Hardware and software usb-hid device for control the PC cursor for people with impaired motor functions

T. N. Ivanilova, M.A. Shumilina, A.V. Kushnerov, S.A. Chichikov
Reshetnev Siberian State University of Science and Technology, Krasnoyarsk

Abstract: The use of information technologies in the tasks of medical rehabilitation is an effective method, but it is often complicated by the problems of using standard control devices and input into the computer by people with motor impairments. The developed hardware and software complex allows one to obtain data on the orientation of the joint in space, "turning" them into the movement of the mouse pointer, allowing one to interact with computer software, instead of the mouse manipulator. By changing the sensitivity of the sensors, the process of rehabilitation of patients is corrected. The used component base of the complex being developed and the technologies used make it possible to form a significantly lower cost, the possibility of using it outside the clinic, working without the help of specialists, application in control actions with computer software not only for rehabilitation but also for people with disabilities. The paper defines the tasks and functions that are solved by the hardware and software complex. In the 3D editor, the body frame and the internal arrangement of components are modeled, hardware and software tools are selected to ensure the implementation of the project. The functional scheme of the "Limbtracker" device has been developed. During the execution of the project, the following was implemented: reading data from sensors and writing them to a text file, filtering data by the Kalman algorithm, calibration of the device.

Keywords: hardware and software complex, home rehabilitation, neurorehabilitation, STM32, microcontroller, device design, USB-hid.

Introduction

The active development of information technologies makes it possible to use new methods and devices for the medical rehabilitation of people with disabilities or disorders of the central nervous system.

A motor analyzer is located in the cortex of the frontal lobe of the brain. It maintains communication with the spinal cord and other parts of the brain and is responsible for the smoothness, accuracy and plasticity of movements, as well as the sensitivity of the motor system. If this part of the nervous system is damaged and the conduction of impulses is impaired, the motor function is limited. The severity of motor disorders depends on the level of the pathological process and their degree. Among the main reasons it is worth noting the post-stroke condition, parkinsonism, Huntington's disease, damage to the cerebellum, etc. regardless of the occasion that caused the disorder, the neurologist provides assistance to all

patients, preventing changes in the quality of life. Standard medical rehabilitation after diseases such as stroke, traumatic brain injury, Parkinson's disease is carried out using well-known clinical techniques: craft therapy, conservative prevention, massages, physical therapy exercises, but as practice shows, these rehabilitation methods are not enough [1]. The organization of patients' interaction with a computer through modern information technologies allows to significantly expand the possibilities of rehabilitation measures [2]. Therefore, it is necessary to introduce information and communication technologies into medicine, which will allow providing a more efficient and comfortable life for patients.

Full rehabilitation of patients takes from two months to several years. The reason for the long recovery is the limited time spent by the patient in the clinic, as well as a decrease in the patient's motivation due to the monotony of the exercises performed by one [3]. Rehabilitation therapists of the Krasnoyarsk region believe [4] that the patient should be involved in the rehabilitation process not only in the clinic but also in their daily life in conditions as close as possible to the real world.

According to the website of the Russian Federal State Statistics Service https://rosstat.gov.ru / [5] in recent years, the number of young people who have violations of sensory and musculoskeletal functions of the body has been growing, therefore, the relevance of developing a hardware and software complex for rehabilitation is significantly increasing.

The purpose of the hardware and software complex development is to create a universal hardware and software complex based on the STM32 microcontroller, which will turn any joint of the body into a computer mouse, and, thanks to this, control the computer and solve the tasks of rehabilitation and communication of people with motor pathologies.

The development presented in the article can be successful when used in out-of-hospital conditions by people with disabilities or undergoing rehabilitation.

Applicability

The areas of application of hardware and software complexes are quite diverse: database management, healthcare industry, manufacturing processes, gaming industry, etc.

The applicability of the developed hardware and software complex is the healthcare industry. The use of information technologies in health care in the information-oriented society is usually assessed according to two criteria:

- solving specific social and economic problems;

- improving the quality of diagnostics and treatment while reducing costs.

Let's take a closer look at the medical problems solved by the described development.

