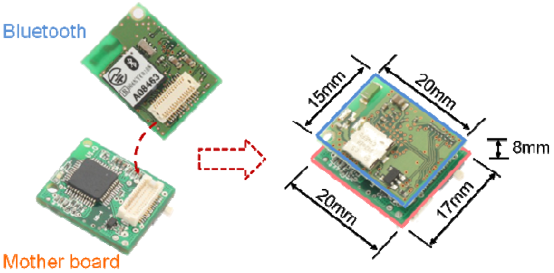

Fig. 2. Two-layer configuration for WB-4 mother board and Bluetooth module.

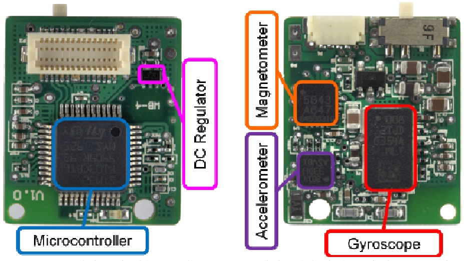

Fig. 3. MCU side (left) and sensor side (right) of the mother board.

C. *Orientation Estimate Method*

Quaternion-based extended Kalman filter (EKF) is used in this study for the orientation estimate of WB-4. In addition, an R-Adaptive algorithm is implemented to evaluate the measurement covariance matrix used in the EKF. In this way, the EKF can better overcome the problems on the correction of pitch and roll angles when there are strong linear accelerations in respect to the gravity. Quaternion is used to represent space orientation to improve computational efficiency and avoid singularities. After EKF running, the computed quaternion could be translated into roll, pitch and yaw angles, through transformation equations [6]. The continuous-time, non linear system equations of EKF are [7]:

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{\omega}) + \boldsymbol{w} \tag{1}$$

$$\boldsymbol{y} = h(\boldsymbol{x}) + \boldsymbol{v} \tag{2}$$

where $\boldsymbol{x} = [\boldsymbol{q}\ \boldsymbol{b}_\omega]^T$ represents the state of the system composed by the quaternion $\boldsymbol{q} = [q_w\ q_x\ q_y\ q_z]$ and the rate gyro bias $\boldsymbol{b}_\omega = [b_{\omega x}\ b_{\omega y}\ b_{\omega z}]$; $\boldsymbol{\omega}$ is the angular velocity vector $[\omega_x\ \omega_y\ \omega_z]^T$; $\boldsymbol{y} = [\boldsymbol{a}\ \ \boldsymbol{m}]^T$ is the measurement vector composed by the acceleration measurement and magnetic measurement $[a_x\ a_y\ a_z\ m_x\ m_y\ m_z]^T$; $\boldsymbol{w}$, $\boldsymbol{v}$ are the state and measurement noise, respectively.

In a strap-down inertial navigation system, the rigid body angular motion is described by the differential equation:

$$\dot{\boldsymbol{q}} = \frac{1}{2}\begin{bmatrix} 0 & -\boldsymbol{\omega}^T \\ \boldsymbol{\omega} & [\boldsymbol{\omega}\times] \end{bmatrix}\boldsymbol{q} \tag{3}$$

where

$$[\boldsymbol{\omega}\times] = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \tag{4}$$

with the assumption that $\|\boldsymbol{q}\| = 1$.

Using the sensor model described in [8], in quasi static condition, the acceleration acting on the body is negligible compared to the gravity acceleration as described by:

$$\begin{cases} \boldsymbol{\omega} = \boldsymbol{G}_g\boldsymbol{\omega}_r + \boldsymbol{b}_\omega + \boldsymbol{v}_g \\ \boldsymbol{a} = \boldsymbol{G}_a[\boldsymbol{C}_n^b(\boldsymbol{q})(\boldsymbol{g})] + \boldsymbol{v}_a \\ \boldsymbol{m} = \boldsymbol{G}_m[\boldsymbol{C}_n^b(\boldsymbol{q})(\boldsymbol{H})] + \boldsymbol{v}_m \end{cases} \tag{5}$$

