Metrological parameters of information and measurement systems for the study of a kinematic portrait of a person

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Abstract. When developing measurement procedures and means, it is necessary to carry out an analytical description of errors and their characteristics. The report discusses the methods of metrological analysis when creating a portable information and measurement system for evaluating walking techniques. The paper describes the metrological analysis of estimates of total error components of the measurement results of informative parameters for the task.

1. Introduction

Today, special attention is paid to the development of portable information and measurement systems (IMS) for the study of movement parameters, so the systems implemented on the basis of inertial sensors and Kinect controllers are of interest, however, the latter are not included in the category of portable systems. It should be noted that an important issue when creating such systems is the formation of metrological requirements.

The papers of a number of authors [Shull P.B., Nukala B.T., Senanayake S., Sun B., Budkov V.Yu., Denisov A.V., etc.] are devoted to the creation of information and measurement systems (IMS) for the study of movement parameters in the field of medical diagnostics, rehabilitation measures, and training processes.

In the paper [1], the authors consider a measurement system consisting of inertial sensors and magnetometers. A zero speed update method was proposed, which involves zeroing the speed during the support phase (every 0.5 s) at each step in order to correct the position and the drift speed.

The paper [2] estimates the characteristics of the inertial system installed on the leg, intended for use in pedestrian navigation.

The paper [3] presents a method for correcting movement parameters using the dead count algorithm (course and step size) for a pedestrian navigation system. In this method, the compass offset error and the step length error can be estimated during the period when a global positioning system (GPS) signal is available. The goal of this paper is to increase the accuracy of determining the course of movement and step length.

The paper [4] presents the development results of simultaneous visual tracking of robotic system objects. The camera is installed behind each robot, represented by an electronic washer, on which a marker is attached. To get a trajectory, the resulting picture is converted to an image in gray for further processing: defining markers when compared with the threshold value.
In the paper [5], the authors proposed a system that includes a Kinect controller (contactless touch game module). This controller has a colored RGB camera, CMOS (complementary metal-oxide-semiconductor structure) infrared projection. 4 marks are attached to the lower extremities of the subjects, the controller is installed at the level of the knees (on a moving structure). The system is designed to control the kinematics of walking movements of elderly people in order to monitor the degree of influence of rehabilitation measures. The moving structure is intended to provide safety of subjects during movement.

In the article [6], the authors describe a device called Free Walker, which includes 8 pressure sensors and 2 inertial sensors. The advantages of this system are low cost and mobility.

The paper [7] describes a system based on inertial sensors designed to compare the differences in performance of two subjects (sportsmen) and identify factors contributing to these differences.

The paper [8] describes a portable device for monitoring the characteristics of a swimming technique. This device consists of a three-axis accelerometer, flash memory, microcontroller, and battery. The solution [9] is used as feedback. Measuring modules are located between the shoulder blades, on the lower back, as well as on the wrists. Feedback is represented by acoustic, visual, and tactile devices. The possibility of supplementing the system with a high-speed camera, pressure sensors [10] in order to analyze the physical parameters of the subject was also considered, as well as the possibility of real-time feedback using a wireless optical infrared transceiver [11]. In order to correct the performance of exercises, swimming glasses have built-in LEDs, according to the color of which the subject determines the correctness of the movements.

The paper [12] describes a system for assessing the leg angle profile in the field of cycling. This system is necessary to minimize injuries and increase the effectiveness of a sportsman. The system includes an accelerometer mounted in the foot area, which provides information about the pedal position.

The paper [13] presents a portable system consisting of inertial sensors for a temporary analysis of the process of playing tennis. Sensors are fixed on the subject’s legs and racket in order to adjust movement coordination. The software classifies the types of strokes, as well as records the steps of the subject and the movement of the racket. Such information will allow the sportsman to coordinate the movements of his arms and legs. The papers [14; 15] describe the use of sports gadgets in order to fix the swing phase with a racket and identify the point of the swing arc.

2. Information and Measurement System (IMS)

For a full assessment of walking techniques, it is necessary to take into account the totality of a number of different spatiotemporal properties, which is especially difficult to perform not in the laboratory, but in a hospital.

From the point of view of reducing errors in assessing the reliability of measurement results that characterize the kinematics of human movement, there is a need to implement information and measurement systems that do not affect the structure of motor actions [16].

A distribution scheme for measuring modules for a mobile wireless measuring system has been developed.

Figure 1 illustrates the distribution of sensors in a wireless mobile system.
Microcontrollers with wireless data transmission and linear and angular motion sensors in a single design.

Figure 1. Distributed mobile system for the study of human motor actions.

The distribution of the measuring channels in this way (Figure 1) is necessary to control the walking parameters, namely: the correctness of steps (lifting the legs, setting the heel, the transfer phase), control of coordination ability (cross movement when moving legs and arms), general control over the patient’s movement speed, balance, control of the position of the shoulders relative to the pelvis [17].

