Gait Dynamics Sensing Using IMU Sensor Array System

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Abstract. *The article deals with a progressive approach in gait sensing. It is incorporated by IMU (Inertia Measurement Unit) complex sensors whose field of acting is mainly the motion sensing in medicine, automotive and other industry, self-balancing systems, etc. They allow acquiring the position and orientation of an object in 3D space. Using several IMU units the sensing array for gait dynamics was made. Based on human gait analysis the 7-sensor array was designed to build a gait motion dynamics sensing system with the possibility of graphical interpretation of data from the sensing modules in real-time graphical application interface under the LabVIEW platform. The results of analyses can serve as the information for medical diagnostic purposes. The main control part of the system is microcontroller, whose function is to control the data collection and flow, provide the communication and power management.*

Keywords

Accelerometer, gait, gyroscope, IMU, LabVIEW, MEMS, microcontroller, MPU-6050, walking.

1. Introduction

Motion is an essential part of every human being. It is a complex term which includes many motion activities including gait. Correct evaluation of human motion is a subject of a complex approach and knowledge in the area of biomechanics. Its application is in orthopaedics, therapy and in rehabilitation. It also allows medical personnel to determine the background of motion defect reasons and impacts.

The main part of human motion is a result of rotating motion of particular joints. The angle of considered segments is generally expressed by correlative orientation of segments. Human body gait, from the physical point of view, is an alternation of rotational motion of concerned joints that is transformed to linear motion of the body. It is a cyclic repetitive motion of the human body by double-step style.

At standard gait, there is a uniform repetitive flexion and extension of joints present, compared to a person with certain disability. Appropriate methodology of analysis can serve as an appropriate rehabilitation process for patients with gait malfunction. Right here there is the working field of systems for sensing and evaluation of gait properties and its deformation [1].

In early years of modern MEMS (Micro-Electro-Mechanical-System) accelerometric devices, the Massachusetts Institute of Technology has developed a suit that can capture motions of the entire human body using MEMS accelerometers. Potential application was a movement analysis of patients undergoing physical therapy. Later, in connection with MEMS components progressing development, many works has dealt with motion analysis for various medical and health care purposes. Particular systems utilize MEMS devices at various locations of human body according to application [1], [2], [3] and [4]. Moreover, human body detection and analysis is increasingly implemented in mobile devices for other than medical purposes [5].

2. Gait Motion Capture

Motion capture process includes raw motion parameters acquisition by sensing elements, their conditioning and interpretation such as the position and orientation of an object in space. The sequence of such data is further processed and evaluated to obtain motion dynamics. Analysed dependences are utilizable in biomedical, military and various industry areas. As a key element of the system, the sensing component represents a physical system which is sensitively responsible for respective physical parameter(s).

Electronic acquisition systems are recently the most sophisticated systems for sensing of any kind of motion and are utilized in cooperation with other systems for complex monitoring of motion. They allow measuring the components of motion scheme, alternation of hinge joint angles etc. in real time. On such basis it is possible to diagnose the gait parameters and its deviations caused by various reasons. Inertial sensing systems for position and orientation sensing include an accelerometer, gyroscope and potentially also a magnetometer. The accelerometer is based on variation of motion velocity sensing, the gyroscope detects the variation of angle velocity, which provides the information about object rotation. Both these sensing devices are produced as one, two and mostly as three axis sensing types and eventually are integrated in one common package. Also integration with motion pre-processor is available. In orthogonal system the 3-axis interpretation is needed (Fig. 1).

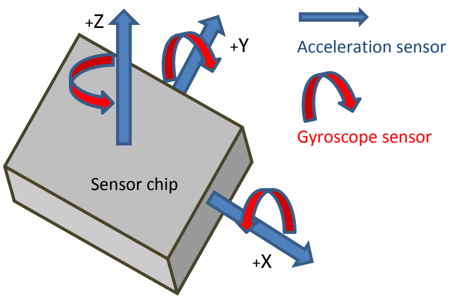

Fig. 1: Graphical interpretation of orthogonal system of 3-axis accelerometer unit combined with 3-axis gyroscope to form the inertial system with six degrees of freedom (6DOM). A gyroscope sensor allows detecting the rotation angle and inclination of an object. Together with acceleration sensor allows to measure direct movements to the X, Y and Z axes for movement and orientation recognition (LG CNS).

