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A Novel Low-Cost 4-DOF Wireless Human Arm Motion Tracker

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***Abstract*— A human arm can be described as a five degrees-of-freedom (DOF) serial manipulator. The fifth degree - rotation around the forearm axis only contributes to the wrist orientation. Hence, if it is ignored the elbow and wrist joint positions can be tracked using an upper arm orientation and the elbow joint angle. The paper presents a novel low-cost design of a 4-DOF human arm wearable tracker system for wireless dynamic tracking of upper limb position and orientation. The proposed design utilizes a single inertial measurement unit coupled with an Unscented Kalman filter for the upper arm orientation quaternion and a potentiometer sensor for elbow joint angle estimations. The presented arm tracker prototype implements wireless communication with the control PC for sensor data transmission and real-time visualization using a Blender open source 3D computer graphics software and was verified with an Xsens MVN motion tracking system. The demonstration video is available at the authors' research web-site** `www.alaris.kz`.

I. Introduction

Human arm motion capture plays an important role in many research areas. It mostly concerns with medical diagnostics and rehabilitation, teleoperation of robot-manipulators, video games and learning, animation, navigation and sport [1]–[3]. The general objective is to mimic the human arm motion by tracking upper limb kinematics. Traditionally, human motion tracking is accomplished by cameras, wearable sensors or combination of those, depending on the task and the environment. However many of the human tracking devices are expensive and not affordable to general public [4].

Human upper limb tracking systems can be classified into four methods [5]: vision based systems with markers, markerless vision based systems, robot guided tracking systems and non-vision based tracking systems.

Vision based tracking system with markers track human arm motions using markers, usually placed on human limbs, and receivers. Normally, the markers are light sources or magnetic generators. VICON [6] and CODA [7] are excellent examples available on the market. These systems reconstruct human limb motions from dynamically recorded marker positions on a user. This is a robust technology that requires a dedicated environment with no external light interruption. Since the method is strongly dependent on the setup, the vision based human upper limb tracking systems with markers are not portable and are not suitable for extensive use.

Markerless vision method tracking systems use advanced receivers such as cameras and depth sensors in order to detect human upper limb boundaries. In this technology markers are omitted and arm tracking can be performed through visual data processing. This is an active research area due to existing complexities and limitations of image processing techniques. In many environments a mutual occlusion problem still may need to be resolved. The mutual occlusion occurs when digital image looses some pixels due to the light intensity [8]. This problem forces the vision based tracking system without markers to be specific about the environment in which it is utilized.

Robot-guided systems are used to detect and interact with dynamic torques/forces. In medicine, patients interact with a robotic manipulator by touching the manipulator end-effector, thus translating the torque/force information to the robots system. This information is used to perform analysis of a human upper limb. Patients may also have wearable sensors on arms. Generally, this approach is applied if a dynamical analysis of human arms is needed [9], [10]. However, for kinematic analysis purposes the use of this approach is expensive and not intuitive in terms of fast implementation. An MIT robot-guided rehabilitation robot is an example of this approach [11].

Human body segments can also be tracked using non-vision based systems [12]–[16]. In these systems, wearable sensors are attached on human arm and interact with controller mostly implemented on a personal computer (PC). Small-scale micro-electromechanical systems (MEMS) technology based inertial measurement unit (IMU) sensors are mostly utilized as wearable sensors in current human tracking solutions [13], [17]. Unlike vision based systems, non-vision based systems are independent from a light source, are portable and can be used in a wide range of surrounding environments. However such systems do not provide absolute position data of human limbs in the global space. Instead limb positions are calculated with respect to a certain static joint. In most of design solutions, non-vision human arm tracking systems utilize at least two IMU sensors to define full motion of the arm [2], [18], [19]. In these applications only the arm moves, hence the position of the shoulder is assumed to remain constant. Then arm segments positions are found using corresponding orientation data. Naturally, this requires a prior knowledge of sensor placing, limbs lengths and initial positions.