The distributed measuring system includes microcontrollers, modules with a radio channel and micromechanical sensors of linear and angular displacements. The measurement results are transmitted to a computing device using a module containing a radio channel with WiFi wireless technology. Data is transferred to a PC. The axes of the sensors are oriented as follows:

- sensor Y axis is directed vertically,
- sensor X axis is directed horizontally, parallel to the direction of movement (to the sagittal axis of the human body)
- sensor Z axis is directed horizontally, parallel to the frontal axis, and characterizes lateral deviations.

The MPU-6050 sensor used was selected based on the following parameters: gyroscope and accelerometer operating ranges, maximum frequency of the I2C interface, sampling rate, non-linearity, noise, and price.

The structure of the information and measurement system, which includes more than two measuring clients, each of which has 6 measuring channels: three axes of the gyroscope, three axes of the accelerometer, imposes restrictions on the transmission of information. A measuring client is a module of a distributed measurement system that has a sensor and a microcontroller with a wireless network interface.

An experiment was conducted with the structure of an information exchange system with the creation of two clients and a server, which was a PC.
The implemented program loaded into the microcontroller of the transmitting module, sends TCP packets to the server (PC), for which it connects to the same WiFi network as the PC, and then sends a TCP packet containing measurement information to the server’s IP address.

The server part on the PC is implemented using a graphical programming environment. Figure 2 shows a block diagram of the program.

![Figure 2](image_url)

**Figure 2.** Structure of a TCP IP information exchange system with a server implementation on a PC.

where MM 1 and MM 2 are measuring modules with digital output, programmable sampling rate and the ability to transfer data over WiFi; Axel, Gyro, ADC – accelerometer, gyroscope, analog-to-digital converter in a single design; MC – microcontroller, and R/C – radio channel; PC is a computing device (a personal computer that provides storage and processing of measurement results).

3. IMS Metrological Characteristics

The measurement result can be recorded in several ways, which are characterized by recording the result using concepts such as errors or uncertainties. The latter seems to be less promising, since they imply the so-called two-component model of the result without the possibility of further separation. To calculate the metrological characteristics, it is supposed to use a model that includes the components of the total error, the separation of which is caused by the influence on the errors of measurement algorithms and technical means that implement these algorithms, which led to the separation of errors into methodological and instrumental ones.

To evaluate the measurement result, the following record is generally applicable:

\[ \lambda_j^* = \lambda_j + \Delta \lambda_j^*, \]  

where \( \lambda_j \) is a measured value, \( \Delta \lambda_j^* \) – an error of the measurement result.

In this case, the components of the total error of the measurement result for the IMS are:

\[ \Delta \lambda_j^* = \Delta m \lambda_j^* + \Delta r \lambda_j^*, \]  

where \( \Delta m \lambda_j^* \) is a methodical error of the measurement result, \( \Delta r \lambda_j^* \) – instrumental error of the measurement result.
Separation of the total error into methodological and instrumental ones makes it possible to correlate the extreme accuracy possibilities provided by the adopted measurement algorithm with the real accuracy provided by the implementation of this algorithm by technical means.

Traditional metrology has long been using this separation of errors into two types, meaning by instrumental errors the ones caused by the imperfection of the equipment used in the measurement, which are not only the errors introduced by the accelerometer \( \Delta_{\text{acc}} \) and gyroscope \( \Delta_{\text{gyr}} \). In addition, the instrumental error should also include such a relatively new component for metrology as the dating error \( \Delta_{\text{dat}} \). It is caused by the finiteness of the interface performance, which generates a shift in the moment when the measurement result is presented for use (processing) relative to the moment when the measurement result is formed.

The methodological errors, in turn, are initially formed by the error determined by the difference between the experiment and the established method \( \Delta_{\text{exp}} \), it is also necessary to take into account the error of the analog-to-digital converter \( \Delta_{\text{adc}} \) and the error determined by the inaccuracy of the location of the distributed IMS modules \( \Delta_{\text{loc}} \).

\[
\Delta_{\text{acc}} \cdot \Delta_{\text{gyr}} \cdot \Delta_{\text{dat}} \cdot \Delta_{\text{exp}} \cdot \Delta_{\text{adc}} \cdot \Delta_{\text{loc}}
\]

(3)

It is worth noting that it is quite difficult to estimate the methodological component of the total error. Therefore, it is proposed to conduct a metrological analysis on the example of one of the informative characteristics of the assessment of walking techniques using a portable IMS based on inertial sensors.

Metrological analysis (MA) is based on such basic methods as calculation on an analytical basis; with the use of simulation modeling; with the use of metrological experiment. To increase efficiency, these methods can be combined, making up a variety of combinations of the main methods of metrological analysis.