where $\boldsymbol{G}_g$, $\boldsymbol{G}_a$, $\boldsymbol{G}_m$ are respectively gyroscope, accelerometer and magnetometer gain, supposed constant; $\boldsymbol{v}_g$, $\boldsymbol{v}_a$, $\boldsymbol{v}_m$ are respectively gyroscope, accelerometer, magnetometer noise; $\boldsymbol{\omega}_r$ is the gyroscope raw data $[\omega_{rx}\ \omega_{ry}\ \omega_{rz}]^T$; $\boldsymbol{C}_n^b(\boldsymbol{q})$ is the direction cosine matrix in terms of orientation quaternion, that represents the coordinate transformation from the inertial coordinate systems *n* to the sensor body frame *b:*

$$C_n^b(q) = \begin{bmatrix} q_w^2 - q_x^2 - q_y^2 + q_z^2 & 2(q_wq_x + q_yq_z) & 2(q_wq_y - q_xq_z) \\ 2(q_wq_x - q_yq_z) & -q_w^2 + q_x^2 - q_y^2 + q_z^2 & 2(q_xq_y + q_wq_z) \\ 2(q_wq_y + q_xq_z) & 2(q_xq_y - q_wq_z) & -q_w^2 - q_x^2 + q_y^2 + q_z^2 \end{bmatrix} \tag{6}$$

and the $\boldsymbol{g} = [0\ 0\ {-g}]^T$ is the gravity vector; $\boldsymbol{H} = [H_x\ 0\ H_z]^T$ is the local magnetic field in the inertial frame.

The non-linear functions, $f(\boldsymbol{x}, \boldsymbol{\omega})$, and $h(\boldsymbol{x})$ in equation (1) and (2) can be further explained as:

$$f(\boldsymbol{x}, \boldsymbol{\omega}) = \begin{bmatrix} \frac{1}{2}\begin{bmatrix} -q_x & -q_y & -q_z \\ -q_w & -q_z & -q_y \\ -q_z & -q_w & -q_x \\ -q_y & -q_x & -q_w \end{bmatrix} \begin{bmatrix} \omega_{rx} - b_{\omega x} \\ \omega_{rt} - b_{\omega y} \\ \omega_{rz} - b_{\omega z} \end{bmatrix} \\ \boldsymbol{b}_\omega^T \end{bmatrix} \tag{7}$$

$$h(\boldsymbol{x}) = \begin{bmatrix} \boldsymbol{C}_n^b(\boldsymbol{q})\boldsymbol{g} \\ \boldsymbol{C}_n^b(\boldsymbol{q})\boldsymbol{H} \end{bmatrix} \tag{8}$$

Because of its non-linearity, the system is linearized by calculating the Jacobian of f and h functions, therefore the EKF is implemented (Fig. 4). No compensation for external magnetic effects is performed in the work described in this paper.

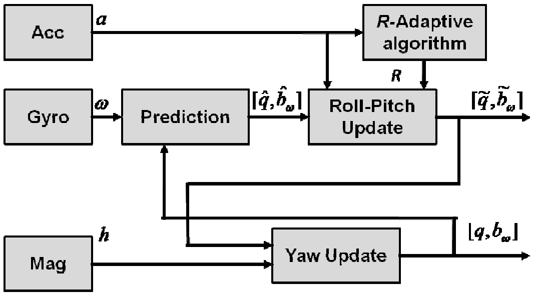

Fig. 4. Block diagram of the EKF algorithm implemented for WB-4.

In the case of human motion tracking (i.e. during walking or running), the linear accelerations could not be negligible compared to the gravity acceleration. It is difficult to set the coefficients of the measurement covariance matrix (***R***) of EKF in this condition. To overcome the problems related to the correction of the attitude using the data from the accelerometer, an R-Adaptive algorithm has been implemented in this study (Fig. 4). The ***R*** is assumed to be in this form:

$$\boldsymbol{R} = \begin{bmatrix} \sigma_x^2 & 0 & 0 \\ 0 & \sigma_y^2 & 0 \\ 0 & 0 & \sigma_z^2 \end{bmatrix} \tag{9}$$

where σ_x, σ_y, and σ_z are the standard deviations of the measurements respectively for the x, y and z axis of acceleration. Considering the sensor axis with the same noise characteristics ($\sigma_x = \sigma_y = \sigma_z = \sigma$), it is possible to model the standard deviation as:

$$\sigma = \sigma_0 + \sigma_d \tag{10}$$

where σ_0 is the standard deviation in static condition, due to the accelerometer noise; σ_d is the standard deviation due to acceleration of the body. σ can be estimated in a temporal window with the following formula:

$$\sigma_k^2 = \frac{1}{N+1}\sum_{i=k-N}^{k}(\|a_i\| - \|a_{i-1}\|)^2 \tag{11}$$

where N is the number of samples of the temporal window; σ_k^2 is the estimated variance at step k; and $||a_i||$ is the module of the acceleration measured by accelerometer.

