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Development and Verification of Software and Hardware Complex of Inertial System for Estimation of Human Motion Parameters of Limbs

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Abstract
The article shows algorithmic and technical issues for the development of an inertial system for estimation of human motion parameters. These type of systems are widely used in medicine for the diagnosis of diseases of the human musculoskeletal system, as well as for monitoring human motor activity during rehabilitation. Such systems are actively used to analyze the characteristics of the sportsman's movements. The article presents a functional diagram of the developed system, shows the choice of algorithms for attitude and heading reference system for a separate inertial measuring unit, reflects the issues of calculating the human movement' kinematic parameters. Considerable attention is paid to the issues of increasing the sustainability of the orientation assessment from the action of external disturbing factors. The paper proposes an original channel separation method for attitude and heading reference system. An important component of the technical complex is the equipment that makes it possible experimentally verify the correctness of the proposed algorithms. For this purpose, a reference stand-simulator of the upper limb has been developed. Study presents stand-simulator kinematics and discusses elements which allow its realization. The described technical complex allows to carry out all the necessary preparations and works to create and verify the correctness of the inertial system for estimation of human motion parameters.

Keywords: AHRS, inertial sensors, human motion parameters.

1. Introduction

The perspective direction of using the stropdawn inertial navigation system (SINS) is the research of the biological objects movement characteristics, also of human motion. Such systems for motion parameters estimation which use several inertial measurement units (consists from micromechanical sensors such as gyros, accelerometers and magnetometer) are called Inertial System for Estimation of Human Motion Parameters (ISEHMP).

ISEHMP is widely used in animation and sports. Recently ISEHMPs are more widely used in medical applications [1]: diagnostics of neurological diseases of movements; assessment of treatment quality; rehabilitation after injury in violation of motor functions of a person; movement registration of a person. Various clinical evaluation methods are used to assess the degree of motor activity disruption [2]. However, these methods are subjective and rude, because they are based on physician' assessments by senses. Clinical methods can't record minor changes in patients motor activity which can vary considerably during the day [3, 4] This can only be done with the help of mobile sensor systems such as ISEHMP. Among other application areas, ISEHMP is used in professional sports to monitor, analyze and improve sports results. Also, ISEHMP is widely used in the virtual reality for positioning and managing the helmet orientation, for the gestures recognition in games [5]. ISEHMP can be used independently for the study of human motion in natural conditions when person performing a wide range of movements.

The article is devoted to the development tasks of ISEHMP and algorithms for its functioning with increased noise immunity and accuracy.

2. Previous works in field of limb's attitude estimation algorithms for use in ISEHMP

To estimate the kinematic parameters of human motion, inertial systems use information about the body segments orientation on which they are installed. In this case, to calculate the joint angles, it is necessary to accept a certain biomechanical skeleton model and to associate the IMU location with the corresponding segment of the model [4]. In many research, the skeleton model is mainly used to calculate the positions of the end nodes of the skeleton. In some studies, the ability to perform correction of movement estimation based on the biomechanical skeleton model is indicated, but none of the authors did so in their works. The correction based on the skeleton model is mainly used at the stage of the initial alignment and calibration of the model parameters. Term "calibration" of ISEHMP refers to determining the length of the skeleton segments and determining the orientation of the blocks relative to the segment coordinate systems (CS) during the execution of special procedures [6].

For inertial and complex inertial systems, information for performing motion parameters estimation is the information about attitude of a separate IMU. Attitude refers to the IMU orientation in the global CS, which is determined by the type and accuracy of the used sensors. IMU attitude relative to the global CS is described by one of kinematic parameters: Euler angles, direction cosine matrix (DCM) or the quaternion. Quaternions are the most convenient and least cost-effective for use in modern algorithms. Algorithms for estimating the IMU orientation are algorithms of systems, which in English tradition are called AHRS (attitude and heading reference system) [7].

Studies [8] describe and analyze the current state of methods for assessing the objects orientation. These papers describe the general approaches that are used to construct orientation evaluation algorithms. The analysis of the methods of attitude estimation is carried out from the point of optimal estimation theory view, ensuring the convergence of the algorithm results and numerical resource costs for the implementation of the methods. According to [8], filtration is performed by combining measurements with their models. These models can be obtained in different ways, the most widely used is the kinematic prediction model which uses gyro signals. This model leads to the creation of complementary filters. Another type of system model is a kinematic model that takes into account the dynamic characteristics of the object. However, such model always contains parameters that are not defined exactly. This fact is taken into account by using different noise laws of sensitive elements, estimating the parameters of random perturbation, methods of adaptation of the basic settings of the described methods. However, these works paid little attention to the influence of methodological algorithms errors caused by the peculiarity of physical principles on which sensitive system elements operate.

