

AUTOMATED SMART HUMANOID ROBOT ARM ON THE ARDUINO PLATFORM

AUTOMATYCZNE INTELIGENTNE RAMIĘ ROBOTA HUMANOIDALNEGO NA PLATFORMIE ARDUINO

Oleksandr POVSTIANO¹ [0000-0002-1416-225X], Lyudmila MARKINA¹ [0000-0003-0735-0743],
Viktor DENYSIUK¹ [0000-0001-9268-5489], Yurii LAPCHENKO¹ [0000-0001-7374-4770],
Viktor SATSYK¹ [0000-0002-7132-3363], Mykhailo PYLYPETS² [0000-0002-4286-9324]

¹ Automation and Computer-Integrated Technologies Department, Lutsk National Technical University, Lvivska Street, 75, Lutsk, Ukraine

² Applied Mechanics and Mechatronics Department, Lutsk National Technical University, Lvivska Street, 75, Lutsk, Ukraine

* Corresponding author: povstjanoj@ukr.net tel.: (+380506611333)

Abstract

The article presents the development of an automated smart humanoid robot hand on the Arduino platform using 3D printing, servo drives, and a sensor glove with flexible sensors. An electrical circuit and a software module for reading and processing signals have been developed, which provides real-time reproduction of the operator's finger movements. Modelling, assembly of mechanical and electronic parts, calibration of sensors and actuators have been carried out. Experimental studies have confirmed the accuracy, speed, and stability of the system, which makes it suitable for educational and demonstration robotics applications.

Keywords: humanoid robot, smart arm, Arduino, flexible sensors, servo drives

Streszczenie

W artykule przedstawiono rozwój zautomatyzowanej, inteligentnej humanoidalnej ręki robota na platformie Arduino, wykorzystującej druk 3D, serwonapędy oraz rękawicę sensoryczną z elastycznymi czujnikami. Opracowano obwód elektryczny oraz moduł oprogramowania do odczytu i przetwarzania sygnałów, który umożliwi odtworzenie ruchów palców operatora w czasie rzeczywistym. Przeprowadzono modelowanie, montaż części mechanicznych i elektronicznych oraz kalibrację czujników i siłowników. Badania eksperymentalne potwierdziły dokładność, szybkość i stabilność systemu, co czyni go odpowiednim do zastosowań edukacyjnych i demonstracyjnych w robotyce.

Słowa kluczowe: robot humanoidalny, inteligentne ramię, Arduino, elastyczne czujniki, serwonapędy

1. Introduction

The modern development of robotics is characterized by the rapid growth of intelligent systems capable of performing complex motor, sensory and cognitive functions inherent in humans. A special place among such systems is occupied by humanoid robots that imitate human movements, behavior and

interaction with the environment. One of the key elements of these robots is a mechanized "intelligent hand", which provides high-precision manipulation of objects, gestures and feedback to the user.

The development of an automated smart hand based on the Arduino platform opens up wide opportunities for creating affordable, modular, and flexible motion control systems. The use of micro-



controllers of this platform allows for synchronization of actions between sensors, servos, and software, as well as the integration of adaptive control algorithms that increase the accuracy and speed of the manipulator.

The relevance of this research lies in the need to enhance robotic systems that can effectively interact with humans in the medical, educational, industrial, and service sectors. An automated smart hand of a humanoid robot can serve not only as a component of complex robotic systems, but also as a training platform for studying the principles of mechatronics, automatic control and artificial intelligence.

The purpose of this work is to develop and study the design, control algorithms, and functionality of an automated smart humanoid robot arm based on the Arduino platform, as well as to evaluate its effectiveness in real operating conditions.

The modern development of service robotics, bionic prostheses, and remote human-machine interaction systems has led to a high level of scientific interest in creating robotic hands and mechanized hands that accurately reproduce operator movements. Such systems are used in medicine (rehabilitation complexes and bionic prostheses), industry (manipulators for precise operations), telerobotics (control of robot avatars at a distance), as well as in the field of service robotics and educational platforms.

The literature presents a number of solutions, among which it is worth highlighting bionic hands based on tendon mechanisms, models with 3D-printed segments (OpenBionics, InMoov, Dextrus Hand), as well as robotic limbs with built-in sensor systems for adaptive grip. At the same time, most of the known designs are either too complex to reproduce in educational and laboratory conditions, or do not provide sufficient accuracy and synchronism of movements during telecontrol. A separate problem remains the integration of flexibility sensors and control algorithms that would ensure smooth and stable reproduction of operator gestures without noticeable delays and mechanical backlash.

The motivation for this work is the need to create an affordable, technologically reproducible and at the same time functional mechanized humanoid robot hand capable of accurately repeating the movements of the human hand. The system proposed in the article combines a mechanical structure made using 3D printing, servo motors, low-friction cable transmission and integrated flexibility sensors that provide interaction with Arduino in real time.

