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Development of the remote-controlled hand-like robotic manipulator system

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The aim of this research work is to research and develop a system of a hand-like remote-controlled robotic arm. Devices of this design are currently in demand in many areas of human life, in particular during rescue operations. The described device must be able to hold an object of arbitrary shape using a gripper, has acceptable positioning and control accuracy. Such a device can be used to work in a harmful or hazardous environment, thereby minimizing the harmful effects on humans. The control system of such a device must provide a protocol for transferring data from the input device to the end handle of the manipulator to perform the corresponding movement. To start the development process, market analysis was conducted, in the process of which several similar products were identified and compared against each other and the system being developed. As a result of that analysis, comparison table was created listing the main features of the system being developed in comparison to existing solutions on the market, to check whether it will be competitive at the current market.

In this article, such system is proposed and later developed with the analysis of modern technical components and taking into account the accompanying scientific and technical research. In the course of the work, the analysis of existing technical solutions was carried out, the principles of operation of individual components were considered, and the process of developing the final system was described. As a processor device, it was decided to use the Arduino Uno and Arduino Nano microprocessor boards, which provide convenient tools for working with ATmega microprocessors with high performance and energy efficiency.

As a result of this work, functional, logical and electrical circuits were created and described, which were used to create a working prototype of the system, as well as a diagram of the model of the manipulator body, which was printed using a 3D printer. Using the created circuits, a working prototype of the described system was built, which was successfully tested, a demonstration of which is given in the work. The created one can be integrated as a subsystem into a larger-scale project.

Keywords: microcontroller, robot, processor, Arduino, servomotor, manipulator, voltage divider, remote control, Bluetooth, 3D printing, modeling.

Introduction

Formulation of the problem. Despite the rapid development of modern scientific and consumer robotics, the question of the possibility of replacing man with a robot on dangerous and hazardous works is quite acute.

To create such a system, it is necessary to achieve high accuracy at low cost. Another problem is the creation of a simple "human-machine" interface, that will provide communication between the operator and the robot itself.

Analysis of recent research and publications. New developments in robotics research gave big push for this industry. Many companies are trying to achieve the ultimate goal of creating comprehensive robot, that can mimic human movements.

Thus, in [1], possibilities of creating a light weight adaptive bionic hand with a compact twisted string actuation system were researched. This work discusses the details about human hand's structure, ability to move and bend fingers and creating prosthetics with such capabilities.

In [2], the idea of a human-robot proportional control of a dexterous myoelectric prosthesis was proposed. The article describes design and algorithms of myoe-

lectric proportional controller that can predict multiple joint angles simultaneously and with high accuracy and implementation of an online control with both able-bodied and amputee subjects.

The article [2] surveys multi-fingered robot hand research and development topics which include robot hand design, object force distribution and control, grip transform, grasp stability and its synthesis, grasp stiffness and compliance motion and robot arm-hand coordination. This article proposes the main goals that have to be achieved on the field of object manipulation.

In [3] a comprehensive grasp taxonomy is developed, which incorporates all major grasp types found in literature. This allows for a detailed description of one handed static human grasping movements. Those movements are recorded, resulting in a dataset that consists of different grasp trajectories. That data is then projected onto a low dimensional space using a nonlinear dimensionality reduction algorithm. That allows to represent the human grasping movements in a more compact fashion.

Some companies already succeeded at developing systems with similar capabilities, although the design and working principle are different from what is described in this article.

For example, in [4], robotic hand that can replicate human motions and copy operator's movements is created.

This system has multiple functions, such as pneumatic movement control, artificial intelligence used to create and memorize patterns of handling objects. Usage of artificial intelligence also provides capabilities to operate autonomously with different types of objects.

System, described in [4], contains a 3D textile knitted fabric, tactile force sensors, flexible printed circuit board, elastomer bellows, two inertial sensors and the airflow plate with integrated pressure sensors.

In the field of medical robotics, systems, such as described in [5], are on the peak of interest right now. Those robotic systems can be used to help medical stuff to perform difficult surgical operations. Most of them operates through complex controllers that require a special training. While being difficult to use for a beginner, those machines provide high accuracy, minimal latency and, while look complex, allow doctors and medical stuff to perform operations much easier than in real life due to ability to pick different angle of view and different pose within one operation

Despite of number of related research papers, most of them share common flaws: high price and hard-to-learn control scheme. Most of them require specific training in order to manipulate properly.