The ISEHMP algorithms are characterized by static and dynamic precision. Moreover, accuracy is not indicated for the motion capture system, but for the algorithm of attitude estimation of a separate IMU. The accuracy of the static systems is up to 1 degree at yaw angle, but 0.2-0.5 degrees at the roll and pitch angles. The dynamic accuracy of these systems is 2 degrees (RMS) [9]. At the same time, the specified accuracy on the yaw is guaranteed only for a homogeneous magnetic field.

The magnetic channel is also exposed to magnetic perturbations from electrical equipment, permanent magnets, and from soft and hard iron effects. In order to eliminate the influence of soft and hard magnetical materials in such systems, an appropriate magnetic calibration is implemented at the installation place. To reduce errors from random magnetic perturbations, special algorithmic methods have been developed which allow flexible gain change of the correction signal from magnetic channel data [10].

It is known that the existing systems have the highest accuracy in a static mode in a homogeneous magnetic field [11]. The motion of the object introduces estimates of the orientation of the object as kinematic and dynamic errors at the source. That is, in the dynamic mode, the accuracy of the system is worse [9].

3. Development of algorithms and hardware for ISEHMP

The number of IMU systems for estimating the movement parameters of the major segments of the human body is 17. Systems recording the movement of the upper and lower limbs contain from two to 10 IMU. A system-level minimum of two IMUs can be used to evaluate the motion parameters of a hand without wrist.

3.1. Biomechanical model of human skeleton

The human body is a complex system that consists of over 200 bones, 600 muscles and innumerable nerve fibers that control their movement. For most practical applications, it is not possible to use a model that takes into account all components. In developing a system for assessing the kinematic parameters of human motion, one must abstract human motion and simplify it by using a skeleton model [12].

In this paper, we will use a biomechanical model of a skeleton consisting of 18 segments-bones and 15 joints (Fig. 1) to describe the human motion. A human skeleton can be represented as a system of rigid segments that are connected in chains by joints. Rigid segments are called chain links, and each two adjacent links are joined by joints.

The elbow, as a rule, is modeled as a hinge with one degree of freedom. This allows you to flex and extense your elbows. The supination and pronation of the forearm are controlled by the movement of the radial-elbow joint, which is between the elbow and the wrist. The shoulder and shoulder belt are one of the most complex joint groups of the human body. This complex joint is simplified using a spherical joint with three degrees of freedom. This allows the hand to carry out movement flexion/extension, abduction/adduction of the shoulder. The shoulder joint can be rotated by hand from or to the center of the body (internal/external rotation).

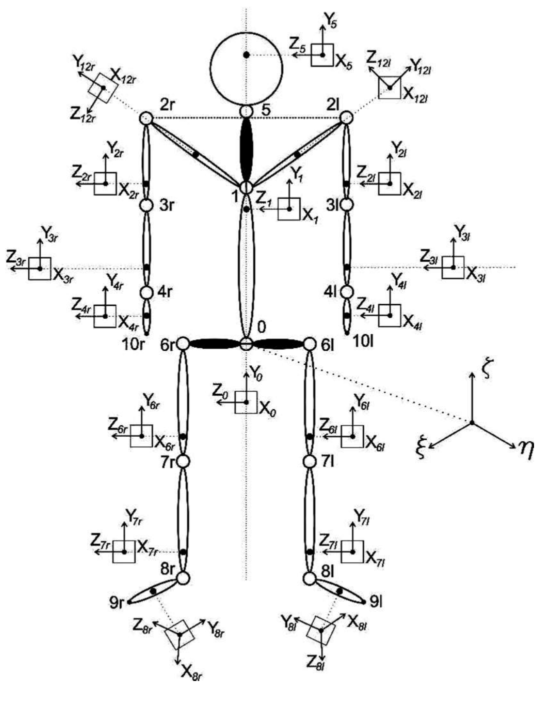

Fig.1 Biomechanical model of the human body with IMU positions and segment's coordinate systems

The process of constructing a hierarchical model of a skeleton of the human body is to determine the key joint nodes of the human body. In order to obtain data on the movement of 15 joint nodes, shown in Fig. 1, the system should consist of 17 IMUs. IMUs are located at the relevant nodes in which algorithm will estimate the movements of specific segments and the corresponding joint. The model of a human skeleton has a structure of a collisional chain.