There is a large number of non-vision based research works that focus on estimating position and orientation of

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a human upper limb using various techniques. In [20] it was proposed to utilize triaxial inertial sensors placed in certain location on the human body for obtaining corresponding real-time orientation with a linear Kalman filter. The Kalman filter produces estimates of states variables using a series of measurements observed over time, containing statistical noise and biases. This has been further developed by Yun et.al [21] where an Extended Kalman (EKF) filter is employed. The EKF provides a first order approximation of the non-linear gyroscope/accelerometer/magnetrometer data fusion done in order to obtain the orientation. Sun et.al [22] proposed an adaptive filter in which sensor data fusion algorithm would adapt to working environments. Recently, Zhang et.al [23] obtained orientations using an Unscented Kalman filter (UKF) with adaptive measurement covariance and anatomical constraints. Unlike the EKF, the UKF maps the uncertainty instead of approximating it. It is done by drawing a certain amount of sample points around the mean, propagating them through non-linear functions and recovering the resultant mean and covariance. In general the UKF is considered to be more precise than the EKF while the computational power requirements are same [24].

A human arm can be modeled as a 5 degrees-of-freedom (DOF) serial manipulator with geometric constraints, i.e. 3 DOFs are located in the shoulder joint, 1 DOF is in the elbow joint and the last DOF is on the forearm axis [2]. The fifth DOF only contributes to the hand wrist orientation. Hence, if it is ignored then the elbow and wrist positions can be tracked using only the upper arm orientation and the elbow joint angle as discussed in detail in Section II of this paper.

In this paper the authors propose a novel design of a 4-DOF human arm wearable tracker system for wireless tracking of upper limb position and orientation. Unlike other systems, the presented design utilizes a single IMU and a potentiometer. The tracker system uses UKF for orientation estimation. A human upper arm orientation is estimated with an IMU sensor located on the upper arm while the forearm (wrist) orientation is estimated using the potentiometer measurements of the arm elbow joint angle. Upper arm and forearm orientations are then used to calculate arm position assuming that the body remains still. The arm tracker implements wireless communication with a control PC for data processing and visualization, which makes the system very portable and easy in use.

The paper has the following structure: Section II outlines UKF based arm trajectory estimation algorithm utilized in the proposed 4-DOF arm tracker system whereas Section III describes the system design. Section IV presents and discusses experimental results, conclusions are summarized in Section V.

II. Arm Trajectory Estimation

It is common to describe a human arm as a 5-DOF serial manipulator with geometric constraints. The shoulder can be described as a spherical 3-DOF joint, 1 DOF is in the elbow joint and the last DOF is on the forearm axis [2]. A single IMU is capable of tracking 3 DOFs, therefore at least two IMUs are required to fully track the arm motions [2]. As a general practice one IMU is placed on the upper arm meanwhile the second IMU is placed on the forearm [2], [18], [19].

It is known that the forearm axial motion only contributes to the wrist orientation and not position. Hence, if the wrist axial motion is ignored the second IMU can be replaced by a potentiometer sensor aligned with the elbow joint axis. This reduces the complexity of the system and allows to drop certain anatomical constraints in the data processing filter. In this design the raw sensor data from the remaining IMU is passed to an Unscented Kalman filter in order to track the upper arm orientation quaternion. It is then used with conjunction with the potentiometer readings to reconstruct the arm 3D position and orientation.

A. Unscented Kalman Filter

The IMU filter system is described by the following equations (1) and (2).

$$\boldsymbol{x}_t = f(\boldsymbol{x}_{t-1}) + \boldsymbol{v}_t; \tag{1}$$

$$\boldsymbol{z}_t = h(\boldsymbol{x}_t) + \boldsymbol{w}_t. \tag{2}$$

Here, $\boldsymbol{x}_t = [\boldsymbol{q}_{u,t} \;\; \boldsymbol{\omega}_t]$ is the state vector that consists of an upper arm quaternion $\boldsymbol{q}_{u,t}$ and an angular rate $\boldsymbol{\omega}_t$, $\boldsymbol{z}_t = [\boldsymbol{\omega}_{z,t} \;\; \boldsymbol{a}_t \;\; \boldsymbol{b}_t]$ is the measurement vector that consists of gyroscope data $\boldsymbol{\omega}_{z,t}$, accelerometer data $\boldsymbol{a}_t$ and magnetometer data $\boldsymbol{b}_t$, $\boldsymbol{v}_t$ and $\boldsymbol{w}_t$ are the process and measurement white noises with a zero mean respectively.

