2022 19th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE).
Mexico City, Mexico. November 9-11, 2022

Unity Lower limb Motion Capture Application.

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Abstract— **Motion capture systems allow us to study human motion, and their applications can help us improve individuals' health or performance in sports. This article presents the design and implementation of a motion capture system based on inertial measurement units. The application runs on Unity motor engine, which might facilitate future immersive applications development. The proposed motion capture system calculates the joint flexion/extension angles of the hip, knee, and ankle by orientation vectors, and was compared with a Vicon system, considered a Gold Standard, obtaining a root mean squared error of 10 degrees.**

Keywords—Inertial Measurement Unit, Motion capture, Unity, Gait Analysis.

I. INTRODUCTION

Motion capture, better known in the literature as Mocap, is defined as the sampling and recording of the motion of living beings and objects as 3D data that can be used for the study of motion or 3D animation [1]. Mocap technology used for 3D animation is commonly found in applications such as movies and videogames [2], while Mocap technology used for the study of motion more concisely, human motion (the recording of global positions of human body segments) has different applications such as health [3], sports training [4], rehabilitation [5], and teleworking and human safety [2].

According to Schaik V. [6], motion capture systems can be classified as inertial sensor based, marker-based, and markerless. In the case of marker-based and markerless motion capture systems, video cameras are commonly used as sensors. Specifically speaking about the systems based on optical markers, it is reported that these have the best spatial accuracy, which according to [6], is said to be less than 1 mm, which is why they are considered the gold standard in motion capture measurements. However, these types of systems are not portable, and usually, two cameras are needed. In addition, they can be costly, up to 150,000 euros [6]. Therefore, these systems are mainly used in laboratories. Examples of market-based systems are the Vicon system (Vicon, Oxford, United Kingdom) and Optitrack (Natural point, Corvallis, Oregon) [6]. On the other hand, markerless motion capture systems use videos as input to which image processing or artificial intelligence algorithms, such as deep learning or machine learning, are applied, making tracking the human body and objects possible.

In the case of inertial sensor-based motion capture systems, we can find suits that use more than two inertial measurement units (IMU) sensors to obtain kinematic and dynamic parameters of human motion. In the case of the suits composed of IMU sensors is reported that the average measurement errors that can be obtained can be lower than one degree [6], [7]. Also, Beshara P. et al. [7] say these devices are portable and light. Moreover, these devices are becoming affordable thanks to technological advancements since their lowest price is around 50 USD per sensor unit [7], making this type of system one of the most widely used apart from those Mocap systems based on the Kinect sensor [5].

The preferred use of IMU-based Mocap is for outside the laboratory assessment [2], and its use for gait assessment has been successful, as demonstrated by [2], [8]. However, existing IMU Based Mocap systems such as Xsens (Xsens, Enschede, Netherlands) and Noraxon(Noraxon, Scottsdale, Arizona) are expensive systems due to their software and high accuracy biomechanical model algorithms (up to 12,000 USD for a full-body suit [7]). Therefore, open source solutions have been proposed, such as the one proposed by Slade [9] that developed a 120 USD dollar system composed of eight IMU mode ISM330DHCX sensors connected to a Raspberry Pi 4b+. They rely on Opensim inverse kinematics solver to compute joint angles. The Root Mean Square Error (RMSE) reported by Slade is 5.6 degrees (DEG).

In the article presented by Borno [10], he reports a toolbox for measuring lower limb kinematics called OpenSense. The OpenSense is a toolbox specifically developed for Opensim 4.2 that uses sensor fusion and an inverse kinematics algorithm to estimate joint angles. They report that they obtained an RMSE less or equal to six degrees. However, their system proposal is not a real-time Mocap system. In [11], Patil K. presents sensor techniques to track human pose estimation. In Kumar's proposal, one Ouster OS-0 lidar and ten Xsens MTW IMU sensors are used. In their application, they use the IMU sensors for body segment orientation.

In this article, our main contribution consists of the design and implementation of the application developed in Unity, as well as reporting the development of an algorithm based on orientations that allow the registration of the goniometry of sagittal body movements of flexion and extension of the hip, knee and ankle joints in real-time. The developed application was tested on a healthy subject and compared to a Vicon system considered a Gold Standard. Furthermore, the RMSE obtained from the proposed system compared to the Vicon system was less than 10 degrees. Therefore, it can be determined that the Unity video game engine is a good platform for developing

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motion capture systems based on IMU sensors since it has a set of programming tools suitable for handling orientations.