The first area of the complex's use is to develop communication among people with disabilities (motor functions), with impossible rehabilitation. For a full-quality life of people with disabilities, an important component is the ability to work and communicate using a computer. Such a complex is necessary for performing everyday tasks, it will be able to communicate, work, study. Even if it is not possible to work with the upper or lower limbs, it will be possible to do this through a computer, since the developed hardware and software complex will successfully help in the problem of difficulty or inability to control a computer mouse. To do this, the capabilities of the complex are used, the device of which is fixed on the active joint of a person.

The second area of use is in the rehabilitation of patients with a neurological profile, namely: for classes on the development of movements of the upper and lower limbs, both in the clinic and at home. Achieving complete recovery of the functions of the nervous system disrupted due to illness or injury, which led to movement disorders, is possible only through constant rehabilitation exercises carried out by the patient. Medical rehabilitation is carried out depending on the

severity of the patient's condition in three stages. The use of the presented hardware and software complex is most important in the third period of medical rehabilitation, which is carried out in the late rehabilitation period, the period of residual phenomena of the course of the disease, in the chronic course of the disease without exacerbation and is a good addition to standard rehabilitation measures such as physiotherapy, physical therapy exercises, reflexology, manual therapy, psychotherapy, medicopsychology, etc.

Using the Limbtracker hardware and software complex, the patient can train the joint intensively both in the clinic and at home or in any other comfortable conditions. Such a method of recovery after injuries or diseases can be about several times more effective than performing exercises in a clinic [6]. The Limbtracker device has the ability to adjust the sensitivity of the sensor. In the initial stages, with a limited moving joint, one small movement leads to a significant cursor move. In the future, the patient will need to make more efforts to also move the cursor for the functional restoration of the joint.

This article presents a hardware and software complex that allows people with musculoskeletal disorders and people with disabilities to work on a computer without a mouse manipulator. The complex is able to adjust to individual parameters and the degree of the patient's disease by adjusting the sensitivity of the sensors.

The research conducted by the authors suggests that the presented development is mainly aimed at improving the quality of treatment and rehabilitation, low cost of the complex, and contributes to solving the problems of socialization of people with impaired functions of the musculoskeletal system.

Goal setting

The aim of the work is to develop a hardware and software complex that allows using a human joint to control a computer mouse, thereby performing

everyday tasks on a computer and solving problems of rehabilitation of people with pathologies, using a "faulty" joint to work on a computer.

The STM32 microcontroller uses a three-dimensional position detection system using an accelerometer, gyroscope, and magnetometer to control the computer cursor [7]. The signals from the microcontroller are transmitted via the USB interface.

The gyroscope and magnetometer on the microcontroller board reflect the three-dimensionality of space and represent a system of directions of rotation from any point of reference, which can be either our own body or any of the objects around us.

The device can be attached to any human joint, for example, as shown in Figure 1, it is attached to the shoulder joint, and the person, moving the shoulder, changes the position of the control cursor on the screen. It is also necessary to develop an emulation of a button, touching which is equivalent to pressing the left mouse button ("Enter") [8]. With the help of a fixed device on the joint, you can: work on a computer, write letters and study.

Let's list the functionalities for implementation in the "Limbtracker" complex:

− control of the mouse cursor of a personal computer using a device fixed on a human joint;

− changing the sensitivity of Limbtracker sensors for an individual human rehabilitation program;

− ability to use "Limbtracker" without assistance at home.

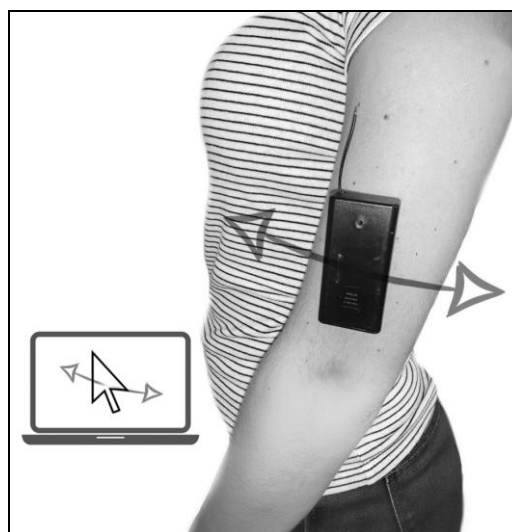These functions are absent in the known analogues [9 - 11].