The process function $f(\boldsymbol{x})$ is described as follows:

$$f(\boldsymbol{x}_{t-1}) = \\ = \begin{cases} \left[\cos\left(\frac{|\boldsymbol{\omega}_{t-1}|\Delta t}{2}\right) \quad \frac{\boldsymbol{\omega}_{t-1}}{|\boldsymbol{\omega}_{t-1}|}\sin\left(\frac{|\boldsymbol{\omega}_{t-1}|\Delta t}{2}\right)\right] \otimes \boldsymbol{q}_{u,t-1} \\ \boldsymbol{\omega}_{t-1} \end{cases}, \tag{3}$$

where $\otimes$ denotes quaternion multiplication operator.

The measurement function $h(\boldsymbol{x})$ is as below:

$$h(\boldsymbol{x}_t) = \begin{cases} \boldsymbol{\omega}_t \\ \boldsymbol{a}_t = \boldsymbol{q}_{u,t}^* \otimes \boldsymbol{g}_0 \otimes \boldsymbol{q}_{u,t} \\ \boldsymbol{b}_t = \boldsymbol{q}_{u,t}^* \otimes \boldsymbol{b}_0 \otimes \boldsymbol{q}_{u,t} \end{cases}. \tag{4}$$

Here, $\boldsymbol{q}^*$ denotes the quaternion conjugate of $\boldsymbol{q}$, $\boldsymbol{g}_0$ and $\boldsymbol{b}_0$ are the initial gravity and magnetic field vectors.

Since the process and measurement equations (1) and (2) are non-linear an Unscented Kalman filter is employed to merge the sensor data and estimate the upper arm orientation.

It should be noted that the IMU sensor utilized in the presented arm tracker prototype has a built-in Extended Kalman filter. Yet, an Extended Kalman filter can only provide a first order approximation of the uncertainty. Meanwhile, an UKF maps the uncertainty by means of the Unscented Transform that gives higher accuracy. In the Unscented Transform a number of sample points (called sigma points) are drawn around the mean and propagated through non-linear functions and collected with appropriate weights to construct corresponding mean and covariance [24].

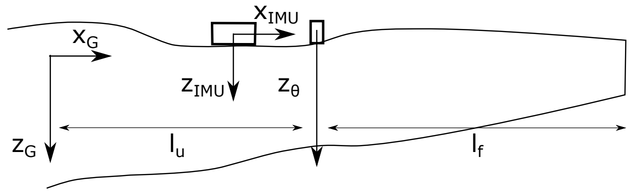

Fig. 1. Reference frames during arm T-pose initialization

B. Arm Trajectory Estimation

The tracking is initialised from a standard T-pose with $\boldsymbol{q}_{u,0} = [1\ 0\ 0\ 0]$ and $\theta_0 = 0$. Here, the global reference frame $\boldsymbol{G}$ is aligned with the IMU reference frame as illustrated in Fig. 1. At any time t the axis of rotation of the potentiometer $\boldsymbol{z}_{\boldsymbol{\Theta}}$ is aligned with $\boldsymbol{z}_{\mathbf{IMU}}$. The upper arm and the forearm lengths are l_u and l_f, respectively.

