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Design and Control of a 3D Printed Humanoid Hand

DISSERTATION ABSTRACT

of a dissertation for the award of the educational and scientific degree "Doctor"

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Scientific supervisor:

Prof. Dr. Ivan Chavdarov

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The dissertation has been discussed and scheduled for defense by an extended seminar of the "Robotic and Mechatronic Intelligent Systems" laboratory at the Institute of Robotics, BAS

The defense of the dissertation will take place in Hall 427, Block 2, at the Institute of Robotics, BAS.

The materials for the dissertation are available in the office of the Institute of Robotics, BAS.

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Relevance of the Topic

Humanoid robotic hands are a popular research topic in robotics. Anthropomorphic (from ancient Greek, anthropos – "human"; and morphe – "form") robotic hands have been studied and developed for years, with one of the early developments being the Belgrade humanoid robotic hand prosthesis, created by Professor Rajko Tomović from the "Mihajlo Pupin" Institute in 1963 [43]. The prosthetic hand was further studied and tested, leading to the creation of an improved version in 1966-67 and the production of 35 units of the prototype [45]. The Belgrade Hand consists of 5 movable fingers that adapt to the surface of the grasped object. The control system is based on a single servo motor with built-in blocking functionality, which allows for the fingers' position to be fixed.

In the early 1980s, most mechanical hands were two-finger grippers or industrial hands with the capability for quick tool attachment. The Salisbury Hand, created by Dr. Kenneth Salisbury in 1982 with funding from NASA, is a three-fingered gripping manipulator designed to be connected to the Unimation 560 (PUMA) robot [44]. Each of the Salisbury Hand's three fingers has three degrees of freedom of movement. The hand is controlled by 12 electric motors with a gear ratio of 25:1, which drive 12 tendons (4 for each finger). For precise feedback, the system includes sensors for tendon tension and optical encoders for each motor.

Since then, humanoid hands have seen rapid development, supported by innovations in electronics, sensing, and control. Today, anthropomorphic hands find application in a number of fields including science, medicine, and industry. In medicine, robotic hands are used as prosthetic replacements for human hands [2]. Another application is in telemedicine (remote surgery) and telerehabilitation of hands, and treating patients from a distance [3,4]. A third application of humanoid hands in robotics is for the remote control of precise movements in environments dangerous to humans, such as space [5, 13], and as part of a constructed humanoid robot.

Goal and Objectives of the Dissertation

The goal of this dissertation is to design and create a 3D printed humanoid robotic hand built on a modular principle, and to investigate its functional capabilities. Each of the hand's fingers is to be driven by an independently controlled motor. The modularity refers to the fingers, including their control hardware and software.

The following objectives stem from this goal:

1. To conduct a literature review and analysis in the field of robotics and medicine concerning the creation of humanoid robotic hands, with particular attention paid to the application of additive technologies in this area.
2. To develop an approach for creating assembled 3D printed fingers for a humanoid hand. Using this approach, to design a model of a humanoid hand.
3. To investigate the basic geometric and kinematic characteristics of human hand fingers.
4. To create a prototype of a humanoid hand with modular fingers, which includes the mechanical and hardware elements of the 3D printed hand.
5. To develop the hardware and software for the control and configuration of the 3D printed modular humanoid hand.
6. To develop software for reproducing signs from sign language (specifically, a sign language alphabet), applicable to the created prototype.
7. To conduct experiments confirming the functionality of the 3D printed humanoid hand.

Structure of the Dissertation

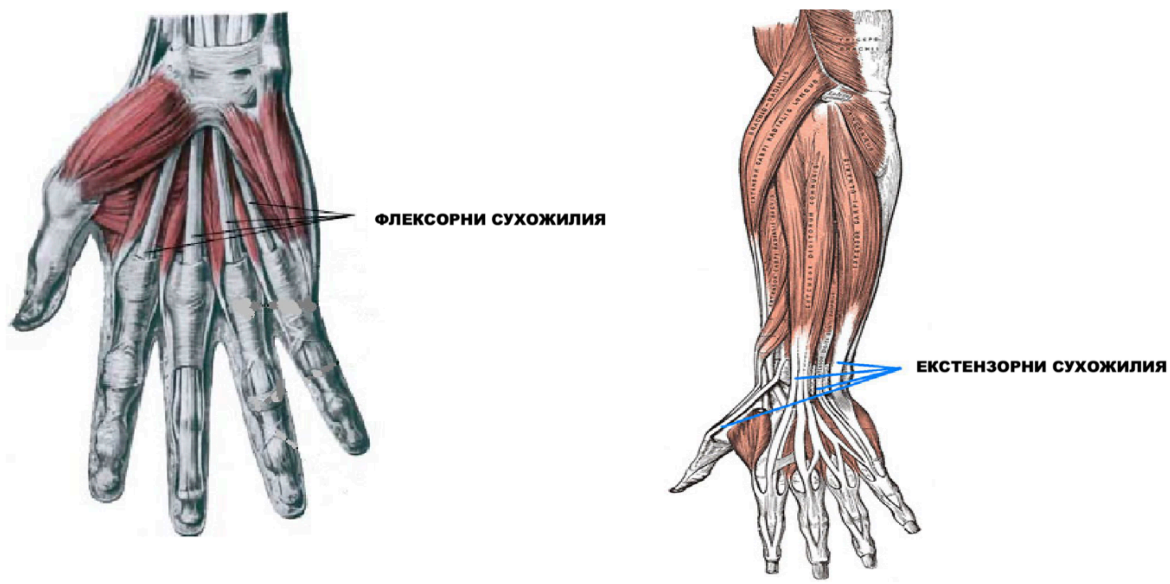
The structure of the dissertation consists of an Introduction, 5 Chapters, and a Conclusion, with a total volume of 115 pages. Included are 53 figures, 9 tables, and 65 sources are cited. In the abstract (or summary of the dissertation), the numbering of the figures and tables corresponds to that of the main dissertation.

1. Review of the Subject Area

Different types of humanoid hands and their applications, as well as the anatomy of the human hand, are reviewed. The main components of a humanoid hand are analyzed, such as actuators, sensors, control systems, as well as hand kinematic models and grasp classifications. Anatomically, the human hand consists of bones, joints, tendons, muscles, nerves, and blood vessels, enclosed by an outer layer of skin. The bones of the hand consist of phalanges, metacarpal, and carpal bones, where a human finger is made up of phalanges and one metacarpal bone. The carpal and metacarpal bones are "hidden" under a continuous layer of skin and are not of interest to this research. The thumb has two phalanges, while the other fingers each have three phalanges. Starting from the phalanx closest to the palm to the furthest, their arrangement is: the proximal phalanx, the intermediate/middle phalanx, and the distal phalanx. In the field of robotics, the term phalanx is equivalent to the concept of a robot link. The bones of the hand are connected to each other by joints. The proximal and intermediate phalanges are connected by the proximal interphalangeal joint (PIP joint), and the intermediate and distal phalanges are connected by the distal interphalangeal joint (DIP joint). The thumb has one interphalangeal joint.

Figure 1. Bones and joints of the human hand

In the control and design of the humanoid hand developed in this dissertation, actuators and tendons (filaments) are used, inspired by the existing muscles and tendons in the human hand. The fingers of the human hand are flexed and extended with the help of specialized muscles. The muscles that allow the fingers to bend inward are called flexors. Flexors start at the elbow, transition into tendons, and reach the fingertips. The flexor tendons in the fingers pass through channels. This prevents them from moving away from the bone. The opposite movement, or the extension of the fingers, is performed by extensor muscles and extensor tendons. They, similar to the flexor tendons, also pass through channels and reach the fingertips. In the developed mechanical hand, DC motors serve the role of the muscles that drive the fingers, but for the purpose of miniaturization and minimization, the motors are concentrated in the palm of the hand. In the design of the robotic hand, openings (channels) were added within the fingers, in which the tendons (filaments) are located, reaching the tips of the mechanical fingers, similar to the channels and tendons in the human hand.



Фигура 2. Flexor and extensor tendons of the human hand

The reviewed humanoid robotic hands from the literature are compared in Table 3 based on the following categories: purpose, number of degrees of freedom of the hand, actuators and mechanics, sensors, and technologies used.

Table 3. Comparative Table of Humanoid Hands

Robotic hand	Purpose	Degree of freedom	Actuators, mechanics	Sensors	Used technologies
Robonaut 2 [5]	Substitute for astronauts in outer space	12 (ръка) +2 (китка)	DC motors, tendons	- Hall sensor - Tendon tension sensor - tactile	- Gold galvanizati-on - tendons woven from special materials
BAS hand [6]	Sign language	10	Servomotors, tendons, elastic spring	- Kinekt sensor - Glove for control	- 3D printing
InMoov hand [9]	Open source of its 3D files and development by many people around the world	14 (hand) +1 (wrist)	Servomotors, tendons	- Kinekt - Hall sensor	- 3D printing
Washington university [10]	Scientific research	20	Pneumatic cylinders, tendons	- tactile	- 3D printing
Shadow ръка [11]	Industrial control of quality, work with dangerous materials	20	DC motors or pneumatic artificial muscles, tendons	- Hall sensor - Tactile (BioTac) - Tendon tension sensor - Pressure sensor	- ROS OS

Robotic hand	Purpose	Degree of freedom	Actuators, mechanics	Sensors	Used technologies
Gifu III hand [12]	Research on precise gripping and manipulation by a robot	16	Servomotors, Four-bar linkage	- Tactile - Force sensors	- RTOS OS
DLR II hand [13]	Substitute for astronauts in space	13	DC motors, belts, bevel gears, Four-bar linkage	- Hall sensor - Potentio-meters - Force and torque sensors	- Design based on tests in virtual environ-ment
DART hand [14]	Work with computer keyboard	16 (hand) +3 (wrist)	Servomotors, Four-bar linkage, tendons	- Hall sensor - Pressure sensor	- 3D printing
Universitat Politecnica de Valencia hand [15]	Prosthetic	15	Servomotors (thumb), Step motors, tendons, pulley	- Pressure sensor - EMG sensor	- 3D printing - 3D scanning
BIT hand [16]	Prosthetic	6	Linear motors	- EMG sensor	- LDA algorithms for intention recognition
KIT hand [17]	Prosthetic	10	DC motors, tendons	- Distance sensor - Camera - IMU - EMG sensor	- 3D printing - Visual perception of the environ-ment via camera

