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Cybernetic suit for interaction with virtual reality

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ABSTRACT

The study in the field of the structure of the processing architecture of a cybernetic suit for working with virtual reality was conducted. Nowadays it is relevant to use such a systems to implement various scenarios of rehabilitation for people, as well as to conduct possible training sessions for operators of mechanized devices and so on. The goal is to achieve the highest possible accuracy in repetition of the operator's movements, i.e. motion capture, at the lowest financial cost. The initial variant of the suit was created on the basis of Arduino and Unity 3D for visualization. 3D human model based on quaternion is built in Unity 3D which repeats all the real person twists and turns. But the first architecture had problems with performance and accuracy. A series of experiments was carried out to improve the effectiveness of the cybernetic suit prototypes. Thanks to the introduction of the proposed new type of architecture, namely the “controller-sensor”, it is possible to completely get rid of the inaccuracy of the received data from the sensors. Also it allows removing the unauthorized change in the position of the body parts of the 3D model and increasing the overall resistance and noise immunity of the product. Software based on the algorithm for processing data from gyroscope and accelerometer sensors is presented, and the possibility of upgrading the design of the hardware part of the suit, aimed at optimizing the output characteristics, is described. To achieve the goal the most stable and noise-resistant transmission of primary data from cybernetic suit to a 3D model with the minimum possible number of errors in the data transmission buses was obtained. As a result, the modernization of the cybernetic suit for interaction with virtual reality has increased the accuracy of data from 66 % to 94.5 % and reduced the amount of interference from 40.59 % to 5.5 %.

Keywords: Arduino; motion capture; virtual reality; Unity 3D

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INTRODUCTION, FORMULATION OF THE PROBLEM

Twenty eight years ago, the computer cartoon “Sinbad: Veil of Fog” was released on the big screen. This is one of the first large-scale projects using Motion capture technology [1]. This technique is used to record the actions of actors, and then is used in computer graphics. Since the human body is as complex as the body of an animal, it is much easier and more convincing to record the actions of an actor or stunt performer and reproduce them in a 3D model than to reproduce and animate them from scratch. The principle of operation of the motion capture system using special equipment is as follows: a suit with special sensors is put on the performer. When he reproduces the necessary movement, the data received from these sensors is entered into a computer and converted there into a three-dimensional model, in order to accurately reproduce all the actions of the performer and based on this, implement character animation. This technology was developed for the entertainment industry and is suitable for controlling robotic mechanisms in areas such as the mining industry. The problem with such suits is their high cost and complexity.

Potential uses include:

1. People with physical disabilities or undergoing rehabilitation after injuries / operations.

Often, a person who has received any kind of injury and spent some time in bed rest may have a rather low motivation for rehabilitation training or exercise. If we add residual pain, muscle weakness, and mental depression here, the motivation for rehabilitation is compromised. The cybernetic suit is designed to raise the interest of a person with physical disabilities or undergoing rehabilitation after injuries or operations to perform various kinds of physical movements by virtualizing the space around him. Colorful worlds, objects that need to be reached or caught, interaction with virtual entities can easily distract a person from his pressing problems.

A striking example is the distracting effect of playing games to relieve a headache or a minor burn on the body. Consciousness trivially switches from pain to the mental powers required to perform certain actions in the game world.

2. Cyber sportsmen

A cybernetic suit for interacting with virtual reality should be classified as a device that transmits contact sensations to the human body.

At the moment, a person receives about 95 % of information through sight and hearing [2], and therefore vibration signals to the skin are not very informative. Rather, they can be attributed to the feeling of immersion in the virtual world - various shocks or blows may well simulate the hit of a bullet or arrow, which can increase the realism of the plot.

In sports, such a hardware and software product can be used to obtain reliable information, for example, on the work of gymnasts on sports equipment, in order to create digital models for analysis, error detection and development of training technologies.

3. Cadets who want to improve the quality of training on virtual simulators through additional muscle memory training.

For example, driving a car. Even the most theory-trained cadet is unlikely to be able to drive effectively a vehicle. You need muscle memory. To obtain it, it is possible to use a virtual space paired with a cybernetic suit, where the world generation system will simulate, for example, the roadway, and the suit will transmit vibrations from movement and braking to the cadet's body.

4. Operators of remote control of robotic devices, telepresence

With the advent of the era of the so-called “Industry 4.0”, robots begin to perform the main work at industrial facilities [3]. In addition, robotization is being introduced, for example, in medicine. For example, the robotic-assisted surgical system “da Vinci”, which is an apparatus for performing surgical operations [4]? With the use of process virtualization and the use of a cybernetic suit, it becomes possible to perform the smallest details not with your own hands, but with the help of machine manipulators. Alternatively, when working as a camera operator in hazardous areas of the mining industry, for example, in uranium mines. Using a man-driven machine from a safe place instead of a living miner significantly increases efficiency and reduces the financial cost of purchasing protective equipment for personnel.

Object of research: Cybernetic Suit Architectures.

Subject of research: the process of transferring primary data in a cybernetic suit from accelerometer, gyroscope and bend sensors on a 3D model.

The purpose of the article is to conduct a study in the field of the structure of the processing architecture of a cybernetic suit for working with virtual reality. The goal is to obtain the most stable and noise-resistant transmission of primary data from accelerometer, gyroscope and bending sensors to a 3D model with the minimum possible number of errors in the data transmission buses. It is proposed to use the Unity 3D software environment [5] to visualize the data received from the accelerometer, gyroscope and bend sensors located on the suit. It is necessary to achieve the highest possible accuracy in repetition of the movements of the operator of the suit at the lowest financial cost.

Tasks to achieve the goal:

1) Development of the initial version of the cybernetic suit.