Dropping time stamps for better readability, the elbow and the wrist joint positions are calculated as follows:

$$\boldsymbol{p}_e = \boldsymbol{q}_u \otimes [l_u\ \ 0\ \ 0] \otimes \boldsymbol{q}_u^*; \tag{5}$$

$$\boldsymbol{p}_w = \boldsymbol{p}_e + \boldsymbol{q}_f \otimes [l_f\ \ 0\ \ 0] \otimes \boldsymbol{q}_f^*. \tag{6}$$

The forearm quaternion $\boldsymbol{q}_f$ is calculated as below:

$$\boldsymbol{q}_f = \left[\cos\left(\frac{\theta}{2}\right)\ \ \boldsymbol{z}_{\mathbf{IMU}} \cdot \sin\left(\frac{\theta}{2}\right)\right] \otimes \boldsymbol{q}_u; \tag{7}$$

$$\boldsymbol{z}_{\mathbf{IMU}} = \boldsymbol{q}_u \otimes \boldsymbol{z}_{\mathbf{G}} \otimes \boldsymbol{q}_u^*, \tag{8}$$

where θ is elbow angle given by a potentiometer and $\boldsymbol{z}_{\mathbf{IMU}}$ is the z-unit vector in the IMU reference frame, which is same as $\boldsymbol{z}_{\boldsymbol{\Theta}}$.

III. Wireless Human Arm Tracker System Design

A. Mechanical Design

A mechanical design of the wireless arm tracker system consists of an IMU case and a two-link potentiometer holder with a potentiometer sensor located in the holder revolute joint. The CAD model of the arm tracker system is designed using the SolidWorks CAD software and is presented in Fig. 2. The IMU case with one link of the holder is attached to an upper arm, whereas the other holder link is attached to a forearm using Velcro strips (not shown in Fig. 2). The system attachment is done in a way that the two-link holder revolute joint axis is aligned with the user's elbow joint axis. Thus, the joint potentiometer measures the elbow joint rotation angle while arm motion. The case and a holder have curved bottom design to ensure more stable setup on a human upper arm.

B. Arm Tracker Embedded System Design

The embedded system of the proposed arm tracker consists of two microcontrollers, a potentiometer and a 9-axes IMU breakout board for orientation estimation, which integrates a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer sensors. Figure 4 demonstrates the hardware architecture of the wireless arm tracker.

Due to its low cost and reliability, an UM7 Orientation sensor from CHRobotics [25] is selected for the arm tracker

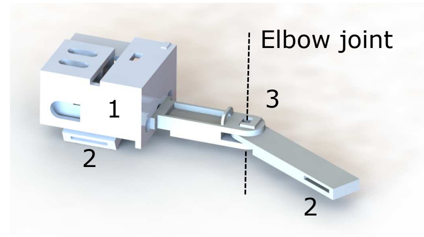

Fig. 2. CAD model of 4-DOF wireless arm tracker: 1 - IMU case, 2 - Velcro strip holes, 3 - two-link potentiometer holder

design. The sensor implements internal orientation estimation with an Extended Kalman Filter. However, only raw gyroscope, accelerometer and magnetometer data are utilized in the proposed tracker system. The sensor uses 100 Hz sample rate for measurement data acquisition and transmits them in TX-RX format with 115700 baud rate to PC.

Wireless communication is implemented using a Wixel reprogrammable microcontroller with embedded CC2511F32 processor [26]. The microcontroller runs with 24 MHz and has 2.4 GHz radio transmission frequency. The microcontroller is also connected to a potentiometer, from which it reads via internal analog-digital converter (ADC) an analog signal proportional to the elbow joint angle.

Main controller of the system is implemented on a PC that receives wireless data from the tracker Wixel microcontroller and implements data processing algorithms for real-time human arm trajectory tracking and simulation. The PC uses another Wixel reprogrammable microcontroller to receive wireless data.

C. Arm Tracker System Prototype

The arm tracker system prototype has been manufacturing using 3D printing technology. It is shown in Fig. 3 placed on human upper limb in different poses.

The bill of materials of the system prototype is given in Table I. It includes the list of utilized components with quantity, cost and source information needed to estimate the overall cost of the proposed arm tracker prototype. The 3D printed part's cost is calculated in accordance with their weight. All calculations in Table I are made with assumption that one kilogram of the ABS plastic costs about USD $40. Sensors, screws, nuts and strips are commercially available at manufacturer's web-sites and can be easily purchased.