Goal of this research paper is to develop system, that will remove those disadvantages and show good performance and scalability.

The aim of the study. Development of the remote-controlled hand-like robotic manipulator system that will surpass similar systems by technical and/or economic indicators.

1. Main part

The development can be divided into 3 parts: the development of a controlled subsystem, the development of a control system and the development of program code.

To create a controlled subsystem, it is necessary to determine the number of limbs of the grip and the principle of bending and moving them.

Market analysis showed that most consumer manipulators have 2 grip limbs controlled simultaneously, without the ability to control them separately with an average price of 1700 UAH.

The proposed system is more efficient, has more grip limbs in general, and more separately controlled grip limbs.

Economic efficiency is proved economic efficiency by comparing the cost and final cost of an average product with similar characteristics and the developed system.

After analyzing the market, a summary table of technical characteristics and a summary table of economic indicators were created (Tab. 1).

Table 1

Parameter	Units of measurement	The value of the parameter		Parameter weight, a_j, b_j	Single parametric indicator, q_j	Single parametric index, i_r, i_e
		new product, P_{jH}	similar product, P_{jA}			
Technical parameters						
Number of grip limbs	pcs.	5	2	0,4	2,5	1
Number of separately controlled limbs	pcs.	5	2	0,6	2,5	1,5
In total				1		2,5
Economical parameters						
Cost of product	UAH	1150	2000	0,7	1,30	0,91
Cost of materials	UAH	1150	1300	0,3	1,56	0,46
In total		830		1		1,37

The weight of the j-th parameter is determined by expert method g_j :

$$a_j \leq 1; \sum_{j=1}^m a_j = 1 \tag{1}$$

– for technical parameters,

$$b_j \leq 1; \sum_{j=1}^l b_j = 1 \tag{2}$$

– for economic parameters.

Unit parametric indicators g_j for each j-th parameter (both technical and economic) (column 6) is calculated by the following formula

$$q_j = \frac{P_{jH}}{P_{jA}}, \text{ if } P_j \rightarrow \max, \tag{3}$$

$$q_j = \frac{P_{jA}}{P_{jH}}, \text{ if } P_j \rightarrow \min, \tag{4}$$

where P_{jH}, P_{jA} – the value of the j-th parameter of the new product and the product of the competing (analogue), respectively.

Calculation of unit parametric indices i_{ij}, i_{ej} is as follows:

$$i_{ij} = a_j g_j \tag{5}$$

– for technical parameters,

$$i_{ej} = b_j g_j \tag{6}$$

– for economic parameters.

The consolidated parametric index is calculated by the formula:

$$I_T = \sum_{j=1}^m i_{Tj} \tag{7}$$

– for technical parameters,

$$I_E = \sum_{j=1}^m i_{Ej} \tag{8}$$

– for economic parameters.

The calculation of the integrated indicator of relative competitiveness (K) of a new product in relation to a competing product (analogue) is calculated by the formula:

$$K = \frac{I_T}{I_E}, \tag{9}$$

If $K > 1$ - the new product exceeds the competitor; $K < 1$ – the new one is inferior; $K = 1$ – both on the same level.

$$K = \frac{2,5}{1,37} = 1,82 \tag{10}$$

$K > 1$, therefore, the proposed new device outperforms the device of competitors.

Based on the requirements for the control part, it is necessary to determine the form factor of the controller.

Joysticks (or joystick systems) are often used to control robotic systems, but in order to create more intuitive user experience for grip control it is decided to use glove-like system.

It is proposed to use servos to move the limbs of the grip due to their wide distribution, accessibility, ease of maintenance and replacement, as well as low cost.

The principle of operation of the servo is based on control by applying a current control signal to the corresponding input of the servo (Fig. 1).

