Design of system for collecting and analyzing of human gait parameters

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Abstract. *Human gait parameters reveal much information about a person's possible health problems. These parameters can be used for the early diagnosis of neurogenerative diseases and to monitor the healing process during rehabilitation after an injury. The methods of monitoring gait parameters can be divided into two basic approaches. The first approach is to monitor the movement parameters of the lower extremities, tracking with the help of a camera system or with the help of accelerometers placed on the patient's body. The second approach is to monitor the loading of individual leg parts during walking. This paper will present the design of a wearable device for monitoring gait parameters, where several Inertial Measurement Units (each containing an accelerometer, gyroscope, and magnetometer) will be used to process and evaluate the data. The presented design will consist of a microcontroller module, 1 to 3 IMU modules (accelerometer+gyroscope), and pressure sensors placed in the shoe's sole.*

Keywords. gait analysis, sensory system, microcontroller, accelerometer

1 Introduction

Walking is a complex activity that requires a high level of coordination between the central nervous system and the body. Currently, the direction of objective data acquisition for the kinematic analysis of human movement in the physiological or pathological plane is focused on commonly used devices. However, implementing sensors in wearable smart devices does not guarantee their use in all situations. Therefore, it appears appropriate to implement sensors for kinematic analysis or monitoring of vital signs for active rehabilitation into adjuvants. Active rehabilitation or active forms of rehabilitation are those in which the patient actively realizes the chosen treatment and does not simply passively receive treatments. The data collected during this process will be processed by multiple independent methods. This paper presents the design of a technical device to acquire inertial data during the rehabilitation or convalescence process. The overall system design consists of a wearable device with a sensor base and communication interface, a software part for data acquisition and a model for data evaluation. The output of this model will be information about the gait parameters according to the specification of a rehabilitation expert. In developing the proposed system, the authors followed proven hardware design practices (Dudak et al., 2011). The aim of the present project is to detect selected gait parameters (such as leg off center or excessive knee joint rotation) from the acquired data. Both analytical and machine learning methods will be used to obtain these data (Dudak et al., 2020).

1.1 Systems for inertial data collection and analysis

There are several articles regarding the design of rehabilitation aids, which implement sensor equipment or are connected in some way to the Internet. Monica Tiboni et al. (Tiboni et al., 2022) produced an extensive analysis of 215 publications on the monitoring of the health status of different body parts, the sensing technologies, and the sensors used. The study was published in 2022 and analyses publications since 1975. However, relevant publications have existed only since 2006. Up to 57% of the analyzed publications deal with lower limb rehabilitation, with the ratio of publications about rehabilitation aid vs. assistive devices being approximately the same. According to this analysis, pressure sensors and Inertial Measurement Units (IMU) are used most widely for the lower limbs, to a lesser extent than force sensors, EEG, and camera systems. The results of this analysis overlap with the topic of this paper - the use of several types of sensors for monitoring selected parameters of human gait in the rehabilitation process. IMU sensors are used in multiple papers. A separate category of wearable devices is clothing with installed sensors. These sensors are most often IMU units, which can obtain information about the nature of the movement being performed or the orientation of the human body or limb. In (Wang et al., 2015), a garment application is presented in the form of a vest, with which the authors monitored a patient's posture.