The hands with the most degrees of freedom (20) are the Shadow Hand and the University of Washington Hand. These hands can perform complex movements and grasps, but their disadvantages include the high cost and the weight of the actuators. The model developed at the University of Washington has positioned the pneumatic cylinders outside the hand. This rules out the possibility of using both mechanical hands as prostheses. In robotics, there are mechatronic systems where the number of actuators is less than the degrees of freedom of movement. This is achieved through passive degrees of freedom, which add an additional degree to the kinematic chain [33]. An example of this is the KIT prosthetic hand, which has only two actuators built into the palm. This reduces the hand's weight but limits its ability for precise grasps. The BAS Humanoid Hand uses an elastic spring element to add an additional passive degree of freedom for each finger. The Robonaut 2 and DLR II hands were created by space agencies and are intended to be part of humanoid robots. The large number of sensors and advanced technologies multiply their cost compared to other mechanical hands. A disadvantage of the DLR II hand is also its smaller number of fingers (4) compared to the human hand. Among the hands reviewed, one stands out for offering open and free access to its design files—the InMoov Hand. This increases the model's popularity and leads to many developments and improvements of the hand by people all over the world. The DART Hand has sufficient degrees of freedom, but its purpose—writing on a computer keyboard—could be replaced by an entirely software solution. The majority of the examples reviewed use tendons to drive the hand's fingers, inspired by the anatomical structure of the human hand. The flexing and extending of the human hand's fingers are performed with the help of flexor and extensor tendons, which pass through channels and reach the fingertips. The humanoid hand of the space robot Robonaut 2 [5] uses a special tendon called Vectran™ to drive the fingers, chosen for its strength and resistance to stretching. Some of the reviewed humanoid robotic hands use 3D printed mechanisms for finger flexion and extension. The BAS Humanoid Hand [6] uses tendons for finger flexion and 3D printed elastic springs that use stored potential energy for finger extension. The InMoov Hand [9] uses 3D printed pulleys to which two tendons are attached—one for flexion and one for extension of the fingers. Some of the reviewed humanoid robotic hands use the four-bar linkage mechanism to drive the fingers. An advantage of this type of design is the rigid links, which, in comparison to tendon-driven systems, are more resilient and stable mechanisms. With repeated flexing and extending of the finger, the tendon changes its length, which compromises the accuracy and repeatability of the finger's movement. A distinctive feature of the mechanism is that the actuator is connected with a rigid link to the finger structure, which enables movement that mimics the trajectory of a human finger. This is achieved by experimenting with different lengths of the rigid links in the mechanism and selecting the lengths that most accurately reproduce the path of human finger movement [14]. Among the reviewed humanoid hands, the most commonly used actuators are DC motors [5, 11, 13, 17] and servo motors [6, 9, 12, 14, 15]. Less common are pneumatic cylinders [10], pneumatic artificial muscles [11], linear motors [16], and stepper motors [15]. Widely used in the literature examples are tactile sensors [5, 10, 11, 12], which provide information about physical contact and allow for work in unstructured environments and the manipulation of unknown objects. Some hands, like [11], use tactile sensors with fluids that change pressure upon contact. Prostheses [15-17] use an electromyography (EMG) sensor, which is used to monitor the electrical activity of muscles. Electrodes are placed on the skin of the human arm over muscles that are key to finger movement. The electrodes transmit the muscle's electrical activity to the EMG sensor. The sensor needs to be calibrated and configured individually for each person beforehand to be used correctly in controlling the hand. Other sensors used in humanoid hands are the Hall sensor, and force and tendon tension sensors. The KIT hand [17] uses computer vision as the primary sensor for environment perception. Computer vision analyzes images to extract information about a given scene, which is crucial for modern robotics. It can be used for object recognition, motion tracking, and actuator control. Object recognition is achieved through a combination of computer vision and an Artificial Neural Network (ANN). An ANN is a machine learning algorithm whose model is inspired by the bioelectrical networks in the brain. It consists of neurons and their connections (synapses). Each neuron in the network receives weighted signals from the previous layer and processes its own output signal, which it transmits to the next layer. To function effectively, the neural network must be pre-trained with a large volume of data, known as the training sample. This training process allows the system to recognize different objects with high accuracy.

Sensors, actuation mechanisms, and other electronic components must be managed by a reliable hardware and software system, powered by a suitable energy source. Miniaturization and minimization of hardware components are necessary for certain prosthetic hand applications. Using fewer hardware components also means lower energy consumption and a more cost-effective and energy-efficient robotic hand. Depending on the application of the humanoid hand, there are various hardware and software implementations for controlling its movements. Control systems based on a microcontroller connected to a computer via wireless Bluetooth technology are found in the literature [47]. Although this control is not suitable for a prosthesis, it is a good starting point for developing and testing a hand prototype. In [48], an Arduino Uno microcontroller together with a Raspberry Pi microprocessor are used to control the movements of a robotic hand. By replacing the large computer with a smaller microprocessor for logic and control processing, the hand can be worn outdoors, which is applicable to prosthetic hands. Examples of Field-Programmable Gate Array (FPGA), also known as a programmable logic array, used for controlling humanoid hands are also found in the literature. However, a disadvantage is that FPGAs have limited resources such as look-up tables, registers, DSP signal processors, and block RAM [49]. Software solutions for controlling humanoid robotic hands range from a computer-based control system [12] to more advanced techniques such as machine learning and neural networks [50].

2. Design and mechanics of 3D printed robotic humanoid hand

An innovative design for a humanoid robotic hand is presented. The innovative elements and design in the presented humanoid hand are the modularity of the fingers, the printing of fully assembled fingers, and the fact that all control and actuation elements fit within the palm. The goal of the current work is to develop an affordable humanoid hand that has good functionality and the capability for size customization. The solution to this challenge was found by utilizing the advantages of 3D printing technology and modular design. Polylactic acid (PLA) material was used for the hand's construction. The human hand possesses 27 degrees of freedom of movement [52], allowing for a wide range of motion and dexterity. Reproducing this level of complexity in a robotic hand is a significant challenge. For the purpose of minimizing hardware components, some of the degrees of freedom for the fingers and wrist were omitted in the design of the described humanoid hand. Actuation mechanisms, such as DC motors and tendons (filaments), are used to generate the forces required for finger movement and object gripping. The design of the fingertips was engineered with appropriate shapes for effective object grasping. In most cases in the literature, the construction of a 3D printed humanoid finger involves an assembly process from several parts to achieve the final desired result and functionality. In the design of the developed robotic humanoid hand, each finger consists of 4 elements (Fig. 24) that are directly assembled through the 3D printing technology. This way, time is saved from the finger assembly process, and the overall assembly of the hand is simplified.

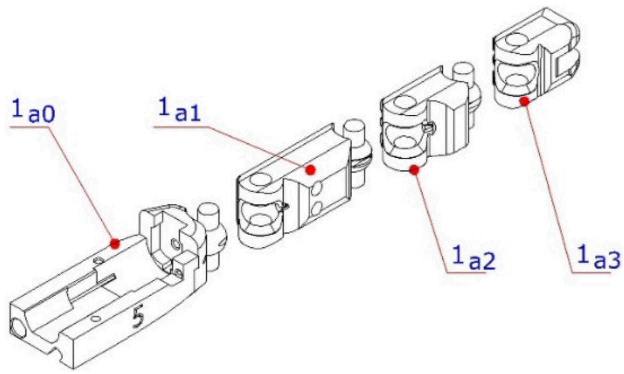


Figure 24. Finger components

A Fused Deposition Modeling (FDM) printer is used to create the fingers and the joints connecting the individual finger components. The shape of the joints is specially adapted for 3D printing, so that the elements can be built simultaneously and be directly assembled without the application of support structures during printing. In the design of assembled rotational joints created with FDM printing technology, it is suggested that the following principles be observed:

- The axis of cylindrical and conical sections should be positioned perpendicular to the 3D printer bed:

For example, if we print an object with a circular hole whose axis is parallel to the plane of the build platform, the hole will be deformed by the force of gravity

- The 45-Degree Principle::

When printing, the joint connections must not stick together so that the finger can perform rotational movements. This is achieved by rotating the joints by 45 degrees during the printing process, which is half of the possible movement of the joint connection.

- The Two-Support Principle:

When creating an assembled mechanism, there are often surfaces that must be parallel to the build platform. Sections larger than 1 to 1.5 millimeters cannot be manufactured without using support structures (supports), which practically creates two supports.

- Minimal Clearances in Bearing Sections

Another important aspect when designing bearing sections is ensuring a clearance between the assembled elements. This clearance is necessary to prevent friction, which could lead to overheating or damage. For plain bearings with a diameter of 6 millimeters, the optimal clearance is typically in the order of 0.03 millimeters. This allows for effective lubrication and proper functioning of the bearing while simultaneously minimizing the play that could lead to instability or vibrations.

- Selection of the Minimum Diameter for Plain Bearings

The selection of the minimum diameter for the plain bearings (or sliding bearings) is determined by several key factors. On one hand, a smaller diameter leads to a reduction in the resistant frictional torque, which improves the mechanism's efficiency. Another significant advantage is that this generally results in compact dimensions and a reduction in the overall cost of the mechanism. Despite these advantages, there are also technological limitations. For example, when manufacturing with a 3D printer, the minimum diameter is limited by the machine's capabilities; in this case, bearings with a diameter of less than 4 millimeters cannot be printed. Furthermore, the bearing diameter must be considered in relation to the dimensions of the human hand.

Based on the previously described principles, a finger model with directly assembled elements has been designed and manufactured. The correct and reliable functioning of the finger joints, such that they have minimal resistance during movement, is determined by many factors. Among them are the joint diameter, the clearance between the elements, the printing material, and the printing processes. The clearance between the joint elements is a critical factor. It has been experimentally verified that a clearance of 0.2 millimeters is sufficient to create functional joint connections. This value was chosen as the minimum possible to allow movement without resistance, compensating for the insufficient accuracy of the printing process. The selection of a minimum joint diameter of 5.2 millimeters is also made with the goal of reducing frictional resistance and achieving a more compact and lightweight finger design, which is essential for humanoid robotic hands. After the 3D printing procedure is complete, the joint connections need to be manually articulated. No other additional post-processing of the printed finger is required. The fingers of the hand have a modular design (they are identical), differing only in the lengths of the phalanges and the joint limits. In the design of the fingers, the dimensions of the various phalanges were taken from real medical studies of patients [7]. The modular design allows for quick disassembly and assembly of a new finger if necessary. The modular design of the finger includes an identical mechanical, sensor, and control system as shown in Fig. 26. The finger is composed of six 3D printed elements: 1 - body with phalanges; 2 - cover; 3 - drive pulley; 4 - tension roller; 5 - pressure cap; and 6 - movable spring cap. These elements are produced using FDM 3D printing technology.