In the biomechanical model, bone segments are joined by joints. The relation between the segments motion parameters is convenient to describe as the relation of the parent-child between nodes of the model. To describe the motion of a skeleton, you need to select the root node-joint. If you want to perform a description of the motion of the whole body, then such a node is pelvis node. This node is marked 0 in fig.1. Table 1 shows the description of joints, their degrees of freedom, parent segments and the type of motor activity.

3.2. Joint angles and calibration of ISEHMP

An important aspect of using ISEHMP is the assessment of the values of joint angles. The information on the basis of which the calculation of the joint angle is performed, are data about the segments orientation. In the developed system for calculating joint angles, the DCM data of complex algorithms for the attitude algorithm work of the one IMU, which are installed on the human body segments, and assumptions about the biomechanical skeleton model, are used. This allows to calculate joint angles in accordance with the recommendations of the International Society for Biomechanics [13].

Table 1. Description of segments and joints of a biomechanical model of a human skeleton

Joint name	Denotation on fig.1	Parent segment	Biomechanical type joint-hinge	Restrictions of human motor activity (degrees)
Back joint *	1	--	--	0-50
Cervical	5	The backbone of the chest	Spherical hinge	0-70
Shoulder	2r, 2l	Clavicular segment	Spherical hinge	0-180
Elbow	3r, 3l	Shoulder bone	Cardan hinge	0-145
Wrist	4r, 4l	Forearm bone	Cardan hinge	0-80
Pelvis	6r, 6l	Pelvis node	Spherical hinge	0-180
Knee	7r, 7l	Thigh	Cardan hinge	0-140
Ankle	8r, 8l	Ankle bone	Cardan hinge	0-45
Clavicle	1	Spine	Cardan hinge	0-30

* Complex joint, which reflects the angular orientation of the back relative to the pelvic knot.

Joint angle is defined as orientation of the distal segment C_d^{gb} relative to the proximal C_p^{gb} :

$$C_{dp} = \left(C_p^{gb}\right)^T C_d^{gb} \quad . \tag{1}$$

We will write the formulas for parametrization of the shoulder joint angles using the Euler-Krylov's angles. Kinematics of relative shoulder movement is shown in Fig. 2.

In order to find the relative orientation of the shoulder, you need to know the attitude of the systems $X_1Y_1Z_1$ and $X_{2r}Y_{2r}Z_{2r}$ in the navigation coordinate system, in order to guarantee the uniqueness of the angle orientation of each IMU. The matrix describing the relative position is determined according to formula (1).

Angles shown in Fig. 2, can be defined as follows:

$$q_1 = -arctg\frac{C_{dp1}(2,1)}{C_{dp1}(1,1)};\ q_2 = arctg\frac{C_{dp1}(3,1)}{C_{dp1}(1,1)};\ q_3 = arctg\frac{C_{dp1}(3,2)}{C_{dp1}(3,3)}.$$

Similarly, you can write formulas to determine all other joint angles.

As already mentioned, for the estimation of the kinematic parameters of human motion, each of the IMUs of the ISEHMP must be installed on a definite segment of the body. However, CS of IMU can't be perfectly aligned with the CS associated with the body segment. In addition, for the precise estimation of the joint angles it is necessary to use information on the number of degrees of freedom of the joint of the biomechanical model. This is due to the fact that the joint angles are defined around the functional visage joints. To reduce this kind of error, the "native calibration" procedure is used.