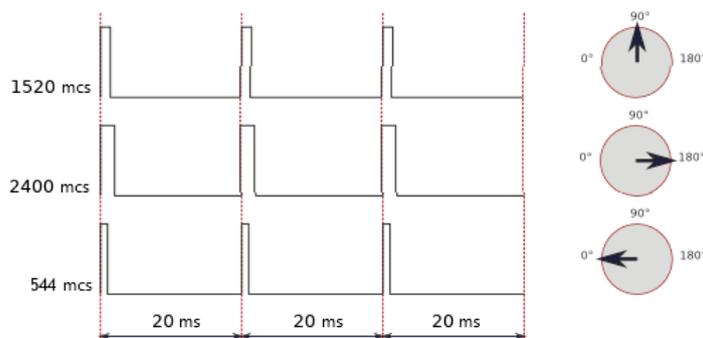


Fig. 1. Input control signals

The structure scheme of servo is shown in Fig 2. From it, it is easy to see that there are not too many components, therefore it is easier to fix.

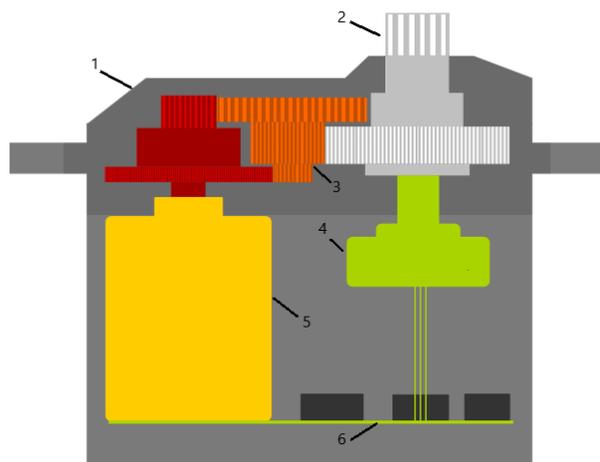


Fig. 2. Structure of Servo:

1 – housing, 2 – output shaft, 3 – gears, 4 – potentiometer, 5 – DC motor, 6 – PCB

The position of the shaft depends on the pulse length. When the signal enters the control circuit, the pulse generator, present in it, produces its own pulse, the duration of which is determined by the potentiometer. The other part of the circuit compares the duration of the two pulses. If the duration is different, the electric motor is turned on. The direction of rotation is determined by which of the pulses is shorter. If the pulse lengths are equal, the electric motor stops.

The main characteristics when choosing a servo are torque and speed.

The moment of force, or torque, is a vector physical quantity equal to the product of the radius vector drawn from the axis of rotation to the point of application of force on the vector of this force (Fig. 3).

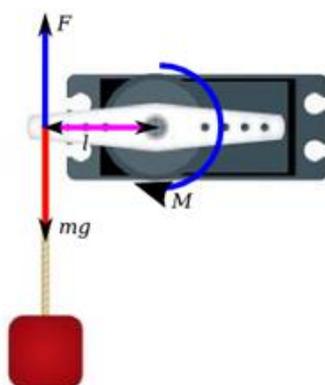


Fig. 3. Torque of Servo

To read the coefficient of flexion of the fingers a strain gage is often used - a resistor whose electrical resistance varies depending on its deformation.

The principle of operation of strain gages is based on the phenomenon of piezoresistive effect. With the help of strain gauges, you can measure the deformation of mechanically connected elements.

The basis of the strain gage is a sensitive element, metal or semiconductor, the electrical resistance of which varies in proportion to the mechanical stress on the surface of the object of study.

The principle of operation is as follows: when stretching the conductive elements of the strain gauge, their length increases and the cross section decreases, which increases the resistance, when compressed - vice versa. This principle is used in the Wheatstone Bridge circuits.

General schematics of a Wheatstone Bridge circuit is shown on Fig. 4.

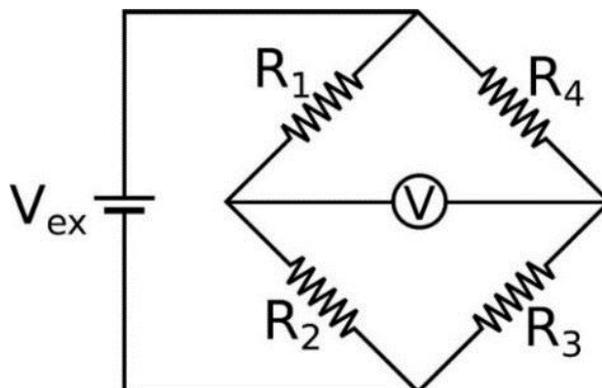


Fig. 4. The Wheatstone Bridge Circuit

The Wheatstone Bridge circuit can be a quarter, half or full bridge type, depending on the number of transducers and the required accuracy. Its principle of operation is based on the voltage equilibrium between the two arms of the circuit. In order to have voltage equilibrium, $V = 0$, the relation in $(R_1/R_2=R_4/R_3)$ must be satisfied. [6]

