Inertial Measurement Units: A Brief State of the Art on Gait Analysis

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***Abstract*— Gait analysis systems are monitoring systems that establish a symbiosis relationship with Ambient Assisted Living (AAL) environments. Human locomotion analysis has a very important role always aiming at improving the quality of life both for individuals needing treatment or rehabilitation, as well as for healthy and elderly people. In fact, a deep and detailed knowledge about gait characteristics at a given time, and not least, monitoring and evaluating over time, will allow early diagnosis of diseases and their complications, and contribute to the decision of the treatment that should be chosen. There are several techniques used for gait measuring such as: Image Processing, Floor Sensors, and Wearable Sensors. Among the wearable sensors, has emerged an electronic device that combines multiple sensors designated by Inertial Measurement Unit (IMU). This device measures angular rate, body's specific force, and in some cases the magnetic field, and this information may be used to monitor human gait. In this article, the aim is: i) to verify the sensors that build up the IMUs, and the resulting designations that the device may have depending on the sensors it contains; ii) to list the applications of the IMUs on gait analysis; iii) to be aware of the devices available on the market and the associated commercial brands; and iv) to list the advantages and disadvantages associated with the device compared to other gait analysis systems. Concerning the literature in the scientific community, although there are some studies that focus on gait analysis or IMUs, none of them aggregates the purposes that will be addressed in this article.**

Keywords*— *Inertial Measurement Units (IMUs), gait analysis, and ambulatory assessment.

I. Introduction

Gait analysis involves measurement, description and assessment of quantities of gait parameters that characterize human locomotion [1], [2]. In order to quantify these gait parameters, there is a set of several techniques [3] used for gait measuring: (1) Image Processing where a map of distances from a viewpoint is calculated by a collection of technologies such as Stereoscopic Vision (camera triangulation), Time-of-Flight Systems (ToF), Structures Light, Infrared Termography (IRT) and Laser Range Scanner. Important elements of the image with a better and faster real-time process are obtained by these techniques. (2) Floor Sensor where sensors are placed along the floor on the force platforms. Force platforms and pressure measurement systems are two types of floor sensors in which gait is measured by pressure or force sensors and moment transducers when the subject walks over them. (3) Wearable Sensors which includes, e.g., pressure and force sensors, accelerometers, gyroscopes, active markers, extensometers, inclinometers, goniometers, ultrasonic sensors, IMUs, and electromyography (EMG). These are placed on various parts of the patient's body to measure different characteristics of the gait.

A. Wearable Sensor Units and IMUs

Wearable sensor units are a type of monitoring systems that reveal an extreme potential to monitor ambulatory activities in the home environment, and can establish a symbiosis relationship with AAL environments that is truly promising [4],[5],[6]. Considered as continuous and ambulatory, wearable sensor units have an outstanding importance in: 1) the detection of risk situations such as fall detection in elderly patients [6]; 2) the process of rehabilitation in injured patients, generating input for health interventions (real-time personalized feedback), design of treatment plans, and follow-up monitoring [7]; and 3) the diagnosis and treatment of patients with neurological diseases [8].

An IMU can be described as an electronic device that can combine multiple sensors such as accelerometers, gyroscopes, and magnetometers. This electronic device may be equipped with an antenna (wireless technology), or a secure digital (SD) card or even an output pin logged by wire to a base station. IMU is the most common designation for this electronic device [9], [10], [11]. However, when a magnetometer is present, some authors used other designations: magnetic/inertial measurement unit (MIMU) sensor [12] or even magnetic angular rate and gravity (MARG) sensor [13]–[15]. Thus, in this article the term IMU is the general designation to mention IMU, MIMU or MARG sensors.