II. Methodology

The methodology has been divided into two sections. In the first section, we discuss the development of the application, while in the second part, we describe the proposed experimental comparison with a Vicon Mocap system.

A. Application design

The proposed application uses an Xsens Xbus Kit system to obtain data from seven Xsens MTx model inertial sensors. The IMU MTx sensors are connected to a base system called XbusMaster, which acquires the data from the inertial sensors and sends them via Bluetooth to a receiver connected to a Lenovo PC model C321 with Ryzen 5 processor with 6 Gb RAM and running Windows 10 operating system. For the operating system to recognize the Xsens system receiver as a peripheral, the MVN software has been installed, which contains the necessary drivers, and includes the Xsens MT SDK (Software Development Kit). The Xsens MT SDK is a C++ library that allows sending and receiving information packets from the Xsens system and calculates the sensors' Euler and Quaternion angles. To communicate the data to the application, we have created a C++ application that integrates the Xsens MT SDK library, which works as a local TCP/IP protocol server that sends and receives JSON serialized data objects.

We have implemented a three-layer architecture for the application. The upper layer corresponds to the visual management and interface with which the user can interact. This interface shows the orientation of seven inertial sensors, and the visual model is a skeleton that moves the joints according to the angles calculated through the second layer.

The second layer of the implemented system calculates the angles between the IMU sensors. To perform these calculations, we first reference the orientations of the Euler angles to the Unity plane, removing the rotation offset for each sensor. Once we reference our sensors to the Unity planes, we obtain the Euler angles rotation matrix (M) as shown in Eq. 1, where U, V, and w are orthogonal vectors with unit norms representing the orientation of a 3D object.

$$M = \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix} \quad (1)$$

Subsequently, we use Eq. 2 to know the angle θ between A and B IMU sensor vectors.

$$\theta = \cos^{-1}\left(\frac{A \, . \, B}{|A| \, |B|}\right) \quad (2)$$

In our lower limb proposed model, we have placed seven MTx IMU sensors as follows : (2) foot sensors, (2) leg sensors, (2) thigh sensors, and (1) pelvic sensor, as shown in Fig. 1. Also considering Fig. 1, the corresponding calculations between vectors to obtain the corresponding angles for the hip flexion/extension, knee flexion/extension, and ankle flexion/extension, from the left and right sides are expressed in Eq. 3 to Eq. 8.

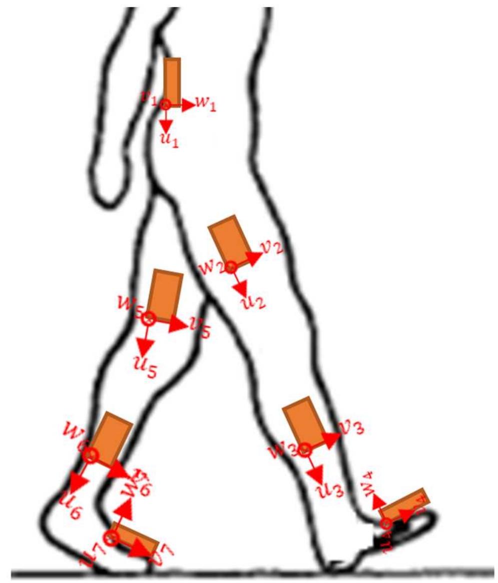

Fig.1. The orange color boxes indicate the Xsens MTx IMU sensor placement. While red arrows indicate the sensor vector orientations, and sensor number.

$$\text{Right Hip} = \cos^{-1}\left(\frac{v_1 \, . \, u_2}{|v_1| \, |u_2|}\right) \quad (3)$$

$$\text{Left Hip} = \cos^{-1}\left(\frac{v_1 \, . \, u_5}{|v_1| \, |u_5|}\right) \quad (4)$$

$$\text{Right Knee} = \cos^{-1}\left(\frac{u_2 \, . \, u_3}{|u_2| \, |u_3|}\right) \quad (5)$$

$$\text{Left Knee} = \cos^{-1}\left(\frac{u_5 \, . \, u_6}{|u_5| \, |u_6|}\right) \quad (6)$$

$$\text{Right ankle} = \cos^{-1}\left(\frac{v_5 \, . \, u_3}{|v_5| \, |u_3|}\right) \quad (7)$$

$$\text{Left ankle} = \cos^{-1}\left(\frac{v_7 \, . \, u_6}{|v_7| \, |u_6|}\right) \quad (8)$$

Finally, the third layer of the system implemented a TCP/IP protocol connection client that connects to the implemented local server and allows us to communicate with the inertial sensors through serialized objects. The proposed three-layer architecture is shown in Fig. 2.