Despite the ease of installation and use of strain gauges have a high cost, which increases the cost of the final development dozens of times. In addition, tensor resistors are made on a thin substrate and using thin conductors, which increases the probability of failure of the tensor.

It is proposed to use a photoresistor and an LED in pairs for each of the operator's fingers as a control element.

Photoresistor is a photoelectric semiconductor radiation receiver, the principle of operation of which is based on the effect of photoconductivity - the phenomenon of reducing the resistance of a semiconductor in the case of excitation of charge carriers by light (Fig. 5).

It is characterized by the same conductivity regardless of the direction of current flow.

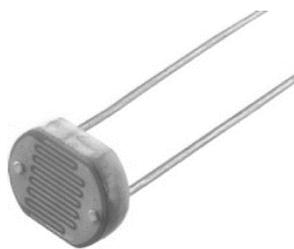


Fig. 5. Photoresistor

The light-emitting diode (LED) is a semiconductor device that emits incoherent light when an electric current is passed through it (an effect known as electroluminescence).

The emitted light of traditional LEDs lies in a narrow part of the spectrum, and its color depends on the chemical composition of the semiconductor used in the LED.

Modern LEDs can emit light from the infrared part of the spectrum to close to ultraviolet light. There are methods of expanding the radiation band and creating white LEDs. Unlike incandescent lamps, which emit a wide range of light flux, evenly in all directions, conventional LEDs emit light of a certain wavelength and in a certain direction.

The principle of operation of such a sensor is based on the principle of a voltage divider and is as follows: when the finger is extended, the LED fully illuminates the photoresistor, as a result of which its resistance is maximum. With the gradual bending of the finger, the amount of light falling on the LED decreases, which increases the resistance of the photoresistor.

The signal from the LED is processed in the ADC, and then converted into a voltage pulse of a certain length for the servo.

To properly handle all the input signals, correctly transform and transfer them, it is necessary to use some sort of a processor.

Due to field of use of developed robot, specifically that controller and controlled part are located separately, it is optimal to use microcontroller board to read signals from the control unit and another microcontroller board to process them on the controlled unit.

The recent technological advances have contributed to the popularization of "All-In-One" microcontroller boards. Due to the low entry threshold, ease of installation and use, as well as native support for a programming language based on C ++ with a huge catalog of user libraries, the Arduino family of prototyping boards based on the ATmega family of microcontrollers made by Atmel, became very common and affordable.

Arduino platforms are distinguished by the fact that they have their own programming language, based on C ++, adapted for simplicity and intuitiveness, and sold in the form of ready-to-use boards, which include a microprocessor and most of the other components necessary for their use in different scenarios, eliminating the need for the user to create complex electronic circuits in order to use the microcontroller.

Arduino Uno and Arduino Nano, based on ATMEGA microcontrollers, were chosen as control cores, which simplifies development and maintenance and increases the number of compatible components.

A connection between the two devices must be established to ensure the transmission of information from the sensors to the grip-part of the robot.

While data transmission via cables provides sufficient speed and low error rate, this method requires costs depending on the distance between the operator and the manipulator, and also creates additional difficulties in the installation of wires.

The use of Bluetooth wireless technology eliminates these problems and allows you to freely use the manipulator at a distance of up to 20 meters (provided there are no obstacles).

HC-06 / HC-05 Bluetooth Module are an easy to use Bluetooth SPP (Serial Port Protocol) module, designed for transparent wireless serial connection setup [7] (Fig. 6).