(a) Flexion (b) Extension

Fig. 3. 4-DOF wireless arm tracker mounted on a user with different arm poses

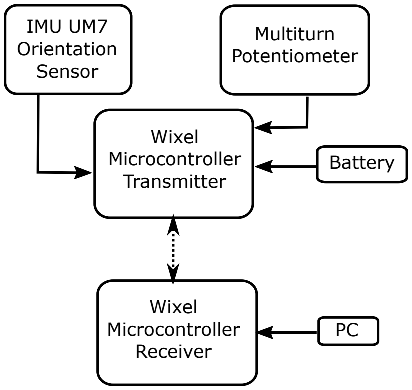

Fig. 4. Communication loop of 4-DOF wireless arm tracker

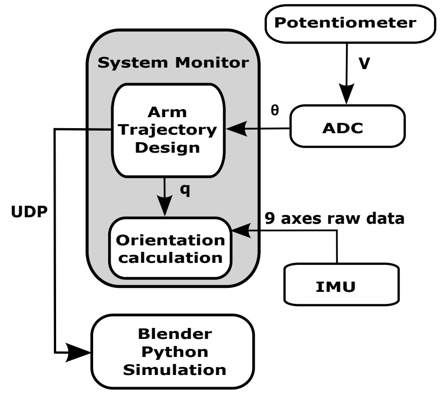

Fig. 6. PC based control system of 4-DOF Wireless arm tracker

Rough estimates show that the overall cost of the tracker prototype do not exceed USD $200 which makes the tracker manufacturing very attractive in terms of the cost comparing to similar purpose commercial wearable sensor systems with price of about several thousands USD.

D. PC based Control System Design

The arm tracker transmits the following data via wireless communication to a control PC: triaxial uncalibrated raw measurement data from the IMU accelerometer, gyroscope and magnetometer, elbow angle value measured by the potentiometer sensor. Upon receiving the data the control PC runs data calibration and processing on a software level. C++ Qt cross-compilation programming environment [27] has been chosen for hand tracking software development on PC. Qt is very useful for developing multi-threaded GUI applications efficiently utilizing multi-core processor capabilities of a control PC.

The detailed PC based control structure for the wireless arm tracker system is presented in Fig. 6. The developed control software consists of 3 task threads communicating with each other. Each thread strictly handles a separate task defined as follows.

- **Main** *thread*. The Qt thread setup wireless communication with the tracker, i.e. configures COM port, baud rate, etc., and runs on background. It also monitors the child thread and can interrupt or stop the system if an error occur.

Fig. 5. 4-DOF arm tracker system prototype and Xsens MVN suit on a human user for comparative analysis

TABLE I
BILL OF MATERIALS OF 4-DOF WIRELESS ARM TRACKER PROTOTYPE

Item	**Source**	**Quantity**	**Total Cost**
Microcontroller holder	3D printed	1	$0.30
Forearm holder	3D printed	1	$0.10
Velcro strip 5’	VEX	2	$19.98
Microcontroller	Wixel	2	$39.95
Single turn potentiometer	FPOT-10K	1	$0.63
Wire	Pololu	3	$0.25
UM7-LT orientation sensor	CH Robotics	1	$129.95
Screw	M2	6	$0.5
Total		1	$191.66

- **Data Acquisition and Orientation Calculation** *thread*. This Qt thread communicates with the arm tracker, parses and process the sensor measurements for orientation estimation. It generates quaternion based orientation data, elbow and forearm (wrist) position with regard to an stationary global coordinate system. These data are then broadcasted to a local machine UDP socket for visualization in the next thread.
- **Visualization** *thread*. This is implemented as a Python script in the Blender Open Source 3D computer graphics software [28]. Blender is a free and open source 3D creation suit that can be used 3D modeling, animation, motion tracking and game creation. Through the UDP socket communication the thread receives the orientation estimates for the user’s arm segments that are used to rotate an implemented 3D human arm model for real-time visualization without noticeable to a human time delay. Since the 3D simulation is run in a separate program environment, it cannot affect the first two threads running data acquisition and orientation estimation.