Fig.1. - An example of using a hardware and software complex

Analysis of similar solution

Currently, existing foreign analogues, for example, YouGrabber virtual reality system (Switzerland), the Jintronix system (Canada), OpenSesame (Israel), either do not perform the necessary functions when used or have a very high cost [12].

People with disabilities need active work with modern information and communication technologies, which makes it possible to get basic education, complete vocational training, and also find a job.

There are methods of rehabilitation based on computer games. For example, using sensory gloves "Sensorehab" [9], which were developed by specialists from Krasnoyarsk. The complex is a set of computer games aimed at developing the motor functions of the hand of patients after a stroke. Exercises with a sensory glove were carried out as follows: the patient puts on a sensory glove on the paretic hand, which is a set of 5 flexible bend sensors that respond to movements (flexion and extension) of the fingers; the glove is connected via a USB cable to a personal computer. The method of restoring hand function using a sensory glove in patients has been shown to be effective in neurorehabilitation. This method of neurorehabilitation is applicable only to the hands, and not to any human joint.

There were also a number of patients who were unable to fulfill even the simplest motor requirements and lost interest in the game.

Another similar system "Trust M" is designed to diagnose posture, objectively assess the effectiveness of the treatment, and to restore the balance function using the method of biologically active communication [10]. The system is close in terms of internal components, dimensions, and data transmission channels to the Limbtracker complex being developed. The Trust M complex was created to carry out a full cycle of restoration of human musculoskeletal functions in clinical conditions under the supervision of a specialist. The Trust-M complex has a number of disadvantages: the inability to use the system for rehabilitation at home, since it is intended for rehabilitation in a clinic, the high cost of equipment (from 1,000,000 rubles), and the mandatory assistance of a specialist.

Table №1

Comparative analysis of similar solutions

	LimbTracker	*Kinect*	*SensoRehab*	Ortorent Virtual	Trust-M
Independent use	+	+	+	-	-
Versatility of fixation	+	+	-	+	+
Tracking accuracy	+	-	+	-	+
Wireless	-+	-	-	-	+
Hardware and software complex	+	+	+	-	-
Designed for rehabilitation	+	-	+	+	+
Cost, rub.	8000 – 35 000	40 000	62 000	650 000	1 000 000

Analysis of existing complexes suggests that the Limbtracker device has a lower cost, can be used outside the clinic and without the help of specialists, and as

a result, can be used not only for rehabilitation but also for people with disabilities solving everyday tasks.

To work with the hardware and software complex, no specialized software is required, the device works with the standard USB-hid protocol for input and output devices, and can be used with standard drivers.

In the process of studying similar products, several prototypes were designed and the most suitable for the listed technical parameters and dimensions were selected.

Analysis of existing complexes suggests that the Limbtracker device has a lower cost, can be used outside the clinic and without the help of specialists, and as a result, can be used not only for rehabilitation but also for people with disabilities solving everyday tasks.

To work with the hardware and software complex, no specialized software is required, the device works with the standard USB-hid protocol for input and output devices, and can be used with standard drivers.

In the process of studying similar products, several prototypes were designed and the most suitable for the listed technical parameters and dimensions were selected.

Development of a hardware and software USB - hid device

The development of a hardware and software complex can be divided into two parts: hardware and software. Hardware development consists of the creation of a prototype and a microcontroller program. The development of the software part consists of the designing of the software code of the microcontroller.

The device consists of a plastic case with snaps and an elastic fixing strap attached to it. The body frame was modeled in a 3D editor and printed using a 3D printer.