D. Experimental Setup

The performance evaluation of WB-4 IMU is calculated in comparison with Vicon system (VICON Company).

To construct the data set for the analysis, the WB-4 IMU was linked with a metallic L-frame using adhesive as shown in Fig. 5. The metallic L-frame has four reflective markers in order to determine its exact attitude in the global Vicon reference system. Three trials were executed in order to evaluate respectively the roll, pitch and yaw's performance. For the first trial, the system was rotated around the x-axis of the L-frame (X_1-Y_1-Z_1) at different speeds with several repetitions. In the second and third trials, the L-frame was rotated about the y and z axis at different speeds, respectively. All the data were logged and off-line compared.

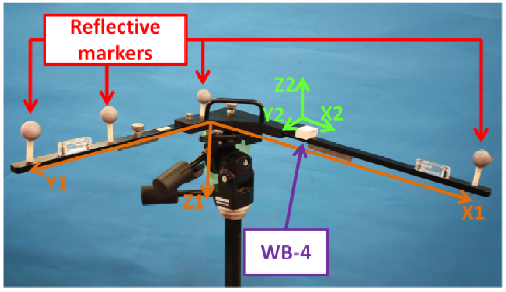

Fig. 5. Experimental setup.

III. EXPERIMENTAL RESULTS

The resulting root mean square (RMS) errors of orientation estimate by WB-4 wireless IMU are presented in TABLE I. It had the RMS errors of 1.75deg for the roll angle; 1.96deg for the pitch angle and 5.46deg for the yaw angle. It is clear that WB-4 IMU had much better dynamic performance in the rotations about x and y axis. The error of yaw angle of WB-4 IMU is relatively bigger than the roll and pitch angles, which might be due to the magnetic interference from the force plate in the structured Vicon room. More detail information about all the results is showed form Fig. 6 to Fig. 11.

TABLE I

SUMMARY OF WB-4 PERFORMANCE EVALUATION.

RMS Roll Error [deg]	RMS Pitch Error [deg]	RMS Yaw Error [deg]
1.75	1.96	5.46

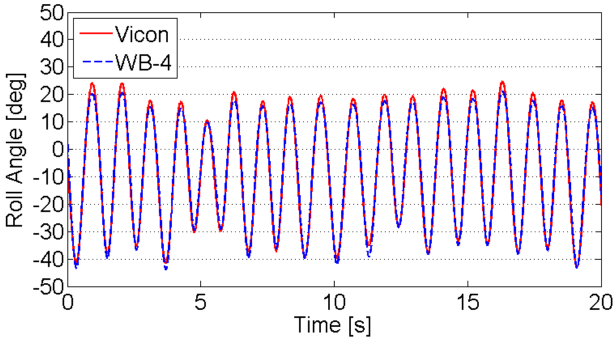

Fig. 6. Comparison of WB-4 and Vicon during rotations about x axis.

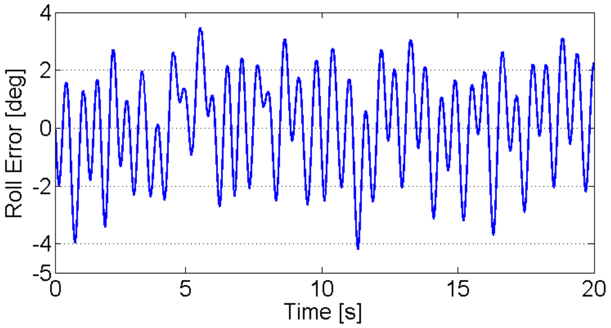

Fig. 7. Roll errors of WB-4 compared to Vicon system.

Fig. 6 and Fig. 7 show respectively the roll angle and its error during the whole rotation procedure. It is clear that WB-4 IMU could follow the trajectory of Vicon system well. There were some critical errors at the peaks of the signal, which were related to the turning moments of the rotation movements. At these turning points, there were strong changes of angular speeds. The computation of EKF might be too heavy to be updated fast enough with the movements. This will affect the performance of "Roll-Pitch Update". More clear results of these errors were happened in the angles of pitch (Fig. 8 and Fig. 9). The pitch had good performance during the whole procedure, but it showed angle error spikes at the turning moments. Fig. 10 and Fig. 11 show the results of yaw angle and its corresponding errors. The results give evidence that WB-4 could follow the trajectory of Vicon system in yaw angle, but it was also accompanied with bigger dynamic error.