Using wide utilized capacitive MEMS accelerometric structure, the actual acceleration is proportional to capacitance change or, after conversion, to the voltage change:

$$a = \frac{k \cdot d}{m \cdot U} U_0 \quad (\mathrm{m \cdot s^{-2}}), \tag{1}$$

where k is the spring constant (stiffness of polycrystalline silicon spring), d is idle state gap between electrodes, m is related to a mass of the seismic element. Real accelerometer consists of a large amount of capacitive elements in differential arrangement. The capacitive type accelerometer, due to its principle, can sense dynamic as well as gravitational (so-called static) acceleration in contrast to the piezoelectric type [4], [5], [6] and [7].

Recently used gyroscopic systems utilize MEMS vibration mode units, in which the Coriolis force is proportional to angular velocity of rotation. Sensing element is also capacitive type, but the capacitance change is proportional to measure of the angular velocity:

$$\omega = \frac{\mathrm{d}\Phi}{\mathrm{d}t} \quad (\mathrm{rad \cdot s^{-1}}), \tag{2}$$

where angular velocity is proportional to velocity of slew change $\mathrm{d}\Phi$ according to time t.

Concerning 3D space, the 3-axis accelerometer combined with 3-axis gyroscope is needed for 3D representation of motion. They are produced as MEMS devices, in which the mechanic parts (microsensors, microactuators and microelectronics) are integrated for motion processing [7].

3. System for Gait Sensing Utilizing the IMUs

The specific requirement analysis resulted in a system based on sensing, control and processing unit integration, which was designed as a modular type system. The sensing part is composed of seven sensing modules at the base of MPU-6050 inertial MEMS sensors, intended to be located at human body segments. Actual values of acceleration and angles are directed through I^2C to the microcontroller module with the ATmega328P RISC microcontroller, configured for data sensing and flow control (Fig. 2) [8], [9] and [10].

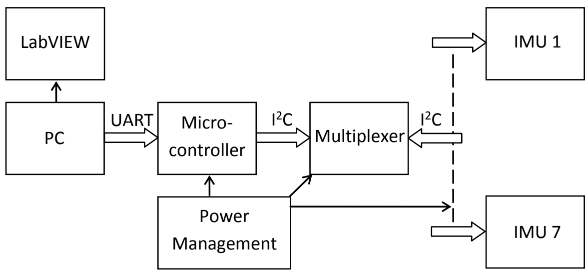

Fig. 2: Block schematics of electronic/software system for gait evaluation.

MPU-6050 sensing elements are complex sensing units consisting of 3-axis accelerometer, 3-axis gyroscope, digital motion processor and peripheral controller. The key characteristics are in the following summary:

- programmable accelerometer range: ± 2 – ± 16 g,
- prog. gyroscope range: ± 250 – $\pm 2000\ ^\circ \cdot \mathrm{s}^{-1}$,

- prog. output data rate: max 1 kHz,
- I^2C and SPI communication interface,
- internal Digital Motion Processing engine [9].

Control microcontroller program structure includes communication protocols setting, inertial sensor MPU-6050 modules initialization, data acquisition, transmission of data through I^2C bus, mathematic processing to the acceleration and angular velocity components and transmission to the application under the LabVIEW system for further processing and graphical representation [11] and [12].

Electronic system includes the plug-in module serving as the interconnection structure with interfaces for particular peripherals. Due to the absence of the possibility of more than two IMU direct addressing, the multiplexing of I^2C bus was realized by the CD4051B CMOS multiplexer to override this disability (Fig. 3). In the (Fig. 3): 1 is A-type USB connectors for external IMUs, 2 is HC-05 Bluetooth module, 3 is GY-521 module with MPU-6050 IMU and 4 is CMOS multiplexers. Plug-in module is attached onto AVR ATmega328 microcontroller module. Programmable channels are connected to particular digital pins defined by program application.

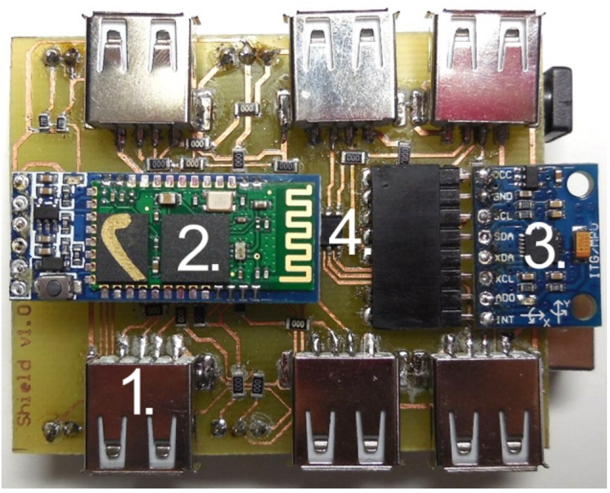

Fig. 3: Plug-in module of system for data acquisition from IMU modules.