2) Analysis of series of experiments to improve the performance of a cybernetic suit in the field of transmitting data from sensors to a 3D model in Unity 3D.

3) Development of an improved hardware architecture of the suit, contributing to an increase in noise immunity and the integrity of the primary and processed sensor data.

4) Creation of transmission of answers from the virtual space to the person.

1. ANALYSIS OF EXISTING SOLUTION

There are two main types of Motion capture systems [6]:

1. The use of special marking equipment to detect the movement of the system. The actor puts on a suit with sensors, performs the necessary actions, stands in the agreed positions and reproduces the necessary actions; the data from the sensor is recorded by the camera and transmitted to the computer, where it is transformed into a single high-precision 3D model. Further, on the basis of this model, the actions of the actor are reproduced in a realistic manner, and then character animations are created on its basis. This method also allows you to reproduce the actor's facial expression.

2. Technology that does not require labeling, special sensors or devices. The non-marking technology is based on computer vision and image recognition technologies. An actor can be filmed in any clothing, which allows filming complex actions (running, jumping, etc.). An ordinary camera and computer are used for recording. Examples of such systems are solutions such as Leap Motion and Kinect [7, 8].

Considering the existing analogs presented in Table 1, we can note the high cost of finished samples.

Table 1. **Existing analogues of the system**

Analogues	Price	Ease of operation	Safety for the suit operator	Limited body movements of the operator	Transfer of the answer from the computer to the operator	Constructor of scenarios
Leap Motion / MS Kinect v2	~4000 UAH	Low (We need a person who understands the system)	Safely	Works only in frontal projection	Impossible	None
Motion Capture Suit from OptiTrack	~8000 UAH	High (Instructions for use required)	Irradiation with signals from IR transmitter	None	Missing	None
Motion Capture Suit from NANSENSE	178000 UAH	High (Instructions for use required)	Irradiation with signals from IR transmitter	None	Missing	None
Keywish Gesture Motion Tracking glove	1376 UAH	High (Instructions for use required)	Safely	Only the operator's hand	Possible	None
The proposed project of Cybernetic Suit	~4000 UAH	High (Instructions for use required)	Safely	None	Possible	Present

Source: **compiled by the authors**

Leap Motion / MS Kinect v2 is an emerging motion capture technology for human-computer interaction. It uses infrared cameras in its work to track the movement of a person's fingers and hands, as well as other objects with high accuracy. The price of these devices is low. However, there are a number of disadvantages. For example, the capture of human movements can be carried out only in the frontal projection of the camera. A person cannot stand sideways to the device. In addition, devices of this kind, in principle, are not capable of transmitting any tactile responses to a person from the virtual space.

Motion Capture Suit from OptiTrack [9] and NANSENSE [10] are similar in design to the proposed project, except that all sensors in such suits use a WiFi network for data transmission, which negatively affects humans due to the high radiation of the transmitters. In addition, such suits are not designed to transmit a response from a virtual environment to a person, but only to collect data, which makes them applicable only in the field of cinematography and the gaming industry. The lack of response from the virtual world does not allow one to fully immerse oneself in the simulated situation, navigate in artificial space and develop muscle memory in the suit operator. In addition, the lack of a modular design forces the user to purchase the entire suit, even if only a part of it is required.

The Keywish Gesture Motion Tracking glove [11] was developed by a team of enthusiasts. It reads data from a single human hand. The proposed cybernetic suit project has a similar glove built into the system and which can be used separately if the user wishes.

Moreover, all of the above analogs lack the so-called constructor of scenarios for interacting with the virtual environment. The constructor is a program where the user can independently simulate and customize the virtual environment with which he would like to interact using a cybernetic suit or its individual parts, and customize the cybernetic suit according to his desires.

Today, manufacturers such as Vicon, Acty, Advanced Mechanical Technology, Motion Analysis, PhaseSpace, Phoenix Technologies, and Polhemus are leaders in the motion capture industry. For example, the Vicon 8 system showed the best results in terms of processing speed and material accuracy.

Vicon 8i is the second-generation product of the V8 series and the first motion capture system designed specifically for CGI animation. The system is based on passive sensors and markers to indicate critical areas.

The system is optimized for processing large amounts of data; it can record the actions of multiple actors.

Support 24 cameras to work; there is also the possibility of real-time work. It also does not limit the number of marks on the model. Usually about 120 markers are used. However, up to 400 markers can be used offline.

A certain quality of input data is required to determine the actor's movement and avoid manual data processing. The camera developed by Vicon Mcam2 serves as the source of information.

If we analyze all this from a physical point of view, we can conclude that acoustic, magnetic, optical and mechanical motion detection systems are widespread today. In a speaker system, a set of acoustic sensors selects sound from a sound source located on the actor. To determine the position of each sound source in space, the distance between a transmitter and multiple receivers is calculated. The obvious disadvantage of this system is the influence of noise sources and the limitation of the number of sensors. The magnetic system is accurate and fast enough to detect simple movement of an object. The principle of operation is based on changing the position of the magnet relative to the detector. Such a system is relatively expensive, but it has many disadvantages associated with the possibility of overlapping magnetic fields, which are caused by different magnetic structures and cause interference. Optical systems have become more user-friendly, but at the same time more expensive due to the use of high-definition cameras and sophisticated software. At the same time, the technique worn by the actors is very simple, does not hinder movement, has a special mark and is monitored by the camera. In mechanical systems, sensors located on the human body are used to determine the spatial position at specific points. Such system is fairly easy to design, but a wireless system is very expensive and can be hazardous to health when exposed to ultra-high frequency energy from a transmitter. The wired option is the cheapest and most promising.