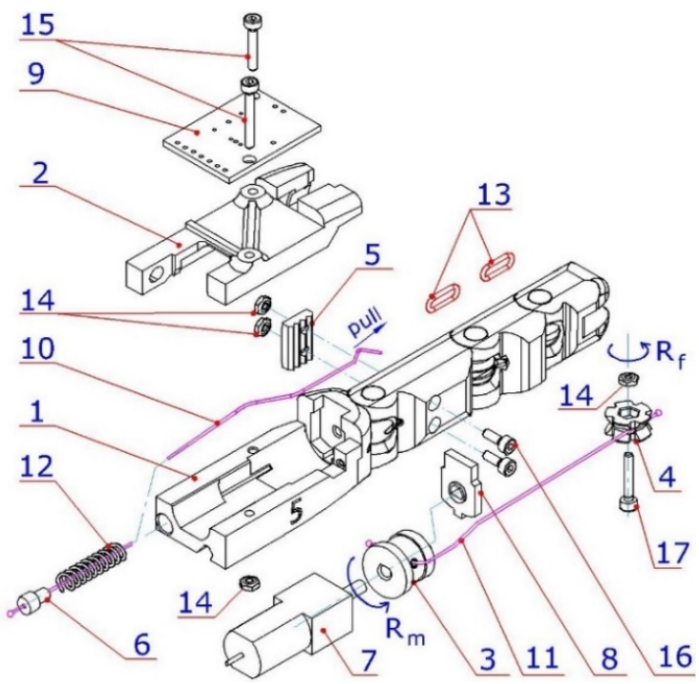


Figure 26. Main components of finger

1 - body with phalanges; 2 - cover; 3 - drive pulley; 4 - tension roller; 5 - pressure cap; and 6 - movable spring cap; 7 – DC motor; 8 – potentiometer; 9 - Printed Circuit Board (PCB); 10 and 11 – tendons; 12 – spring; 13 – Elastic bands; 14 to 17 – Fasteners.

The fingers of the hand can perform two movements: flexion (bending) and extension (straightening). The flexion of a finger is achieved by motor 7 (Fig. 26), on whose shaft the drive pulley 3 is secured. A tendon 11 passes through channels in the interior of the finger. One end of tendon 11 is tied to the drive pulley 3, and the other end is secured to roller 4, mounted at the tip of the finger's distal phalanx. If necessary, tendon 11 can be tensioned by rotating roller 4 via rotational movement Rf. After the tendon is fixed, roller 4 is tightened with bolt 17. Upon a command to flex (or extend) the finger, the DC motor 7 performs a rotational movement Rm, which leads to the winding (or unwinding) of tendon 11 around pulley 3. This movement, combined with the fact that tendon 11 is tied to the fingertip, causes the finger to flex. The reverse action (extension) of the finger is aided by a spring 12 (working under compression), tendon 10, and two rubber bands 13. Tendon 10, which assists in finger extension, is fixed at one end to the movable spring cap 6, and at the other end is secured by the pressure cap 5. The elastic potential energy from the elements—spring 12, rubber bands 13, and tendon 10—causes the finger to extend the moment motor 7 releases tension on tendon 11.

The dimensions of the palm and hand are identical to those of an average human. Similar to the human hand, the thumb is opposable to the other fingers for easy gripping of objects and handling various tools. The hand was designed using the AutoCAD Mechanical program and consists of 5 modular fingers, a base, and a front cover, with each of these elements printed on an FDM 3D printer. 3D printing technology allows for the construction of parts with cavities, which can serve as a good foundation for the development and testing of prototypes. For the purpose of miniaturization and minimization, the interior of the hand is hollow to accommodate the controlling hardware, connecting cables, and modular fingers within the palm. One motor is used to actuate the three phalanges of a given finger. This results in a compact and lightweight design (hand weight - 324 grams) while simultaneously maintaining strength, functionality, and increasing the prototype's efficiency. For easier assembly of the fingers, sliders and screws were added to the hand's design, to which each finger is attached. Furthermore, each finger is numbered and printed with a digit from 1 to 5, which further aids in the hand's assembly. The palm of the hand is designed to be concave to facilitate the fingers' easy gripping of spherical objects. Two openings were added to the outer shell of the hand during design: one for external power supply and one for connecting a USB I2C interface module for transmitting commands to the hand.

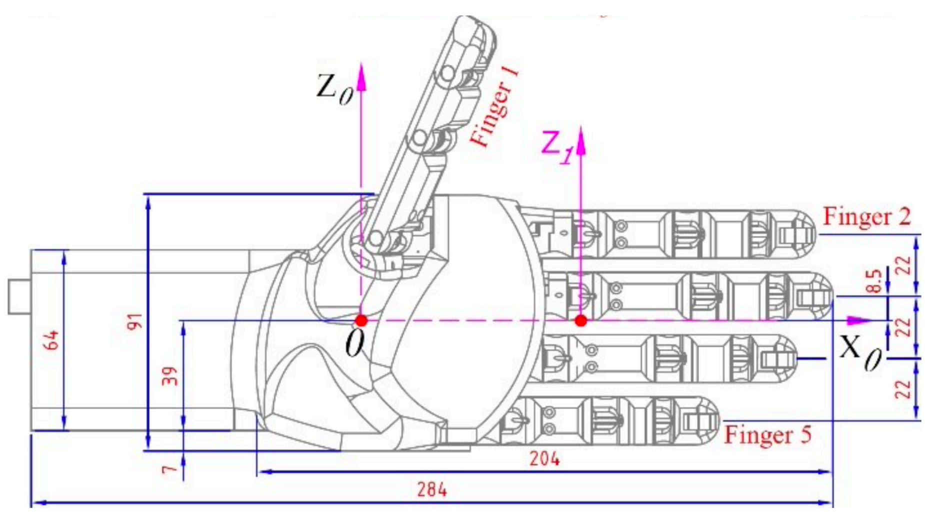


Figure 29. Schematic of the humanoid robotic hand

3. Hardware

The hardware of the developed humanoid robotic hand is presented, which plays a primary role in determining its functionality, its ability to apply force, and its capacity for gripping objects. The execution of tasks with high accuracy and repeatability by the robotic hand depends directly on the proper selection of its hardware components. The developed robotic hand utilizes a set of hardware components such as DC motors, position sensors (potentiometers), and the I2C communication protocol for data exchange. The modular finger design also includes its hardware system. Each finger of the hand has its own integrated control circuit and can be controlled independently of the others. The hardware components of a given finger and their connectivity are shown in Figure 30.

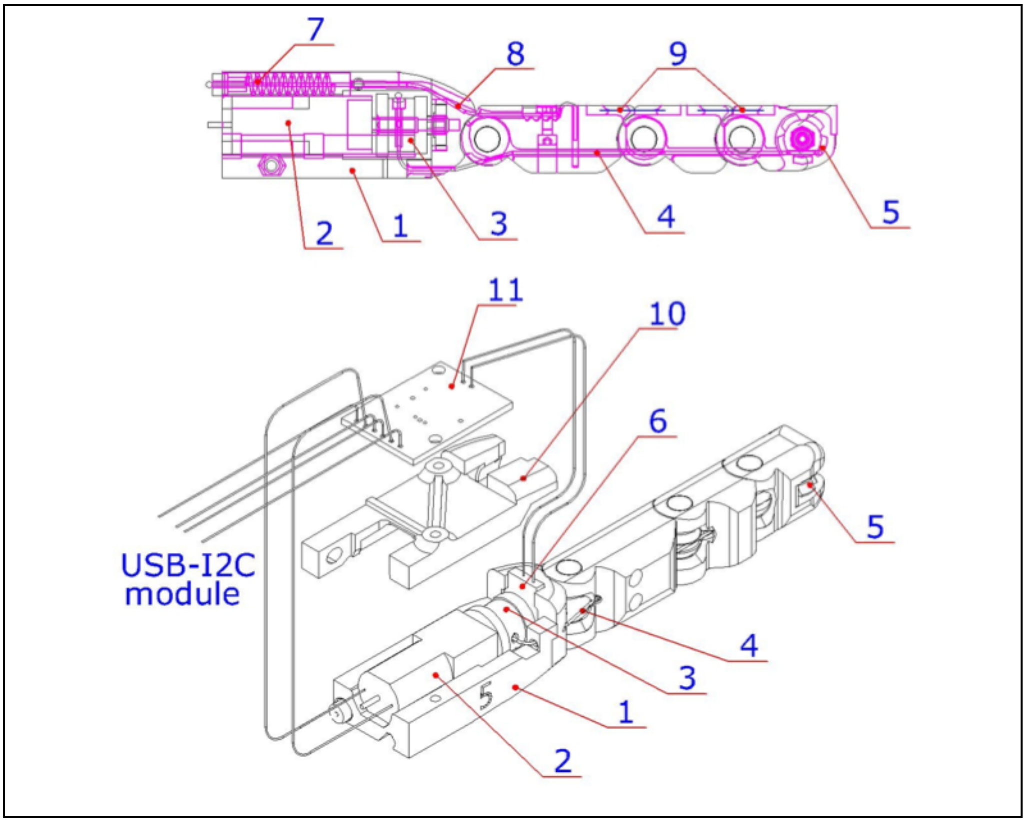


Figure 30. Hardware and mechanical components of the finger

1 – finger body; 2 – DC motor; 3 – pulley; 4 – tendon for finger flexion; 5 – roller; 6 – potentiometer; 7 – spring; 8 – tendon for finger extension; 9 – rubber bands; 10 – cover/cap; 11 – integrated circuit (IC).

The finger control module 11 is directly connected to a USB I2C communication module, which is used to send control commands to the fingers. The finger control module 11 is also connected to the two outputs (positive and negative) of the brushed DC motor 2. Since there are only two outputs, the direction of rotation of the brushed DC motor is controlled by reversing the polarity of the applied voltage. If we supply voltage from the power supply's "+" to the motor's "+" and from the "-" to the motor's "-", it moves in one direction. If we reverse the polarity, it will move in the other direction. The polarity reversal is achieved using an H-bridge, which is composed of four switches that allow voltage to be supplied to the motor in both directions. The control module 11 is also connected to the position sensor 6 (a resistive potentiometer), which serves as position feedback for the finger. The resistance of the potentiometer is directly dependent on and changes with the movement of motor 2, as the sensor is fixed onto pulley 3, which is mounted on the motor's shaft.

Each integrated circuit for finger control is designed to be identical to the others, turning every finger into a separate and fully independent control unit. This modular approach significantly simplifies design, maintenance, and eventual component replacement. The control module itself is extremely compact, fitting onto a single integrated circuit board with dimensions of only 30×20 millimeters (Fig. 31), which is securely fastened with bolts to a specially designed 3D printed cover. The power supply for this miniature control board is external, providing a voltage of 5V, which is standard for digital electronics.