As an example of metrological analysis, it is proposed to study such a characteristic as the step length \( \ell \), which during the experiment will form the aggregate with a total number \( N \).

As it is known, the step length depends on two parameters: angular velocity \( \omega \) and linear acceleration \( a \), which in turn behave differently in three-dimensional space. Thus, a collectively formalized description will look as follows

\[
\{ \Lambda_n \}_{j=1}^N = f(a_i, a_j, \omega_i, \omega_j) = f(a_i, \omega_i)_{i=1, \ldots, 3}.
\]

(5)

Having indicated the relevant dependence of the parameters, it is necessary to evaluate the initial value \( \Lambda_n^\star \), after which it becomes possible to talk about the difference between this value and its estimate

\[
\Delta \Lambda_n = \Lambda_n^\star - \Lambda_n.
\]

(6)

The error \( \Theta(\Delta \Lambda_n) \) in this case can also have an estimated characteristic and is determined by three factors – the inadequacy of the used models of input influences, procedures, means and conditions of measurements, the finiteness of the sample size and the imperfection of the transformations performed in the framework of metrological analysis.

The description comes down to summing up each component,

\[
\Theta(\Delta \Lambda_n^\star) = \delta_m \Theta(\Delta \Lambda_n^\star) + \delta_h \Theta(\Delta \Lambda_n^\star) + \delta_\theta \Theta(\Delta \Lambda_n^\star),
\]

(7)
where

\[ \delta_n \Theta_0^{\ast} \Delta \Lambda_n^\ast = \lim_{N \to \infty} \sum_{j=1}^N \left( f^\ast (a_j, \omega_j) \right) / N - \lim_{N \to \infty} \sum_{j=1}^N \left( f (a_j, \omega_j) \right) / N \] - an error due to the inadequacy of the models used in the metrological analysis,

\[ \delta_n \Theta_0^{\ast} \Delta \Lambda_n^\ast = \sum_{j=1}^N \left( f^\ast (a_j, \omega_j) \right) / N - \sum_{j=1}^N \left( f (a_j, \omega_j) \right) / N \] - an error due to the finiteness used in the metrological analysis of the sample size,

and \[ \delta_n \Theta_0^{\ast} \Delta \Lambda_n^\ast = \sum_{j=1}^N \left( f (a_j, \omega_j) \right) / N - \sum_{j=1}^N \left( f (a_j, \omega_j) \right) / N \] - an error due to imperfection of transformations.

Depending on the selected combined method of metrological analysis, the estimation of the error in determining the step length can change its composition.

Thus, an experimental calculation method can be used to determine the characteristic of the mathematical expectation for the error in determining the step length obtained by the following formula

\[ \Delta \Lambda_n^\ast = \Lambda_{En}^\ast - \Lambda_{Te}^\ast, \] (8)

where index E is the experimental step length value found as the average of all empirical values; T is a theoretical value dependent on anthropometric features.

Estimation of the value of mathematical expectation is the average for all N-results

\[ M^{\ast} \Delta \Lambda_n^\ast = \Delta \Lambda_n^\ast / N = (\Lambda_{En}^\ast - \Lambda_{Te}^\ast) / N. \] (9)

This method makes it possible to combine the constituent parts of a complex IMS and implies analytical support that does not load the initial system. The error in estimating the step length for the indicated method of metrological analysis includes all the previously described error components \( \Theta_0^{\ast} \Delta \Lambda_n^\ast \), which appear due to the finiteness of the sample size of the experimental values, the imperfection of the transformations performed in the framework of the metrological analysis, and the inadequacy of the models used.

In turn, prior to the experiment, the calculation-simulation method allows evaluating the characteristics of interest using the well-known tuple of a priori knowledge. On the example of calculating the variance of a value \( D[\Delta \Lambda_n^\ast] \), which in turn includes the mathematical expectation, an estimate of which was found above.

\[ D[\Delta \Lambda_n^\ast] = \int_{\Delta} \omega(\Delta \Lambda_n^\ast)(\Delta \Lambda_n^\ast - M[\Delta \Lambda_n^\ast])^2 d(\Delta \Lambda_n^\ast). \] (10)

As can be seen, to find the variance of the error, it is necessary to know the probability distribution density \( \Delta \Lambda_n^\ast \). According to the central limit theorem, a sample with a large volume will tend to the normal distribution law. Thus, having provided an acceptable sample size, we can say that \( \omega(\Delta \Lambda_n^\ast) \) is distributed according to the Gauss law.

Regarding the error in estimating the value \( \Delta \Lambda_n^\ast \), it is worth noting that the properties of the components of the total error \( \partial \Theta_0^{\ast} \Delta \Lambda_n^\ast \) are similar to those described above. But in this case, increasing the reliability of the results of metrological analysis is achieved by reducing the component \( \delta_m \Theta_0^{\ast} \Delta \Lambda_n^\ast \) due to the exclusion of the procedure for deducing the calculated ratio with accompanying assumptions and approximations.