2. CIBERNETIC SUIT DEVELOPMENT DESCRIPTION

2.1. Creation of the initial variant

The cybernetic suit, made on the basis of Arduino [13] and a network of sensors located on the human body, belongs to the first type and allows you to get rid of the problem of finding the wearer of the suit “in the lens” of other devices, for example, such as Leap Motion. The sensors are accelerometers and gyroscopes connected on one MPU6050 board [14] and bend sensors based on an optocoupler [15].

The following lines represent the structure of the suit:

1) “Head-Chest” (two accelerometers and gyroscopes located on the head and chest).

2) “Hand”, which is divided into a “Hand” (accelerometer and gyroscope located on the wrist and 5 bend sensors attached to extremities of the fingers) and “Elbow” (bending sensor, accelerometer and gyroscope located on the elbow joint).

3) “Leg”, which is divided into “Foot” (accelerometer and gyroscope located on the foot) and “Knee” (accelerometer, gyroscope and sensor bends located at the knee joint) .

4) The central node, which is located on the back in the waist area and includes an Arduino Mega board with an ATmega2560 microcontroller, a shield splitter and a TCA9548A I2C bus switch.

In addition to the development of the suit itself, work was carried out to visualize the movements of a person in a cybernetic suit on a computer screen. The visualization process was carried out in the Unity 3D programming environment.

To establish contact between Unity 3D and Arduino, a special sketch was written for the ATmega2560 microcontroller, which allows the Arduino board to send data from all sensors of the suit to the Serial port. Data transfer is carried out using a USB cable. The programming language is C#. Receiving data in Unity 3D is carried out by the Receiver class, which opens a connection to a COM port to which a cybernetic suit is attached and reads data, and their further distribution to other classes of a 3D human model has arrived. The 3D model itself repeats all the twists and turns of a real person. Each class, which is responsible for one or another part of the body, is equipped with a condition for checking the correspondence of the received data using a check number. If the number corresponds to the class, the data obtained using mathematical expressions turns into quaternion’s, a system of hypercomplex numbers that form a vector space of dimension four over the field of real numbers. Each axis of the Cartesian space has its own quaternion.

At first, when the cybernetic suit was connected to the 3D model, the limbs of the latter bent at unnatural angles; it looked a bit like the reflection of a real person. The body parts of the 3D model were calibrated in stages, with the sequential inclusion of one body part after another. To eliminate distractions, such as transferring data from sensors of body parts that were not used during calibration, their reading and subsequent data transfer were turned off at the software level. As a result, per unit of time, only that part of the model with which the calibration manipulations were carried out was in the “working” state. By performing multiplication by minus one with the angles of inclination along the x, y or z axes, application or subtraction of integers selected experimentally, it was possible to minimize the false bends of the limbs of the model, or completely get rid of them.

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The following sections 2.2-2.6 provide an overview of the hardware solutions used in the development of the cybernetic suit.

2.2. MPU-60X0 Overview

A MPU-60X0 on 0 is the world's first integrated 6-axis motion tracking device. It integrates a 3-axis gyroscope, a 3-axis accelerometer and a digital motion processor (DMP) in a small 4x4x0.9mm package. It uses a dedicated I2C sensor bus to directly accept input from an external 3-axis compass to provide a complete 9-axis MotionFusion output.

MPU-60X0 enables manufacturers to eliminate costly and complex selection, integration and integration at the discrete device system level, and ensure the best motion for consumers. MPU-60X0 is also designed for non-inertial digital sensors, such as the pressure sensor on its auxiliary I2C port.

MPU-60X0 has three 16-bit analog-to-digital converters (ADC) for digital gyroscope output, and three 16-bit ADCs for digital accelerometer output. The built-in 1024-byte FIFO allows the system to read sensor data in bursts and go to sleep when the MPU collects more data, thereby helping to reduce power consumption. MPU-60X0 has all the necessary on-chip processing components and a sensor required to support many motion-based use cases, uniquely supports the use of low-power MotionInterface applications in portable applications, and reduces CPU processing requirements. With its built-in MotionFusion output, the DMP of the MPU-60X0 removes the MPU-6050 from the computationally intensive MotionProcessing requirements of the MPU-6050, minimizing the need to frequently poll the motion sensor output.

To provide flexibility in power supply, MPU-60X0 operates within the VDD supply voltage range of 2.375 to 3.46 V. In addition, MPU-6050 has a VLOGIC reference pin, which determines the logic level of the I2C interface.

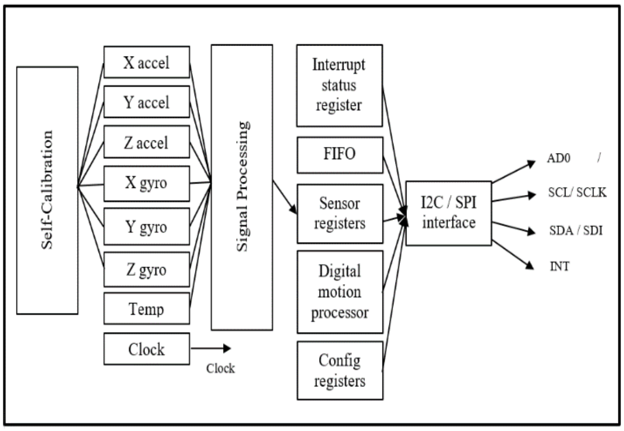

Fig. 1. **MPU-60X0 structure**
Source: **compiled by the authors**

2.3. Gyroscope features

The three-axis MEMS gyroscope in MPU-60X0 has a wide range of functions:

1) Digital output X-axis, Y-axis and Z-axis angular velocity sensors (gyros), with user-programmable ±250, ±500, ±1000, and ±2000 °/s full ranges.

2) The external synchronization signal connected to the FSYNC pin supports image, video and GPS synchronization.

3) Integrated 16-bit ADC supports simultaneous scanning of gyroscopes.

4). Improved sensitivity offset and temperature stability reduces the need for user calibration.