Among the methods for gait data evaluation, neural networks are widely used. The advantage of using the machine learning algorithm is the ease of use for monitoring specific target parameters. As an example, we refer to (Kantoch, 2017), where the authors could discern a patient's activity level by monitoring heart rate and blood oxygenation. In (Prochazka et al., 2018, p. 1209), an application of machine learning algorithms is presented to determine the relationship between the level of physical exertion of the monitored subject and its heart rate. Machine learning algorithms are also suitable for recognizing human hand gestures. Geng Yang et al. created a wristband application (Yang et al., 2018) that detects which forearm muscles are used and can recognize the hand gesture (open/closed palm, thumbs up, raise index finger, and other gestures). The fundamental task in projects of this type is the selection of sensors suitable for sensing the monitored parameters. In human gait analysis, it is possible to focus on dynamic parameters such as stride length, stride rate, and others, for which the IMU sensors are most commonly used. In (Gujarathi and Bhole, 2019), the principle of using IMU sensors for gait monitoring is presented. The authors presented the basic design of the measuring device and algorithms for estimating stride length, standing time, and time of limb movement during walking. For the calculations, they used a basic mathematical model. Time domain analysis was also used by Wang et al. in (Wang et al., 2016), where they used 2 IMU sensors placed on the thigh and at the base of the shin. The use of machine learning algorithms in evaluating gait parameters is described by Nguyen et al. (Nguyen et al., 2020), where they used 7 IMU sensors (3 for each leg and one in the pelvic region) and used a convolutional neural network for evaluation. A similar methodology is also used in (Mundt, 2020), where the authors used an analytical motion model as the first method and, as the second step, created a neural network model. In (Sunarya, 2020), the authors Sunarya et al. present an extensive feature analysis of smart shoe sensor data, including pressure sensors, accelerometer, and gyroscope signals. They also investigated the optimal length of data segmentation based on gait cycle parameters. The results show that the highest accuracy (88.44% - 89.76%) was achieved by the data fusion of the accelerometer and gyroscope data and a support vector machine model (SVM).

The second interest group is the parameters of body weight distribution on the foot surface in contact with the walking surface. In this case, several types of sensors can be used, such as piezoelectric (Chandel et al., 2019), pneumatic (Kong et al., 2009), or resistive (Paredes-Madrid et al., 2017).

This paper deals with designing a wearable system for collecting sensor data from various sources. IMU sensors placed in the lower extremities will be used as the primary method. Resistive sensors for measuring pressure in different parts of the foot in contact with the walking surface will be used as a second data source.

Since the authors of the article have established cooperation with the Slovak Medical University, Faculty of Public Health, specifically with the Department of Physiotherapy, the presented data collection system emerged as an intersection of expertise from technical and health fields. The result of joint discussions was the design of a system that would be able to sense human gait parameters in two modes: a) during rehabilitation under the supervision of a specialist, and b) during home rehabilitation. In this paper, we present a redesign of the solution, where the primary focus is on use in the supervised rehabilitation mode. This paper presents an initial design of the system and will be optimized in the future with respect to its ease of use. The system will also include a mathematical model that will identify and evaluate parameters related to possible health defects.

2 The design of the wearable system for data acquisition

The proposed system consists of a controller unit which incorporates a microcontroller to which the sensors are connected, a communication sub-module, and software for data collection and analysis. For easy attachment of the sensors to the lower extremity, a mechanical design is proposed for the placement of sensors in the form of wearable electronics.

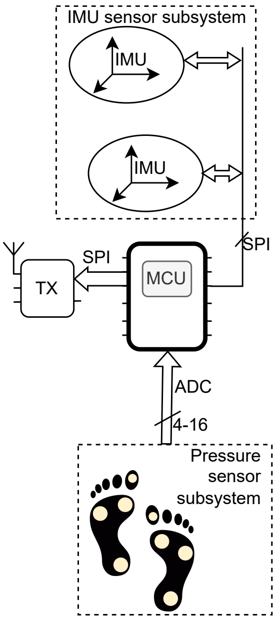

Figure 1: Block diagram of the proposed system

Figure 1 shows the main block diagram of the design. It is an application for collecting data from a single lower limb. This design consists of an STM32L432 microcontroller, NRF24L01 wireless data transmitter, and sensor modules:

- IMU sensor submodule. It contains 1 to 4 IMU sensors placed on the lower limb of the monitored person. In the initial design, we expect to place two sensors: one sensor will be attached to the calf and the other above the knee. The communication interface used is SPI.
- Pressure sensor submodule. It contains a pressure sensor module for one foot. The number of sensors in one module can range from 3 to 16. Since the physical principle of the sensor works with the change of electrical resistance depending on the pressure exerted on the sensor, the A/D converter interface of the MCU unit is used for the data measurement. Due to the magnitude of the measured electrical resistance change, each pressure sensor will be connected to a voltage divider circuit.