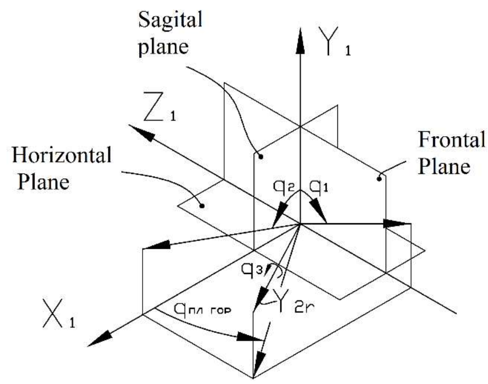

Fig.2. Shoulder's Kinematics.
q_1 – abduction/adduction;
q_2 - shoulder flexion-extension;
q_3 – rotation

3.3. AHRS algorithms for estimation of limb's orientation

The basic algorithms by which the orientation of the segments of the human body is evaluated by ISEHMP are algorithms of free platform-oriented vertical axes. These algorithms are also needed for the initial alignment of ISEHMP, which is based on the use of the integrated SINS algorithm invariant to accelerated motion of the limbs. Next, in this part we will consider the main proposed novelties in the algorithm of the platform-free course of the vertical, which uses as a kinematic parameters a matrix of directional cosines C^{bn}. The kinematics of a free platform illumination is shown in Fig. 3.

In the first stage of the algorithm, the current value of the DCM $\hat{C}_{k+1}^{bn}$ is calculated from the data of attitude in the previous step $\hat{C}_k^{bn}$, numerically integrating the Poisson equation with the gyro data. At the second stage correction of DCM $\hat{C}_{k+1}^{bn}$ is performed according to data of accelerometers and magnetometers.

Details of used AHRS algorithm are described in the author's paper [14]. Let's consider in more details the principle of AHRS channels correction separation.

Accelerometer signals are used to correct roll and pitch angles, and magnetometers should be used to correct the yaw angle. Information about the yaw contains in horizontal component of the Earth magnetic field induction (EMFI), and therefore when forming correction from magnetometers data we need to get rid of the influence of the vertical component. In this algorithm you can get rid of the vertical component of EMFI without a priori information about it and generate a correction signal only on the basis of data on the horizontal component of EMFI. The possibility of such implementation is most easily demonstrated using DCM sequential transitions for kinematics on Fig. 3:

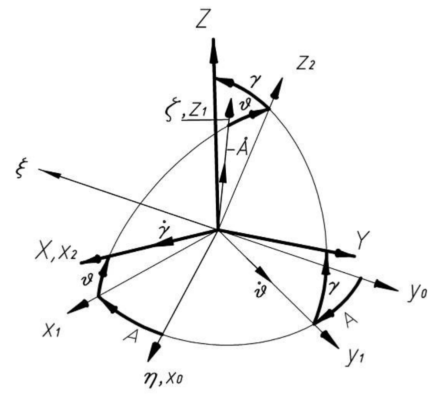

Fig.3. AHRS kinematic

$$\xi\eta\zeta\,(x_0y_0z_0)\xrightarrow{A}x_1y_1z_1\xrightarrow{\vartheta}x_2y_2z_z\xrightarrow{\gamma}XYZ\,.$$

Each such transition from one CS to another can be described by elemental DCM:

C_A	ξ	η	ζ
x_1	cos$A$	-sin$A$	0
y_1	sin$A$	cos$A$	0
z_1	0	0	1

C_ϑ	x_1	y_1	z_1
x_2	cosϑ	0	sinϑ
y_2	0	1	0
z_2	-sinϑ	0	cosϑ

C_γ	x_1	y_1	z_1
X	1	0	0
Y	0	cosγ	sinγ
Z	0	-sinγ	cosγ

Summary rotation is recorded as $C^{bn} = C_\gamma C_\vartheta C_A$. To explain forming a correction signal, it is necessary to pay attention to the CS $x_1 y_1 z_1$ and the DCM C_A (transition between $\xi\eta\zeta$ and $x_1 y_1 z_1$), $C_{\vartheta\gamma} = C_\vartheta C_\gamma$ (transition between $x_1 y_1 z_1$ and XYZ). From the above formulas for DCM it is clearly seen that the matrix C_A depends only on the yaw angle, and the matrix $C_{\vartheta\gamma}$ – the roll and pitch. And so CS $x_1 y_1 z_1$ is rotated relative to the vertical axis ζ at the yaw angle. So it is necessary to achieve such forming of correction signal that these two components of the turn are evaluated independently. The first stage of the correction is performed on signals accelerometers, and therefore after this stage, you can estimate the component of the rotation $C_{\vartheta\gamma}$. Using this information, it is necessary to redesign the magnetometers measurement signal into the system $x_1 y_1 z_1$. In this CS, the signal will consist of two horizontal projections of the magnetic field H_{x1} and H_{y1}, and one the vertical component Z_{z1}. This vertical component is the same as in the original coordinate system $\xi\eta\zeta$. With such a redesigned vector, we can create a signal from magnetometers $m_{x1y1z1} = \left(H_{x1}; H_{y1}; Z_{z1}\right)^T$, which depends only on the information horizontal component of EMFI. That is, for this it is necessary to reset the third component of the vector m_{x1y1z1} – Z_{z1}. Then we get the corrected vector of EMFI measurements $m_{x1y1z1}^{\text{кор}} = \left(H_{x1}; H_{y1}; 0\right)^T$. To perform the correction of the above algorithm, you need to have measurements in the body CS.

