Device and method for the biomechanical analysis of articular amplitude using micro-sensors for the measurement of movement

Mauro Callejas-Cuervo[1]*, Juan C. Alvarez[2], Diego Alvarez[2]

[1]*Faculty of Engineering, Pedagogical and Technological University of Colombia, North Central Avenue 39 – 115, Tunja, 150001, Colombia*
[2]*Department of Electrical and Computer Engineering, University of Oviedo, Viesques, Ed. 2, 33204, Gijón, Spain*

*Corresponding author: Tel: (+57) 302111960; E-mail: mauro.callejas@uptc.edu.co

DOI: 10.5185/amlett.2019.1909
www.vbripress.com/aml

Abstract

The present article describes the creation and operation of a device for biomechanical analysis, which is portable, precise, non-invasive, and which allows us to autonomously obtain the position, orientation and measurement of the articular amplitude of two body segments connected by a joint. The above is carried out with data obtained from a number of inertial and magnetic microsensors. The device, through the application of a series of methods, allows the recording of the movements made by a person while they go about their daily activities without the need of including a computing system that operates it. This can be done in real time or delayed-mode, and for long periods of time, depending on the battery charge of the device. Copyright © 2019 VBRI Press.

Keywords: Microsensors, biomechanical signals, measurement of movement, articular amplitude.

Introduction

In the framework of the capture of human movement, from the point of view of engineering, biomechanics studies the behaviour of the human body, with the purpose of understanding the mechanics of normal and pathological movement, in addition to diagnosing and treating patients with motor deficiencies in order to improve their wellbeing and performance according to their diverse interests and circumstances.

In medicine, as in other areas, knowing with a high precision the movement of healthy and unhealthy people is very useful for the diagnosis, monitoring and understanding of disorders and pathologies, as well as of capabilities and limitations. In sports medicine [**1-3]** it is important for monitoring movement with the aim of improving performance or analysing problems that may cause future injuries.

In occupational therapy, it is useful for the evaluation of activities so as to reduce the impact of injuries due to a bad posture [**4-6**]. In veterinary medicine, it can be used for rehabilitation and the evaluation of movement in animals [**7-9**]. It can also be used in designing active video games [**10-12**], in the recreation or construction of animated silhouettes from human movement, among other uses.

This research presents a new device that is capable of obtaining data on the position, orientation and measurement of the angular amplitude of a human articular system. To this end, a number of inertial and magnetic microsensors are used, which are located in each segment joined by an articulation, allowing each microsensor to contain information on its own global and local frame of reference and thus being able to reproduce a three-dimensional movement in a precise way, along with the measurements of the orientation and the independent position between segments. In addition, a non-linear estimator was used, based on the Unscented Kalman filter, which is applied for each of the measurements given by the microsensors that the research uses in order to obtain information and to be able to calculate with precision the position, orientation and joint measurement. The device also has a data storage system related to the movements generated by a person performing their daily activities, which is integrated into a control unit and allows the instrument to maintain its utility as an independent and ambulatory device, which can be directly operated by a computer system remotely.

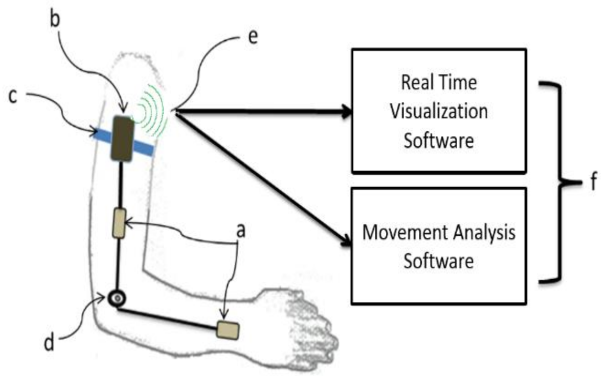

Fig. 1. Inertial and magnetic capture platform.

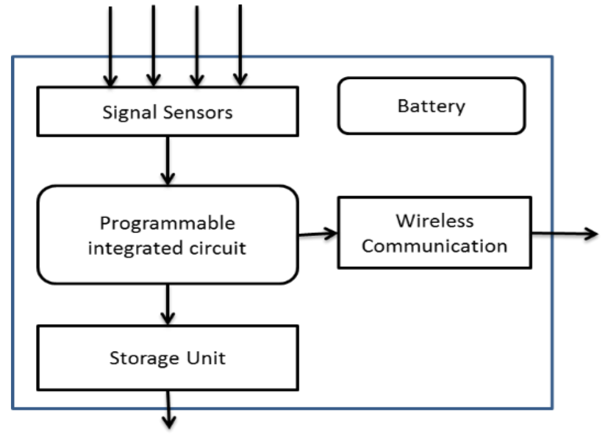

Fig. 2. Control unit.