The block diagram of the device describes the processes occurring in individual parts of the device (sensors) or the device as a whole. Figure 2 illustrates the block diagram of the microcontroller:

− mini-USB – mini-USB connector for connecting to a computer;

− Embedded STLink – ST-Link programmer/debugger integrated on the board;

− SWD – SWD interface programming connector;

− I/O – microcontroller i/o ports;

− RESET – microcontroller reset line;

− P1-Header/P2-Header– external pin connectors;

− LD1, LD2 – LEDs describing the work of the MK. LD1 - red LED COM - designed to indicate USB communication between the PC and the ST-Link module;
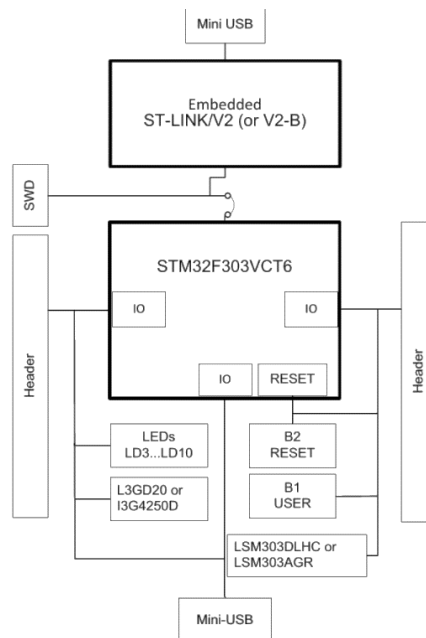
− B1, B2 –user, reset buttons [13].

Fig. 2. - Functional diagram of the internal components of the device

As can be seen from the diagram in Figure 2, the implementation of all functions is assigned to the microcontroller, including the processing of USB data.

The device transfers data from the computer to the microcontroller using the USB hid protocol. Data transfer from sensors (accelerometer and gyroscope) to the microcontroller is carried out via the SPI protocol and the I2C bus.

The developers of such systems face the problem of optimal choice of both hardware and software that ensure the implementation of the project with minimal time and money. To solve this problem, it is necessary to choose a development environment and programming language that is convenient for programming for a microcontroller.

Development tools

The development of the program code for the microcontroller is carried out in the high programming language C. The computer software being developed uses Python - a high-level programming language [14].

The program for calibrating accelerometer and magnetometer sensors is written in Python in the PyCharm development environment. The choice of the Python programming language is due to the fact that it is designed for mathematical calculations and programming of robotics and electronic devices. The code uses exception interception, that is, if there is an error in the program, it will not be completed, but will correct itself and continue its work.

The STMCubeIDE development environment was chosen as the programmer-debugger. STM32CubeIDE is a multifunctional development tool that is part of STM32Cube by STMicroelectronics company. STM32CubeIDE includes build and stack analyzers that provide the developer with information about the project status and memory requirements. STM32CubeIDE also includes standard and advanced debugging functions, including the kernel, memory, and peripheral register representations, as well as real-time variable value viewing, Serial Wire Viewer interface, and fault analyzer [15].

Determining the orientation of the device in space

Determination of the orientation of the device in space is carried out in real-time using readings from orientation sensors of the MEMS type. The accelerometer and magnetometer measure the acceleration and magnetic field vectors in three mutually perpendicular axes X, Y, Z. The gyroscope measures the rotation speed along three axes. Measurements are carried out in an inertial frame of reference [16]. Fig.3 shows an image of a board with sensors, the axes are indicated.
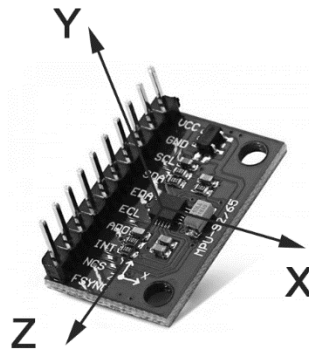
Fig.3. - Board with orientation sensors

The STM32 microcontroller accepts raw data from MEMS orientation sensors as input and outputs it in high-level representation (transforms it) as commands for changing mouse coordinates or as a data stream to a virtual com port [17].

Data transformation in the form of changes in the coordinates of the mouse cursor occurs according to the following algorithm. At the first stage, the data obtained from the sensors is multiplied by a matrix of correction factors. Then they are normalized. Next, the values of the orientation angles are calculated relative to the initial position. At the final stage, the values of the angles are processed using the Kalman filter.

