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Real-time estimation of upper limbs kinematics with IMUs during typical industrial gestures

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Abstract

In the context of Industry 4.0, collaborative robotics can be improved by implementing appropriate reactive behavior schemes between human and the robot within the shared workspace. Inertial Measurement Units (IMUs) are widely used for real-time capturing of the human motion in clinical and sports applications, while less attention has been dedicated to IMUs for human-robot interactions in manufacturing industrial field. The aim of the present study was to validate an IMU-based method for real-time estimation of upper limbs kinematics during typical gestures required for industrial assembly tasks. To avoid ferro-magnetic disturbances typical of manufacturing environments, the magnetometers were excluded from the estimate of IMUs orientations. Shoulder and elbow angles were assessed in real-time during pick and place tasks through three IMUs fixed on the upper body of six participants. Results were validated through a stereophotogrammetric motion capture system. Errors associated to the proposed method were moderate and amounted to 2.4 and 3.5 deg on average for shoulder elevation and elbow flexion-extension angles, respectively, confirming their suitability for an industrial context of human-robot collaboration.

Keywords: IMU, Industry 4.0, human-robot collaboration, sensor fusion, joint kinematics, inertial, stereophotogrammetry

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1. Introduction

The concept of automation promoted by the fast technological development of Industry 4.0 can be realized supporting workers with robotic systems. In this context, the human-robot collaboration has become an emerging research field focused on optimizing the performance, effectiveness, and applicability of human–robot systems [1]. The required coexistence of human and robot in the same workspace entrusts a key role to safety. In detail, collisions with static and dynamic obstacles can be avoided though the integration of the robot with sensors recording and processing human motion [2]. However, safety is not enough to guarantee an optimal human-robot collaboration. Indeed, an appropriate reactive behaviour can be developed by both the human and the robot to improve the collaboration performances [3]. This operation requires the tracking of the human motion, which is usually performed with vision devices such as stereophotogrammetric systems and RGB-D cameras [4]–[7]. Despite their high accuracy, these systems are not ideal for many industrial contexts because they suffer from occlusion, encumbrance, low output data rate (RGB-D cameras) and long times of set-up and calibration.

The recent diffusion of micro-electro-mechanical systems has promoted the development of wearable motion capture technologies such as Magneto-Inertial Measurement Units (MIMUs), which are portable, easy to wear, low-cost and non-invasive. In addition, they do not suffer from problems such as occlusion, limited working range and long preparation and computational times. Accordingly, MIMUs have become important tools for the real-time capturing of the human motion in different contexts such as clinics [8], sport [9], and industry [2]. Concentrating on the manufacturing field, wearable sensors have also been adopted to identify the most significant features of human upper limbs motion, to distinguish among different gestures and consequently to improve the human-robot collaboration [10]–[12]. To this end, the accurate estimation of the human upper limb joint kinematics is fundamental.

A MIMU typically integrates on a single chip a triaxial accelerometer, a triaxial gyroscope, and a triaxial magnetometer. The complementary information provided by these three sensors can be exploited by means of a sensor fusion algorithm [13] to estimate the absolute orientation of the MIMU. The global coordinate system is generally defined with the vertical axis aligned along the gravity direction and one horizontal axis aligned with the projection of the Earth's magnetic field on the horizontal plane. To estimate the orientation, the first step consists in integrating the gyroscope readings over time, given the initial conditions usually set considering the accelerometer and magnetometer readings only during a static part at the beginning of the recording [14]. However, this operation leads to an orientation drift which grows unbounded over time since the angular velocity readings are affected by a slow-varying bias. To compensate for this drift, the information provided by the accelerometer and the magnetometer is employed to limit the drift in the inclination (i.e., roll and pitch angles) and in the declination (also known as yaw angle or heading). However, when data are collected in a manufacturing environment, the magnetometer readings cannot be considered a reliable source of information due to the high amount of ferromagnetic disturbances [15]. When excluding the magnetometer readings from the sensor fusion process, the drift occurring around the vertical axis can no longer be compensated for. Furthermore, the relative orientation on the horizontal plane among two or more units, fundamental to estimate the segment pose and consequently the joint kinematics, is unknown. To overcome these limitations, several studies have been proposed by the community of the human motion analysis to estimate the lower limb joint kinematics using only the IMU signals with additional biomechanical constraints and specific calibration procedures for clinical applications, e.g. [16]–[19]. However, less attention has been devoted to the estimation of the upper limbs kinematics based on inertial sensors only (IMUs) in the manufacturing environment.