The new scientific contribution of the work consists in:

- development of a mechanized hand design with optimized phalanges and cable channels that

reduce backlash and improve movement accuracy;

- integration of a circuit solution of flexible sensors with a calibration algorithm that increases the repeatability of gestures;
- development of an algorithm for direct reproduction of operator hand movements with increased smoothness due to signal normalization and delay compensation;
- practical demonstration of the full technological cycle: from 3D printing of parts to programming and testing of a robotic limb.

Thus, the work fills the gap between complex industrial prototypes and accessible educational designs, offering a comprehensive approach to creating a robotic hand with precise and stable telecontrol functions.

2. Research object

The object of the study is an automated smart humanoid robot arm, created on the basis of the Arduino microcontroller platform and the open source project OpenSource Humanoid Robot (InMoov), which combines 3D printing, mechatronics, and automatic control systems technologies (Fig. 1).



Fig. 1. Design of an automated humanoid robot arm based on the Arduino platform

The object under study is a mechanized arm with an integrated control system, which includes:

- 3D printed hand and finger design;
- servos that provide controlled joint movement;
- a sensor glove with flexible sensors to reproduce the operator's movements;
- Arduino microcontroller as a central control module;
- communication interface with a computer or tablet for configuration and testing.

The object of study is also the process of designing, developing and optimizing the hardware part of the installation, including the integration of

electronic, mechanical and software components into a single robotic system.

Thus, the research focuses on the creation and improvement of a hardware-software complex of a controlled humanoid robot arm capable of accurately imitating human movements in real time and providing interaction with the user through a sensor system.

3. Research methodology

The research methodology is based on an integrated approach that combines methods of system analysis, computer modeling, mechatronic systems design, and experimental verification of the robotic capabilities of the developed automated smart arm of a humanoid robot.

The following main stages and methods were used in the work process:

1. Analytical stage – an analysis of existing solutions in the field of robotics and open projects (in particular InMoov, OpenSource Humanoid Robot), which served as the basis for choosing constructive and functional solutions, was carried out. A systematization of technical requirements for robotic manipulators based on Arduino was carried out.

2. Design and construction stage – 3D modeling of the mechanical part of the hand was carried out in the CAD environment and models were prepared for 3D printing. Electrical circuits for connecting flexible sensors, servo drives, and the Arduino controller were developed.

3. Software and algorithmic stage – the software code for the Arduino microcontroller was developed and improved, which provides control of each finger separately. Algorithms for reading data from flexible sensors and converting them into servo movement commands were implemented.

4. Experimental stage – assembly of the hand prototype, installation of the sensor glove, adjustment of the switching and calibration of the system were carried out. Experimental tests were performed to check the accuracy, speed and synchronization of the movements of the humanoid robot fingers relative to the movements of the operator.

5. Evaluation of results – an analysis of the functional efficiency of the installation was carried out, the correspondence between the specified and actual finger bending angles was determined, and the stability of the sensors and drive system was assessed.

The research uses modular approach tools, which allows for independent modernization of both hardware and software components of the system. This provides flexibility, scalability, and the ability to adapt the automated smart hand for various applications –

from educational and demonstration purposes to integration into complex robotic systems.

Based on the analysis of modern publications and experience in the use of micromanipulators, requirements for the design and functional parameters of the system have been formed. The key requirements include: ensuring high positioning accuracy (up to units of micrometers and below), sufficient working range of movements, high rigidity and minimal nonlinearity of element deformations, low level of vibrations and speed, integration with high-precision displacement sensors, energy efficiency of piezo-electric actuators, as well as modularity of the design for the possibility of adaptation to various tasks.

3.1. The process of designing a demonstration installation of a humanoid robot arm simulator-avatar

The design of the demonstration installation of the humanoid robot hand simulator-avatar was carried out taking into account the basic principles of ergonomics, biomechanics and mechatronics. The main goal of the development was to create a functional prototype that allows simulating the movements of the human hand with the ability to control it using an Arduino microcontroller.

At the initial stage, a technical task was formed, which included requirements for the number of degrees of freedom, range of movements, speed and accuracy of gesture reproduction. To ensure anatomical similarity, the hand model was developed according to the principle of a segmental structure: each finger consisted of three phalanges connected by hinge mechanisms (Fig. 2).