First of all, the human gait is accompanied by motion of legs by double-step cycle style. The studies in the area coincide by localization of sensing elements in thorax, thigh, tibia and often in plantar area [13]. It is possible to locate the sensing modules in front as well as laterally in proper distance from joints. In the application they are fixed by flexible ribbon and a clamping unit (Fig. 4).

The power source for sensor elements is supplied by microcontroller board. The overall system is primarily supplied from USB, which is also used for data transmission from the sensor module to the PC application. Considering 7 sensor elements in the mode with used digital motion processor with peak current consumption of 3.9 mA, microcontroller peak consumption value of 9 mA, the total power consumption at 5 V supply from USB is 0.18 W, which is deeply under the USB port limit.

Fig. 4: Location of IMUs and control unit for gait sensing.

4. Interpretation of Data Flow from IMU

Accelerometric and gyroscopic units provide raw or pre-processed data. The acceleration sensing unit provides information about actual acceleration (m·s^{-2}), i.e. it is possible to evaluate the dynamic variation of velocity. Using 3-axis acceleration data the angle of tilt Φ, incline ρ and yaw θ can be evaluated using goniometry:

$$\Phi = \arctan \frac{a_x}{\sqrt{a_y^2 + a_z^2}} \text{ (rad)}, \tag{3}$$

$$\rho = \arctan \frac{a_y}{\sqrt{a_x^2 + a_z^2}} \text{ (rad)}, \tag{4}$$

$$\theta = \arctan \frac{\sqrt{a_x^2 + a_y^2}}{a_z} \text{ (rad)}. \tag{5}$$

The gyroscope provides the angular velocity of rotation (rad·s^{-1}) data. Through integration by time fraction $\mathrm{d}t$, the values of angular velocity (ωX, ωY, ωZ) can be evaluated in form of the angular distance φ, where $\mathrm{d}t$ is the time interval between two samples [5]:

$$\varphi_x = \int_{t_1}^{t_2} \omega_x(t)\mathrm{d}t \ \ (\mathrm{rad}\cdot\mathrm{s}^{-1}), \tag{6}$$

$$\varphi_y = \int_{t_1}^{t_2} \omega_y(t)\mathrm{d}t \ \ (\mathrm{rad}\cdot\mathrm{s}^{-1}), \tag{7}$$

$$\varphi_z = \int_{t_1}^{t_2} \omega_z(t)\mathrm{d}t \ \ (\mathrm{rad}\cdot\mathrm{s}^{-1}). \tag{8}$$

Pre-processing of acquired data in LabVIEW system includes digital filtration realized by using a configurable bandpass Butterworth type filter [14]. The purpose is to eliminate the static acceleration (gravity) components as well as higher frequency components which are contributed by noise and signals generated by human body biological processes.

Evaluation of segments relative angle is possible by a pair of accelerometers localized in line at the segments which account direction vectors. Proper method is to utilize the vector algebraic algorithm of cosine law. Through two vectors a and b, characterizing static acceleration (gravity) the relative angle of joint can be obtained:

$$a \cdot b = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} \cdot \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} = |a| \cdot |b| \cdot \cos\alpha \Rightarrow$$
$$\alpha = \arccos \frac{a_x b_x + a_y b_y + a_z b_z}{\sqrt{a_x^2 + a_y^2 + a_z^2} \cdot \sqrt{b_x^2 + b_y^2 + b_z^2}}, \tag{9}$$

where $a \cdot b$ is a scalar product of vectors with absolute value of $|a| \cdot |b|$ [3]. Data handling in LabVIEW is schematically depicted in Fig. 5, graphical interface in Fig. 6.

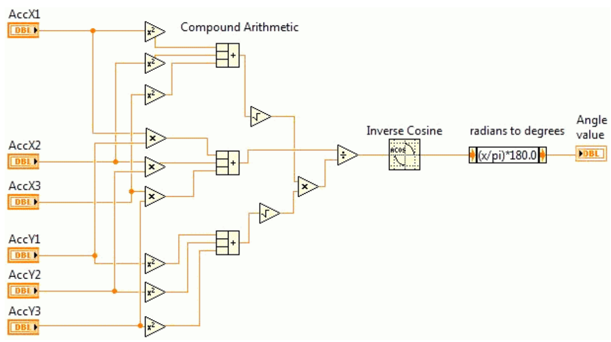

Fig. 5: Schematic diagram of realization of two segments relative angle calculation in LabVIEW application.