The aim of the present study was to adopt and validate IMUs for the real-time estimation of upper limbs kinematics during typical industrial motor tasks. Six healthy young right-handed subjects performed 15 "pick and place" tasks at different heights. Three IMUs positioned on the trunk, upper arm and forearm of participants were used to estimate in real-time the shoulder elevation angle and the elbow flexion-extension angle. Results obtained from IMUs were validated through a stereophotogrammetric motion capture system (SP).

2. Materials and Methods

2.1. Participants

Six healthy young right-handed participants (5 males, 1 female) with no musculoskeletal or neurological diseases were recruited for the experiment through a written informed consent. Subjects' anthropometric data were estimated (mean ± standard deviation): age = 24.5 ± 2.3 years, mass = 75.0 ± 13.5 kg, upper arm length = 0.280 ± 0.037 m, forearm length = 0.283 ± 0.014 m, trunk length = 0.512 ± 0.044 m, acromions distance = 0.362 ± 0.023 m. The study was approved by the Local Institutional Review Board and all procedures were conformed to the Helsinki Declaration.

2.2. Instruments

The instrumentation adopted for the experiment consisted in an IMU-based system (Xsens, The Netherlands) and a SP system (OptiTrack, USA).

The inertial system was composed of three Xsens MTx IMUs, each of them containing a tri-axial accelerometer (range ± 50 m/s^2), a tri-axial gyroscope (range ± 1200 dps), and a tri-axial magnetometer (range ± 75 μT). IMUs were positioned on the participants' upper body using elastic bands supplied by the Xsens kit (Fig. 1): right forearm (RFA), right upper arm (RUA) and thorax (THX). Each unit was fixed manually aligning its long x-axis with the longitudinal axis of the corresponding segment. The communication between IMUs and a PC was established via Bluetooth. Data were acquired through the Xsens proprietary software MT Manager at 50 Hz.

The SP system was composed of an OptiTrack V120:Trio tracking bar and fourteen passive reflective markers (diameter of 14 mm). The bar was self-contained, pre-calibrated, and equipped with three cameras able to detect infra-red light. Markers were positioned on participants' upper body, on styloid processes, humerus condyles, acromions, thorax (T8 and IJ), RFA-IMU and RUA-IMU (Fig. 1). The bar was placed in front of the working table and connected to a PC. Data acquisition was made through the software Motive at 120 Hz.

2.3. Protocol

The test was conducted indoor. The setting was composed of a working table for pick and place tasks and a chair. Reference silhouettes of right and left human hands were drawn on the table, with thumbs 22 cm apart. In addition, a cross was marked in the middle between the hands' silhouettes. Subsequently, three colored boxes of the same size were placed on the right side of the table at different heights: a white box on the table, a black one at a height of 18 cm from the table, and a red one at a height of 28 cm from the table (Fig. 1). The three IMUs were turned on five minutes before the experiments to perform a warm-up period to limit the temperature effect on the angular velocity readings. After that, a static acquisition with the IMUs still on the table was recorded to capture the gyroscope bias to be removed from the dynamic acquisitions.

Subjects were first asked to sit on the chair and to position hands in correspondence of the silhouettes marked on the table. This seated neutral position was maintained for 10 s to allow the skeleton calibration by exploiting the gravity direction. The dynamic test consisted of 7 operations: 1) Assume the neutral position, 2) Pick one of the three boxes according to a randomized sequence, 3) Place the box over the cross marked on the table, 4) Return in the neutral position, 5) Pick the same box, 6) Reposition the box in its initial position, 7) Return in the neutral position. During the tests, subjects were asked to move the trunk as less as possible to focus the analysis only on the right upper limb. For all participants, the pace of the task was imposed by a metronome set to 45 bpm. Each subject performed a randomized sequence of 15 consecutive gestures of pick and place, 5 for every box.

2.4. Signal processing and data analysis

Signals of IMUs and markers trajectories recorded during the experimental session were synchronized in time by using an external trigger. Moreover, markers trajectories were improved through a filling gap process. Angular conventions to calculate shoulder and elbow angles were chosen in accordance with the guidelines of the International Society of Biomechanics [20].

Considering industrial applications of collaborative robotics, the estimation of the shoulder and elbow kinematics from IMUs was designed to be executed in real-time. Preliminary, the acquisition with the subject in the neutral seated position was exploited to mathematically realign the coordinate system of the IMU placed on the THX along the gravity direction to compensate for manual misalignments between the IMU and anatomical axes. The first step consisted in estimating the orientation of the IMUs on THX, RUA, and RFA, separately. To this end, the sensor fusion algorithm from Madgwick *et al*., 2011 [21] was chosen to fuse the inertial signals because of its low execution time [13]. The work from Caruso *et al*., 2020 showed the importance of properly tuning the parameter values according to the experimental scenario under analysis [22]. Based on the magnitude of the segment accelerations and the slow pace, the value of the single sensor fusion parameter was set to 0.01 rad/s to include the accelerometer readings in the fusion process considered as a reliable source of information. The orientation of each IMU was initialized at the first time-step using the algebraic quaternion as defined by Valenti *et al* [14]. As stated in the introduction, the relative orientation on the horizontal plane among the three IMUs was unknown because of the absence of the magnetometer measurements. To overcome this limitation, the standardized manual unit-to-body segment alignment was exploited. Then, for each joint of interest, the orientation of the distal IMU was expressed with respect to the local coordinate system of the proximal IMU. This relative orientation was then decomposed into the triplet of Euler angles following the same convention used for the SP to obtain the time series of the shoulder elevation and elbow flexion-extension angles.