Experimental

Description of the Device

With the purpose of obtaining the information about the position and orientation, and calculating the articular amplitude between two body segments, a portable, precise, non-invasive device, shown schematically in the **Fig. 1**, has been created, composed of a number of inertial and magnetic microsensors integrated in two MEMS (Microelectromechanical System), selecting a 3-axis accelerometer, a 3-axis magnetometer and a 3-axis gyroscope, among others.

The units integrated with the microsensors (**Fig. 1a**), are fixed to the outer side of the arm; the first, between the shoulder and elbow joint, avoiding muscular tissues that add movement to the sensor; the second should be placed in the region between the radial styloid and the ulnar styloid, aligned with the outside of the hand; these units can be fixed to the skin with double sided adhesive medical tape or with Velcro (**Fig. 1c**), so that their initial orientation does not change with the movement of the body segments. The communication between these units is carried out through a conductive wire embedded in a retractable device (**Fig. 1d**), which allows the adjustment of the location where the units are fixed to the skin; the data from the microsensors is sent to a control unit (**Fig. 1b**), which sends the data, transformed into information, to a visualization software product (which can be viewed in real time or stored for later analysis, **Fig. 1f**), through a wireless communication protocol (**Fig. 1e**).

The axes of the units that contain microsensors are aligned with a global reference system, defined by: the direction of the anatomical axis X points upwards, the direction of the anatomical axis Y points forward and the direction of the anatomical axis Z runs parallel to the Earth’s surface.

In the **Fig. 2**, the physical components integrated in the control unit are specified, among which can be found; an input port for signals originating from the microsensors, a programable integrated circuit for data processing, a storage unit, a communication unit, and a power supply system.

Detailed description of the process

The inertial and magnetic microsensors detect all types changes to them, as well as the atmospheric noise. For example, the magnetic sensor should always register magnetic north. However, there are other sources of magnetism that may affect the signal, thus altering the measurement results. For that reason, the control unit (**Fig. 2**) transforms the position, orientation and articular measurement data, through the application of signal transformation algorithms, into angles (See **Fig. 3**). This is done with high precision thanks to the application of algorithms based on an Unscented Kalman filter, which allows for the reduction of the noise which affects the signal of the sensors. The process is implemented as follows:

1. The model is framed in the state-space representation for the non-linear system, which includes the elements of the articular system, to which the uncertainties inherent to this model are incorporated.
2. The observation model which incorporates the measurements of the inertial and magnetic microsensors is outlined.
3. The microsensors send all the signals to the control unit, including the noise added by the process. There, the system calculates and identifies the most probable signals that coincide within the statistical distribution for each one of the models previously defined. These selected points are known as sigma points.
4. To the models described in steps 1 and 2, the Unscented Transform is applied and the measurements and covariances generated by the model in the state-space representation and the observation model are calculated.
5. The cross-covariance between the model in the state-space representation and the observation model is calculated in order to finally calculate the Kalman gain, and the state and the covariance are updated. Steps 3 to 5 are repeated until obtaining the readings of all of the measurements that the articular system has generated.

6. Once the cleaned data has been obtained, a biomechanical model is applied, which corresponds to the movements of the articular system that is be to analyzed, for example:
   - Flexion/extension, which are defined as a rotation around axis Z.
   - Pronation/supination, which are defined as a rotation around axis X.
   - Abduction/adduction, which are defined as a rotation around axis Y.

   After applying the biomechanical model and obtaining the angles of rotation, the position, orientation and measurement of the amplitude of the articular system are obtained.
7. Finally, with this information obtained, it is then transmitted to software through a wireless communication protocol and/or is saved in the storage unit incorporated in the control unit. The information can be presented to a final user in real time using software and/or sent directly to specialized software for its later analysis and evaluation.