5) Improved performance of low frequency noise.

6) Digital programmable low pass filter.

7) Gyro operating current: 3.6 mA.

8) Standby current: 5 mA.

9) Factory-calibrated sensitivity factor.

10) User self-check.

2.4. Network compressing routine

The three-axis MEMS accelerometer in MPU-60X0 provides multiple functions:

1) Three-axis accelerometer with digital output and programmable full-scale values of ± 2 g, ± 4 g, ± 8 g, and ± 16 g.

2) The integrated 16-bit ADC allows the accelerometer to be sampled simultaneously without the need for an external multiplexer.

3) Normal accelerometer operating current: 500 mA.

4) Low-power accelerometer: 10 mA at 1.25 Hz, 60 mA at 20 Hz, 110 μA at 40 Hz.

5) Direction detection and alarm.

6) Touch recognition.

7) User programmable interrupt.

8) User self-check MPU-6050.

2.5. Motion processing

Motion processing is the process of recognizing, measuring, synthesizing, analyzing and digitizing the movement of objects in three-dimensional space. It combines units with digital processing and motion-based applications to enable consumer devices to easily integrate motion while meeting key requirements for cost, size, reliability, and battery life [16].

1) The internal Digital Motion Processing (DMP) engine supports 3D motion processing and gesture recognition algorithms.

2) MPU-60X0 collects gyroscope and accelerometer data, and synchronizes data sampling at a user-defined rate. The complete data set of MPU-

60X0 includes 3-axis gyroscope data, 3-axis accelerometer data and temperature data. The calculated MPU output to the system processor may also include heading data from a third-party digital 3-axis magnetometer.

3) The FIFO buffers the entire data set and reduces the clock requirements of the system processor by allowing the packet processor to read FIFO data. After reading the FIFO burst data, the system processor can save power by entering a low-power standby mode while the MPU collects more data.

4) Programmable interrupt supports gesture recognition; panning, zooming, scrolling, touch detection and camera shake detection functions.

2.6. I2C interface

One of the modern communication interfaces is I2C, the two-wire interface composed of serial data (SDA) and serial clock signal (SCL). In the general implementation of the I2C interface, the connected device can be a master device or a slave device [16]. The master will place the slave address on the bus, and the slave with the appropriate address will confirm the master. When communicating with the system processor, MPU-60X0 always acts as a slave device, so it acts as a master device. SDA and SCL lines usually require pull-up resistors for VDD. The maximum bus speed is 400 kHz.

2.7. Experiments to improve the performance of the cybernetic suit

As mentioned earlier, at first the suit was a fairly simple architecture with a set of sensors and a microcontroller serving them. Experiments in the performance of accelerated physical exercises revealed speed limitations in the operation of the equipment due to incorrect reading from the sensors of the values of the position of human body parts in space, which required changes in the hardware and software.

The first prototype of the suit consisted of a system of 10 MPU6050 accelerometer and gyro sensors, 14 optocoupler-based flexure sensors, a TCA9548A I2C digital bus switch, and an ATmega2560 microcontroller. The microcontroller took turns interrogating all 10 accelerometers and gyroscopes, simultaneously converting the primary data into a value along the x, y and z axes. Flex Sensors have not been tested. During the calibration of the obtained data in the Unity 3D environment, it was possible to transfer the movement of human limbs to a 3D model. However, distortions of the obtained data were noted: the limbs of the model bent spontaneously and after a while their positions did not correspond to the real position of the sensors on the suit. The reason was determined by the switch of the digital I2C bus, and its inability to process 10 sensors of accelerometers and gyroscopes at once, as a result of which incorrect data from the sensor appeared. The decision was made to eliminate the switch by processing each limb with an intermediate microcontroller. As a result, the collecting center began to consist of four Arduino Nano boards and one Arduino Mega, but it was not possible to get rid of the obstacle. The problem was found in the library of the MPU6050 sensor, namely, incorrect mathematical processing of primary values.

2.8. Controller-Sensor Architecture

The third prototype used another library based on the interrupt system, which “stopped” the sensor until the moment when the collecting microcontroller will not ask it for new values. The hardware design has not undergone any special changes. However, the prototype did not make it to experiments: intermediate controllers were unable to work correctly with two sensors at the same time. But during the work, high accuracy was noted in working with one sensor. The data was stable. It was decided to use the controller-sensor communication with the interrupt system. During January-February 2021, new suit architecture was formed from scratch, which can be seen on Fig. 2: now each sensor has its own processing controller, installed with it in the same case. In total, there are seven such local cases: head, elbows, knees and feet.

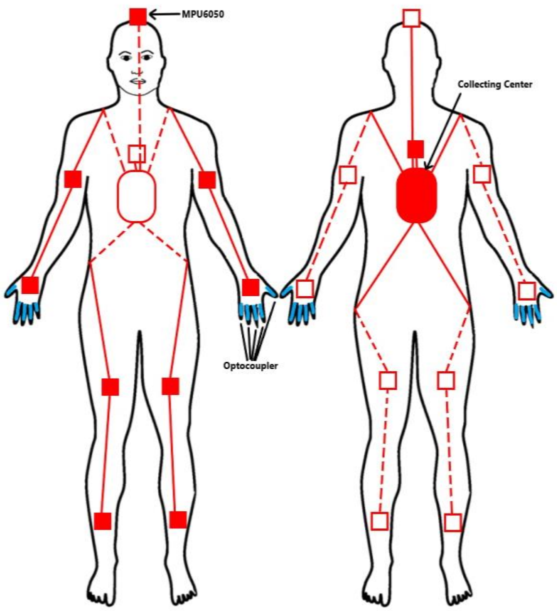

Fig. 2. **Location of sensors on the human body**
Source: compiled by the authors

In the Fig. 3, these local enclosures are located in the far parts of the architecture and are represented as N.Slave + MPU. The Slave prefix means that this device is a slave in the RS-485 communication protocol and is under the control of the master, namely N.Master. The master itself, namely the N.Master, communicates with the Arduino Mega, which is already part of the gathering center.