With the long-term operation of the device, there is an accumulation of error due to the instability of the gyroscope zero-point offset, which are caused by internal imperfections and noise. For periodic correction of the accumulated errors

of the gyroscope, namely, to establish zero values of the gyroscope readings, we use the measured coordinates of the acceleration vector (A) and the geomagnetic induction vector (M) The angle between M and A must remain constant for any position of the device.

The magnetometer and accelerometer are calibrated once before using the device.

Calibration of microcontroller sensors

The main problem of MEMS sensors after mounting into the board are minor deformations that cause negative effects:

  − offset zero position;

  − incorrect scaling of measured values;

  − non-orthogonality of sensor axes

  − misalignment of sensor axes [18].

To achieve maximum measurement accuracy, the accelerometer and magnetometer are calibrated. For calibration, an algorithm is used to determine the magnetic field vector in a geocentric coordinate system, which uses data from a three-component accelerometer rigidly fixed relative to a three-component magnetic sensor.

The calibration task is to calculate the correction factor matrices for the M and A sensors. For each sensor, there are zero-point offset coefficients along the axes, scaling coefficients of the axes, rotation matrices for each axis of the sensor. The coefficients and matrices found are transformed into spatial transformation matrices. During the operation of the device, the uncalibrated M and A vectors read from the sensors are multiplied by the corresponding matrix, thereby correcting the displacement, axis scales, and misalignment of the sensors relative to each other.

The calibration procedure is carried out separately for the accelerometer and magnetometer, correction factor matrices are calculated for each based on the analysis of uncalibrated readings from sensors.

To simplify the procedure of measuring the coordinates of the device itself, a data collection and visualization program has been implemented. The program records sensor readings when the device is stationary and when the device is moving in space. The received data is output to a text file.

In order to visually assess the correctness of the data received from the sensors, a scatter diagram of the readings is built in the data collection and visualization program, which includes 3000 coordinates from the device sensors. The construction of the diagram occurs in the process of uniform rotation of the device around each of the axes. To achieve maximum measurement accuracy, the accelerometer and magnetometer are calibrated. The scatter diagram of the calibrated sensor should be spherical, centered at zero coordinates. This demonstrates the proportionality of the values obtained and the absence of a zero point offset. After taking measurements, the constructed scatter diagram (Fig. 4-7) has an ellipsoid shape, which indicates the need for calibration of the device.

The data obtained from the data collection and visualization program is used as input to the Magneto program. They are used to calculate the displacement vector and the required calibration matrix.
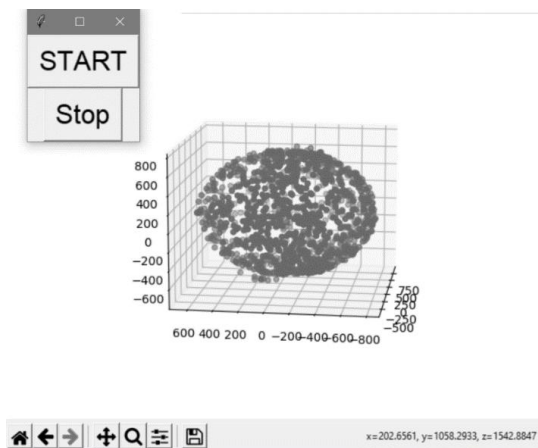

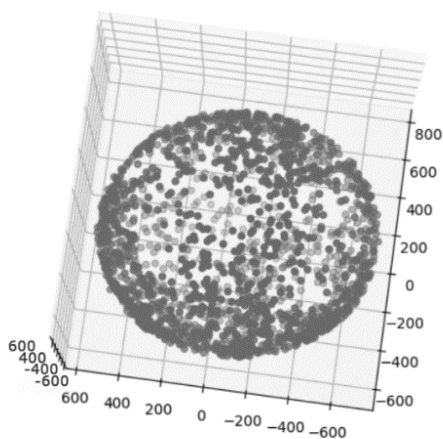Fig.4. - Scatter diagram of data from accelerometer before calibration