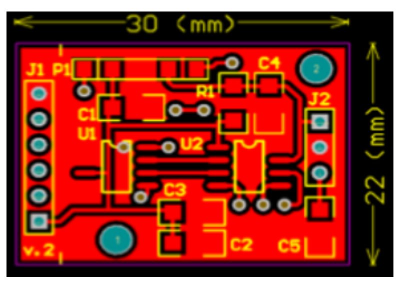


Figure 31. Finger control module

To function correctly, the robotic humanoid hand is built with each finger as an autonomous and modular component. This allows for easy assembly and maintenance. The key to this functionality lies in the effective integration of the hardware elements, visualized through the block diagram in Figure 32. The block diagram shows the logical connections between the main hardware components that make up the modular finger: the potentiometer, the DC motor, the motor driver, the microcontroller, and the I2C communication module. A movement command for a finger is sent from the computer via the communication module. The message is transmitted using the I2C protocol to the corresponding finger's microcontroller. The microcontroller processes the received request and sends a signal to the motor driver to perform the movement. The encoder (referring to the position sensor/potentiometer as a device that provides position feedback) forms the feedback loop for the precise positioning of the finger.

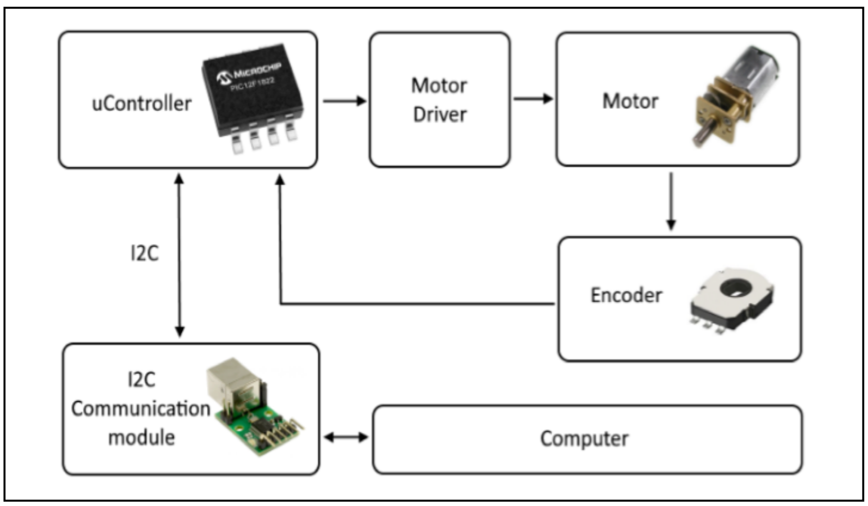


Figure 32. Block diagram of the hardware components

Each modular finger is controlled by an 8-bit PIC12F1822 microcontroller from the manufacturer Microchip, housed in a compact SOIC-8 package. Although this controller has only six input/output (I/O) ports, it is entirely sufficient for the purposes of testing and validating the movement of both the individual fingers and the entire robotic hand. Each finger of the hand is driven by a separate DC electric motor. To provide feedback and precise measurement of the current finger position, a resistive potentiometer EVW-AE4001B14 is attached to the shaft of each motor. The potentiometer's value is converted into a digital signal by a 10-bit Analog-to-Digital Converter (ICSP). Control commands for the finger are transmitted from a computer to the microcontroller via a USB communication module utilizing the I2C protocol. The complete electronic connection diagram for a finger of the robotic hand is shown in Figure 33.

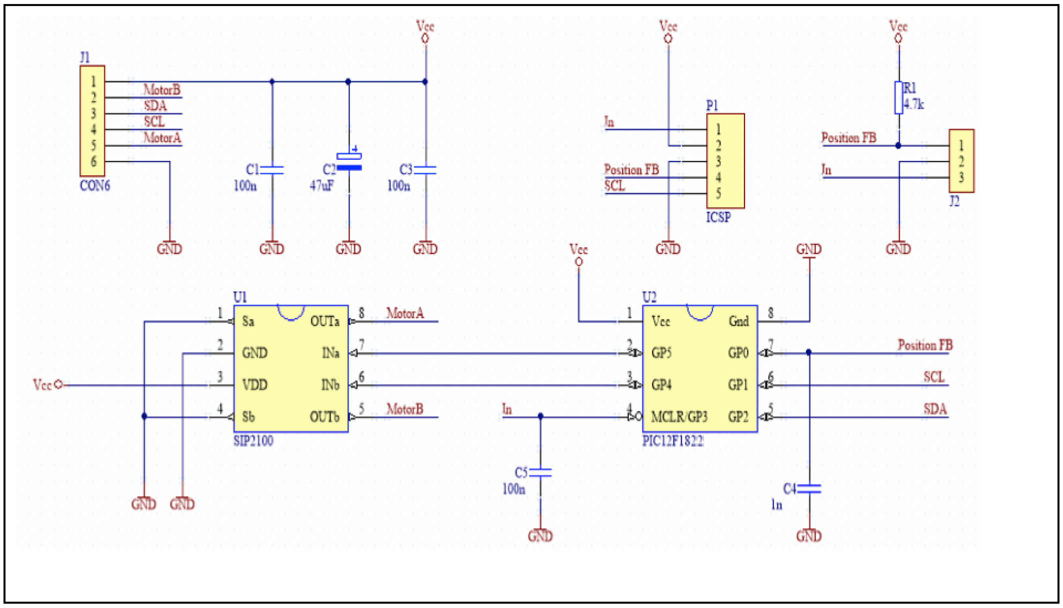


Figure 33. Complete electronic wiring diagram of a single finger

The PIC12F1822 microcontroller is hardware-connected to the SIP2100 motor driver (pins GP5 and GP4) and the resistive potentiometer (pin GP0 - Position FB). Using pins GP1 and GP2, the microcontroller is connected to the I2C communication line via two signals: SDA (Serial Data) and SCL (Serial Clock). More information about these two signals is provided in Chapter 3.5.1. Figure 33 also shows the integrated circuits for the connection of the USB communication module and the resistive potentiometer.

4. Hand Control Software

The first developed program for controlling the humanoid robotic hand, allowing for the verification and testing of its functionality, is shown in Figure 38. The LabView software environment was used as the platform, which is characterized by a graphical programming language that forms logical diagrams resembling block schemes. The program runs on the Windows operating system. The interface first initializes the connection with the main USB-ISS device using a serial communication port. The software can control only one finger at a time by setting the identifier (slave address) of the corresponding finger. The finger addresses are as follows: Thumb 0x34; Index finger 0x36; Middle finger 0x38; Ring finger 0x3A; Little finger 0x3C. Every new finger undergoes a one-time initialization process in the program interface. New modules are programmed with a base identifier of 0x32, and during initialization, the new address is reprogrammed based on the finger's position. Since the finger's starting position (potentiometer orientation) varies, new modules undergo a procedure for setting limit positions—the start position when the finger is fully extended, and the end position when it is maximally flexed. During this process, the operator manually moves the finger to the desired limit positions and marks them as such. The controller identifies the position based on the potentiometer's resistance. All parameters from the initialization process are stored in the EEPROM memory. The program has several sub-menus with a specific function:

- Manual – Here, the operator can control and move the finger in small steps in a specific direction to a given position by pressing a button. Under normal conditions, movement to a position is possible only if it is between the defined limits (start and end position); movements outside of these limits are stopped. In certain cases (such as the initial initialization of the finger), movements beyond the limit points are necessary. In this situation, there is an unlock button that makes this possible. This menu also contains buttons for setting the finger's start and end positions.

- Auto bending (Automatic movement) – A menu with buttons for reaching limit positions. The finger automatically moves to the start or end position and stops on its own when it reaches them.

- Set position – A specific position is set, which is between the limits (start and end position), and the finger moves to this position and stops upon reaching it.

- Change i2C id - allows the I2C slave address of a specific finger to be changed.

- Position - The software has an option to read the current position of the finger (Get current), as well as the limit positions (Get home and Get end).

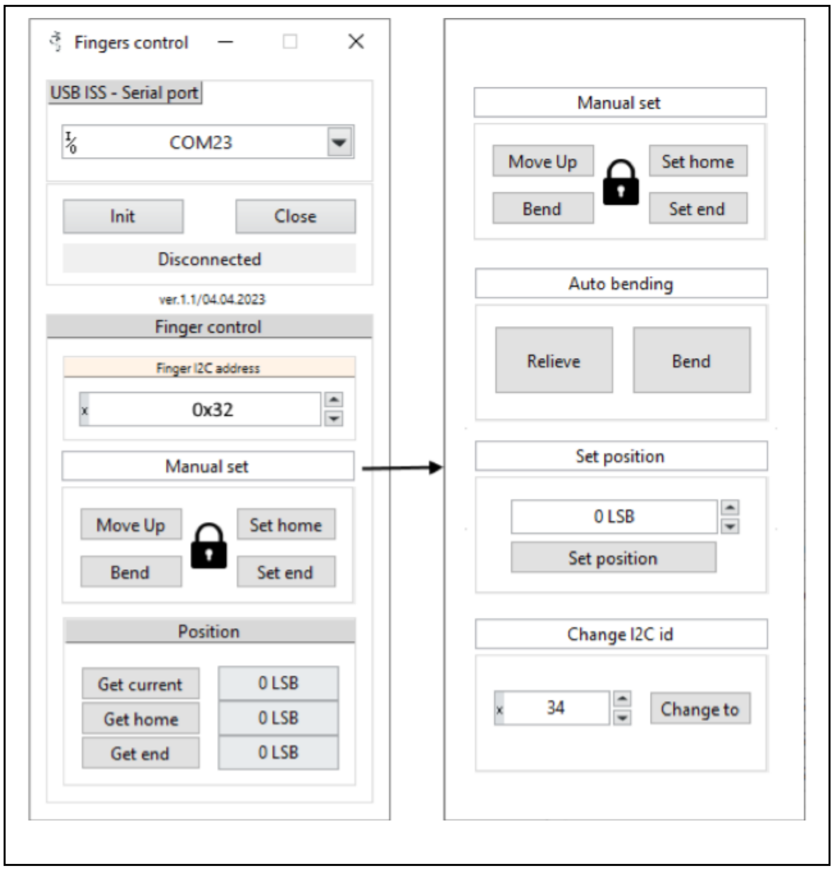


Figure 38. Software interface for finger control

The second application developed for controlling the hand (Fig. 39) was created using the Python programming language. The program can be run on Windows and macOS operating systems. The Graphical User Interface (GUI) was developed using the standard built-in tkinter library. In contrast to the previous LabVIEW-based software, which allowed for the control of only one finger at a time, the current program offers significantly greater flexibility, allowing control of both an individual finger, a set of fingers, or even all fingers simultaneously. This improved functionality significantly expands the possibilities for experimentation and application of the system.