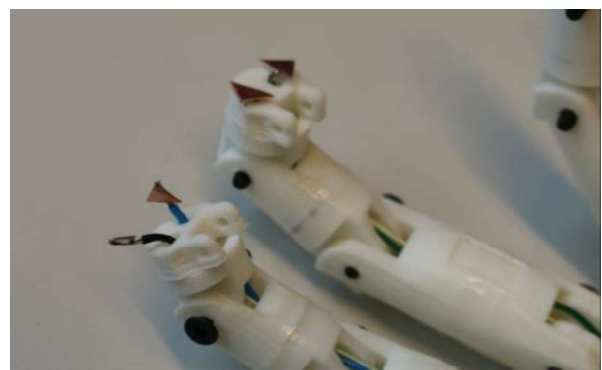


Fig. 2. Design and connection of drive elements of the fingers of a mechanized humanoid robot hand

The structural part was made in the CAD environment SolidWorks, which made it possible to create a 3D model taking into account dimensions, kinematic relationships and movement restrictions. To reduce weight and simplify manufacturing, the main elements of the hand and fingers were printed on a 3D

printer from the polymer material PLA, which combines lightness, rigidity and sufficient strength for experiments.

The drive system was based on the use of SG90 micro-servomotors located in the wrist housing. The transmission of motion to the finger phalanges was carried out through flexible cable elements that ensure smooth and synchronous bending (Fig. 3). To control the position of the fingers, tension sensors and potentiometers were integrated into the system, which form feedback.

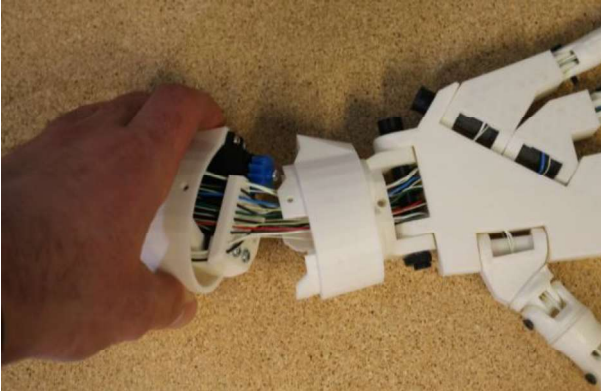


Fig. 3. Assembling the wrist assembly and connecting the electronic modules of the smart hand of a humanoid robot

The simulator is controlled using the Arduino Mega 2560 board, which allows software to coordinate the operation of each servo according to commands received from the sensor glove or control panel. To provide visualization and testing of algorithms, a demonstration setup was created (Fig. 4), which includes a base for fixing the hand, a power supply, a controller, and a computer communication module.

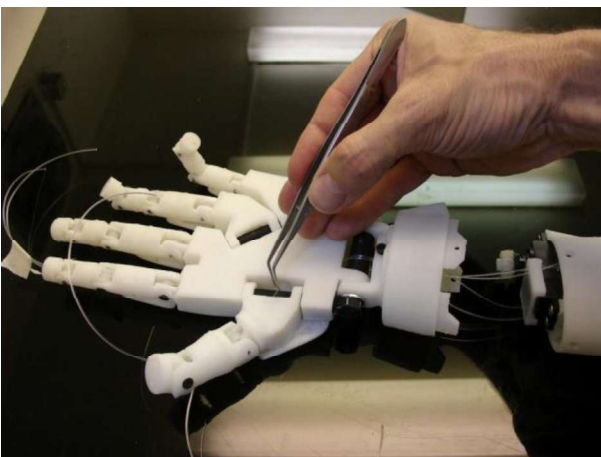


Fig. 4. The process of assembling a demonstration installation of a humanoid robot arm simulator-avatar

The final stage of the design was the assembly and adjustment of the system. The servos were calibrated,

the correctness of the movement transmission was checked, and the feedback was tested (Fig. 5-7). The resulting installation provides imitation of the basic movements of the human hand - flexion, extension, wrist rotation, as well as synchronous finger control (Fig. 8-10).

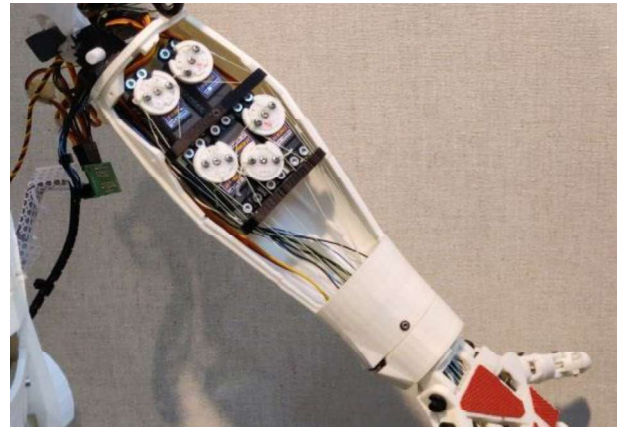


Fig. 5. View of a humanoid robot hand and a control module in the form of a glove with a set of sensors