B. Constitution of the IMUs

Basically, the three sensors mentioned above are the commonly used in IMUs for gait analysis. This happens because they are important sensors for obtaining relevant data to this type of analysis. In particular, an accelerometer is a type of inertial sensor that can measure acceleration along its sensitive axis and can also be classified as either a mechanical or solid state device [1],[16]. A mechanical accelerometer consists of a mass suspended by springs. The displacement of the mass is measured using a displacement pick-off, giving a signal that is proportional to the force acting on the mass in the direction of the input axis. The mass proof can be forced to deflect by the inertial force because of acceleration or gravity according to Newton's Second Law [1], [16], [17]. Solid state

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accelerometers establish a set of various sub-groups that includes surface acoustic wave, vibratory, silicon and quartz devices. They are characterized as small, reliable and rugged [16]. Technically, they are often used to obtain physical activity levels. Accelerations during walking, gait cycle time and number of walking steps can be determined using several accelerometers affixed to the subject. Motion activated functions, free-fall detection, pedometer, display orientation and vibration monitoring and compensation are a few applications this device can perform [10], [17].

In turn, a gyroscope is a spinning wheel or disc in which the axis of rotation is free to assume any orientation by itself. When rotating, the orientation of this axis is unaffected by tilting or rotation of the mounting, according to the conservation of angular momentum. For this, gyroscopes are useful for measuring or maintaining orientation and can be considered as an angular velocity sensor. It can be applied for the measurement of the motion and posture of the human segment in gait analysis by measuring the angular rate, angle of various joints and the flexion angle (integration of the angular rate) [1], [4], [10].

IMUs can also be equipped with magnetic field sensors. This is a device capable to detect and measure magnetic fields. Its operating principle is based on detecting effects of the Lorentz force which may be measured electronically with a change in voltage or resonant frequency or measured optically with a mechanical displacement [18]. Although the necessary concern with the compensation for temperature effects, advanced electronics are used to improve the sensitivity. So, these instruments have medical and biomedical applications, and implemented in an IMU it is mostly used to assist calibration against orientation drift. This allows better performance for dynamic orientation calculation and can be used in multiple applications such as reference measure for body orientation or earth gravity field, compass sensors, linear/rotary position, speed measurement and current sensing [18].

C. *Study Importance and Objectives*

Concerning the literature in the scientific community, although there are some studies that focus on gait analysis or IMUs, none of them aggregates in the same article the devices available on the market, the applications of the IMUs on gait analysis, and their advantages and disadvantages. So, as already mentioned in the abstract, the purpose of this paper is to collect all this information regarding gait analysis and IMUs. Thus, the article pretends to be a good and up-to-date search start for all stakeholders. The remainder of this paper is organized as follows: in Section II the IMUs' applications used in the literature are presented; in Section III the commercial products and brands are reviewed; Sections IV and V present, respectively, the advantages and disadvantages of IMUs and conclusion.

II. Applications of IMUs

In areas like mobile robots, IMUs are frequently used to improve odometry or for flight stabilization or autonomous hovering of helicopters or quadrotors. Moreover, this type of sensors is widely used for localization of airplanes and miniature indoor blimps. However, with regards to the monitoring of the human being, IMUs can be integrated into clothes, shoes or even used with Velcro straps [9], [10]. This way, IMUs enable full 3D location/orientation information and full-body motion capture [9]. So, IMUs show a vast number of applications in this kind of monitoring, allowing, for example [3], [19]: (1) Gait symmetry and gait normality measurements [20]. (2) Creation of fall-risk prediction models. (3) Study of motion of each joint and the body orientations based on portable force plates and motion sensors. (4) Prediction of gait initiation and termination [21]. (5) Estimation of walking speed [22]. (6) Estimation of movements of thighs from movements of shanks to reduce the number of sensing units. (7) Long-term monitoring of human movements. (8) Assessment of energy expenditure. (9) Study physical activity, postural sway, postural orientation [23], activity classification and estimation of temporal gait parameters. And (10) 3D joint or lower limb angle measurement or orientation estimation of lower limbs or joints [24]. The main focus is portable applications, in which small dimensions are essential and existing research prototypes are usually smaller and lighter than commercial products. Nevertheless, in dynamic applications, high raw data rates are required for precise data processing and state estimation, which affects the development of IMUs' designs. Currently, the IMU's performance can be accessed through the bandwidth, drift, linearity and sample rate of its sensors [9].