Therefore, we will form an adjusted magnetometer signal, redesigning $m_{x1y1z1}^{\text{кор}}$ into body CS:

$$m_{XYZ}^{\text{кор}} = \left(C_{\vartheta\gamma}\right)^T m_{x1y1z1}^{\text{кор}}. \quad (2)$$

An experimental verification of the accuracy of the AHRS in the static was performed. Absolute error of determination of pitch angle in the whole range of working angles – 0.4 degrees, errors of estimation of the angle of the roll – up to 1.5 degrees. The mean square error of the system throughout the range of angles is 0.86 degrees. Absolute error in determining the angle of the course throughout the range of working angles – 0.8 degrees.

3.4. Complex SINS algorithm for human motion parameters estimation

The initial information of the system of estimation of human movement parameters is the linear velocities and moving segments, angular velocities and accelerations of segments, joint angles. These data are obtained using a biomechanical skeleton model and data from the IMU. Information about angular velocity of segments is obtained directly from the angular velocity sensors of the corresponding IMU. The acceleration of a segment can be calculated by subtracting the projections of acceleration of the force of gravity from the accelerometer displays of the IMU. That is, you need to know the orientation of the segment in the navigation CS. To determine the segment attitude, its linear velocities and displacements in the developed ISEHMP, the algorithm SINS in the geodetic ENU CS is used.

A generalized scheme of a complex data processing algorithm based on the data of the SINS algorithm and the signals obtained on the basis of the biomechanical model, for a segment is shown in Fig. In this scheme, a closed circuit of SINS complexation based on an aperiodic filter is used. Differential signals ΔV_{Ei}, ΔV_{Ni}, $\Delta V_{\zeta i}$, Δp_{Ei}, Δp_{Ni}, $\Delta p_{\zeta i}$ are passed through low path filter with transfer function $W(p)=\dfrac{1}{Tp+1}$, and then filtrated data $\Delta\tilde{V}_{Ei}$, $\Delta\tilde{V}_{Ni}$, $\Delta\tilde{V}_{\zeta i}$, $\Delta\tilde{p}_{Ei}$, $\Delta\tilde{p}_{Ni}$, $\Delta\tilde{p}_{\zeta i}$ are used in SINS algorithm.

On Fig.4 are used next denotations: C_i^{gb}, $\bar{\omega}_i$ – DCM for current IMU algorithm and angular rate of current segment; C_j^{gb}, $\bar{\omega}_j$ – DCM for another segment IMU and its angular rate; V_{Ei}^{sc}, V_{Ni}^{sc}, $V_{\zeta i}^{sc}$, p_{Ei}^{sc}, p_{Ni}^{sc}, $p_{\zeta i}^{sc}$ – segment's linear velocity and displacement which are got using biomechanical skeleton model; V_{Ei}^{n}, V_{Ni}^{n}, $V_{\zeta i}^{n}$, p_{Ei}^{n}, p_{Ni}^{n}, $p_{\zeta i}^{n}$ – segment's linear velocity and displacement which are got using SINS algorithm for data of IMU installed on current segment. Corrective influences can be shaped in different ways. In this paper, it is proposed to use all available differential signals.