To evaluate the accuracy of the estimates, the root mean square of the difference (RMSD) between kinematics as obtained by the IMU and SP was computed after removal of their eventual offset to enable a direct comparison [23]. Finally, the average execution time for a single iteration of the loop above described was measured for an Intel ® Core™ i7-10510U CPU @ 1.80 GHz (Intel ©, Santa Clara CA, U.S.A.) – Microsoft™ Windows 10 when processing a dataset of 6965 samples without executing any other applications.

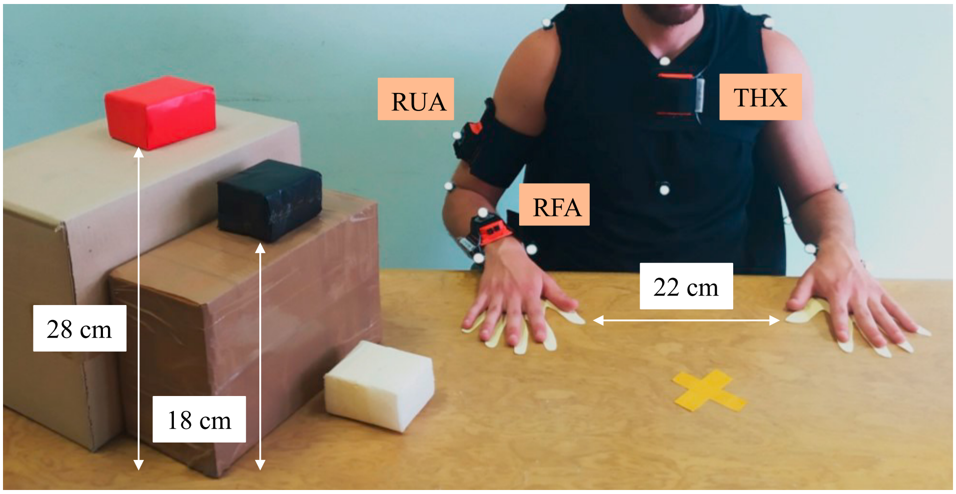

Fig. 1. Setting of the experiment with the positioning of MIMUs and markers on subjects' upper body.

3. Results

The intra-subjects errors (RMSD) of the shoulder elevation and the elbow flexion-extension angles obtained for the six subjects are reported in Table 1. Moreover, inter-subjects mean and standard deviation values of the errors are indicated. As an example, the time series of the shoulder elevation and the elbow flexion-extension angles obtained with both IMU and SP systems (without their offsets whose difference amounted to 10.2 deg and -6.3 deg for the shoulder and the elbow, respectively) can be observed in Fig. 2 for subject 04. The average execution time of a single loop iteration needed to estimate the orientation of the three IMUs and to compute the shoulder and elbow joint angles amounted to 0.109 ± 0.018 ms.

Table 1. Intra-subject and inter-subjects errors of shoulder and elbow joints angles (deg) obtained from IMUs with respect to the SP system.

RMSD (deg)	Shoulder elevation	Elbow flexion-extension
Subject 01	2.0	3.5
Subject 02	4.4	4.3
Subject 03	1.8	1.9
Subject 04	2.6	2.8
Subject 05	1.4	3.7
Subject 06	2.1	4.9
Mean (standard deviation)	2.4 (1.1)	3.5 (1.1)

4. Discussions

According to this analysis, the proposed IMU-based method can be considered a suitable solution to estimate the joint kinematics of the shoulder and elbow in an indoor environment without using the magnetometer data. Indeed, as pointed out by McGinley *et al*., 2009 in [24], systems estimating the joint kinematics can be considered acceptable with RMSD errors lower than 5 deg and excellent with RMSD lower than 2 deg. In this work, the maximum RMSD amounted to 4.9 deg for the elbow, and on average errors were equal to 2.5 and 3.5 deg for the shoulder and the elbow angles, respectively. Furthermore, the variability of the errors was limited to about 1.1 deg.