The instrumental component of the total error can be estimated using technical documentation of the measuring instrument. For example, let’s consider one of the popular MPU-6050 inertial sensors.
Metrological characteristics according to the technical documentation (Table 1) of the used sensor in relative units for the accelerometer $\sigma_a$ and gyroscope $\sigma_g$ consists of the following components, assuming that the distribution of these components is normal:

$$\sigma_a = 3 \cdot \sqrt{\left( \frac{\gamma_T}{3} \right)^2 + \left( \frac{\gamma_n}{3} \right)^2 + \left( \frac{\gamma_t}{3} \right)^2 + \left( \frac{\gamma_c}{3} \right)^2},$$  \hspace{1cm} (11)$$

$$\sigma_g = 3 \cdot \sqrt{\left( \frac{\gamma_T}{3} \right)^2 + \left( \frac{\gamma_n}{3} \right)^2 + \left( \frac{\gamma_t}{3} \right)^2 + \left( \frac{\gamma_l}{3} \right)^2},$$  \hspace{1cm} (12)$$

where $\gamma_T$ is a thermal sensitivity shift; $\gamma_n$ – sensitivity nonlinearity; $\gamma_t$ – transverse axis sensitivity; $\gamma_c$ – initial calibration tolerance; $\gamma_l$ – linear acceleration sensitivity.

The choice of summability method depends on whether the errors being summed are correlated or independent. The errors are added as for independent values [18-20].

Table 1. Metrological characteristics of the MPU-6050 sensor according to the technical documentation.

| No. | Parameters                          | Accelerometer | Gyroscope |
|-----|------------------------------------|---------------|-----------|
| 1   | thermal sensitivity shift           | ±0.02%        | ±2%       |
| 2   | sensitivity nonlinearity            | 0.5%          | 0.2%      |
| 3   | transverse axis sensitivity         | ±2%           | ±2%       |
| 4   | initial calibration tolerance       | ±3%           | -         |
| 5   | linear acceleration sensitivity     | -             | 1.6%      |

Quantization error of the 16-bit ADC of the MPU-6050 sensor:

$$\gamma_q = \frac{1}{65.536} \cdot 100\% = 0.000015\%.$$  \hspace{1cm} (13)$$

Quantization error is a methodological error, however, it is an integral part of the measuring channel error and contributes to the measurement result.

The dating error is as follows:

$$\bar{e}_{\text{max}} \leq \Delta t_{sh} M_1,$$  \hspace{1cm} (14)$$

where $\Delta t_{sh}$ – the shift time of one direct measurement relative to another direct measurement, due to the difference in the synchronization frequencies of the measuring modules; $M_1$ – maximum module of the first derivative of the measured signal; $\bar{e}_{\text{max}}$ – upper estimate of the maximum dating error.

$$\bar{e}_{\text{max}} \leq \Delta t_{sh} \omega_{\text{max}} x_{\text{max}},$$  \hspace{1cm} (15)$$

where $M_1 \leq \omega_{\text{max}} x_{\text{max}}$ – Bernstein’s inequality for the first derivative; $\omega_{\text{max}}$ – maximum frequency in the signal spectrum; $x_{\text{max}}$ – maximum range of the measured signal.

$$\gamma_d = \frac{\bar{e}_{\text{max}}}{2x_{\text{max}}} \cdot 100\%,$$  \hspace{1cm} (16)$$

where $\gamma_d$ – reduced dating error.
Thus, the dating error for a microcontroller with a clock frequency of 80 MHz (with an allowable error of 15% according to the technical documentation), with a signal change rate of 30 Hz and a maximum amplitude of 30 m/s$^2$ is 0.00000125%.

The total error of the measurement result:

$$\gamma_{tot,g} = \sqrt{\gamma_q^2 + \gamma_g^2 + \gamma_d^2} = 3.3\%,$$

$$\gamma_{tot,a} = \sqrt{\gamma_q^2 + \gamma_{acc}^2 + \gamma_d^2} = 3.6\%.$$

where $\gamma_{tot,g}$, $\gamma_{tot,a}$ – measurement result errors for gyroscope and accelerometer.

4. Conclusion

In this paper, we considered the metrological analysis of estimates of the total error components of informative parameter measurement results of the walking techniques assessment using portable IMS. The characteristics indicated as examples can be extended to find the appropriate metrological parameters and their estimates, both for the methodological component and for the instrumental one.

A formalized description of the search for instrumental error components by the example of the considered MPU-6050 sensor can be distributed and supplemented for comparison with similar sensors for the purpose of subsequent optimal selection of one of them for designing a portable IMS with the required accuracy.

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