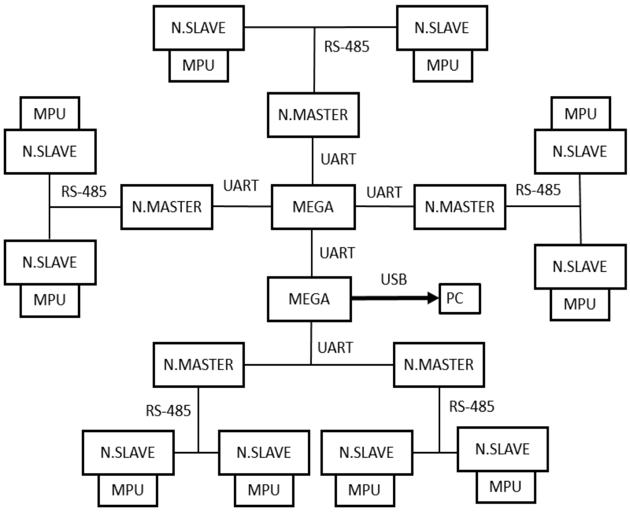

Fig. 3. **Cybernetic suit architecture**
Source: **compiled by the authors**

The torso sensor has been moved to the collecting center. The assembly center of the suit has also received significant changes: the number of processing and connection boards has doubled to two Arduino Mega and six Arduino Nano (one of them is tied to the processing of the torso sensor).

Also experimentally, the optimal speed of the collecting center for communication with Unity 3D was established – 115200 baud per second.

The torso sensor has been moved to the collecting center. The assembly center of the suit has also received significant changes: the number of processing and connection boards has doubled to two Arduino Mega and six Arduino Nano (one of them is tied to the processing of the torso sensor).

In the Fig. 4 shows a general view of a cybernetic suit on a person.

The modernization resulted in the following:

1) Provided easy access to the internal elements of the enclosures.

2) The architecture of the costume received a modular design and the autonomous operation of its parts.

3) All systems and subsystems have become interchangeable and have the same code, which allows in the event of failure of one of the controllers to quickly replace it with a new one.

4) Thanks to the use of a high-precision code for processing the primary data of accelerometers and gyroscopes, it was possible to get rid of the interference.

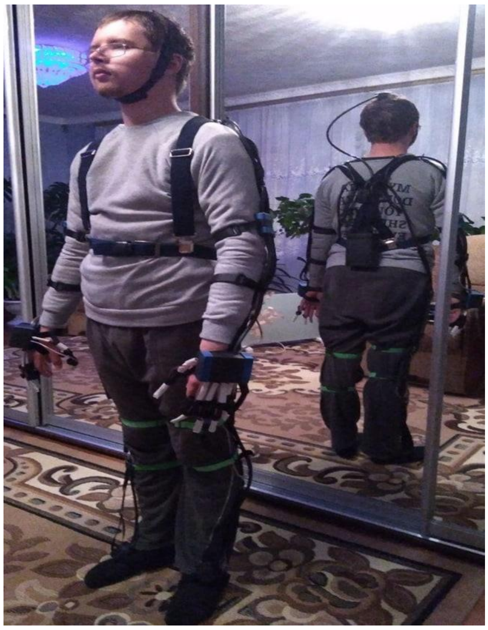

Fig. 4. **View of a cybernetic suit on a person**
Source: **compiled by the authors**

5) An external power supply was added, due to the increase in current consumption, which excluded the failure of the computer's USB bus voltage stabilizer.

6) Distribution of tasks within the system has increased its stability.

Currently, there are some failures in data transmission inside the suit, the cause of which has already been determined (inconsistency of time delays in the RS-485 buses) and will be eliminated in the near future.

2.9. Software

As mentioned earlier, the first prototype of the cybernetic suit consisted of 10 accelerometer and gyroscope sensors, an I2C bus switch, and an ATmega2560 microcontroller.

The software for this version of the suit consisted of the following steps:

1) Creation of MPU6050 sensor objects – at this step, the system loaded the number of sensor objects with which it later needed to work.

2) Initialization of MPU6050 objects – launching sensors, sending commands to access the loaded software of microcontrollers of the sensors themselves for subsequent calibration of acceleration and location relative to the x, y and z axes.

3) Calibration of values – mathematical calculation of the current position of the sensor relative to the x, y and z axes, and the calculation of coefficients for correct operation with the data received from the sensor.

4) Direct start of counting values from sensors.

According to the structure of the I2C bus, two identical device addresses cannot be simultaneously on the data line. The MPU6050 sensor is capable of either 68 or 69 address. This inconvenience limits the use of more than two MPU6050 devices on one I2C bus at the same time. To eliminate this problem, a TCA9548A digital I2C bus switch was used.

I2C multiplexer (switch, expander) TCA9548A is designed to solve the problem of connecting several I2C devices with the same addresses or having different voltages of logic signals to one microcontroller. The device allows full control over the process of access of the master to the slaves via the I2C bus.

The multiplexer is connected via the I2C bus to the microcontroller (master), and the sensors and modules (slaves) are connected to the multiplexer ports. Thus the multiplexer acts as an intermediary in the exchange of data between the master and slaves. First, you need to go to the multiplexer address (by default 0x70) and write the port number you want to work within the multiplexer configuration register. You can specify several ports at once. The active port number is determined by one in the corresponding register bit. For example, 00000100 means the third port will become active.