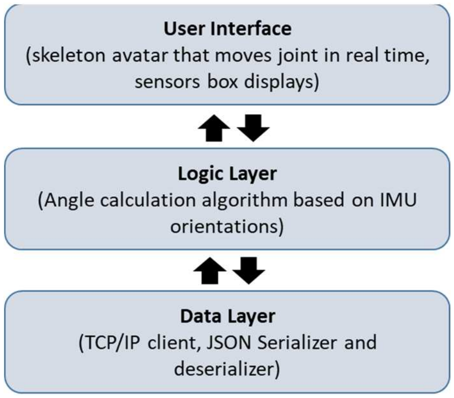

Fig. 2. Software Layer Architecture. The first layer corresponds to the user interface. The second layers calculates the joint angles based on IMU vector orientations. The third layer correnspns to the data

B. *Experimental comparison*

A healthy 29-year-old subject was asked to walk without shoes in a straight line for a seven meters distance. The subject repeated this action five times. It is important to note that we obtained informed consent from the subject to perform the tests.

For motion capture with the photogrammetry system, reflective markers were placed on the subject in the configuration of the "Vicon Plug-in Gait Lower Body" model. The photogrammetry system used is a 15-camera Vicon composed of six Vantage and nine Vero cameras, which captured the positions of the markers at a sampling frequency of 100 Hz.

In the case of the Xsens MTx sensors, the sampling frequency acquired by the sensors was 50 Hz, and using the developed application, the sampling frequency of the articular ranges was 111 Hz. The sensor placing was done as described in the application development subsection and as shown in Fig.1.

To compare the joint goniometer signals obtained by the Vicon photogrammetry system and the proposed IMU-based Mocap system, the goniometer signals from both systems were exported to comma-separated files (CSV). Subsequently, the comma-separated files were imported into Matlab (MathWorks LTD, MA USA) through the "Import data" tool as tables.

We selected the minimums to cut our knee signals from the Vicon and the proposed IMU-based Mocap system to segment all the obtained goniometer signals with the purpose of identifying the gait cycles. The minimums from the knee signals were chosen since it's easy to identify them, and these values are considered to indicate heel strikes.

Once the signals were segmented, in the case of the proposed IMU-based Mocap system signals, a Butterworth-type low-pass filter with a cutoff frequency of 6 Hz was applied. Next, we resampled the IMU-based Mocap system signals to a frequency of 100 Hz.

Finally, the signal segments corresponding to each joint of the Vicon and the proposed Mocap systems, signals were averaged, and their standard deviation was calculated.

To compare the error between the Vicon system signals and the proposed Mocap system, the RMSE defined in eq. 9 was calculated for each joint.

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(y_j - \hat{y}_j)^2} \tag{9}$$

III. RESULTS

The user interface of the developed IMU-based Mocap system is shown in Fig. 3. In this figure, seven boxes in the lower part of the screen show the IMU sensor orientations. The skeleton avatar moving its joints can be seen in the middle of the screen. On the top left of the user interface is a calibration orientation button for the IMU sensors and text boxes where the user inputs the IMU number to get the joint angles as indicated in Eq. 3 to Eq. 8, and a save button that records the joint angles in a CSV file in real-time.

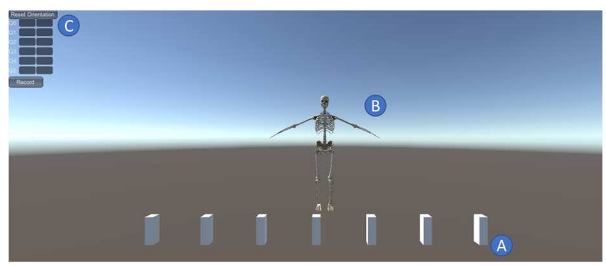

Fig. 3. User interface of the proposed developed IMU-based Mocap system. A) Boxes indicating IMU orientations. B) Skeleton avatar that moves its joints in real time. C) User interaction controls.

Fig. 4 shows an image of the performed test with a healthy subject waiting to start his walking trial.

Fig. 4. Test setup.A)Vicon system cameras placed around the measurement area. B) Test subject with reflective markers and inertial sensors placed over him.