During the design of the module, the following requirements were defined:

1. IMU module
   (a) Sampling frequency min. 200Hz
   (b) Measurement range: 2-16g for accelerometer, 250-2000 $deg * s^{-1}$ for gyroscope
   (c) Resolution: 16 bit
   (d) Integrated low-pass filter
2. Pressure sensor module:
   (a) Number of sensors: min. 4 with proper placement of sensing areas
   (b) Sensor sensitivity suitable for the distribution of human body weight over the sensor area
3. Communication module
   (a) Communication speed: min. 1 Mb/s

3 Hardware design

IMU sensor module. For the IMU module, we have selected the ICM20948 sensor. This sensor contains a 3-axis accelerometer, 3-axis gyroscope, 3-axis compass, and a DMP (Digital Motion Processor) module that allows computations directly on the sensor module. It includes I2C and SPI communication interfaces with a maximum clock frequency of 7MHz for SPI and 400kHz for I2C. The accelerometer range is configurable from +/-2g to +/-16g. The gyroscope range is from +/-250deg*s-1 to 2000deg*s-1. According to the specification (TDK InvenSense, 2021), this sensor is suitable for wearable and IoT applications. The sensor allows for the maximum data acquisition frequency of 562Hz. The resolution for each axis is 16 bits. Additionally, the IMU includes a digital lowpass filter from 197Hz to 5.7Hz for the gyroscope and from 246Hz to 5.7Hz for the accelerometer.

Pressure sensor module. This module consists of multiple FSR sensors placed on a pad (Figure 2). A Force Sensing Resistor (FSR) is a two-terminal passive device that exhibits a dramatic decrease in its electrical resistance when stress is exerted over the Sensor Sensitive Area (SSA). The SSA is usually made from conductive particles randomly dispersed in a nonconductive polymer, resulting in a polymer composite; the SSA is later sandwiched between two metal electrodes to allow electrical measurements; the resulting device is an FSR (Paredes-Madrid et al., 2017). The parameters of the FSR sensor are:

- Dynamic sensing range spans from 0.2 N to 20 N
- Able to withstand millions of actuations
- No-Load resistance > 10 $M\Omega$
- Hysteresis: +5% (FSR datasheet)

MCU control module. The control module is implemented on the STM32L432 microcontroller, which belongs to the reduced power consumption family of STM32 microcontrollers. The created firmware works

Figure 2: Module containing FSR sensors

in two modes: configuration mode, where the connected sensors can be configured (range, digital low-pass filter, and sample rate), and the second mode is the measurement, during which the module operates autonomously, and the measured data are sent over the wireless interface. The principal algorithm is shown in Figure 3. The "IMU ready" and "RX data" blocks represent hardware interrupts from the IMU sensors and the communication interface, respectively. In the "measurement" mode, when the IMU sensors are active, a hardware interrupt is generated according to the sensor settings (5Hz to 562Hz). The meaning of this interrupt is a notification that the data are ready to read.

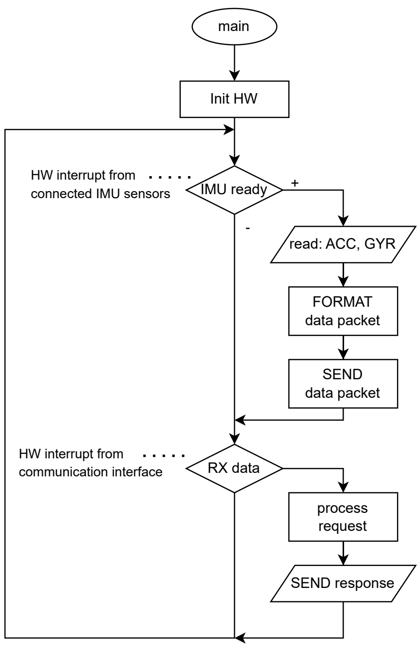

Figure 3: Principal algorithm for the communication with peripherals connected to the MCU

In the initial design phase, we selected the sampling rate of the IMU to be 280Hz. Data from both IMU sensors (Figure 6) and from 8 pressure sensors are available for each measurement. In terms of data intensity, there is a need to send data of at least 64B in one measurement. The structure of the data packet that is sent from the MCU module is shown in Figure 4.