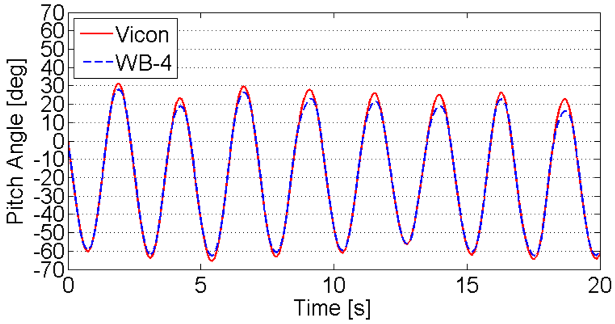

Fig. 8. Comparison of WB-4 and Vicon during rotations about y axis.

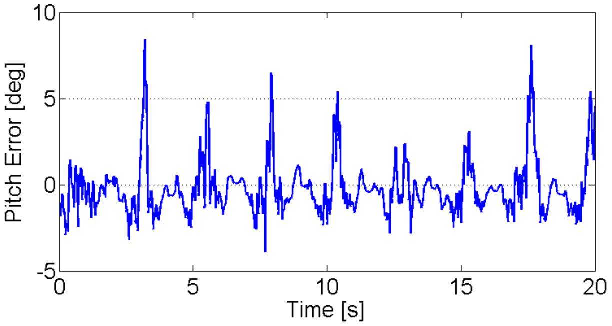

Fig. 9. Pitch errors of WB-4 compared to Vicon system.

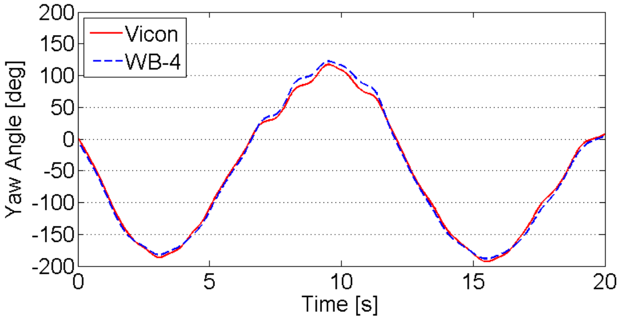

Fig. 10. Comparison of WB-4 and Vicon during rotations about z axis.

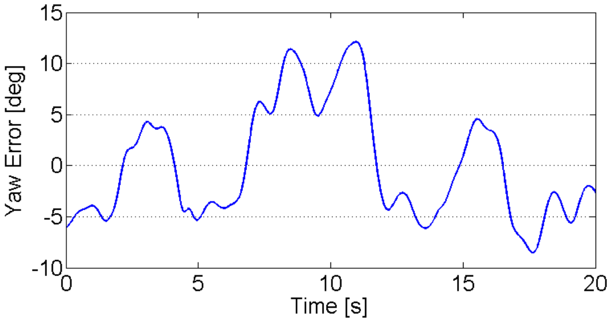

Fig. 11. Yaw errors of WB-4 compared to Vicon system.

IV. CONCLUSION

In this paper the WB-4 wireless IMU has been presented. The WB-4 module was provided with a microcontroller, 9-axis inertial sensors, Bluetooth module and Li-poly battery for realizing wireless motion tracking. The roll, pitch and yaw angles were retrieved by using the quaternion-based EKF for the sensor fusion. The attitudes obtained from WB-4 were compared with the attitudes obtained from Vicon motion capture system. The preliminary results showed that the WB-4 had high accuracy (less than 2deg) at the roll and pitch angles. However, the yaw angle had relatively worse results (about 5deg error) which might be due to the external magnetic interference and the performance of the magnetometer. Some possible differences in the results will be also related to the Vicon system, which had the variation in the 3D position measurements of markers. The performance of WB-4 IMU was evaluated without prior sensor calibration in this experiment, which means that the bias and gain of each sensor were acquired from the default values of datasheets. Therefore, WB-4 IMU could even achieve better accuracy performance after calibrating all the sensors.

The developed WB-4 wireless IMU thanks to its performance, size, weight and wireless communication, could be easily embedded in a tracksuit for realizing total body motion reconstruction.

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