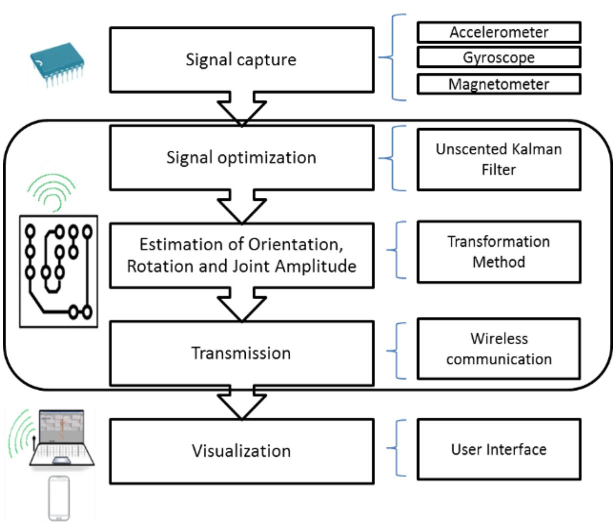

Fig. 3. Flow of the transformation of signals into understandable information for the final user.

Results and discussion

Description of the results

The result of this research is a device to measure the amplitude of an articular system and to digitize the signals issued by the microsensors, autonomously and self-reliantly, and which are integrated by a 3-axis gyroscope with variable sensitivity from 16.4 (LSB/dps) to 131 (LSB/dps), a 3-axis accelerometer with a programmable range from 2 up to 16 g's, and a 3-axis magnetometer with a scale between 800 to 1600µT. In addition, it contains a programmable integrated circuit with a reading capacity of between 8 to 128 bits, and a flash memory that may range from 8 to 512 Kb, SRAM from 8Kb to128 Kb.

Apart from the device, a method is developed to measure the amplitude of an articulated system that employs the following phases:

- The inertial and magnetic microsensors send all the signals to a programmable integrated circuit.
- The programmable integrated circuit combines the data and filters the noise and uncertainty that comes from the inertial and the magnetic sensors.
- The programmable integrated circuit applies a biomechanical model to the corrected signals.
- The information is recorded in the data storage unit.
- The data is exported through a wireless communication module to a visualization device.

Validation tests

A validation process of the sensors' network, used in the created platform and compared to an industrial robotic arm ABB IRB 120, was performed (**Fig. 4**).

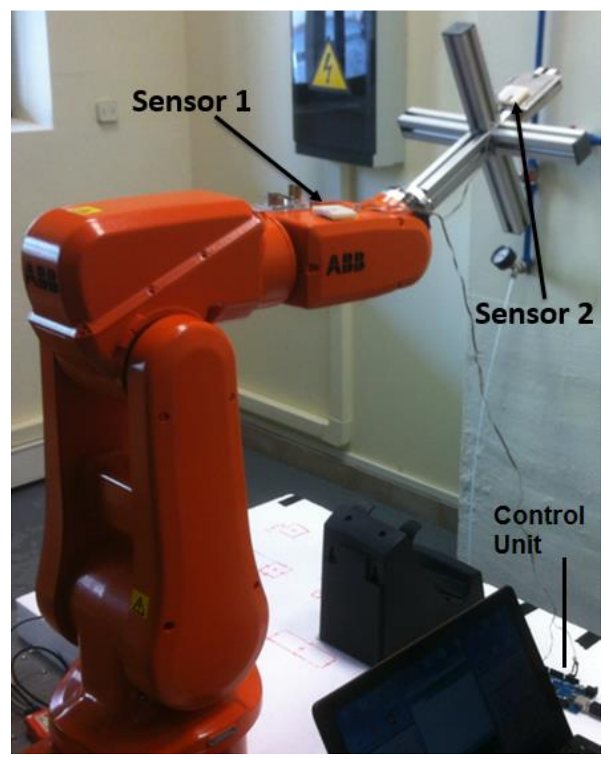

Fig. 4. Test platform (Robot and sensors).

A series of movements performed by the industrial robot were set and monitored by the inertial and magnetic device. Such movements were programmed to start in position 0º and to move to 30º, 60º and 80º. In each repetition, the arm returns to position 0º, with a +/- 2 second delay in each angular-motion shift.

In [**13**], it is shown that the method of data capture with the inertial and magnetic system properly follows the trajectory proposed by the reference system. The validation of the angular measurements of the inertial and magnetic systems, compared to the one recorded by the industrial robot, shows a difference of 2.19° in the flexion/extension movements and a difference of 2.75° in the pronation/supination movements. Even so, the platform is robust enough to capture and analyze biomechanical information.