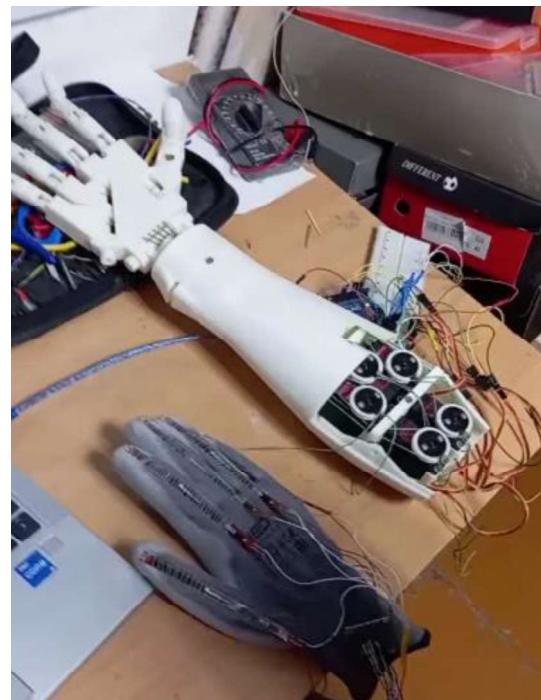


Fig. 6. Controlled arm

Our prototype has the following key engineering features:

1. Modular flexible control architecture that allows for independent calibration of each sensor channel and individual servo drive. Unlike standard solutions, our system implements adaptive compensation coefficients for cable and sensor nonlinearity.

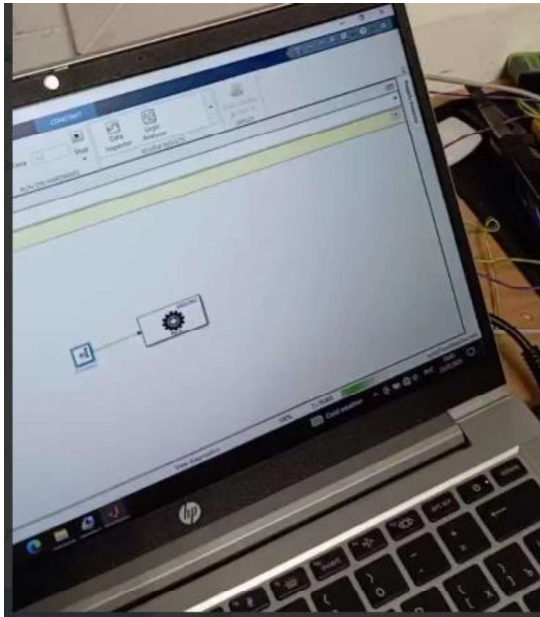


Fig. 7. Computer control panel

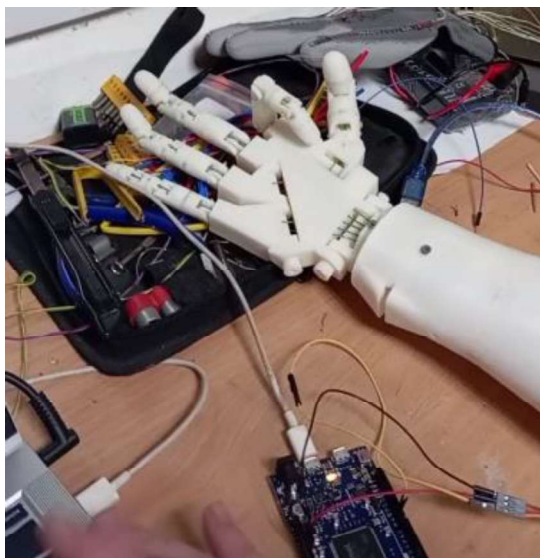


Fig. 8. Finger functionality

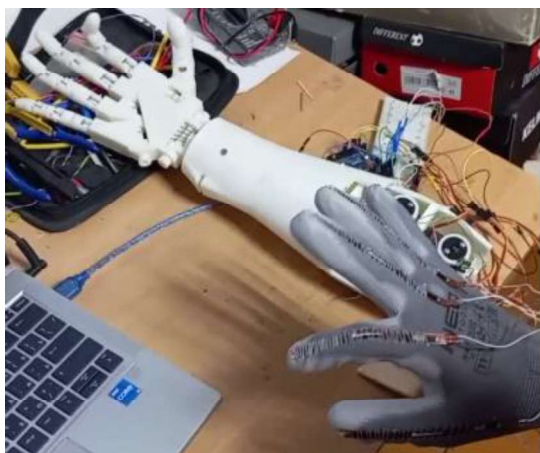


Fig. 9. Controlled finger flexion through a “control glove”