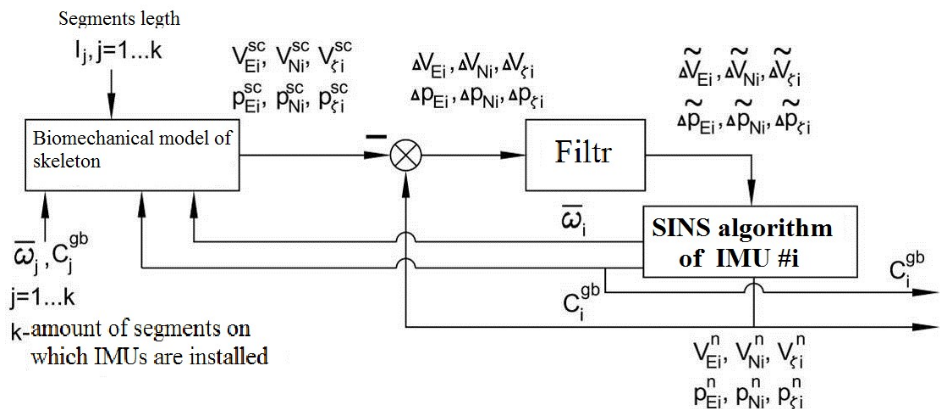

Fig.4 The scheme of data processing in complex algorithm for one IMU of ISEHMP

Formation of correction signals based on biomechanical skeleton model. Consider the question of forming correction signals for the BINS algorithm based on the skeleton model. We describe the formation of a position signal using a biomechanical model on the example of the right lower limb. Movement of the end node of the right thigh:

$$\bar{P}_{7r}=\bar{P}_{6r}+C_{6r}^{gb}\cdot\bar{l}_{6r-7r}, \tag{3}$$

where $\bar{P}_{6r}$ – displacement of node 6r of right part pelvis (father's segment); $\bar{l}_{6r-7r}=\begin{bmatrix}0 & -l_{6r-7r} & 0\end{bmatrix}^T$ – vector of segment length in bounded CS; $C_{6r}^{gb}=C_{6rIMU}^{gb}\cdot C_{6rCLBR}$ – DCM of right thigh orientation MHK in navigational CS; C_{6rIMU}^{gb} – DCM of IMU orientation installed on right thigh; C_{6rCLBR} – calibration matrix which describes IMU's axis $X_{6r}Y_{6r}Z_{6r}$ misalignment from segment anatomical CS. For other segments, this procedure will be similar, because it is based on the use of relationships between segments such as the parent-child.

We will show the finding of a linear velocity signal only for the right thigh:

$$\bar{V}_{7r}=\bar{V}_{6r}+C_{6r}^{gb}\cdot\left(\bar{\omega}_{6r}\times\bar{l}_{6r-7r}\right), \tag{4}$$

where $\bar{V}_{6r}=\bar{V}_0$ – pelvis node's absolute velocity (father segment) in navigation CS which is calculated in SINS algorithm, or is provided by external reference system or equals 0 in case of immovable pelvis. Using the biomechanical model of the skeleton, you can obtain information about the displacement and linear velocity of the elements of the model. These signals allow to calculate correction signals and use them in the complex algorithm (Fig. 4).

3.5. Stand-simulator of the upper human limb

This part is devoted to experimental full-scale validation of developed algorithms for ISEHMP with consideration of two variants of system construction: ISEHMP using algorithms AHRS and ISEHMP using the complex algorithm (see 3.4). The algorithm presented in section 3.3 was used as the AHRS algorithm. To test the accuracy of the developed systems and the correctness of the embedded algorithms, a special stand was created that simulates the upper limb (Fig. 5.a). Its kinematic drawings are shown in Fig. 5.b.

The Stand-simulator consists of one immovable and two moving segments. The fixed segment is designed to simulate the back and is firmly fixed to a certain base (table, wall, etc.). Two other segments (having a square cross-section) implement the shoulder and forearm, the full lengths of these segments respectively – 0.4 m and 0.295 m. These segments are connected by means of four single-hinged joints, and allow to realize the angular motion of the stand-simulator.

This stand has 4 angular degrees of freedom, which are marked on the drawing as $q1$, $q2$, $q3$, $q4$.,. It is designed to simulate the shoulder and forearm movements, and the shoulder kinematics is reproduced only in the angles of flexion-extension ($q1$) and rotation ($q2$). The relative angular motion of the forearm is completely reproduced: joint angle of flexion-extension of the forearm – $q3$, joint angle of the forearm rotation - $q4$. In order to evaluate the accuracy of the system, it is necessary to have the ability to specify or measure, with a certain reference device, with the high precision the parameters that should be evaluated by the ISEHMP. These output parameters are: Euler-Krylov's corners, joint angles, linear velocities and displacements. It should be noted that the measurement of angular motion in the stand considered is the easiest to implement technically, and it is possible to achieve the required accuracy of measuring joint angles.