Both types of sensing device bring some measurement error into resultant values given by used sensing principle. The accelerometer is subjected to dynamic

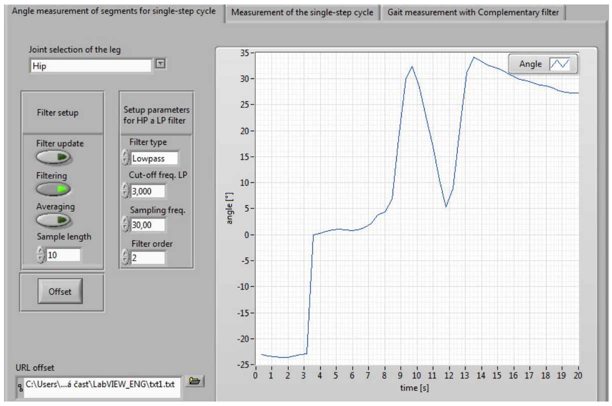

Fig. 6: Graphical interface for evaluation of segments relative angle in LabVIEW application.

error by mechanic oscillation and, in contrast, the gyroscope is subjected to long term drift. These two opposite errors can be markedly reduced by using complementary filtration with appropriate type and coefficients.

A frequently used concept is to use the Kalman's filter type or simpler low/high pass complementary type filter which combines accelerometer and gyroscope data to attain the corrected angle:

$$\omega = c(\omega_{gyro}) + (1 - c) \cdot (\omega_{accel}) \ \ (\mathrm{rad}), \tag{10}$$

where c is a constant which can be experimentally obtained for given construction. In practice, the coefficient has obviously the value of ≈ 0.96. A real system can be subjected to a long time evaluation and resultant errors can be composed to the error constant estimation [15].

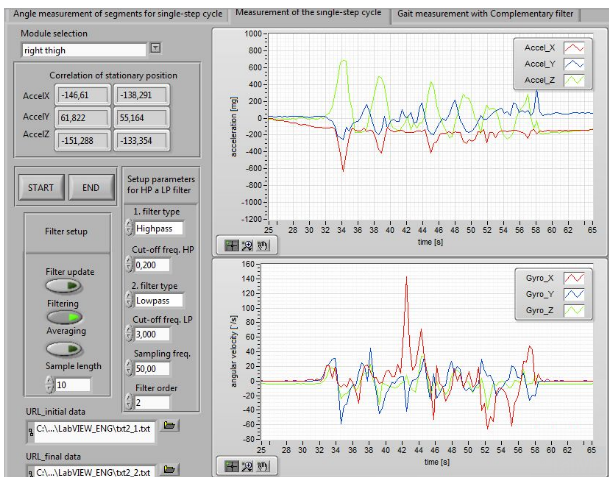

Fig. 7: Graphical interface for measurement of motion dynamic components during gait cycle in LabVIEW application.

In the LabVIEW application, there is a possibility to select the particular human body joint using the draw-out menu and additional parameters including type and parameters of filtration. Also, some additional parameters and functions are available as the offset, sample rate and averaging.

A gait cycle can be sensed with possibility of one or more step evaluation including long-term gait motion. Dynamic components can be acquired for human body motion analysis which can provide the information about gait disorders. Particular sensing module can be selected and active filtration is applicable with variable type bandpass filter and parameters (Fig. 7).

5. Conclusion

Continuing advance in electronics technologies enable advance in investigation of motion including human body gait. Analysis of gait and correlation with knowledge in the medical area allow gaining the information about actual body motion apparatus, potentially to state the diagnosis and as well as enabling the rehabilitation process to be more effective and flexible.

By application of recent gait dynamics knowledge the sensing system at the base of MPU-6050 inertial MEMS sensor (IMU) modules was realized. Using microcontroller and support circuitry it allows acquiring both static and dynamic parameters and profiles of human body motion apparatus activities during gait. Acquired and pre-processed data can be interpreted using graphical user interface in LabVIEW application that was built for this purpose. It has been programmed as a configurable tool for evaluation of acceleration, angular velocity, angle of joint segments and evaluation of dynamic components during a gait cycle, including long-term gait tracking. An analysis of sensed data allows evaluating the motion scheme, better understanding of dynamic effects connected with gait as well as diagnostics of gait defects caused by various degradation factors.

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