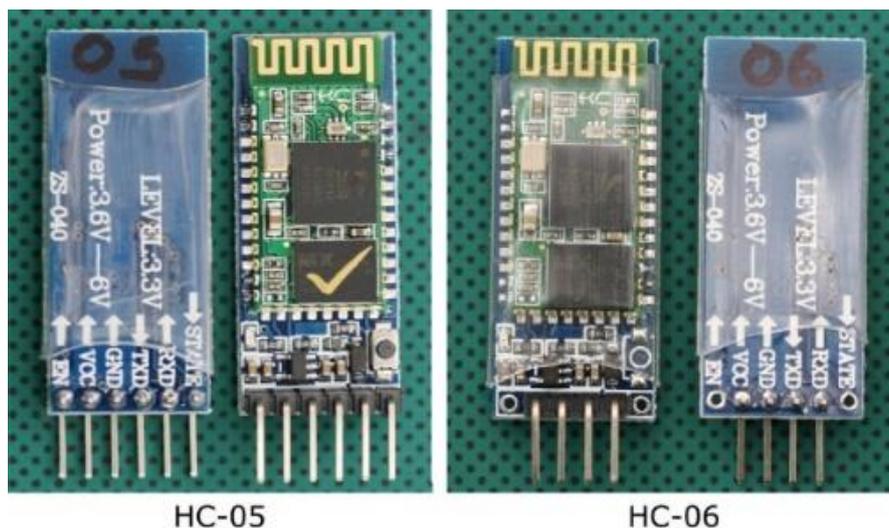


Fig. 6. Bluetooth modules

They have the same purpose, but differ in operating modes: HC-06 in Master mode, which allows it to initiate a connection, but does not allow other modules to initiate a connection with it. The NS-05 module can work both in the Master mode, and in the Slave mode that allows to change them without hindrance depending on a configuration.

The selection of the operating mode, together with the setting of other parameters of the module, is performed by entering it in the so-called AT mode, in which the module instead of transmitting information through the serial port, the module executes AT commands.

The principle of their operation is as follows: the module is connected to the serial port of the transmitting control board, after which the data received through it will be transmitted to another module, that is connected to the receiving board.

This method of data transmission requires an additional computing core that will read the data from the glove and transmit it to the control core of the grip.

For proper operation, it is necessary to configure the modules for data transmission and reception from each other and write program code that would process the data from the glove and prepare them for transmission. When working with modules, the receiving (Slave) module must be configured. During the setup, it is needed to determine the role of the module, its address and body rate. To do this, the module NS-05 provides a special mode of Attention commands (AT commands).

In order to enter AT mode, module have to be connected to the board in a special way. Each of the pins is responsible for a separate function of the board:

- STATUS pin is connected to the LED on the module;
- pin RXD - RECIEVER, all data coming to the board through this pin will be retransmitted via Bluetooth;
- pin TXD - TRANSMITTER, all data coming to the board via Bluetooth will be transmitted on this pin to the microcontroller;
- GND pin - GROUND pin that connects the board to the "ground";
- pin VCC - POWER pin, it is powered by the board (3.2-6 V);
- pin EN - ENABLE, pin switch, switches the board between Data Mode and AT command mode. Set to work in Data Mode by default.

A special connection scheme is used to enter the AT mode, shown in Fig. 7.

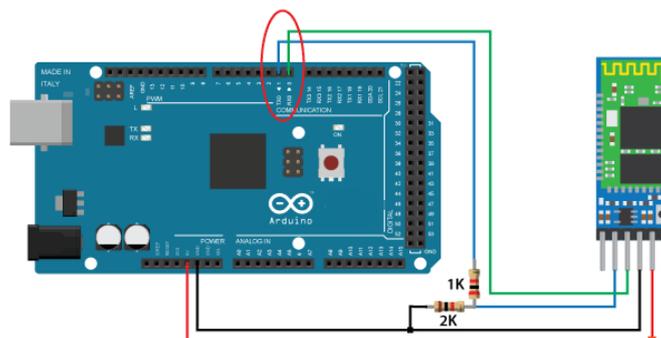


Fig. 7. The AT mode connection

Simultaneously with connecting the Arduino board to the power supply, press and hold the key on the housing of the HC-05 module until the LED on the module board starts flashing every two seconds - this will mean that the module is successfully switched to AT mode.

HC-05 modules, as described previously, can operate in both Master and Slave mode. In Master mode, the module has the ability to both initiate a connection and receive connection requests, while in Slave mode, the module cannot initiate a connection to other modules.

Thus, in order to connect the two parts of the developed system with each other, it is necessary to switch one of the Bluetooth modules to Master mode.