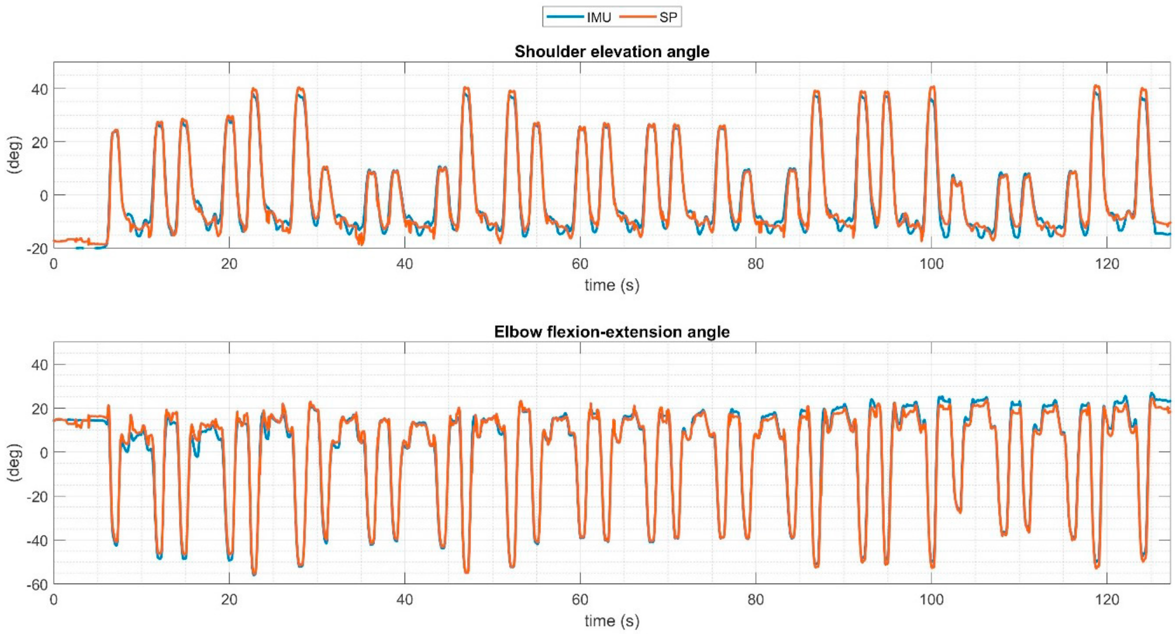

Fig. 2. The time series of the shoulder and elbow kinematics obtained with the IMU (blue) and SP (red) systems are represented for the subject 04, as an example.

By observing Fig 2, it is possible to qualitatively appreciate that the waveform of the two time series are very similar after the removal of their mean values, whose discrepancies can be justified by a different definition of the anatomical axes for the IMU and SP systems [23]. In particular, the definition of the axes for the former relies on the manual alignment of the IMUs along the segment longitudinal axis and this simple procedure, although effective for reducing subject preparation time, inevitably leads to differences in the estimates when compared to the marker-based one. Alternative approaches have been proposed in the literature to provide a closer estimate of the anatomical axes. These methods include the functional approach, where subject are asked to perform pure movements around one anatomical axis at a time, or the sensor-to-segment alignment using additional instruments [25]. Since these approaches are more time-consuming, they can be implemented before the data acquisition in manufacturing contexts where rapidity for subject preparation does not represent a fundamental requirement.

As Fig. 2 shows, the amplitude of joints angles differs according to the height of the performed pick and place gesture (low, medium, high). Previous studies have exploited IMUs signals to classify the gestures through an algorithm based on mean and standard deviation values [11] or through Linear Discriminant Analysis [12]. The present study suggests improving the classification procedure also considering joints angular trends in addition to IMUs signals. Indeed, since the time needed for a single iteration is far below the sampling period (≈ 0.100 ms vs 20 ms), the proposed method is suitable for a real-time estimation of the joint kinematics. This aspect could be also exploited to perform a real-time identification of the gesture based on both IMUs accelerations and joints angles.

5. Conclusions

The present study aimed at validating IMUs for the real-time estimation of upper limbs kinematics during typical industrial gestures of pick and place. Results demonstrate that the proposed IMU-based method for the assessment of the shoulder and elbow angles is adequate to the industrial context for different reasons. First, the adoption of IMUs instead of vision systems guarantees portability and wider working ranges, and it reduces the preparation and computational times. Then, ferromagnetic disturbs typical of a manufacturing environment can be avoided because the estimate of IMUs orientation is ensured excluding the magnetometer. Finally, the possibility of obtaining in real-time both the human kinematics and the classification of the human gesture can be exploited to develop control algorithms for the robot and consequently to improve the human-robot collaboration in a shared workspace.

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