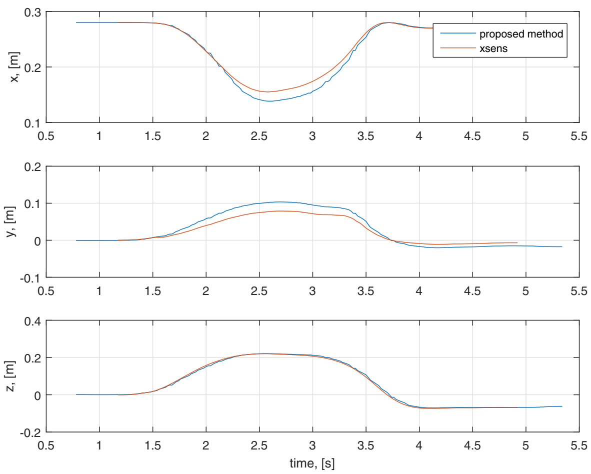

Fig. 7. Elbow coordinates generated by 4-DOF arm tracker and Xsens MVN suit during a motion

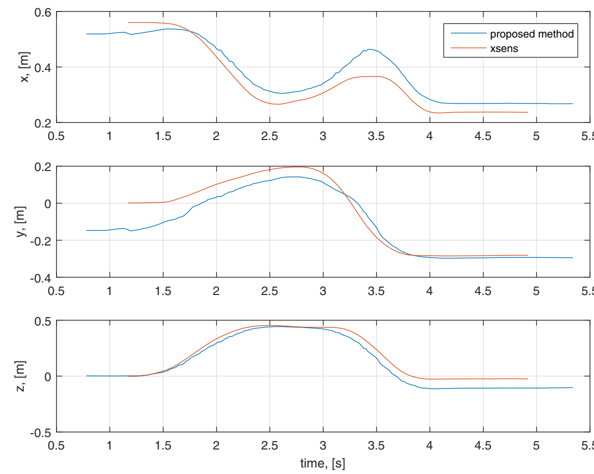

Fig. 8. Wrist coordinates generated by 4-DOF arm tracker and Xsens MVN suit during a motion

IV. Results and Discussion

The experimental validation of the proposed 4-DOF arm tracker system was conducted using a comparative analysis with a commercially available Xsens MVN motion tracking system [29]. Fig. 5 illustrated a human user wearing the 4-DOF arm tracker prototype and the Xsens upper body suit for simultaneous arm position and orientation data acquisition. The Xsens IMU sensors provide $\boldsymbol{q}_{u,xsens}$ and $\boldsymbol{q}_{f,xsens}$ quaternions that are used to estimate the elbow and wrist positions similarly to equations (5) and (6) [13]. It should be noted that the Xsens upper arm IMU sensor is tilted by $-\pi/2$ around the $\boldsymbol{x}_{\mathbf{IMU}}$ axis due to the suit layout.

The proposed system was tested with arm motions that represent every day activities such as picking an object or giving directions. Furthermore, the system was also tested with motions that ensure adequate tracking when reaching hyper flexion/extension, hyper abduction/adduction and full elbow flexion of the arm. During tests a total of 60 samples were collected which showed a 4cm average root mean squared error on the elbow position and a 10cm average root mean square error on the wrist position. A simple arm motion measurements are illustrated in Figs. 7-9 with elbow and wrist coordinates comparison as well as overall 3D motion trajectories. The observed slight timing mismatch in the graphs is due to the fact that the data was measured at different rates by the two systems in parallel. In general, the upper arm quaternion measured by the proposed system is very similar to those of the Xsens, therefore, the correlation between the measured elbow positions is very high. At the same time, the wrist positions differ more. This is attributed to the mismatched initialization. The elbow might not be fully extended during the T-pose, i.e. $\theta_0 \neq 0$. Nevertheless the Xsens sensor would initialize it as a full extension, whereas the potentiometer sensor, utilized in the proposed system, initializes closer to the true extension.