After entering the port monitor, the following parameters must be configured using the following commands:

- check the correct connection of the module to the board (command "AT");
- check the baud rate of the module (command "AT + UART?");
- set the role (command "AT + ROLE = 1" to switch to Master mode);
- set the connection mode (command "AT + CMODE = 0" to switch to the fixed address connection mode);
- set the address to which the module will be automatically connected (command "AT + BIND = 98d3,31,3069b0", where 98d3,31,3069b0 is the address of the receiving module obtained earlier).

After the setup, both modules can be connected to their respective boards to use.

The control core of the grip also needs additional settings to receive the processed data and further movement of the limbs accordingly.

When building the software, it is necessary to identify the main tasks that should be solved.

After the analysis of functions and features revealed, that the three main tasks are:

- development of an algorithm for converting the obtained data into a rotation angle;
- determining the type and type of the created control array;
- development of a data transfer protocol.

The conversion of the value of the resistance obtained from the sensor in the angle of rotation is done using the map function. The function translates the data passed to it as the first argument from the input range to the analog in the output range.

As a control array it is necessary to use the most universal data type, the format of which can be changed depending on the configuration of the manipulator. This type is a string type, which can store any sequence of Unicode characters.

The data converted by the map function is written to a string variable, separated by a comma. At the end of the line, a hyphen is placed as the end of one message, and the finished line is passed to the receiving module.

The test bench consists of two separate units: controller and receiver. In order to test the quality and flexibility of the system two different controllers were built: one using the self-made voltage divider, that was described earlier, and another using the strain gauges.

The first controller test bench consists of the following elements:

- glove;
- 5 photoresistors;
- 5 LEDs;
- 5 resistors (for brightness control of LEDs);
- 5 resistors (for photoresistors);
- 5 lightproof tubes;
- HC-06 Bluetooth module;
- 5V power supply;
- infrared obstacle sensor YL-63;
- Arduino Nano board;
- micro-USB cable.

The scheme, that describes the connection of the elements with the board, is shown in Fig. 8.

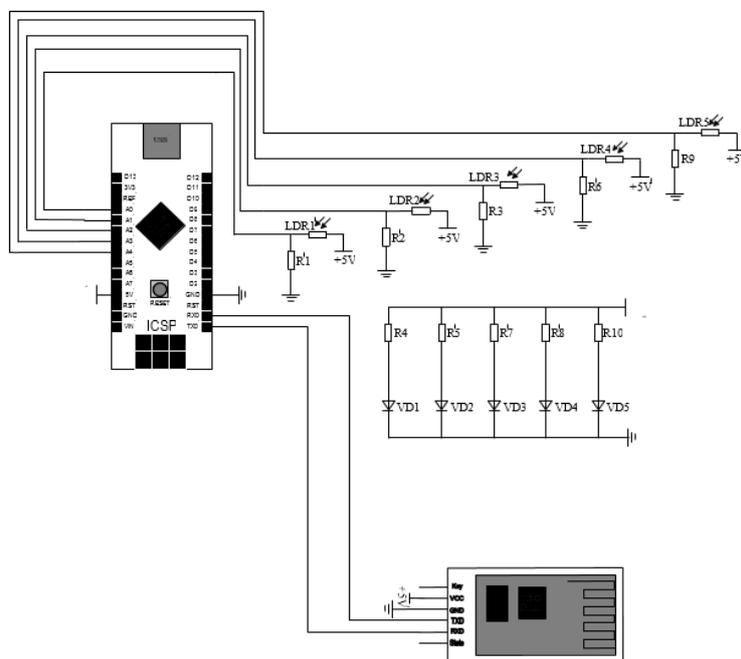


Fig. 8. Connection scheme of elements with Arduino board:
 1 – set of photoresistors and their respective resistors, 2 – Arduino Nano board, 3 – set of LEDs and their respective resistors,
 4 – HC-06 Bluetooth module

In order to debug the software, it is connected to a laptop with Arduino IDE. Using the serial port (COM port) reader, that is built-in into the Arduino IDE, it is possible to see what data is sent to Arduino from sensors and what data Arduino sends to Bluetooth module. Data is sent in format (XXX,XXX,XXX,XXX,XXX\n), where XXX – number between 0 and 255.