Further, the work is carried out in the same way as if the slave was connected directly to the microcontroller. That is, you can use the familiar libraries and refer to the address of the slave device (display, sensor, etc.).

If it is necessary to switch to another device, then for this it is enough just to write the number of the desired port into the multiplexer register.

It should be noted that if the address of any peripheral device matches the address of the multiplexer, then it is necessary to change the multiplexer address using ports A1, A2, A3.

In addition, the multiplexer can operate as a logic level converter independently for each channel.

Based on the principle of operation of the TCA9548A switch, the ATmega 2560 microcontroller processed only one of 10 MPU6050 sensors at a time, while the rest were in the “sleep” mode, waiting for the multiplexer to access them for a new portion of data. The traversal time for all 10 sensors took about 10 milliseconds, which was an extremely high processing speed.

However, as noted earlier, this version of the software could not prove itself due to low reliability. During testing and debugging, an unauthorized increment of values along the z axis was noticed.

The software for the second prototype of the suit was supplemented with four reseller microcontrollers, namely the ATmega328 / P. The ATmega328 / P are a microcontroller of the AVR family, like all the others, it has an 8-bit processor and allows you to execute most of the instructions in one clock cycle.

Each of the four ATmega328 / Ps was connected to a pair of MPU6050 sensors, with addresses 68 and 69 respectively. Communication was carried out via the digital I2C bus. The task of the ATmega328 / P was to convert the received data from the MPU6050 microcontrollers into ready-made values along the x, y and z axes, and then send them to the central ATmega2560 controller. Communication with the ATmega2560 was carried out via the analog UART bus.

A universal asynchronous receive transmitter (UART) is a computing device node for communicating with other digital devices.

Serializes the transmitted data so that it can be transmitted to another similar device over a physical digital line. This transformation method is well standardized and widely used in computer science.

UART is a logic circuit that, on the one hand, is connected to the bus of a computing device, and on the other hand, has two or more pins for external connections.

Data transfer to the UART occurs one bit at regular intervals. The time interval is determined by the specified UART speed and is specified in baud rates for a specific connection.

For the safety of data transmission, at the beginning of each data transmission from the ATmega328 / P, the system added some personal character. Each ATmega328 / P had a unique symbol and was not repeated anywhere.

As a result of this circuit, the load on the ATmega2560 central microcontroller has been significantly reduced. However, this concept could not eliminate the unauthorized increase in values along the z axis. As stated above, the problem was in the base library MPU6050.

The third prototype used a library used primarily for software for light aircraft such as drones. The principle of data counting in this library is based on the DMP interrupt system.

DMP refers to the processor built into the MPU6050 that can directly compute the quaternion and position without the need for additional math operations. The use of DMP greatly simplifies the development of 4-axis code. DMP stands for Digital Motion Processor. As the name suggests, the mpu6050 is not just a sensor, it also contains a processing unit that can independently execute the orientation calculation algorithm. For example, the advantages of using DMP to implement an algorithm for combining sensors in a design are obvious. The position computation algorithm implemented by DMP relieves the microcontroller of the pressure of the algorithm processing. What the microcontroller has to do is wait for the external interrupt generated after the DMP computation completes and read the position computation result in the external interrupt.

The single-chip microcomputer has a lot of time for other tasks such as controlling motor speed, which improves the system's real-time performance.

MPU6050 initialization steps when using an interrupt-based library:

1) Initialization of the interface in I2C. Initializing SDA and SCL data lines connected to the MPU6050.

2) Reset the MPU6050 so that all registers inside the MPU6050 are restored to their default values. After reset, restore the default power register and then wake up the MPU6050.

3) Setting the full scale range of the gyroscope sensor and accelerometer.

4) Setting the full range of the two sensors, respectively, via the gyroscope configuration register and the acceleration sensor configuration register.

5) Set other parameters, disable interrupt and disable I2C and FIFO interface, set gyroscope and accelerometer sampling rate.

6) Configuring interrupts, I2C interface and FIFO.

7) Configure the system clock source.

8) Activation of the yaw rate sensor (gyroscope) and the acceleration sensor.

The suit's architecture with the interrupt system allowed for extremely accurate calculations of the sensor values along the x, y and z axes. The DMP sensor is operated by the ATmega328 / P. Communication between the ATmega328 / P and the controller intermediaries is carried out via the RS-485 interface.

RS-485 is used to exchange data between several devices over a two-wire communication line (twisted pair) in half duplex mode. Transmission occurs simultaneously in only one direction. Reception is not possible. To receive data, the transceiver must switch to receive mode.

In terms of electrical characteristics and communication principles, RS-422 is fully compatible with RS-485, but in full duplex mode. One twisted pair is always used for receiving data and the other for transmitting data.

The principle of operation with data transmission via RS-485 is like the UART protocol: at the beginning of sending data, there is the address of the device from which the intermediary device, or master, wants to read the data. Further, the receiving device, which is also a slave, receives the address and verifies it with its own. If the address is correct, the slave sends the data to the master in fractional format. It is possible to transmit only 8 bits of information per unit of time via RS-485, and since the fractional value along the x, y and z axes occupies 32 bits in memory, the system divided the data into 4 parts and sent them to the successors. After that, the intermediaries transfer the finished data to the ATmega2560, where they format and collect data from all sensors, and send them to Unity3D.

3. PRODUCT RESEARCH RESULTS

A series of experiments was carried out to evaluate the effectiveness of the robotic prototypes of the cybernetic suit.

The robot of the first prototype of the cybernetic suit was grounded on a digital bus switch I2C TCA9548A. Were used eight sensors of the accelerometer and gyroscope in the commutate, two of them were processed directly by the Arduino Mega board. Efficiency testing was carried out with the help of the built-in middleware of the Arduino IDE. In the course of experiments, the speed of data exchange between the cybersuit picking center and Unity 3D reached 9600 baud per second. The number of data in one iteration of processing is 10 values of the x-axis, 10 values of the y-axis and 10 values of the z-axis, a total of 30 values of the y-axis of the fractional number format.