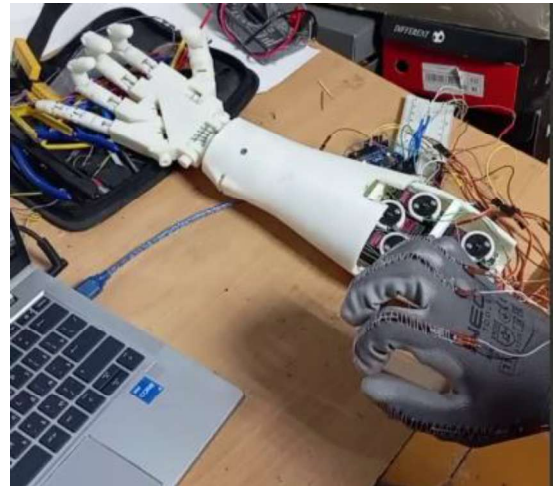


Fig. 10. Controlled palmar flexion

2. Proprietary sensor glove control scheme with redesigned voltage divider architecture that increases the accuracy of reading analog signals and ensures stability during long-term repetitive flexions.

3. Optimized cable system that reduces joint play and allows for higher gesture reproduction accuracy (average error 4.5-5°), exceeding the performance of basic tools in open projects.

4. Modified 3D design of fingers and phalanges, supplemented with stiffening ribs and modified cable channels, which minimizes friction and increases mechanical reliability.

5. Own demonstration installation of a “simulated avatar”, which contains not only a mechanical hand, but also a full-fledged hardware and software platform for testing, calibration and visualization of movements in real time.

6. Developed an algorithm for live transmission of movements with digital filtering of sensor noise and compensation of delay in PWM channels, which ensures stable reproduction of movements in real time.

3.2. Implementation of the process of creating a mechanized humanoid robot arm

Creating a mechanized humanoid robot hand involves a combination of hardware components, sensors, control electronics, and software. The system is based on: 3D-printed hand and finger elements, servo drives, an Arduino board as a central controller, a glove with flexible sensors, a cable transmission system, and auxiliary assembly elements.

The glove is a key element of the control interface. Flexibility sensors, which are variable resistors with a nonlinear deformation characteristic, are fixed on its surface. When the finger is bent, the sensor resistance increases, which changes the voltage at the divider output. The Arduino board reads the voltage change and generates pulse-width modulation (PWM) control signals, which are fed to the corresponding servos. The

servos, in turn, transmit mechanical movement to the fingers through a system of cables that work on the principle of human tendons. This configuration allows you to achieve natural bending kinematics.

Implementation stages.

Stage 1. Preparation of materials and assembly of the structure.

The list of required materials is shown in Figure 11. The kit includes:

- MG946R (or MG995/MG996) servos;
- 4.5-inch flexible sensors;
- Arduino Uno or compatible board;
- 22 k Ω resistors, 6.0–7.2 V power supplies,
- breadboards, mounting wires, cables, fasteners,
- control glove, tools and materials for assembly,
- 3D printer for manufacturing parts.

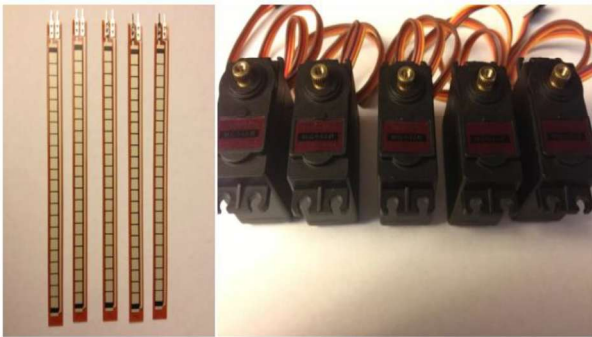


Fig. 11. Flexible sensors and servos used in the control system of a mechanized humanoid robot arm

At this stage, the initial preparation of the working environment is also carried out: setting printing parameters, calibrating tools, checking servos and sensors, and selecting the strength of cables for transmitting traction forces.

Stage 2. Printing parts of the mechanized hand on a 3D printer (Fig. 12).



Fig. 12. Stages of manufacturing a mechanized humanoid robot arm: size comparison with a human arm, set of printed parts and 3D printing process

The structural parts of the hand are used from the open InMoov project, which contains standardized models of finger segments, phalanges, palm base, and wrist. The parts are printed in PLA or ABS plastic, depending on the required strength and thermal stability.

The average printing time is 13–15 hours, but this figure varies depending on:

- layer height (0.1–0.25 mm);
- print speed;
- filling density;
- the need for support.

Special attention is paid to printing the finger phalanges. To reduce friction and ensure smooth rotation of the joints, they are printed at standard or high resolution, which minimizes the roughness of the internal cable channels and rotation surfaces.

In this work, the main parts of the hand and fingers are made of PLA plastic with standard material characteristics:

- young's modulus 2.8-3.2 GPa;
- tensile strength 55-60 MPa;
- specific density 1.24 g/cm³;
- permissible working deformation up to 4-6% without failure.