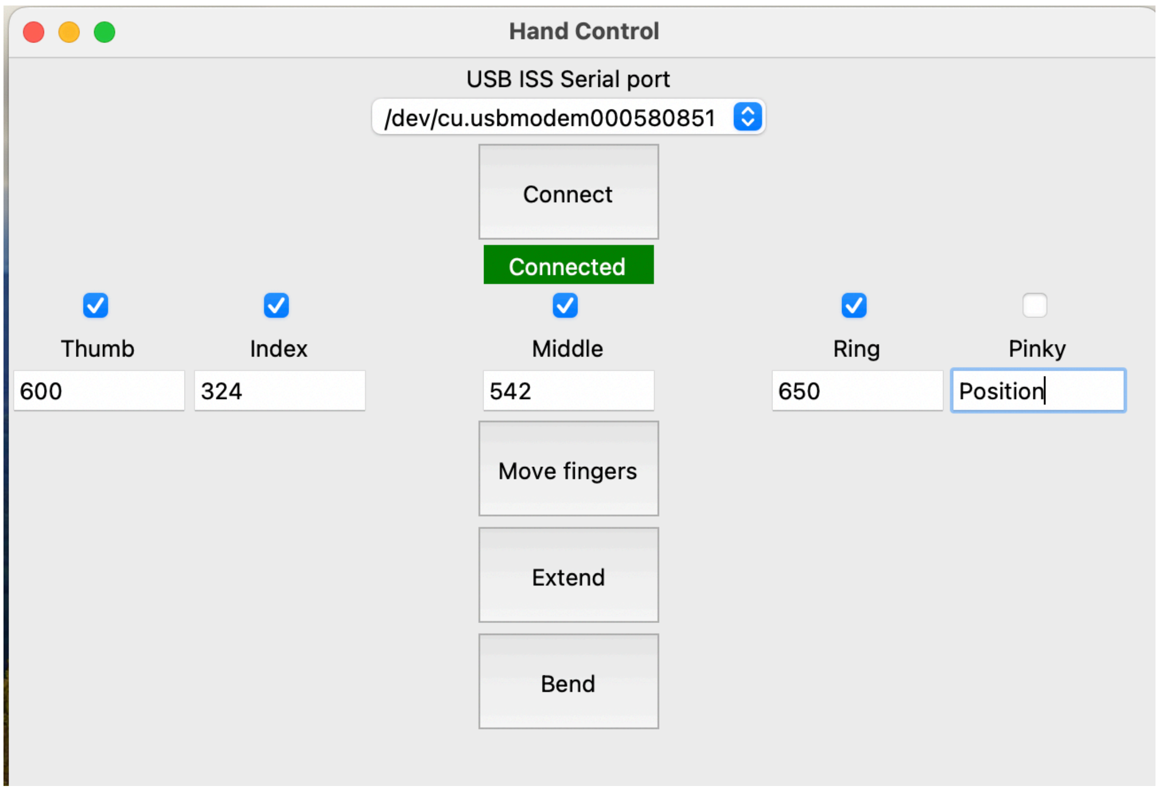


Figure 39. Software interface for hand control

The program features checkboxes for each finger, which allow for easily selecting which fingers should be actuated. Additionally, "Position" fields have been added to the interface where the user can enter a specific value to which the corresponding finger will move. It's important to note that movement is executed only within the pre-defined interval between the finger's start and end positions; movement is not possible outside these limits. This restriction ensures safety and protects the robotic hand from potential damage.

A third software application has been developed, which is an innovative application for sign language (Figure 40), specially designed to form gestures from the American Sign Language (ASL) alphabet. This application provides excellent opportunities for in-depth testing of the dexterity, precision, and mechanical limits of the humanoid robotic hand. The American Sign Language alphabet includes 26 complex gestures, each corresponding to a specific letter of the English alphabet. The program integrates buttons for connecting the device ("Connect"), for full finger flexion ("Bend"), and for full finger extension ("Extend"). A key element of the interface are the buttons corresponding to each letter of the ASL alphabet, allowing for the direct execution of the respective gesture. An important safety and user awareness feature is the integrated warning system. If a specific gesture corresponding to a letter proves impossible to execute due to the mechanical limitations of the hand, a warning window automatically appears. This ensures that the operator is promptly informed about the robot's physical boundaries and protects the system from potential damage.

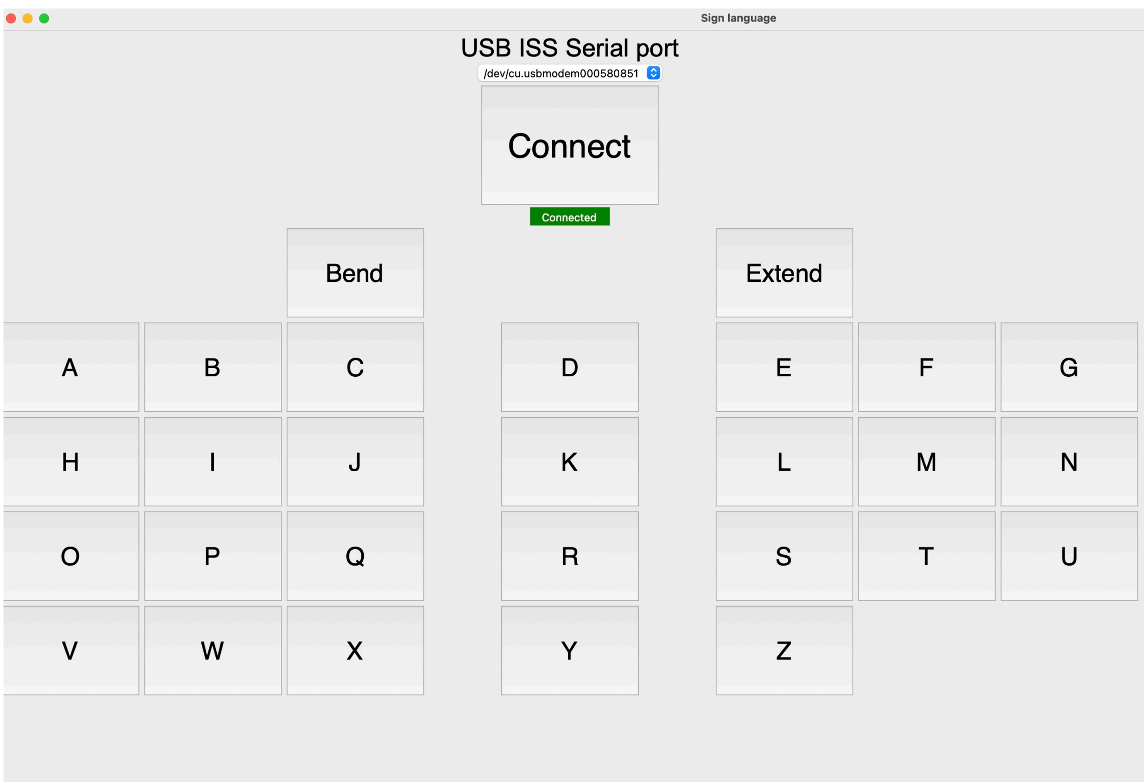


Figure 40. Software Interface for Sign Language Alphabet Signs

A fourth program has been developed for gripping spherical and cylindrical objects (Fig. 41). The main function of the program is to realize grasps of spherical and cylindrical items with diameters ranging from 10 to 60 millimeters by using a different set of fingers. A sphere or cylinder with a given diameter and a defined finger configuration can be grasped using the corresponding button in the program. As an example from the program's menu, a spherical grasp using the thumb and index finger can be executed by using any of the buttons for a spherical object with a diameter of 10, 20, 30, 40, or 50 millimeters.

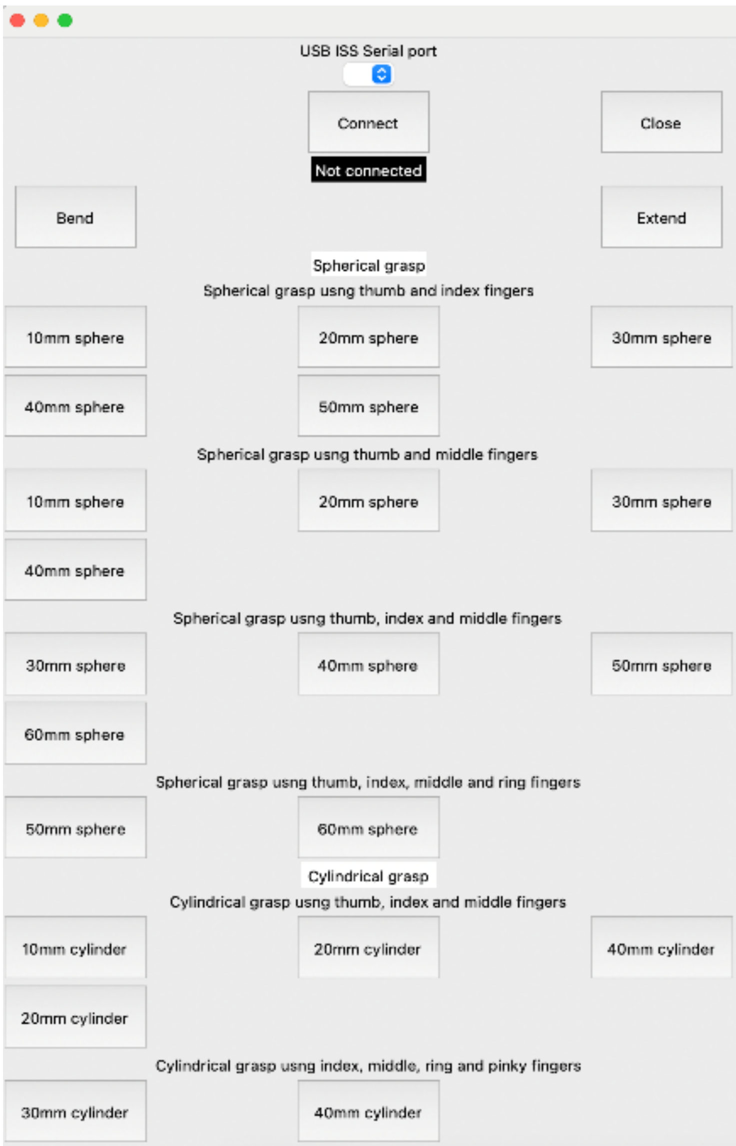


Figure 41. Software Interface for Gripping Spherical and Cylindrical Objects

5. Experimental verification using a 3D printed model

The testing process of the 3D printed humanoid hand is an important stage in the development lifecycle that is critical for ensuring the reliability, safety, efficiency, and longevity of the final product. It is also important to define the workspace—the operational area of the hand's fingers in which various objects can be manipulated. A program was created in Visual Lisp for AutoCAD that allows for the graphical representation of the workspace and the reachable points of the humanoid hand's finger.