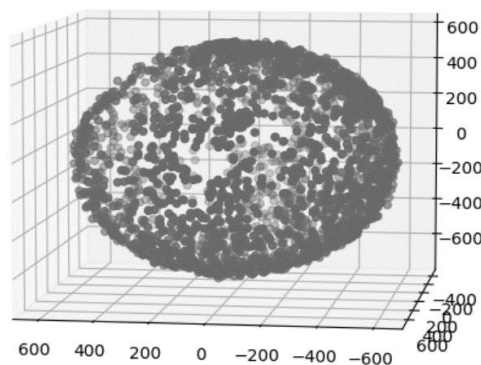Fig.5. - Scatter diagram of data after accelerometer calibration

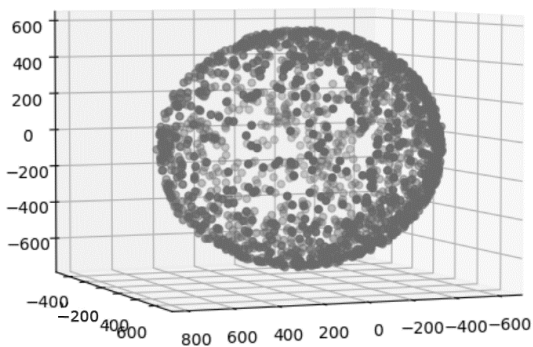Fig.6. - Scatter diagram before magnetometer calibration

Fig. 7. - Scatter diagram after magnetometer calibration

After calibration and new measurements, the data is a ball, the radius of which is the magnitude of the external impact, and the center is the desired value of the zero offset.

The device is calibrated, it is necessary to filter the signals received from the sensors to eliminate various types of noise.

Implementation of the Kalman algorithm

When working with sensors that read orientation in space, there is often a problem with the noise level of the received data. To ensure that errors in the received values do not lead to errors in the functioning of the system as a whole, data from sensors must be aggregated. When using several sensors in the measuring system, the characteristics of which depend on the influence of external factors, it is difficult to use "classical" filtering. Therefore, when developing the hardware and software complex, the Kalman algorithm was implemented.

The Kalman filtering algorithm works iteratively. At each step, noisy sensor data and the state vector from the previous step are taken; these data are used to determine the state of the system at the current step. Using a filtering algorithm, noise and signal spikes are removed.

In the Kalman filter, it is possible to set in advance the necessary information about the nature of the system, the relationship of variables and, based on this, obtain an accurate estimate.

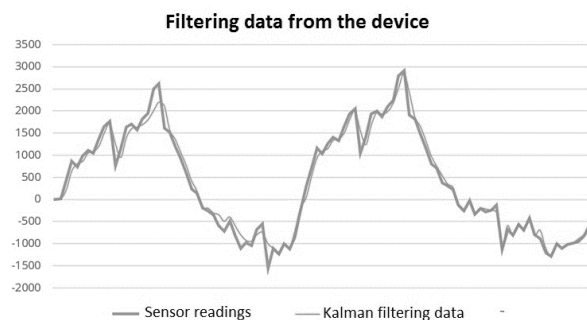Figure 8 shows a graph of data filtering along the x-axis of the gyroscope.

Fig. 8. - Gyroscope data filtering graph

To work with the filtering algorithm, it is necessary to calculate the mean square deviation, the average value, the maximum and minimum values of the data, and select the K coefficient - the reaction rate to data changes. We enter the necessary obtained values into the program code and execute the Kalman filtering function implemented in the C language.

To smooth out the received data from the device, a Kalman filter is used, which reduces the noise that inevitably appears during the operation of the gyroscope, accelerometer, and magnetometer. In the algorithm of the Kalman filter, the K coefficient is set, which determines the reaction rate of the system, and the relationship of variables. Experimentally, the value of this parameter was selected, minimally distorting the input data. But as can be seen from Figure 11, with a sharp movement, we observe a "lag" as a result of data filtering, but it is much less than the required response time of the system and does not lead to inconvenience when working with the device.