Geometric and structural characteristics of the printed hand:

- hand length – 178 mm, width – 85 mm;
- finger lengths – within 65-92 mm depending on the phalanx;
- weight of the entire structure without servos – 84 g.

Stage 3. Assembling the mechanical part of the hand and fingers.

After the components are manufactured on a 3D printer, the mechanical assembly stage is performed. The finger phalanges are connected into hinge mechanisms using screws of the appropriate diameter. Additional grinding and sandpapering are performed in places of friction to achieve smooth movement.

It is important to ensure the accuracy of the location of the cable holes, as the uniformity of traction and symmetry of finger movements depend on this.

The palm and wrist segments are connected into a base platform, to which the servos will later be attached. At this stage, the geometric parameters of the printed parts are also checked to ensure that they match the design dimensions.

Stage 4. Installation of servo drives and laying of cables.

The servos are installed in special mounting slots inside the palm body. The position of the servos is fixed with screws, which prevents displacement during operation.

A separate cable is used for each finger, which acts as an artificial tendon. One end of the cable is attached to the servo arm, after which it is laid through the internal channels of the phalanges. The other end is fixed to the tip of the finger.

To ensure smooth movement, the cables are tensioned with equal force to avoid uneven bending of the fingers. If necessary, guide sleeves or additional rings are used to reduce friction.

Stage 5. Soldering, connecting electronic components and testing sensors.

At this stage, the electronic components are connected according to the control circuit. The flexibility sensors are mounted as voltage dividers, for which one side of the resistive sensor is connected to the power supply, and the other to the 22 k Ω resistor and the input of the Arduino analog port.

After soldering, each sensor is tested separately. Arduino reads the resistance value through the voltage at the divider output. According to the received data, an initial calibration is performed, which allows setting the minimum and maximum bending values for each finger.

The servos are also tested for functionality by applying PWM test signals. The full range of rotation and the angle of rotation are checked to ensure that they meet the expected parameters.

Stage 6. Programming Arduino and calibrating movements.

The Arduino software is created based on an algorithm that directly reproduces the operator's hand movements. The code includes the following modules:

- reading analog values from flexibility sensors;
- normalization of received signals;
- converting the sensor signal into the corresponding servo angle;
- generating PWM signals on output ports;
- implementation of protective algorithms against drive overload.

The calibration process is performed in several stages:

- defining bending thresholds for each sensor;
- establishing linearity or mathematical dependence of the transformation "bend \rightarrow angle";
- eliminating delays between the operator's hand movement and the response of the fingers.
- checking the synchronism of movements of all drives.

The result is smooth and accurate reproduction of the operator's hand gestures.

Stage 7. Final testing and debugging of the control system.

Final inspection is performed after the mechanical and electronic parts are fully assembled. The purpose of this stage is to assess:

- accuracy of movements and repetition of gestures;
- servo response speed;
- reliability of traction transmission through cables;
- power supply stability and temperature conditions of servo drives;
- ergonomics of wearing gloves with sensors.

A series of experimental tests are performed: squeezing and unclenching the hand, element-by-element bending of the fingers, reproduction of complex gestures. The level of errors that arise due to signal delay, sensor inaccuracy, or mechanical play is analyzed.

After identifying deficiencies, debugging is carried out - adjusting the cable tension, correcting the servo angles, and recalibrating the sensors.

3.3. Dynamic and kinematic characteristics of the system

The study of the dynamic and kinematic characteristics of a mechanized humanoid robot arm is an important stage in assessing its operability, accuracy, and adaptability to operator movements. Since the system reproduces movements in real time, the key parameters are the speed of servo drives, the linearity of the response to signals from flexibility sensors, and the kinematic accuracy of finger movements.

The kinematic structure of the mechanized hand corresponds to the scheme of a multi-link system, where each finger consists of three phalanges connected by hinge joints. The movement is controlled by one servo drive for each finger, which, through a cable transmission, ensures the bending of the phalanges according to the principle of a "single tendon".

The kinematics of the fingers of an automated smart hand of a humanoid robot describes the geometric relationships between the joints and the endpoint of the finger, without taking into account the forces acting on it. Each finger is modeled as a sequence of links connected by rotational joints (usually three phalanges: base, middle, terminal). Forward kinematic modeling allows you to determine the position of the fingertip in space through the angles of rotation of the joints and the lengths of the phalanges. Inverse kinematic modeling provides the calculation of the necessary joint angles to achieve the desired tip position, which is critical for controlling servos on the Arduino platform. Kinematics also defines the working space of the fingers, which sets the reach area of the tip.

Kinematic analysis was performed based on determining the dependence of the finger bending angle on the servo lever displacement. The obtained dependence is nonlinear due to the elasticity of the cable and additional friction losses at the bending points. To compensate for this nonlinearity, correction coefficients approximated by a second-order polynomial model were used in the software.