To test how well software performs to acquire data from different environments, the second test bench was constructed, using strain gauges instead of LEDs and photoresistors (Fig 9).

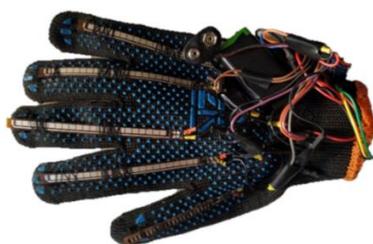


Fig. 9. Sender Test Bench

The first controller test bench consists of the following elements:

- glove;
- 5 strain gauges;
- HC-06 Bluetooth module;
- 5V power supply;
- infrared obstacle sensor YL-63;
- Arduino Nano board;
- micro-USB cable.

Both testing models performed well with quick response time and accurate data acquiring from sensors. Data readings from both test benches was correct without any changes to the code, which confirms flexibility of the software.

Next goal is to build test bench of the receiver sub-system. Architecture of the system in whole is shown in Fig. 10.

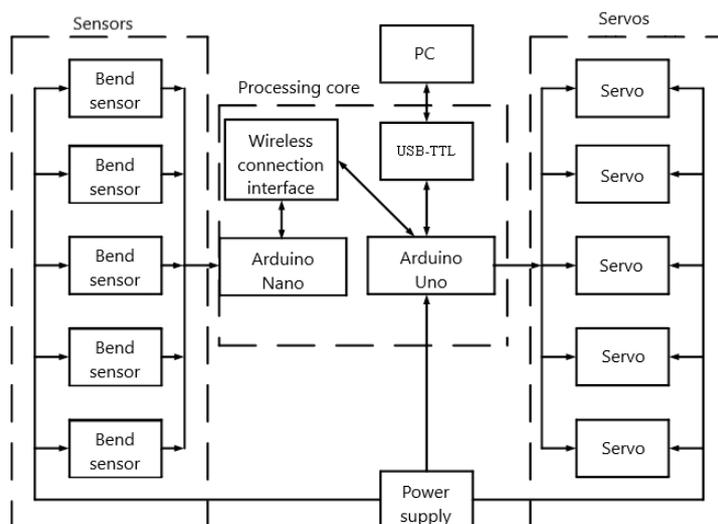


Fig. 10. Structural schematics of the system

To achieve this architecture, it is needed to construct another sub-system to receive data from sensors, transform it into angle of rotation and send it to the respective servomotors. Housing is a model of human hand. A model consisting of two parts: the wrist with fingers and the forearm, pre-designed in the SolidWorks system and printed on a 3D printer was developed (Fig. 11).

3D printing starts by making a virtual design of the object you want to create. The virtual design is used as a template of the physical object to be created. [8]

Forearm acts as housing of servomotors, while wrist holds the fingers (grip limbs). In order to move fingers according to movements of the operator, fingers are connected to servomotors using string. With this, rotation of the output shaft of the servomotor will bend the finger.

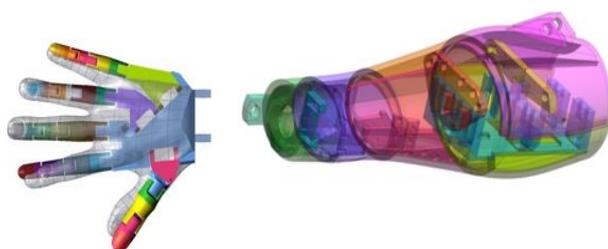


Fig. 11. 3D Model of Manipulator

The receiver test bench (Fig. 12) consists of the following elements:

- 3D-printed housing;
- Arduino Uno board;
- 5 servomotors;
- connecting wire
- HC-05 Bluetooth module;
- 5V power supply;



Fig. 12. Reciever Test Bench

The scheme, that describes the connection of the elements with the board, is shown in Fig. 13.

This test bench was connected to a laptop, through which, using Arduino IDE, control commands were sent. Servomotors can be controlled with Arduino boards using special library called "Servo". This library allows to natively control servomotors, using angle in plain text as input data for the board. Then, Arduino processes this data and formulates the control signal to a servo according to a current position of the finger and desired position.