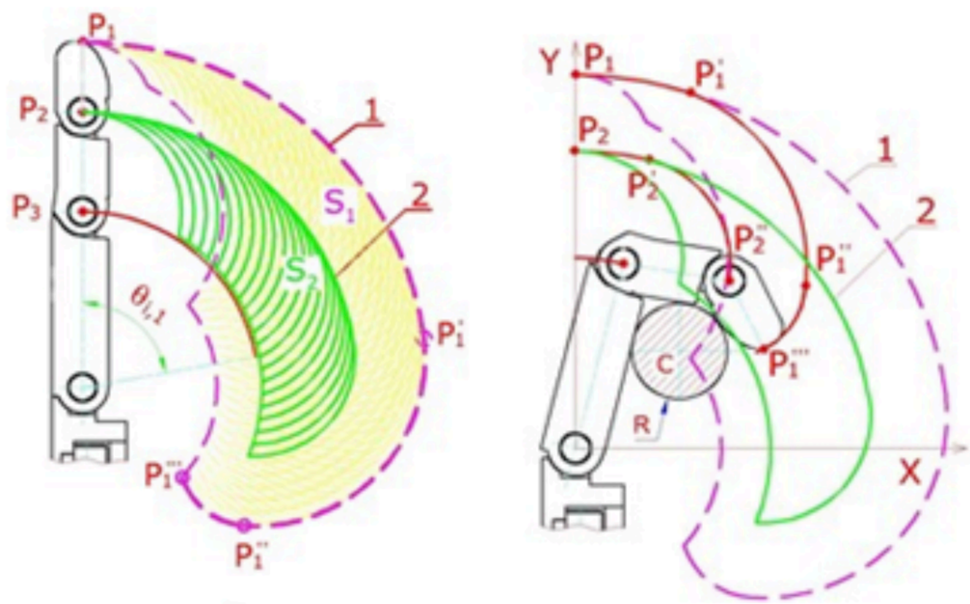


Figure 42. Workspaces of points P1, P2, and P3. Trajectories of points P1, P2, P3 of the index finger when grasping a cylindrical object with a diameter of 20 [mm] and coordinates Cx = 21 [mm], Cy = 20 [mm].

Point P1 is located at the tip of the index finger, while P2 and P3 are points on the links of the distal and middle phalanges. If there is no object in the finger's range, point P1 will move along the arc P1P1′P1″P1‴(Fig. 42 left). The situation is different if there is an object in the workspace (Fig. 42, right). Initially, the motor drives the finger only by changing the angle θ1, until the proximal phalanx reaches the cylindrical object. Since the object exerts a resistive force against this movement, it stops, and the second joint angle θ2 begins to rotate until the medial phalanx reaches the object. Finally, the distal phalanx performs a movement, changing the angle θ3 until it reaches the object.

The trajectories of points P1, P2, and P3 are presented in Fig. 42, right. Depending on the position and dimensions of the gripped object, point P1 will have different trajectories in the workspace. In this sense, the zone S1 can be described as the conditional workspace for the fingertip of the designed finger.

The manipulability coefficient allows for the selection of a joint configuration that can be used to perform the desired task with the highest speed. For this purpose, a joint configuration is sought where the value of the manipulability coefficient is the greatest. Figure 43a) illustrates the change in the manipulability coefficient within the workspace of the index finger. The maximum manipulability coefficient is determined for every point in the workspace. It is evident from the figure that this finger has a low manipulability coefficient at the boundary of the workspace and a high one in its interior part. This means it is difficult to control precise movements in the boundary areas, whereas accurate movements can be performed in the central area. Figure 43b) presents S1, S2, ks(n), and the maximum values of the manipulability coefficient km. It is seen from Figure 43b) that the middle finger has the largest areas (S1, S2) as well as the greatest maximum value for the manipulability coefficient Max(km) [61].

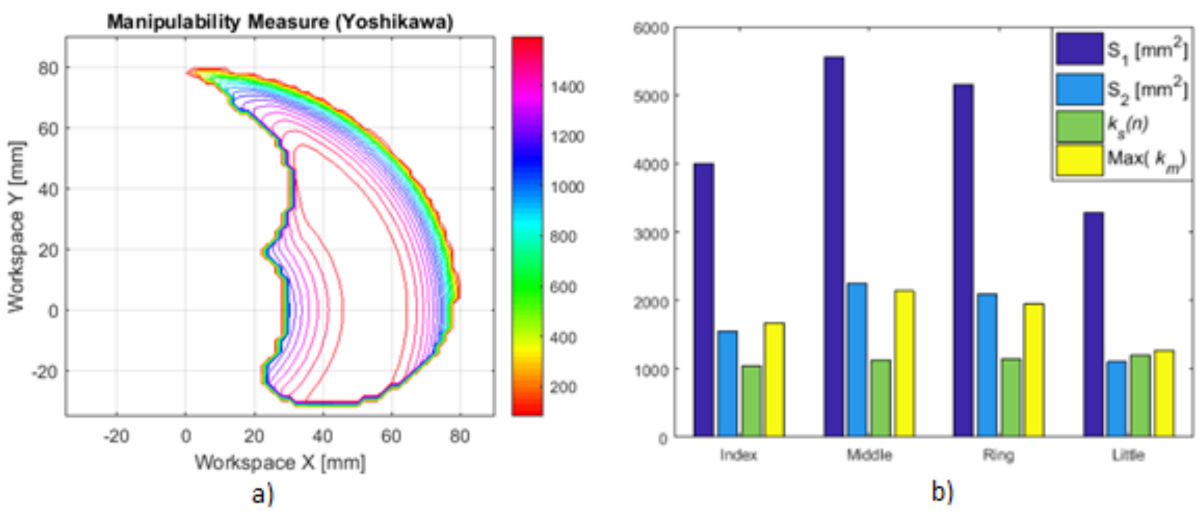


Figure 43. a) Maximum manipulability coefficient for every point in the workspace of the index finger. b) Comparison of the areas, ks(n), and the maximum manipulability coefficient of each finger.

Figure 44 (left) presents a diagram of the hand with a fixed coordinate system (OXYZ), localized at the center of the palm, as well as a second coordinate system for the thumb ($O_TX_TY_TZ_T$). By using the forward kinematics problem and changing the joint angles within their limits, the reachability points of the fingertips are obtained (Fig. 44, right). The four fingers (1 to 4) perform planar movements, defining their individual workspaces (W_1 до W_4). In contrast, the thumb is opposable and has its unique workspace (W_T), which allows it to interact with the other fingers and perform more complex activities such as gripping and holding objects. It is obvious that for an object to be grasped, its surface must fall within the workspace of one finger or in the intersection of several workspaces. The greater the overlap, the more stable the grasp is. For instance, grasping a large object often requires the combined action of several fingers, while for a precise grasp of a small object, the interaction between the thumb and one of the other fingers is sufficient.

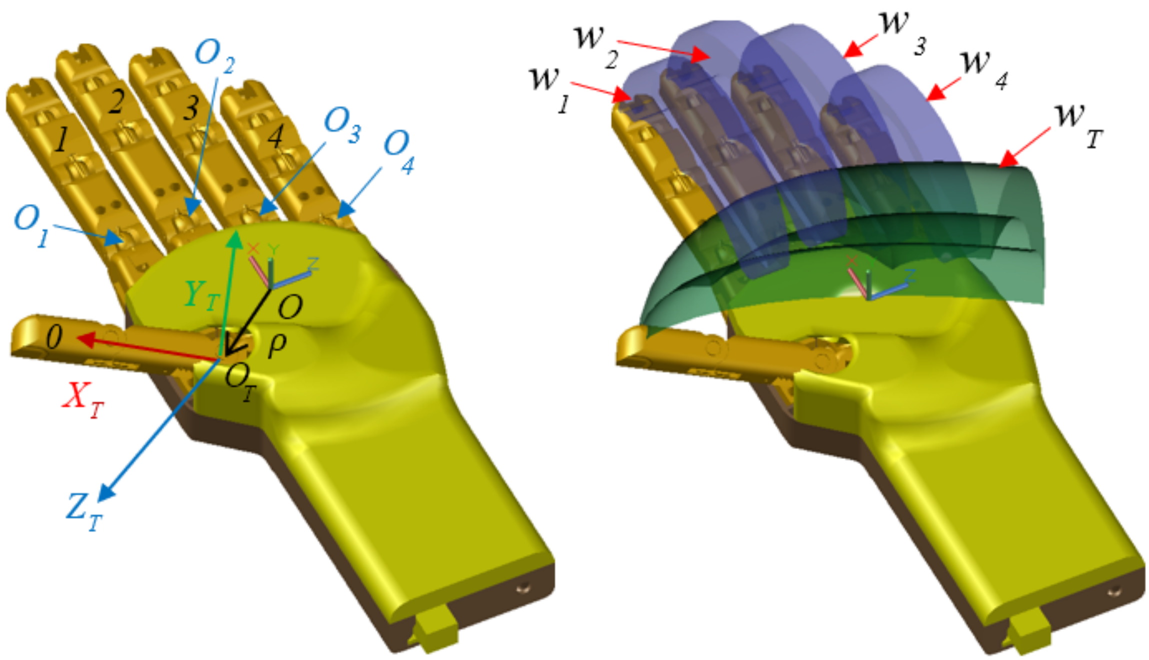


Figure 44. Coordinate systems and 3D model of the fingers' workspaces.

To investigate the real-world capabilities of the robotic hand, it's necessary to conduct functional experiments involving the gripping of various everyday objects such as a coffee cup, a pen, pliers, and others. These experiments reveal weaknesses in the design as well as the effectiveness of the sensors and control algorithms used. For example, gripping a cardboard cup requires a fine judgment of force, while handling a tool like pliers necessitates a firm grasp and stability. Tests were performed for gripping objects such as a cardboard cup, pliers, a computer mouse, a pen (Fig. 45), a remote control, and a magnifying glass. As evident from the photos of the experiments conducted, the robotic hand has the ability to successfully and reliably manipulate medium-sized objects. Gripping very small objects, such as a USB flash drive, remains difficult to achieve with the hand's current mechanical structure.