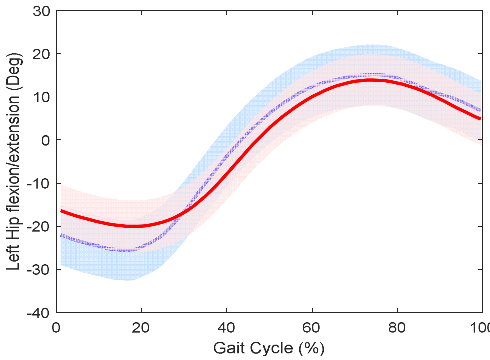

Fig. 5. Left Hip flexion/extension joint kinematics. In blue color kinematics obtained with Vicon. In red color kinematics obtained with the proposed system. The shaded areas represent 1 mean standard deviation of the signals. RMSE=4.58 DEG.

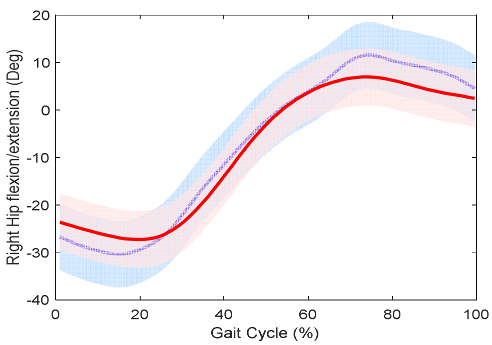

Fig. 6. Right Hip flexion/extension joint kinematics. In blue color kinematics obtained with Vicon. In red color kinematics obtained with the proposed system. The shaded areas represent 1 mean standard deviation of the signals. RMSE=2.96 DEG.

The results from the experimental comparison, where the flexion/extension gait cycles of the hip, knee, and ankle joints, are shown in Fig. 5 to Fig. 10. All the presented curves are averaged values, and their standard deviation is shaded. In the case of RMSE calculated for left and right hip flexion/extension, shown in Fig. 5 and Fig. 6, it was 4.58 DEG and 2.96 DEG, respectively. In the case of left and right knee goniometry shown in Fig. 7 and Fig.8. the RMSE obtained was 9.9 DEG and 3.42 DEG, respectively. In the case of the signals corresponding to the left and right ankle, as shown in Fig. 9 and Fig. 10, the RMSE obtained was 3.26 DEG and 2.97 Deg, respectively.

The different joint RMSE Errors are shown in Table. I. In the Table. II. The ranges of the evaluated joints of both the Vicon system and the proposed system are compared to the literature [12].

IV. Discussion

From the graphs shown in Fig. 5 to Fig. 10, it can be seen that the average ranges of motion for each joint coincide with those in the literature. For example, as shown in Table II. This indicates that the angles we obtain with the proposed system give us an approximation of the subject's joint ranges.

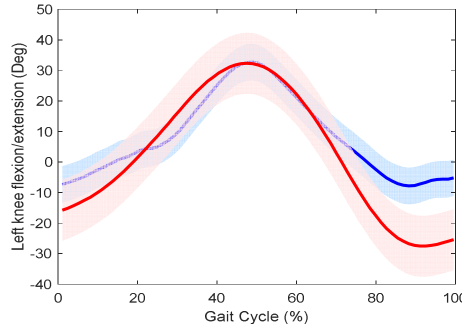

Fig. 7. Left Knee flexion/extension joint kinematics. In blue color kinematics obtained with Vicon. In red color kinematics obtained with the proposed system. The shaded areas represent 1 mean standard deviation of the signals. RMSE=9.9 DEG.

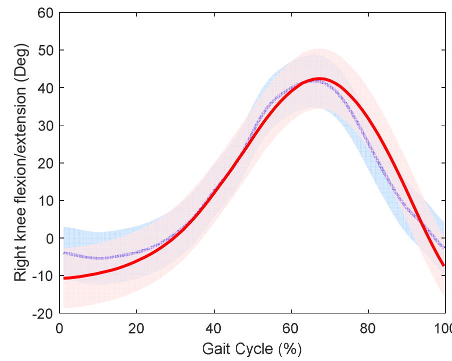

Fig. 8. Right Knee flexion/extension joint kinematics. In blue color kinematics obtained with Vicon. In red color kinematics obtained with the proposed system. The shaded areas represent 1 mean standard deviation of the signals. RMSE=3.42 DEG.

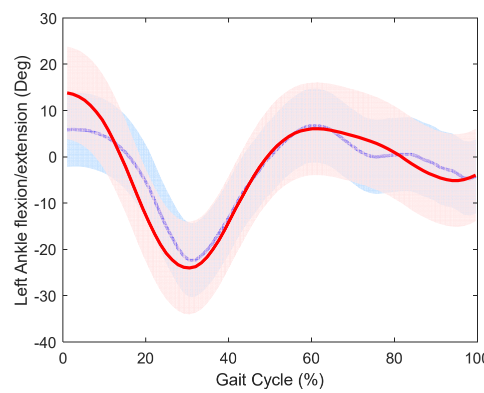

Fig. 9. Left Ankle flexion/extension joint kinematics. In blue color kinematics obtained with Vicon. In red color kinematics obtained with the proposed system. The shaded areas represent 1 mean standard deviation of the signals. RMSE=3.26 DEG.