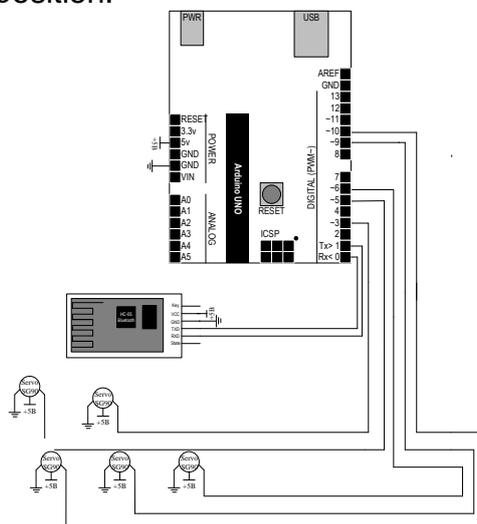


Fig. 13. Connection scheme of receiver test bench

After initial testing both parts were connected via Bluetooth and tested together. Fig. 14 shows the operator, bending his finger, and the manipulator, performing similar action with corresponding limb.



Fig. 14. Demonstration on the test bench

Conclusion

In this article the basic principles of development of the remote-control system for the robotic manipulator are researched.

In the course of the study, the program code was developed in the Arduino programming language for the Arduino board, which performs the function control system, as well as the bench for testing and demonstrating the performance of the program.

This research work fully describes all the aspect of creating such system, with requirements on full detail. With this information it is possible to do a further research, analysis and implementation of such system in many fields, such as consumer robotics or special robotics for work in hazardous or dangerous environments.

As a result, after the completion of the work, control system was implemented, which allows the manipulator limbs bending according to bending of the operator's fingers. The results of the study will be useful when designing a robotic system with complete human-robot control interface, which, at this stage of the development of the robotics, exists only in the form of prototype samples and has high cost.

Usage of the system, described in this research, can potentially save many lives and shift focus on areas, where human workers are put in risk. This system can be also used to enhance and improve human performance in many different areas.

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Розробка системи ручного робота-маніпулятора з дистанційним управлінням

Метою даної дослідницької роботи є дослідження і розробка системи ручного робота-маніпулятора з дистанційним управлінням. Пристрої такої конструкції в даний час затребувані в багатьох сферах життєдіяльності людини, зокрема при рятувальних операціях. Описується пристрій, який повинен вміти утримувати об'єкт довільної форми за допомогою хвату, мати прийнятну

точність позиціонування і управління. Такий пристрій можна використовувати для роботи в шкідливих або небезпечних середовищах, тим самим зводячи до мінімуму шкідливий вплив на людину. Система управління такого пристрою повинна забезпечувати протокол передачі даних від пристрою введення до кінцевої ручці маніпулятора для виконання відповідного руху.

Для початку процесу розробки був проведений аналіз ринку, в процесі якого було виявлено кілька схожих продуктів, які порівняли між собою і з розроблюваною системою. В результаті цього аналізу була створена порівняльна таблиця, в якій перераховані основні характеристики майбутньої системи в порівнянні з існуючими рішеннями на ринку, щоб переконатися, що вона буде конкурентоспроможною на поточному ринку.

У даній статті така система пропонується і пізніше розроблюється з урахуванням аналізу сучасних технічних компонентів і супутніх науково-технічних досліджень. В ході роботи було проведено аналіз існуючих технічних рішень, розглянуті принципи роботи окремих компонентів, описаний процес розробки кінцевої системи.

У якості процесорного пристрою було вирішено використовувати мікропроцесорні плати Arduino Uno та Arduino Nano, які надають зручні інструменти для роботи з мікропроцесорами ATmega з високою продуктивністю та енергоефективністю.

В результаті цієї роботи були створені і описані функціональні, логічні і електричні схеми, які були використані для створення робочого прототипу системи, а також схема моделі корпусу маніпулятора, яка була роздрукована на 3D-принтері. За створеними схемами та моделями був побудований робочий прототип описаної системи, який був успішно протестований, демонстрація чого приведена в роботі. Створена може бути інтегрована як підсистема в більш масштабний проект.

Ключові слова: мікроконтролер, робот, процесор, Arduino, сервомотор, маніпулятор, дільник напруги, дистанційне керування, Bluetooth, 3D-друк, моделювання.

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