III. Commercial IMUs

Today, at a commercial level, there are many companies interested in the production and improvement of IMUs. Obviously, at this level of competition, there is a constant race by companies to improve product characteristics at competitive prices. Companies like Xsens, InterSense, Technaid, IMeasureU or Noraxon offer a wide range of products related to IMUs with own distinctive characteristics. For example, Xsens has products like isolated IMUs (MTi1–series, MTi10–series and MTi100-series) and two hardware versions of a full-body human measurement system based on inertial sensors that require the use of suit with trackers (MVN Awinda and MVN Link). MVN Awinda has 17 wireless trackers and a station per actor which requires 17 batteries with 6 hours of life. In terms of accessibility, it is characterized by wearable straps and one-size-fits-all. In turn, MVN Link has 17 wired trackers and one access point for multiple actors which requires only one battery with 9.5 hours of life. It is described by a Lycra suit with 5 sizes. This company also offers a software for motion capturing called MVN Studio. This software is able to exhibit, for example, real-time 3D visualization and data integration, and playback and editing of motion capture data [25].

InterSense motion tracking products are industry solutions, being integrated into the next generation position, navigation and stabilization systems. This company produces three degrees of freedom (DOF) and 6-DOF trackers. 3-DOF trackers belong to InertiaCube line of orientation sensors. From this line there are two products known as: 1) InertiaCube4TM that offers superior performance over its predecessors while minimizing size and price, and is ideal for real-time applications in simulation and training, virtual and augmented reality, motion capture, and human movement analysis; and 2) InertiaCube BTTM that provides real-time orientation data via a standard Bluetooth interface to computer. It is a wireless sensor for human movement analysis. In turn, in 6-DOF trackers category there are also three products: IS-900 system, IS-1200+ system, and IS-1500 system. The first one is the choice for precise position and orientation (6-DOF) tracking in military and industrial simulators, immersive displays, virtual prototyping and film production. This system is immune to metallic interference, while offering real-time tracking in various environments. IS-1200+ system is a recent optical and inertial based 6-DOF tracking system. The system offers tracking data using a fusion of inertial-optical technology. Finally, IS-1500 system is also an optical-inertial device designed for augmented reality and robotic navigation applications [26].

Technaid is a company developing technology for several applications such as biomechanics, rehabilitation, motion analysis, virtual reality and robotics. In respect to motion analysis, this company developed recently the Tech IMU V4 series. IMU V4 series represents the last versions of inertial sensors developed by this company. Each Tech IMU integrates three different MEMS (Micro-electro-mechanical system) sensors, a 3D accelerometer, a 3D gyroscope, and a 3D magnetometer. IMU CV4 and IMU V4 are two examples of developed inertial sensors from V4 series, and three types of communication interfaces are available: CAN (Controller Area Network) Standard, tech MCS (Motion Capture System), and USB (Universal Serial Bus). Technaid also has a motion capture system Tech MCS which is a complete wireless motion analysis solution, based on one of the lighter and smaller inertial sensors of the market (Tech IMU). It is similar to MVN Link from Xsens because it also has a wired tracker and one access point for multiple actors which requires only one battery. It is important to refer that motion capture system from Technaid is not a Lycra suit but comes with textile and plastic adapters. The company also developed a software that accompanies each Tech MCS package. It is able to record and show whole human performance in real-time on PC [25], [27].

IMeasureU is a wearable technology company from New Zealand that build solutions capable to provide high fidelity athlete movement and workload data used to characterise fatigue, enabling optimal recovery, training and performance. Concerning to their product, they have a small, lightweight sensor that contains a 9-axis IMU, where data sampling up to 1 kHz can be stored on the device or transmitted via Bluetooth Smart to a computer or phone. This way, IMU measures and quantifies an athlete's motion in his natural environment. The system accurately measures sports-specific movement and quantifies biomechanical workload used to identify athlete fatigue and up to 8 sensors can be synchronised simultaneously through IMU software [28].