According to the articles by Slade [9] and Borno [10], it is reported that the highest RMSE obtained in their applications is 5.6 DEG and 6 DEG. In the proposed system, the highest RMSE obtained was in the left knee joint with a value of 9.9 DEG, and we consider that this value was obtained because of the sensor placement. However, it is important to point out that in the other evaluated joints, the obtained RMSE ranges from 2.96-4.58 DEG, coinciding with the results of Slade and Borno. Furthermore, from the obtained results, it can be seen in some

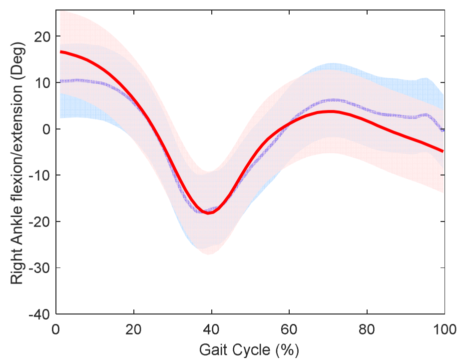

Fig. 10. Rigth Ankle flexion/extension joint kinematics. In blue color kinematics obtained with Vicon. In red color kinematics obtained with the proposed system. The shaded areas represent 1 mean standard deviation of the signals. RMSE=2.97 DEG.

goniometry signals, as in the left knee (Fig. 7), in some moments of the signal, an absolute error greater than 10 degrees can be observed. We consider that these errors greater than 10 degrees are due to the fact that we are not considering a biomechanical model that compensates for the internal rotations when rotating the joints. By not compensating for these rotations, the vectors obtained from the sensor orientations no longer coincide.

TABLE I. JOINT RMSE CALCULATED ERROR BETWEEN THE VICON SYSTEM AND THE PROSED ALGORITHMS USING MTX XSENS IMU SENSORS.

Joint	*Left RMSE [DEG]*	*Right RMSE [DEG]*
Hip	4.58	2.96
Knee	9.9	3.42
Ankle	3.26	2.97

TABLE II. MAXIMUM AVERAGE HUMAN JOINT RANGE OF MOTION (ANGLES IN DEGREES) COMPARISON

Joint	*Hamilton et al. Maximum*	*Vicon*	*Proposed IMU-based Mocap*
Hip flexion/ extension	110	40	33
Knee flexion/ extension	120	52	61
Ankle flexion/ extension	50	28	37

From the obtained results, we can say that this system can be useful for measurements that do not require high precision, such as interfaces for video games and robot interaction systems, and even for portable motion analysis systems, where it may not be necessary to have a high degree of accuracy. Therefore, its recommended use could be oriented for rehabilitation, where this type of system can show graphs and keep track of patients' advances in therapies. Furthermore, this type of system can help people who suffer from neurological diseases such as Parkinson's or stroke, among others.

It can also be shown that the proposed application can be used with any inertial sensor brand. This is because, in the third layer of the system design, the system only needs Euler angles stored in JSON packets. Therefore, new sensors to be integrated must send their Euler orientations stored in JSON packets by TCP/IP protocol. Although, in our case, we are currently using the Xsens MTx sensors, to avoid the system having large increases in latency when processing the data from these sensors (this also applies to others), this data is processed in the C++ programming language from which the Euler angles are calculated from accelerometer and gyroscope data. Once we obtain the Euler angles, we package them in the format of serialized JSON objects to our application that is executed in Unity, where the algorithm is executed to calculate the angles between the vectors formed by obtained Euler angles.

V. CONCLUSION

In this project, we have presented the development of an application that runs on Unity and allows the capture of hip, knee, and ankle flexion/extension movements. The highest RMSE obtained from this system is 9.9 degrees, so that this application may be ideal for the interaction of a subject with video games or interfaces with robotic applications.

The proposed application can have great potential since the third layer of the system design, which currently consists of communication with the Xsens system, can be extended to be used with other brands of low-cost commercial sensors. Another advantage of this application is that it will facilitate the development of applications for rehabilitation or virtual immersion when implemented in the Unity video game engine. For future work, we will validate our system with more subjects.

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