In the data parsing process, a mimic increment of all 10 z-axis values was assigned. After 2-3 iterations of the microcontroller, the z-axis value was increased by one unit. If you take all 30 values, which are seen by the microcontroller of the selecting center, as 100 %, then the overshoot, which is measured, becomes one third of the given values, which is, rounded 33 %. Also, the correctness of the data can be roughly estimated at only 66 %. In addition, the architecture of the first prototype did not allow for an increased number of sensors and did not allow access to the hardware architecture of the suit.

The hardware and software architecture of another prototype cybernetic suit was grounded on the UART protocol (Universal asynchronous receiver/transmitter) and on the Arduino Nano intermediary boards, the skin of which completed one specific technique. Two sensors of the “Head-Chest” line were used in the main Arduino Mega board, as in the first prototype. Efficiency testing was carried out with the help of the integrated middleware of the Arduino IDE and the Saleae logic analyzer. During the analysis, the speed of data exchange between the cybersuit selection center and Unity 3D varied between 9600 and 115200 baud per second, the best speed was experimentally set to 9600 baud per second. With increased speed of exchange, the freezing of Unity 3D software was noted, as well as a strong jam in the new pack of data from the select center.

The number of data in one iteration of processing was left unchanged – 10 values of the x-axis, 10 values of the y-axis and 10 values of the z-axis, a total of 30 values of the fractional number format. The address of the limbs is not indicated.

In the process of data parsing, the same involuntary increment of all 10 values of the z axis, which is in the first prototype, was noted. After 2-3 iterations of the microcontroller, the z-axis value was increased by one unit. In addition, in the buses, the data exchange UART between the intermediary boards and the central board began to prevent the creation and loss of data along all axes of all finiteness. With an average count of interference from 3 to 17 distortions and losses can be noted per 100 iterations of the collecting center. If we take all 30 values, which are seen by the microcontroller of the selecting center, as 100 %, then the average increment on the z axis becomes one third of the given values, which is, rounded, 33 %.

Therefore, the correctness of the data can be rounded up to 66 % on the x and y axes, assuming there is no interference or distortion. Given the above observation, it can be noted that the correctness of the values of the x-axis and every 100 iterations in the presence of interference is from 27.4 % to 32.01 % of the initial 33 %. Summing up, it can be noted that the overall accuracy of the data of the second prototype averaged 59.41 %. In addition, the second prototype retained the design flaws of the first prototype, namely, it did not involve an increase in the number of sensors and did not allow quick access to the elements of the suit's hardware architecture.

As it was planned earlier, the hardware and software architecture of the third prototype of the cybernetic suit was redesigned for the new concept “Controller – sensor”. This concept conveys that the skin sensor of the cybernetic suit is re-equipped with only one microcontroller. Like a microcontroller, the Arduino Nano wins. The given architecture includes the high migration to the microcontroller and allows the center, whatever it chooses, to implement only the functions of selecting data from the existing microcontrollers and the power of them in Unity 3D. In addition, in the third prototype, the MPU6050 6of library was introduced by Erik Oliman, as he knew his position in unmanned aerial vehicles and drones. The work of the library is characterized by 99.99% accuracy of data along the x, y and z axes. When the new high-current algorithm was stopped, it was necessary to allow a involuntary increment value along the z-axis and turn off the presence of the transfer of ready data on the side of the microcontroller-intermediary. For the collection of ready-made data, the selection center uses the last peripheral interface SPI (Serial Peripheral Interface), which allows the central microcontroller to process an independent number of intermediaries.

In the initial version of the third prototype in the collecting center, distortions of all values along the x, y and z axes were noted. To eliminate them, a system of digital filters was introduced. The task of the filters is to check each value for a sharp increase or decrease in the number compared to the previous one.

Also, filters do not allow value types such as: –0.00; 0.00; –180.0; 180.0. However, the filter system is not able to catch a value type like “nan”. The frequency of occurrence of “nan” per hundred iterations of all values is from 2 to 9 units, which is from 2 to 7 %. From this we can conclude that the overall correctness of the data is on average 94.5 %. In addition, the new “Controller – Sensor” architecture allows you to quickly access the elements of the suit's hardware architecture.

As a result, the modernization of the cybernetic suit for interaction with virtual reality has increased the accuracy of data from 66 % to 94.5 % (Fig. 5).

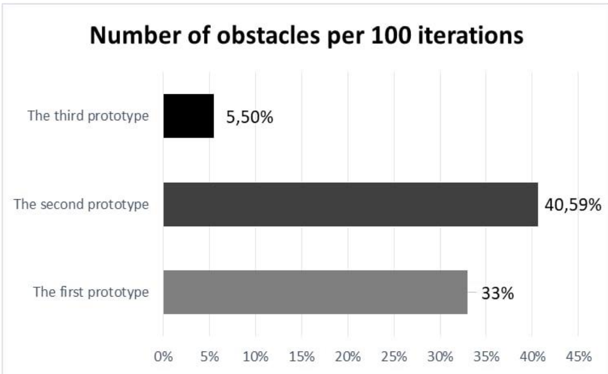

Fig. 5. **Number of interference per 100 iterations**
***Source:* compiled by the authors**

As well as reduced the amount of interference from 40.59 % to 5.5 % (Fig. 6).