FIg.5a. Stand-simulator of upper limb

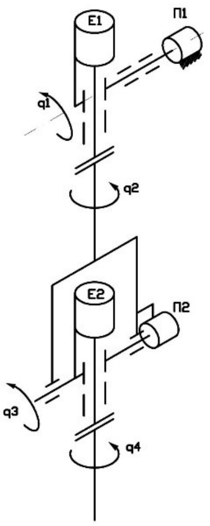

Fig.5b. Kinematic drawing of upper limb Stand-simulator

Two-phase incremental encoders LPD3806 600BM G5 24C (E1 and E2) having 600 pulses per revolution and 2400 rotating states, respectively, were used to measure the rotation angles of each segments. The resolution of the rotation angle measurement of the stand is 9 minutes, and the frequency of the poll of each encoder is 5 kHz. This allows to measure without span of pulses of rotation of segments with an angular rate up to 720 $^o/s$.It which significantly exceeds the required dynamic range of gyro measurement and the dynamic range of object motion where IMU installed. The measurement of the angles of bending-extension of the segments of the stand is realized with the help of absolute meters – the potentiometric angle sensors (П1 and П2). To ensure high accuracy, you need a stable power supply and a high-precision analog-to-digital converter (ADC). As an ADC, 16-bit precision delta-sigma ADS1115 from Texas Instruments was selected. This ADC contains 4 channels with a multiplexer and can perform conversions at up to 860 conversions per second per channel.

4. Experiments

A series of experiments were carried out on the slow and fast movements of the stand-simulator segments. This angular motion was directly measured by the angle sensors of the stand, as well as calculated ISEHMP using two different algorithms that were described in part 3. ISEHMP has used three IMU of ADIS16400/ADIS16405 from Analog Devices. For the correct operation of ISEHMP, using the algorithm AHRS, using a complex algorithm to perform "body calibration ". That is, the combination of CSs bounded with the IMU, with axes connected with the human body segments according to the model of the exo-skeleton (in our case with the CS, connected with the segments of the stand). In our experiment, the information that was used for "body calibration" is the a priori knowledge about the orientation of the stand-simulator at the beginning of the experiment. The fact that the initial values of the joint angles, evaluated by ISEHMP with the use of both algorithms, are close to 0°. The correctness of the body calibration is confirmed by this.

On Fig. 6-8 shows the results of the conducted experiment, which consisted in the execution of fast random movements of both segments simultaneously. The graphs of the change of joint "shoulder" angles during this experiment, recorded by the stand-simulator sensors, are shown in Fig. The comparison of the accuracy of the work of the two ISEHMP was performed by the selected characteristic points on the joint angles.

The joint angles, which were evaluated by ISEHMP using the AHRS algorithm, are shown in Fig. 7, and using the complex algorithm, are shown Fig. 8.

From the obtained results it is evident that at fast motion of the stand-simulator, the ISEHMP with a complex algorithm has lower values of errors, especially in the rotation angles of the segments. For ISEHMP with the AHRS algorithm, as in the slow experiment, larger errors are characteristic for large values of joint angles. In this study, the error of the ISEHMP with the AHRS algorithm begins to vary significantly (see point number 7 for the rotation of the shoulder – more than 4°, see point number 3 for the rotation of the forearm – more than 9°) from the error of the ISEHMP with a complex algorithm at rotation angle greater than 40°. Regarding the errors of the estimation of the angles of flexion/extension of the stand segments, the ISEHMP with the AHRS algorithm does not significantly inferior to the ISEHMP with a complex algorithm. It is also necessary to note that graphs of joint angles obtained from ISEHMP with a complex algorithm represent a better form of reproduction of reference measurements, especially in the vicinity of the point number 6 of the rotation pattern of the forearm.

With a rapid motion, we can observe the tendency that the errors of the ISEHMP with the complex algorithm remained at the level of slow stand motion, and the errors of the system with the algorithm AHRS increased. This is due to an increase in the rates of acceleration that operate on the IMU. And as it was shown in this section, the AHRS is very sensitive to accelerations and has significant errors. The complex algorithm is much less sensitive to this kind of interference, because it uses the SINS algorithm, which is invariant to relative object accelerations. It is also necessary to say that the graphs of the joint angles fully adequately reflect the initial movement of the stand.