Paying attention to the proximity of the true data with the received and filtered values, it is possible to identify areas of the code in which there is a loss of significant digits for single-precision numbers for both the extended and sigma − point Kalman filter.

After the sensors are calibrated and the data from them is filtered from external influences, you can start working with the software component of the complex.

Description of working with the hardware and software complex

The program of the Limbtracker complex includes the following modules:

− main function module, with a call to the function of initializing sensors, calibrating sensors, and filtering the obtained values;

− sensor connection module, reading and transmitting data from sensors;

− module for calculating calibration matrices, gravity vector, rotation matrix (Euler angles);

− calibration module.

The program is loaded by connecting USB to the computer, the device is recognized in the manager as a USB-hid interface (input-output). The input data for the program is the data received from sensors: accelerometer, gyroscope,

magnetometer. This data is initialized, filtered, and calibrated in the program modules.

The output data are:

– graphical information displayed on the screen;

– files in one of the graphic and text formats – copies of the image of the received values and files in the format .csv, .txt (calibration data).

The main file main.c implements the functions of initialization and configuration of peripheral devices of the microcontroller. Accelerometer, magnetometer, and gyroscope are initialized via I2C, SPI buses, setting clock rate, data range, and amplifier gain are set (since the signal from the gyroscope is weak, it must be increased).

After checking the operability of the sensors, the received values are read from the device. The obtained values are calibrated using calibration matrices and the displacement vector.

The operation of the device begins with the configuration of the STM32 microcontroller. GPIO initialization is performed (input-output interface health check) and I2C, SPI, usb_devise buses.

After the sensor data is calibrated and filtered by the Kalman algorithm, the modified data is transferred via USB to the cursor coordinates.

The infinite loop of the main.c file checks the pressing of the button on the microcontroller and performs the corresponding LED indication. To collect data or terminate the program, you can use the reset button. Figure 9 shows the algorithm of operation of the device with a software implementation.
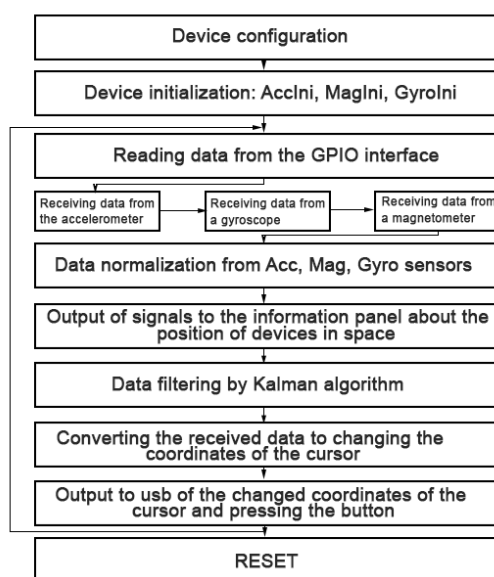
Fig. 9. - The algorithm of the hardware and software complex

After connecting the device, checking the operability of the sensors, and calibrating the device, the software, and hardware complex can be used in full, namely: control the PC cursor, perform the necessary functions for everyday work at the computer, thereby solving the problems of patient rehabilitation.

Conclusion

The article describes the development of a hardware and software USB-hid device "Limbtracker", designed for the rehabilitation of people with impaired motor functions and people with disabilities. The complex is implemented as a real-time motion tracking system. The selected sensors of the device use a three - axis accelerometer, a three - axis gyroscope, and a three - axis magnetometer.

The development and application of a hardware and software complex based on the STM32 microcontroller is a universal solution, as it provides several options for modification and expansion of functionality.

The "Libtracker" device allows you to take the readings from sensors and calculate the orientation in space. In order to achieve maximum measurement accuracy, the accelerometer and gyroscope are calibrated, the Kalman filtering

algorithm is implemented, with the help of which noise and signal spikes are removed [19].

Further lines of research are related to the search and development of more effective methods for filtering data and improving the dynamic properties of "Limbtracker".