It was observed that the system performance was generally deteriorated during rapid accelerations and near full elbow flexion. It is common for rapid accelerations to have a negative effect on inertial tracking systems since the UKF process noise is tuned for medium accelerations. This problem could be solved by adaptive noise settings as proposed in [18]. Meanwhile, the accuracy drop near full flexion of the arm is attributed to an imperfect mechanical state of the system. It is planned to redesign the tracker casing aiming to improve the system reliability and make it more user friendly.

The arm tracking is also visualised in the Blender Game Engine in real-time as presented in Fig. 10 and the demonstration video available at `www.alaris.kz`. This makes the proposed system a suitable basis for further use with interactive software for post-stroke rehabilitation therapies.

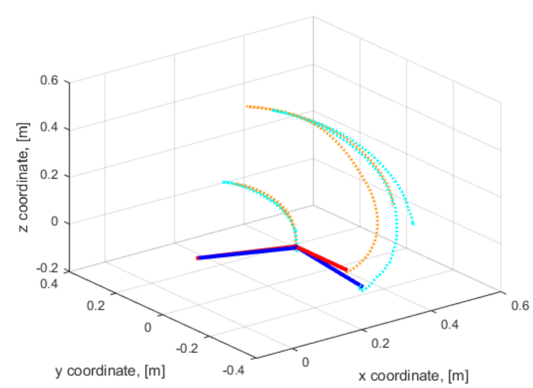

Fig. 9. Arm trajectory comparison: blue/cyan lines represent 4-DOF arm tracker, red/orange - Xsens MVN suit. Solid lines represent arm segments, doted lines - trajectories.

V. Conclusion and Future Work

Overall it can be stated that the proposed system adequately tracks human arm motions and can be used to substitute more expensive upper limb motion tracking systems. The measurements obtained by the prototype UM7-LT IMU sensor and processed through the UKF were sufficient to produce accurate upper arm quaternions. At the same time, a simple potentiometer sensor was used to track the elbow

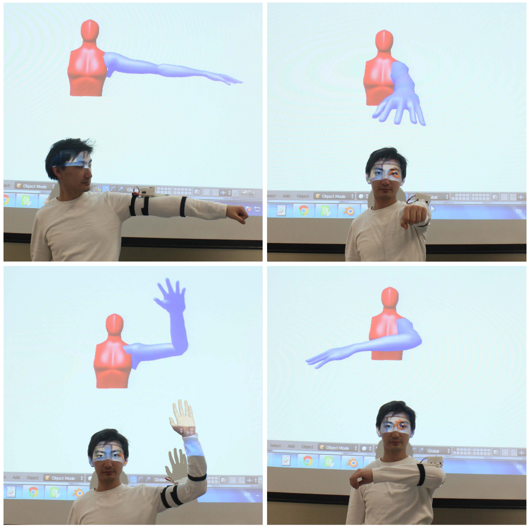

Fig. 10. Real-time arm tracking visualisations with Blender software

joint rotation. Combining both upper arm quaternions and elbow joint angles, the elbow and wrist positions are tracked. The proposed 4-DOF wireless arm tracker performance was validated with the Xsens MVN motion tracking suit. Additionally, the Blender Game Engine was used to visualise arm motions in real-time.

The authors plan to redesign the mechanical part of the system with higher reliability and user friendliness in mind. The updated design will ensure precise alignment of the tracker system with the arm elbow joint. Furthermore, since the UM7-LT IMU has a number of redundant features it will be replaced with a lower cost alternative in order to reduce the overall cost of the system down. More sensors can be added to allow tracking of palm motions, torso and head motions. Finally, it is planned to build on the Blender visualisation and produce software applications for post-stroke rehabilitation and entertainment.

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