Finger dynamics describes the relationship between applied joint torques and finger motion, taking into account joint inertia, frictional forces, and gravitational moments. In a simplified form for Arduino, joint torques are proportional to given angles of rotation, and dynamic constraints are implemented through servo speed and acceleration constraints. This allows for smooth and precise finger motion, ensuring reliable grasping and manipulation of objects, as well as the reproduction of complex gestures.

To evaluate the dynamics of the system, the following parameters were determined:

- angle setting time after signal is given – on average 120–180 ms;
- average system response delay from the moment the sensor bends to the actuator movement – 0.18–0.22 s;
- the maximum finger flexion speed was 200–240°/s;
- working angle range – approximately 0 to 90° of flexion in each finger.

The speed of servo drives is limited by the mechanical load and inertia of the cable transmission, which requires optimizing cable tension to increase accuracy and reduce backlash.

During the research, it was found that the maximum force that can be transmitted by the mechanism of one finger does not exceed 0.3–0.35 kg×s, which is sufficient for performing demonstration manipulations: grasping light objects, holding small parts, and performing gestures.

Dynamic loading is concentrated in the hinge areas, so when printing parts, an increased filling density (35-50%) was used, and stiffeners were also provided in the phalangeal segments to avoid destruction during maximum bending.

The accuracy of the repetition of movements was assessed by comparing the actual bending angles with the expected values determined from the signals of the flexibility sensors. The results showed:

- average error of angle reproduction – no more than 4.5-5°;
- deviation between repeated gestures – 3-4°;
- linearity of movement reproduction – 92-94%.

The following factors had the greatest impact on accuracy:

- uneven cable friction;
- elastic deformations of mechanical assemblies;
- internal noise fluctuations of analog signals from sensors.

The use of digital filtering and actuator correction in the Arduino firmware allowed us to reduce noise components and improve the stability of movements.

3.4. Creating an electrical circuit for flexible sensors

Flexible sensors require the development of an appropriate circuit so that they are compatible with the Arduino platform (Fig. 13).

The voltage divider has the following features: the corresponding flex sensors are variable resistors, and when paired with static value resistors, the change in resistance (in this case the bending of the sensor) can be sensed through the change in voltage across the resistors. This can be measured using the Arduino via its analog inputs.

The developed circuit looks like this (red color reflects the positive voltage pole, black - negative, blue switch is connected to Arduino).

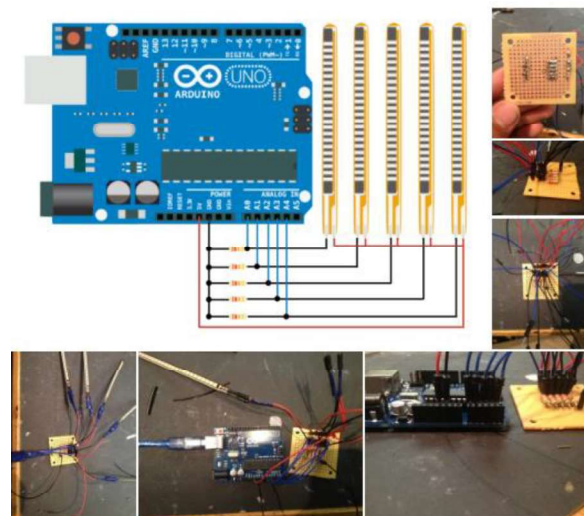


Fig. 13. Structural electrical diagram of connecting flexible sensors to the Arduino controller: power supply, voltage dividers on 22 K resistors and connecting signals to analog inputs A0–A4

The resistors are 22K. The main GND (ground) cable, which connects to all the individual GND wires from the sensors, is connected to the Arduino GND. The +5V voltage from the Arduino is fed to the mains, and the positive voltage cable, and each blue cable is connected to a separate analog input.

The circuit is soldered onto a small PCB from RadioShack, one that can easily be mounted on a glove. The cables to the sensors are also soldered, using heat shrink to prevent short circuits.

Next, you need to insulate the area where the cables connect to the sensors with electrical tape to stabilize the sensors. Near the bottom where the wires are attached, the sensors are a little weaker, and the tape ensures that they don't bend too far and get damaged.

3.5. Installation and assembly of the mechanized arm control module

The stage of installation and assembly of the control module of a humanoid-type mechanized hand involves a complex of works, including the integration of flexible sensors, assembly of actuators, connection of electronic modules and final calibration of the movement. These works are performed in a clear sequence to ensure the correctness of data reading and the accuracy of the transfer of movements from the user to the mechanized hand.