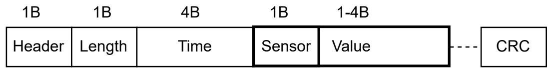

Figure 4: Format of the measurement data packet

The communication packet begins with a header, followed by the total packet length information. A mandatory part of the packet is the measurement timestamp. The time value is relative, and the timer is restarted at the beginning of the measurement process. The resolution of the time base is 0.1 ms. The next part is the data from the connected sensors. Each sensor has a label on which data can be correctly identified during data processing (Figure 4, Sensor section). This byte is followed by the value read from the sensor (value). This part contains data from all 3 axes for the accelerometer and gyroscope.

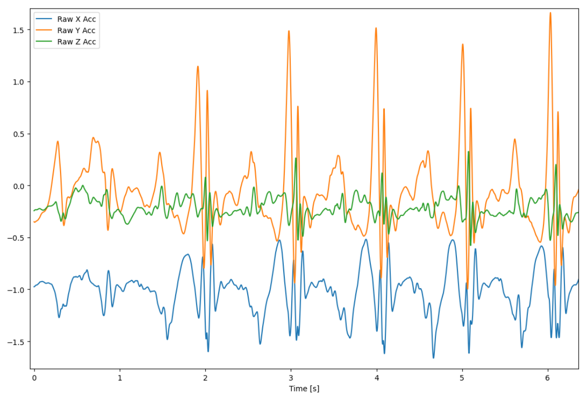

Figure 5: Result form Ambulatio software - data visualization

For data collection and evaluation, the software "Ambulatio" is being developed to configure the parameters of the IMU sensors, and also, in this software, basic visualization of the measured data is possible. In Figure 5 is a preview of the result of the "Ambulatio" software. The graph shows the data visualization from the IMU1 accelerometer in all 3 axes.

4 Conclusions

The embedded sensor system (Figure 1) forms the basis of a comprehensive data collection and analysis system in the recovery and rehabilitation process of the patient. The design presented in this paper forms the basis of the system, its hardware part, which is responsible for collecting and transmitting measured data. In the current version of the implementation, 2 IMU sensors are connected to a control module with a microcontroller.

Figure 6 shows the first prototype of this system. The IMU sensors are placed in a housing designed for this application. This housing design assumes that it will be attached to the lower limb of the monitored person - the shape of the housing is adapted to this. In Figure 6, these covers are marked with a yellow tag. In the current version of this system, a cover for the microcontroller is also included. In the next iteration of development, the MCU module is planned to merge with the IMU sensor module.

Figure 6: Ambulatio system prototype - IMU sensor placement

Using of system. In planning the functionality of the human gait monitoring system, it will be necessary to create a working prototype of a device that would monitor the parameters of both lower limbs. From a tactical standpoint, eliminate unnecessary cabling so that the device falls into the category of wearable electronics. Next, develop models to identify key parameters from the sensed data. To identify situations where persons with certain motor impairments are monitored. Tasks related to the last point will be addressed jointly with a rehabilitation expert. The first users of the proposed human gait monitoring system will be patients in the rehabilitation process. The patient will be fitted with 2 sensors on each lower extremity using straps (Figure 6). The aim is that these modules do not affect the patient's movement abilities in any way. 3D printing was used to create the mechanical design of the prototype hardware modules. In the next version, it is envisaged to minimize the dimensions and overall weight of the entire module. Currently, one module is approximately 200g. In the planned stage of the solution (rehabilitation under expert supervision), the system will be used for data collection and subsequently to confirm or modify the conclusions of the rehabilitation expert.

In the next step of system development, we will focus on the analysis of the collected data. The goal is to find suitable methods to analyze the measured data for later online analysis of qualitative gait parameters. We expect that both analytical and neural network models will be developed. Using these models, it will be easy to identify wrong walking habits or wrong habits for patient rehabilitation.

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