Conclusion

The innovation development process, in its different basic, technical and practical aspects, makes the device an easily scalable tool, that is, that it has the capacity to capture the movement of any articulation of a human and animal body, and of objects in diverse scenarios and applications. It is important to mention that this scalability depends on adjustments and developments of the biomechanical model, but not on conceptual or structural changes to the product, given that the data generated remains the same (acceleration, angular velocity and magnetic north).

Starting from the point that the movement capture product developed is efficient and adaptable to different fields, it is important to highlight its usefulness in areas such as artificial intelligence and robotics, since, through the automation of the movements carried out by an object, it will be possible to infer certain behaviours conducive to predicting and consequently correcting or optimizing the actions of the object prior to their execution, constructing an agile feedback process, and designing an object that is autonomous and self-reliant in its movements.

Acknowledgements

This work was supported by the laboratory Multisensor Systems and Robotics of the University of Oviedo (SIMUR) and the Software Research group GIS from the Pedagogical and Technological University of Colombia UPTC.

Author's contributions

All authors contributed in each of the stages of project development (literature search, system architecture design, hardware and software testing). Authors have no competing financial interests.

References

1. Chambers, R.; Gabbett, T.J.; Cole, M.H.; Beard, A., *Sports Med.*, **2015,** *45*, 1065.
   DOI: 10.1007/s40279-015-0332-9
2. Herbort, M.; Domnick, C.; Raschke, M.J.; Lenschow, S.; Förster, T.; Petersen, W.; Zantop, T., *Am. J. Sports Med.*, **2016**, *44*, 126.
   DOI: 10.1177/0363546515611646
3. Ghasemzadeh, H.; Loseu, V.; Jafari, R., *J Ambient Intell Smart Environ*, **2009**, *1*, 173.
   DOI: 10.3233/AIS-2009-0021
4. Valero, E.; Sivanathan, A.; Bosché, F.; Abdel-Wahab, M., *Appl. Ergon.*, **2016**, *54*, 120.
   DOI: 10.1016/j.apergo.2015.11.020
5. Cutti, A.G.; Chadwick, E.K., *Med Biol Eng Comput.*, **2014**, *52*, 205.
   DOI: 10.1007/s11517-014-1143-0
6. Umer, W.; Li, H.; Szeto, G.P.Y.; Wong, A.Y.L., *J Constr Eng Manag.*, **2017**, *143*, 1.
   DOI: 10.1061/(ASCE)CO.1943-7862.0001208
7. Nadimi, E.S.; Jørgensen, R.N.; Blanes-Vidal, V.; Christensen, S., *Comput. Electron. Agric.*, **2012**, *82*, 44.
   DOI: 10.1016/j.compag.2011.12.008
8. Kumar, A.M; Hancke, G.P., *IEEE Sens. J.*, **2015**, *15*, 610.
   DOI: 10.1109/JSEN.2014.2349073
9. Nogami, H.; Arai, S.; Okada, H.; Zhan, L.; Itoh, T., *Sensors*, **2017**, *17*, 687.
   DOI: 10.3390/s17040687
10. Böhm, B.; Hartmann, M.; Böhm, H., *Games Health J.*, **2016**, *5*, 189.
    DOI: 10.1089/g4h.2015.0058
11. Velasco, M.A.; Raya, R.; Muzzioli, L.; Morelli, D.; Iosa, M.; Cincotti, F.; Rocon, E., Evaluation of Cervical Posture Improvement of Children with Cerebral Palsy After Physical Therapy with a HCI Based on Head Movements and Serious Videogames; In Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics, Ortuño F., Rojas I. (Eds.); Springer, Cham, **2016**, 495.
    DOI: 10.1007/978-3-319-31744-1_44
12. M. Callejas-Cuervo, M.; Díaz, G.M.; Ruíz-Olaya, A.F., *DYNA-Colombia*, **2015**, *82*, 68.
    DOI: 10.15446/dyna.v82n189.42066
13. Callejas-Cuervo, M.; Alvarez, J. C.; Alavarez, D., Capture and analysis of biomechanical signals with inertial and magnetic sensors as support in physical rehabilitation processes, in Proceedings of the 13th International Conference on Wearable and Implantable Body Sensor Networks (BSN), IEEE (Eds.); **2016**, 119.
    DOI: 10.1109/BSN.2016.7516244