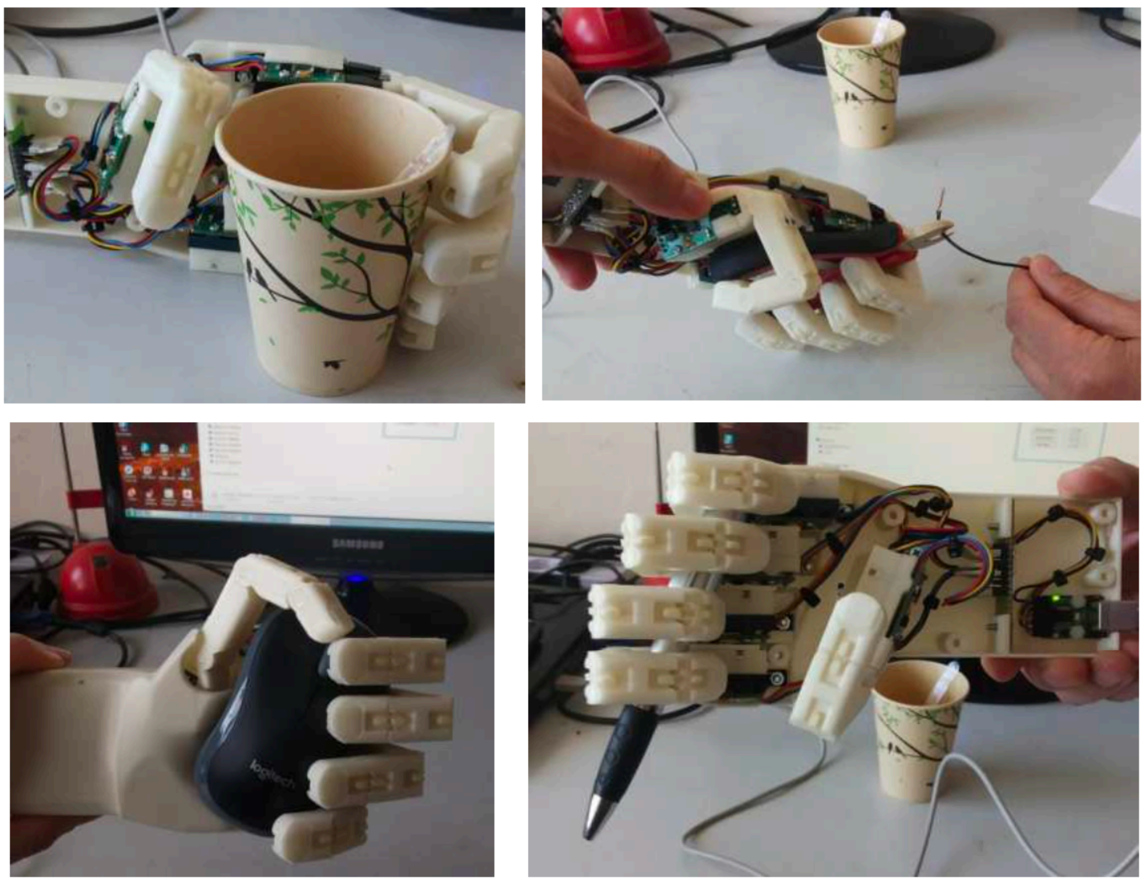


Figure 45. Experiments with object gripping: cardboard cup, pliers, computer mouse, pen.

The gripping of basic geometric shapes such as spheres and cylinders is a fundamental requirement for any manipulator in the field of robotics and, in particular, for humanoid robotic hands. Holding a sphere with a hand poses a challenge due to the lack of flat surfaces to ensure a stable grip. This necessitates precise control of force and accurate positioning of the fingers to prevent slippage. For the purpose of the study, several spheres with diameters ranging from 10 to 60 millimeters were 3D printed (Fig. 48). The experiments consisted of attempts by the robotic hand's fingers to grip the created spherical objects, with the grasp being executable by various finger configurations. The tests show that the gripping of smaller spherical objects involves only two fingers—the thumb and the index finger. This grip is extremely effective for precise manipulation and provides sufficient stability by creating two contact points. The force is distributed evenly between the two fingers, which prevents slippage. The gripping of larger spherical objects requires the use of a combination of three or more fingers. In this case, the fingers envelop a larger part of the sphere's surface, creating multiple support points. The larger the object, the more fingers are required to distribute the force and ensure a stable grip. The thumb plays a key role as a support, while the other fingers adapt to ensure complete envelopment of the object.

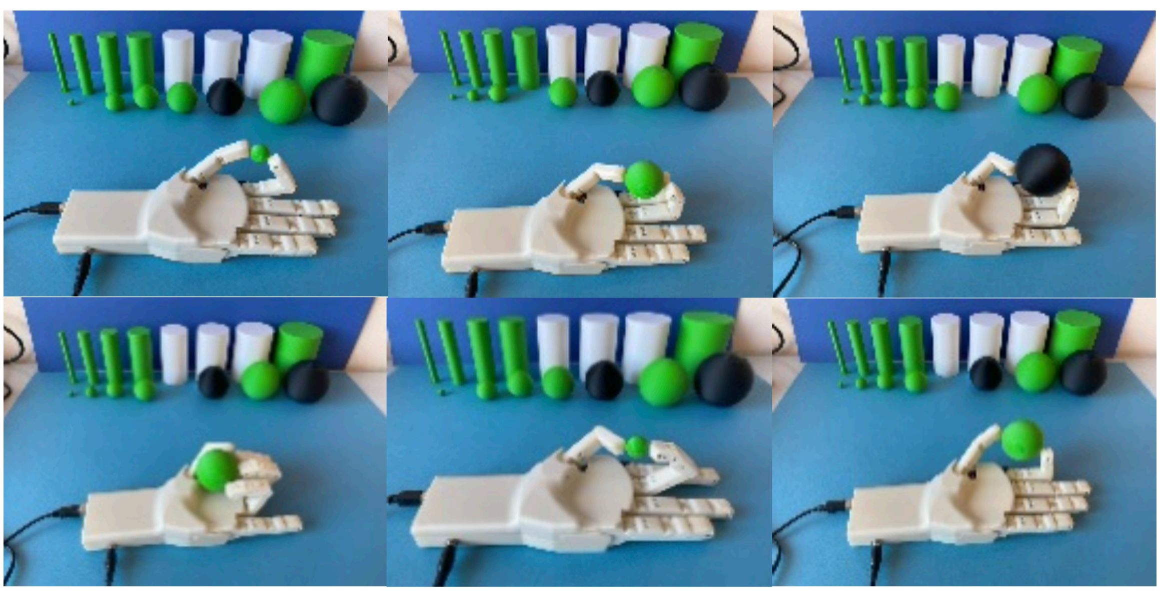


Figure 48. Experiments with 3D printed spheres.

Manipulating cylindrical objects such as a bottle, a cup, or a door handle poses completely different challenges for a robotic hand compared to spherical objects. Although a cylinder has two flat surfaces (the bottom and the top), gripping is most often performed along the curved side surface. Accurate gripping depends on the correct distribution of force across the surface. If the force is too small, the object can slip; if it's too great, the object might be damaged, or the hand may expend unnecessary energy. To evaluate the effectiveness of the grasp, functional tests were performed with cylinders of various diameters and weights. Small-diameter cylinders require a more precise grasp, often between the thumb and one or two other fingers, while larger cylinders necessitate the use of all fingers for envelopment. Weight is also a key factor—heavier objects require a greater grip force, which must be distributed evenly to avoid straining individual fingers or joints.

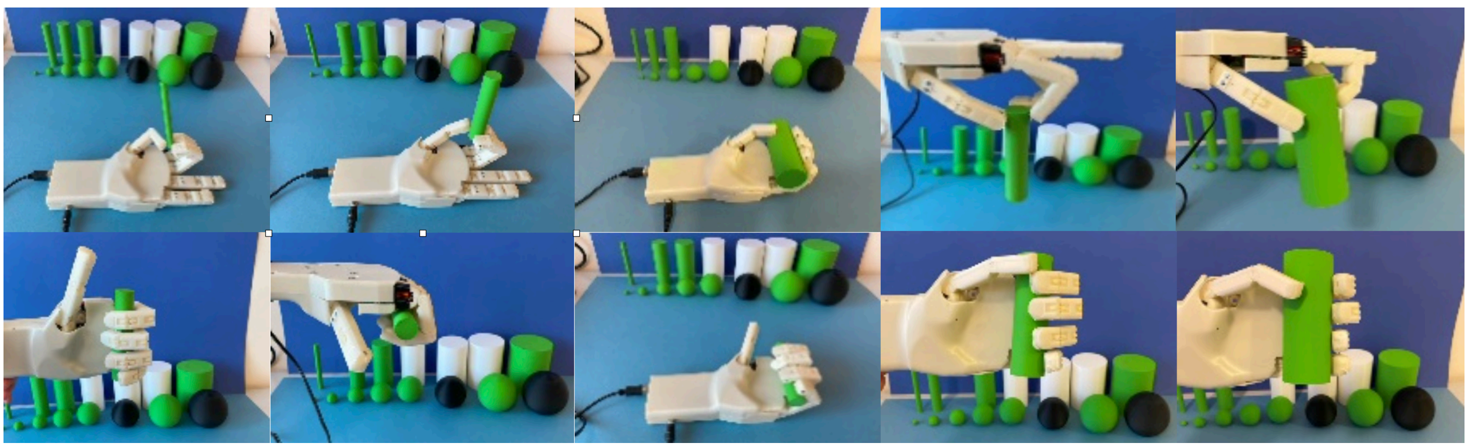


Figure 49. Experiments with 3D printed cylinders.

During the conducted functional tests of the robotic hand, the results show remarkable adaptability to various object shapes and sizes. The hand demonstrated the ability to successfully grip spheres with diameters from 10 to 60 millimeters and cylinders with diameters from 10 to 40 millimeters. This proves the flexibility of its design and the effectiveness of its control, allowing for the manipulation of a wide spectrum of objects. However, the robotic hand struggles to grip spheres with a diameter of 70 millimeters and cylinders with a diameter of 50 millimeters.