The hardware and software complex is at the stage of implementation in the Professorial Clinic of the Krasnoyarsk State Medical University named after Professor V.F. Voino-Yasenetsky. Testing it on real patients will make it possible to track the effectiveness of "Limbtracker" in the rehabilitation process.

References

1. Trayner P. Using Software Technology in Neurorehabilitation to Facilitate Effective, Time-Efficient Goal-Setting. Archives of Physical Medicine and Rehabilitation, Volume 101, 2020. pp. 49-50.

2. Winstein C., Requejo F. Innovative Technologies for Rehabilitation and Health Promotion: What Is the Evidence? Physical Therapy, Volume 95, Issue 3, 2015. pp. 294–298.

3. Fischi M. Information technology is changing the way society sees health care delivery, Int. Med. Informatics, vol. 66. – №1. –2002. pp. 85-93.

4. Suxix V.G., Chexa V.A., Stepanova M.V. Informacionnye texnologii v reabilitacii invalidov [Information technologies in the rehabilitation of the disabled: a methodological guide]. Krasnoyarsk, KGBU SO Kompleksnyj centr social`nogo obsluzhivaniya naseleniya, 2011. p. 150.

5. Uroven invalidizacii v Rossii: Federal`naya sluzhba gosudarstvennoj statistiki [The level of disability in Russia: Federal State Statistics Service]. URL: rosstat.gov.ru/folder/13964 (accessed: 25/03/2021).

6. Kilbride Ch., Nowicky A., Warland A. Rehabilitation Using a Novel Home-Based Digital Therapy Device for The Upper-Limb Post Stroke

(RHOMBUS). Archives of Physical Medicine and Rehabilitation, Volume 102, 2021. pp. 1- 11.

7. USB HID for STM32 in STM32IDE. URL: ixbt.com/live/diy/usb-hid-interfeys-dlya-stm32-v-stm32ide.html (accessed: 07/04/2021).

8. Ivanilova T.N., Dneprovskaya M.A., Chichikov S.A., Kushnerov A.V. Yuzhno-Sibirskij nauchnyj vestnik, № 2. DOI 10.25699/SSSB.2021.36.2.027, 2021. pp. 47-54.

9. SenoReHab URL: sensorehab.com/ru. (accessed: 09/04/2021).

10. Biomexanika Trast-M [Biomechanics Trust M]. URL: neurocor.ru/product/biomehanika-trast-m (accessed: 15/04/2021).

11. Prokopenko S.V., Mozhejko E.Yu. Patent №2494670 Rossijskaya Federaciya. Sposob korrekcii melkoj motoriki s ispol`zovaniem sensornoj perchatki [A method for correcting fine motor skills using a sensory glove]. Krasnoyarsk. No. 2011150588, Byul. №17, 2013. p. 8.

12. Masabaev, E. S. Primenenie IT-texnologij v reabilitacii postinsul`tnyx bol`nyx. Molodoj uchenyj, 2016. № 30. URL: moluch.ru/archive/134/37531/ (accessed: 15/04/2021).

13. Dogan I. Arm-Based Microcontroller Multitasking Projects. Elsevier Science, 2020. p. 524.

14. PlasDzh.Vander Dzh. Python dlya slozhny`x zadach: nauka o danny`x i mashinnoe obuchenie. Spb, 2018. pp. 263 - 376.

15. Rossi M., Toscani N., Mauri M., Castelli Dezza F. Introduction to Microcontroller Programming for Power Electronics Control Applications. CRC Press. 2021. pp. 9 - 20.

16. Martin M. Insajderskoe rukovodstvo po STM32 [Insider Guide to STM32]. URL: istarik.ru/file/STM32.pdf (accessed 05/11/2021).

17. ST life augment. URL: st.com/en/microcontrollers-microprocessors/stm32-32-bitarm-cortex-mcus.html (accessed 20/05/2021).

18.   Platt Ch. Logic chips, amplifiers, and sensors for beginners. BHV, 2020. p. 448.

19.   Algorithms for programmers ideas and source code. URL: dsp-book.narod.ru/fxtbook.pdf (accessed 10/05/2021).