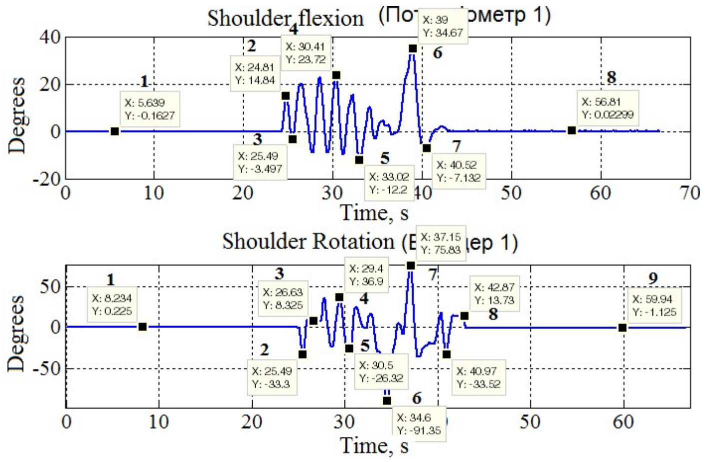

Fig.6. Joint angles of stand-simulator shoulder

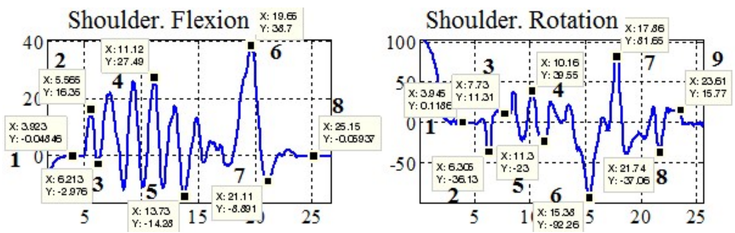

Fig.7 Joint angles of ISEHMP using the AHRS algorithm

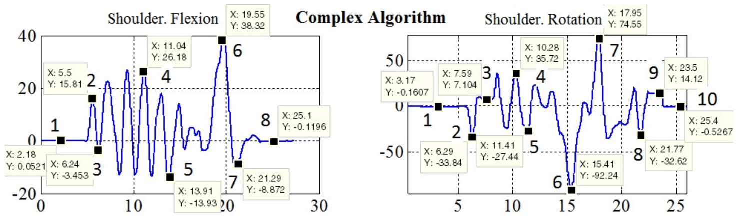

Fig.8 Joint angles of ISEHMP using a complex algorithm

5. Conclusions

The article highlights the main stages of methodological and algorithmic support for the development of ISDNL. The paper proposes several original solutions that allow to increase the accuracy and impedance of algorithms of such systems, namely: the use of the developed principle of separation of channels of correction AHRS and the use of a complex algorithm in the work of ISEHMP.
The article proposes and formulates the principle of separation of channels for AHRS. The practical realization of this principle allows to exclude the influence of measurements of magnetometers on the attitude estimation of the AHRS algorithm in relation to horizontal plane. The complex algorithm for an inertial system for estimating human movement parameters is invariant to accelerated limb movement, correction signals for velocity and displacement are formed on the basis of a biomechanical model of a human skeleton. The implementation of the complex algorithm has allowed to reduce the errors of the ISEHMP in the performance of human movements with a significant level of acceleration, in comparison with a similar ISEHMP, which uses the algorithm AHRS.

The article shows the results of field tests on the own developed stand-simulator of the upper limb. The results of the tests confirmed the correctness and efficiency of the developed algorithms of ISEHMP. The stand-simulator sensors are capable of measuring the angles of rotation of the segments with an accuracy of 9 angular minutes, flexion/extension – 2 angular minutes. Comparison of the experimental results of the ISEHMP in various modes of the object showed the advantages of a developed integrated algorithm with correction on a biomechanical model of a human skeleton. This is especially effective for estimating parameters of fast objects movements. The use of complex algorithm in ISEHMP in comparison with the use of AHRS algorithm allows to reduce system errors on 5-6 degrees in measuring rotation angles with significant range. Also, for fast movements, the accuracy of the measurementof stand flexion/extension increased by 1.5-2 degrees.

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