Noraxon is an American company that has been a leader in manufacturing and distributing high-end measurement and training devices, such as EMG, gait analysis, biofeedback, and 2D/3D motion analysis that enables a unique approach to a fully equipped analysis and therapy concept for evidence-based clinical and research applications. As products they have myoMOTION that enables the capture of human motion in 3-DOF, wirelessly. Translational data via double integration is simple and accurate with a built-in math tool kit. The entire process is portable by using IMUs placed on any segment of the body that precisely tracks the 3D angular orientation of that body section. This concept is easily expandable from a single joint of interest to a simultaneous full body measurement across all major articulations. The software provides orientation data and/or linear acceleration data [29].

SparkFun is an online retail store that sells components and widgets, and offers classes and online tutorials designed to help educate individuals in the world of embedded electronics. This company also sells IMUs with six and nine DOFs [30]. Other companies such as Arduino, InvenSense, and x-io Technologies Limited also sell products like those mentioned above constituting a group of alternatives. However, trademarks are not the only entity focused on IMUs. Research groups are also engaged in efforts to improve this technology. According to some research groups, efforts are being made to extol certain characteristics like the miniaturization of the device to apply this technology to the gait analysis [9]. Benocci et al. [31] used the IMU ADIS16350 which integrates a digital 3-axes accelerometer and a digital 3-axes gyroscope in 22x22x22 mm with high resolution, bandwidth and sensitivity to communicate via Bluetooth with a base station to monitor gait. With the same type of sensors, IMU used by Macedo et al. [10] was the MPU-6000 with a Honeywell 3-axis Digital Compass IC HMC5883L connected to a CC2530EM module to allow a Radio Frequency transmission. Höflinger et al. [9] presented a wireless Micro-IMU based on MEMS sensors with large scale integration which can be integrated into clothes or shoes for accurate position estimation in mobile applications and location-based services. Barton et al. [32] also presented a cubic IMU design and wireless technology. Tsai et al. [33] showed 1 cm3 wireless IMU without gyroscopes and Lim et al. [34] made a combination of ordinary accelerometers and gyroscopes with a line encoder with a small size.

IV. Advantages and Disadvantages

Taking into account all that has been mentioned about IMUs, multiple parameters like precision, conformability, usability or transportability demonstrate that the portable systems based on body sensors are promising methods for gait analysis [3]. As advantages, when compared to other systems IMUs are lighter, smaller, cheaper, portable, wearable, non-invasive, do not alter natural movement patterns, and they have the advantage of identifying human motion in a wide variety of environments [4], [35], [36]. Even the gait analysis when using wearable sensors becomes cheaper, more convenient and provides an indication of the intensity level of physical activity [5]. In this type of analysis, the use of 3D-sensors allows the recording of motion in three planes and provides more information [5].

Despite all this, there are some characteristics with negative connotation that should be taken into account. Accelerometers and gyroscopes data cause computational problems for determining the angles [19]. Concerning to the magnetic sensor, the presence of magnetic disturbances (as induced, e.g., by ferromagnetic material) may limit the accuracy of the orientation estimates by means integration [37]. Like any machine, a wearable sensor system has imperfections. Some of these imperfections are sensor attachment errors, regular calibration maintenance, external signal noise, signal filtering errors and integration drift, and it is computationally complex [3], [36]. Therefore, IMUs' systems are less accurate than laboratory systems [35]. A further disadvantage is the need to place devices on the subject's body, which may be uncomfortable or intrusive [1]. Lastly, power consumption is an important limitation of the current gait analysis systems, which affects directly the measurement capacity of the system and monitor the gait parameters over long time period [3]. Thus, IMUs are still being studied and improved by trademarks and research groups in order to make IMUs' systems more precise and reliable as the optical systems are.

V. Conclusion

As described throughout the paper, it can be retained that IMUs are devices with a wide range of applications in human gait, where their use can bring about quite interesting advantages and approximates the gait monitoring of the AAL environments. Nowadays, this device, whose constitution is easy to understand, presents innumerable variants of its concept through trademarks that constantly try to overcome the disadvantages of this device, making it more perfect. However, research groups have also contributed greatly to this evolution.

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