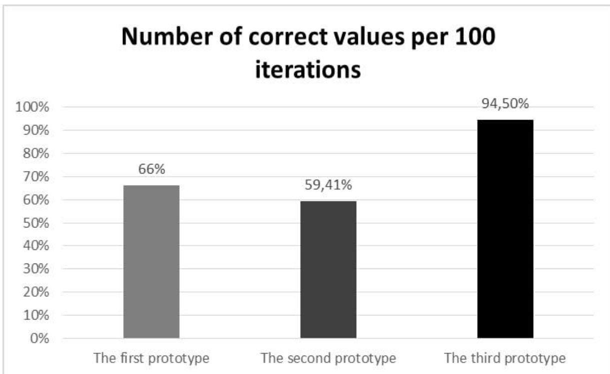

Fig. 6. **Number of correct values per 100 iterations**
***Source:* compiled by the authors**

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4. DISCUSSION

Motion capture technology is widely used in the field of cinematography and recording of in-game clips and so-called cutscenes. With its help, it is much easier for computer animation specialists to create the movements of the heroes of films and games, since they do not spend a lot of time drawing all the movements from scratch. As mentioned earlier, there are several types of Motion capture, from optical to gyroscopic, which ultimately boils down to one thing – 3D character models. The only significant difference between the systems from each other is their cost. In the competitive analysis, some of the most well-known prototypes of Motion capture suits were considered, from which it can be seen that it is rather problematic to purchase such a product for a commercial organization of middle and lower level, especially if such a product is needed for seasonal use. The project proposed by us is spared the problem of high cost, since it uses publicly available Arduino elements and parts in its work. Based on the low cost, about 4-5 thousand UAH, the project can be purchased by anyone and customized to his or her needs. In addition, due to the modular layout of the system, it is possible to use individual parts of the suit, for example, the wrist, without losing efficiency. Each part of the suit is completely independent, be it an arm, a leg, or a combination of both. As a result, of the modernization of the third prototype of the cybernetic suit, in case of failure of any of the system elements, it can be quickly replaced by changing the control board or sensor and / or rewriting the control code.

Also, based on the initial idea of creating a device for interacting with the virtual space, the cybernetic suit is planned to be divided into two subsystems: reading and receiving. The reading subsystem will be responsible for scanning the position of human body parts in space and sending information to a 3D model in the Unity 3D development environment. The receiving subsystem will have to receive responses from various objects in the simulated virtual space in Unity 3D, including from the aforementioned 3D model, and, in the event that the 3D model has physical contact with any object in the virtual space, transmit them to a person by turning on sensors built into the cyber suit in those places with which contact occurred in the virtual space. Example: A ball has been launched into a 3D model in virtual space. The ball hit the 3D model in the left shoulder. The system considered the place of physical contact between the 3D model and the ball, and, after checking the matrix of response sensors on the suit, transmitted a signal to activate the part of the matrix that is responsible for the left shoulder of the suit. As a result, the suit operator will feel the vibration on his left shoulder. Response sensors will be represented by vibration sensors and Peltier elements.

CONCLUSIONS

The presented work considered information on the initial version of the cybernetic suit, its first hardware and software architecture, presented an analysis of series of experiments to improve the performance of the cybernetic suit in the field of transmitting data from sensors to a 3D model in Unity 3D. As a result, due to the introduction of a different mathematical processing part, it was possible to significantly increase the accuracy of the “raw” data received from the accelerometer and gyroscope sensors, and also, due to the parallelization of the data reading and processing process, to reduce the load on the collecting center.

In the process of developing a cybernetic suit for interaction with virtual reality, designed to implement various scenarios of a rehabilitation nature for people in a post-traumatic situation, as well as to conduct possible training sessions for operators of mechanized devices to obtain muscle memory and the effect of telepresence, research in the development of a new cybernetic suit architecture, its debugging, solution and elimination of emerging difficulties and problems was carried out. Thanks to the introduction of a new type of architecture, namely the “controller-sensor”, it was possible to completely get rid of the inaccuracy of the received data from the sensors, remove the unauthorized change in the position of the body parts of the 3D model and increase the overall resistance and noise immunity of the product.

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Кібернетичний костюм для взаємодії з віртуальною реальністю

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АНОТАЦІЯ

Проведено дослідження в галузі структури архітектури кібернетичного костюма для роботи з віртуальною реальністю. На даний час актуальним є використання таких систем для реалізації різних сценаріїв реабілітації людей, а також для проведення можливих занять з навчання операторів механізованих пристроїв тощо. Ціль полягає в тому, щоб домогтися максимально можливої точності повторення рухів оператора, тобто захоплення руху, при найменших фінансових витратах. Початковий варіант костюма створювався на базі Arduino та Unity 3D для візуалізації. Тривимірна модель людини на основі кватерніону побудована в Unity 3D, яка повторює всі повороти реальної людини. Але перша архітектура мала проблеми з продуктивністю і точністю. Було проведено серію експериментів щодо підвищення ефективності прототипів кібернетичного костюма. Завдяки впровадженню запропонованого нового типу архітектури, а саме «контролер-датчик», вдається повністю позбавитися неточності даних від датчиків. Також дозволяє прибрати несанкціоновану зміну положення частин корпусу 3D моделі та підвищити загальну стійкість та перешкодозахищеність виробу. Представлено програмне забезпечення, засноване на алгоритмі обробки даних із датчиків гіроскопа та акселерометра, та описано можливість модернізації конструкції апаратної частини костюма, спрямовану на оптимізацію вихідних характеристик. Для досягнення мети було отримано максимально стабільну і перешкодостійку передачу первинних даних з кібернетичного костюма в 3D-модель з мінімально можливою кількістю помилок у шинах передачі даних. В результаті модернізація кібернетичного костюма для взаємодії з віртуальною реальністю дозволила підвищити точність даних з 66 % до 94,5 % та знизити кількість перешкод із 40,59 % до 5,5 %.

Ключові слова: Arduino; захоплення руху; віртуальна реальність; Unity 3D

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