1. Glove preparation and installation of bending sensors.

First, the final stitching of the carrier glove is carried out, which serves as the basis for attaching the sensors. After this, the following steps are performed:

- a small technological hole is drilled in the plastic part of each flexible sensor in the upper zone, where the resistive element ends, taking into account the prevention of mechanical damage to the active area;
- the glove is put on the operator's hand and the projections of the finger joints are marked with a pencil. The resulting landmarks allow the precise position of the sensors to be set relative to the natural biomechanics of the fingers;
- the sensor tips are fixed to the upper phalanges of the fingers, after which the resistive tapes are additionally sewn into the joint areas. The thread holds the sensor in a stable position and prevents axial displacement during operation;
- the printed circuit board with the circuit tracks and connectors for Arduino is rigidly sewn into the wrist area. This arrangement minimizes the tension of the wires and reduces the risk of mechanical damage during hand movements.

After installation, the sensors are electrically connected to the cables and the contact nodes are heat-shrunk, which ensures insulation and mechanical stability.

2. Assembling the mechanized arm and installing servo drives.

Assembling a robotic arm includes preparing the fingers and drive links:

- before gluing the finger segments, their correct orientation is checked according to the kinematic diagram;

- to ensure smooth movement, the 3mm hinge screws are fixed so as not to create unnecessary friction; the outer parts are reinforced with drops of hot melt glue;
- servos are mounted in the forearm segment according to the designed seating positions.

For initial testing, the servos are connected to a small-sized breadboard:

- all positive (red) wires are connected to the common +V bus;
- all negative (black/brown) - to the GND bus;
- it is important to provide a common ground point with the Arduino, as a broken ground will cause the control signals to malfunction.

3. Downloading and debugging the Arduino control program.

After checking the electrical connections, the software is loaded, which performs:

- reading analog signals from flexible sensors;
- normalization and linear/nonlinear transformation of bending amplitude;
- generation of appropriate PWM signals to control servo drives.

The operator puts on the glove and performs test movements. Performed:

- calibration of bending thresholds for each specific sensor;
- determining the minimum and maximum operating values of analog signals;
- setting servo limits to avoid overloading the mechanisms.

In case of incorrect operation of the servos, potential wiring errors are checked, especially the common ground.

4. Installation and calibration of finger drive rods (strings).

After confirming the operability of the servos, one of the most important stages is performed - installation of the rods (cable drive of the fingers). The strings are attached to the servo pulleys using drops of hot melt adhesive, which ensures reliable fixation without slipping.

Calibration is performed for each finger separately:

- the operator bends the corresponding finger in the glove;
- the servo drive is positioned in the appropriate angular position;
- The "relaxing" and "pulling" strings are tensioned and fixed in the corresponding holes of the servo ring.

The main requirement is a maximally stretched string without prior bending of the finger, which guarantees the accuracy of the transmission of

movements and the symmetry of bending and unbending.

The procedure is repeated for each finger until smooth and synchronous movement is achieved.

5. Final tests and verification of kinematic compliance.

After installation is completed, the following is carried out:

- test bending of all fingers,
- assessment of the synchronism of all tractions,
- tension adjustment in case of uneven bending,
- control of work in different ranges of force and speed of movements.

The resulting control module provides high-precision reproduction of the operator's hand movements thanks to a combination of flexible sensors, servos, and an Arduino microcontroller.

4. Conclusions

The paper presents a comprehensive approach to the design, creation and research of an automated smart humanoid robot hand on the Arduino platform, which reproduces the movements of the human hand in real time. Based on 3D printing, servo drives, cable transmission and a sensor glove with flexible sensors, a functional mechatronic system was formed, capable of providing precise and smooth control of the fingers and wrist.

An optimized mechanical design of the fingers and phalanges, an improved cable system with reduced backlash and a modular control architecture were developed, which allowed achieving high repeatability of movements and an average error of gesture reproduction at the level of 4.5-5°. A scheme for integrating flexible sensors with a calibration algorithm that compensates for nonlinearity and reduces the impact of noise on the signal is proposed. The developed algorithm for direct translation of movements ensured stability, low delays and natural kinematics of the manipulator.

Experimental studies have confirmed the effectiveness of the mechanical and electronic parts of the system, the adequacy of digital signal processing, as well as the accuracy and speed of synchronous finger control. The created demonstration installation of the avatar simulator allows testing, calibration and visualization of movements in real time, which makes the system suitable for educational, research and demonstration tasks in the field of robotics.

The practical significance of the work lies in the possibility of reproducing the design in educational laboratories, as well as in the potential for adapting the development for telerobotics systems, rehabilitation equipment and service manipulators.

Further research can focus on improving force feedback, integrating pressure sensors and tactile sensors, expanding the degrees of freedom of the wrist, utilizing machine learning algorithms to predict movements, and enhancing the system's adaptability to the individual characteristics of the operator.

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