For a more in-depth study of the possible grasps and capabilities of the robotic hand, additional test objects were selected—a cylinder and a rectangular prism. The design of the shapes was drawn using the AutoCAD program, and then they were 3D printed on a Fused Deposition Modeling (FDM) printer. The geometric shapes have an identical height of 125 millimeters, with the top and bottom sides being expanded by 10 millimeters to prevent the test objects from slipping and being dropped by the hand. The base of the prism has a side length of 35 millimeters, while the expanded part has a length of 45 millimeters. The interior of the objects is hollow. The experiments conducted in Figure 51 investigate the hand's ability for a stable grasp with all fingers and a precise grasp with two fingers (thumb and index finger). It is checked whether the hand can hold the test object reliably and without slipping. The conducted experiments show that the hand has a more stable grasp when working with the cylindrical object, as the fingers easily adapt around the round cylinder. Gripping the rectangular prism is possible but is achieved with more difficulty compared to the cylindrical object. It is evident from the experiments performed that the opposable thumb prevents the geometric object from slipping.

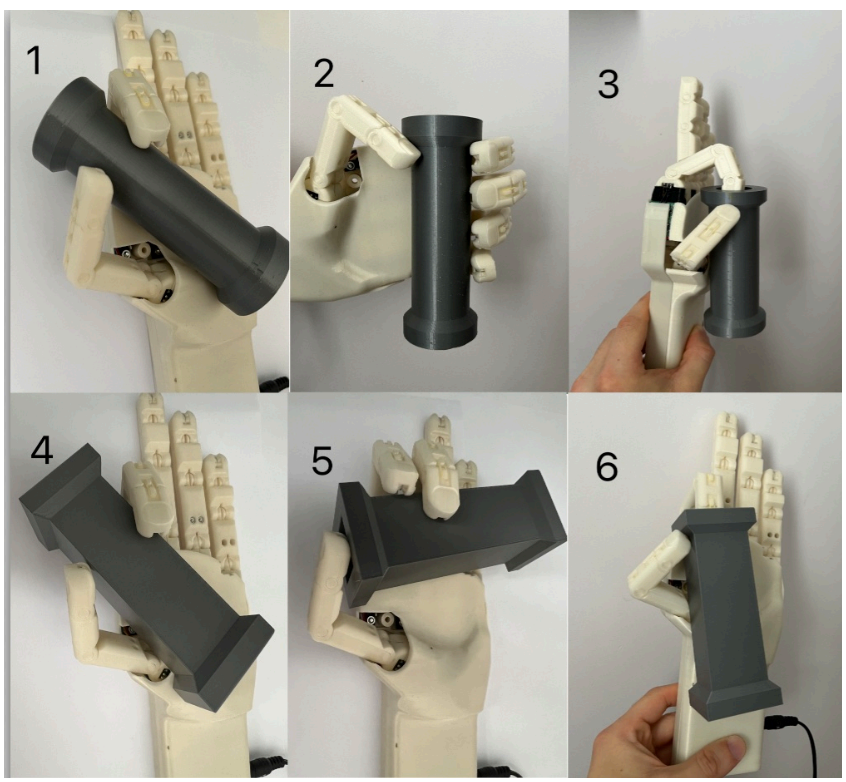


Figure 51. Experiments with a cylinder and a rectangular prism.

Sign language provides good opportunities for testing the dexterity and mechanical limitations of the developed humanoid robotic hand. Hand signs require exceptional precision, flexibility, and fine motor skills, which are key to any complex manipulation. The American Sign Language (ASL) alphabet includes 26 complex gestures, each corresponding to a specific letter of the English alphabet. Every gesture in the language is a combination of a specific configuration and arrangement of the fingers and the orientation of the hand. The experiments conducted with the robotic hand show that 20 out of the 26 hand gestures are possible [65]. The remaining 6 hand gestures cannot be reproduced for the following reasons:

- Lack of an additional degree of freedom for the thumb (letters "M", "N", and "T")

- inability to perform adduction/abduction movement of the finger (letters "R" and "V")

- The finger cannot change only the angle of rotation between the metacarpal bone and the proximal phalanx without this also affecting the remaining angles (letter "P").

The addition of more motors, providing additional degrees of freedom (DoF), could help with the enumerated problematic gestures. There is space in the palm of the hand for an additional motor for the thumb, thereby increasing its degree of freedom. This modification would make the gestures for the letters "M," "N," and "R" feasible, and in doing so, would significantly reduce the number of impossible gestures.

The term adduction refers to the movement of body parts toward the median plane, i.e., the fingers moving closer to the middle finger of the hand. The opposite movement of the fingers moving away from the middle finger is called abduction. The current mechanical design of the hand lacks the functionality to perform adduction and abduction movements. The inability to perform adduction/abduction movement of the finger can be overcome by adding a new motor. This would control the adduction/abduction of all fingers (excluding the thumb) simultaneously and would make the gestures for the letters "R" and "V" possible.

The last remaining unsuccessful hand gesture, for the letter "P," could become possible if there were actuating mechanisms controlling each of the finger's phalanges independently. This would require three motors per finger. However, adding additional motors for all fingers would make it impossible to fit all actuating mechanisms into the palm of the hand. Developing a wrist with two or three degrees of freedom might be useful for distinguishing between the letters "I" and "J," because these gestures are identical, but the second letter requires the hand to be tilted. The letter "B" is the gesture involving the fewest fingers—only the thumb is bent. On the other hand, the most complex gestures, where all fingers are involved, are the letters "X," "S," "O," and "E."

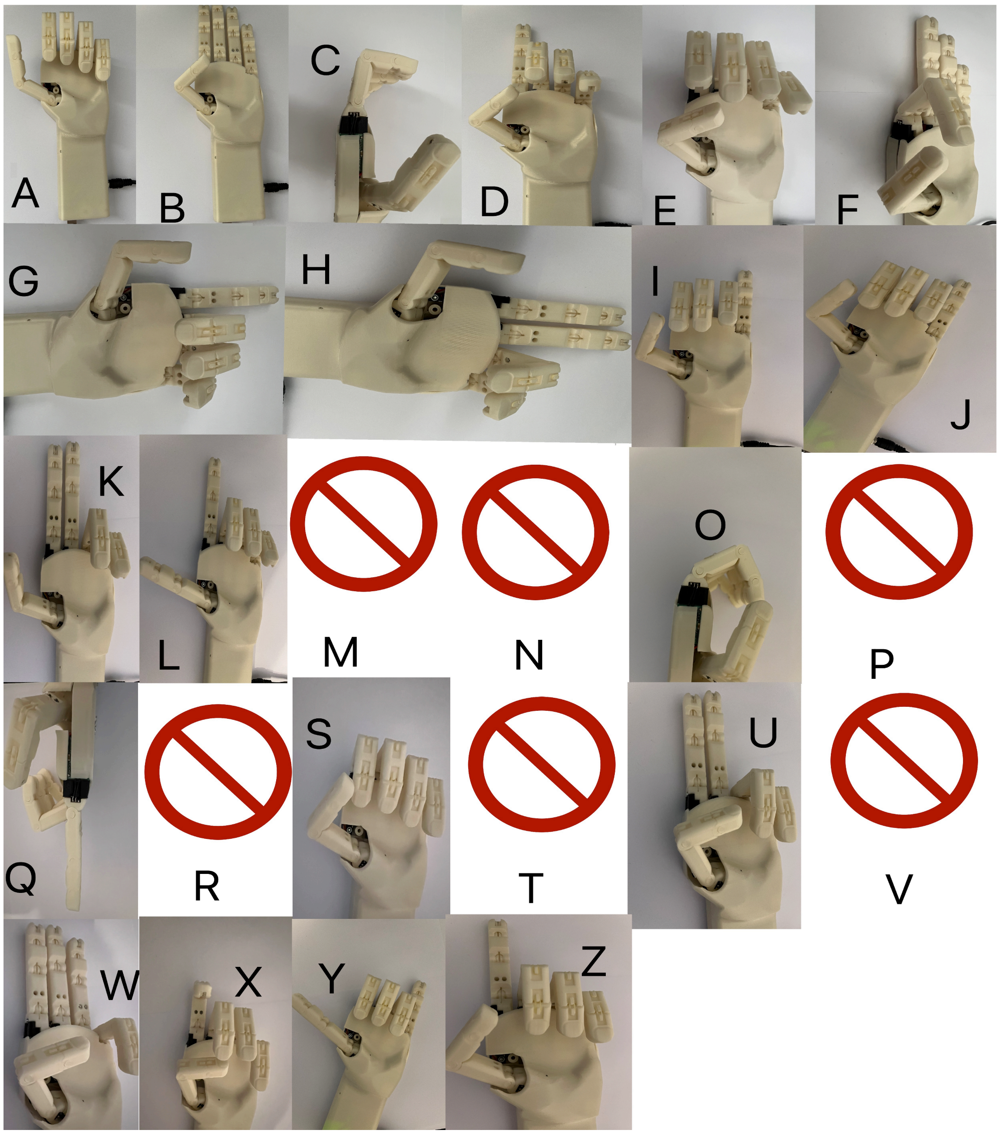


Figure 53. Experiments with sign language gestures.

Conclusion

Humanoid robotic hands have made significant progress in recent years, inspired by the complexity and dexterity of human hands. Although researchers still face a number of challenges, robotic hands are increasingly capable of executing tasks once thought to be exclusively within the realm of human capabilities. One of the main challenges in designing anthropomorphic robotic hands is achieving a balance between strength, precision, and adaptability. Human hands excel at a wide spectrum of tasks, including precise manipulations and strong grasps. Reproducing this multi-functionality in a robotic hand requires careful analysis and consideration of factors such as the selection of actuators, appropriate sensor technology, control algorithms, and joint design. Recent research has focused on developing more complex grippers, utilizing more accurate actuators, and taking advantage of innovations in the fields of sensorics and control systems. Moreover, the integration of artificial intelligence (AI) and machine learning (ML) allows humanoid robotic hands to learn from experience and improve their performance over time. Despite this progress, current robotic hands still face limitations. A significant challenge is finding the balance between good functionality and the low cost of the robotic hand. A good imitation of human hand movements requires using a sufficient number of motors, but in some cases (like prosthetics), the devices consist only of the palm, requiring the actuators to be contained within it. Optimal cost for robotic hands can be achieved through 3D printing technology, which allows for experimentation and improvement of the hand's design through functional tests. The design phase of any prototype is the most crucial because errors at this stage lead to delays in the entire project and a return to the initial position. Nevertheless, the design and development of a robotic hand is an iterative process, requiring continuous improvement and optimization based on tests and experiments. Studying the anatomy and biomechanics of the human hand provides crucial insights for designing effective and functional robotic prototypes.

Future Development Perspectives

The development of the 3D printed humanoid hand has great potential, and the following improvements can be made in the future:

- The addition of an extra motor specifically for the thumb of the robotic hand would lead to significant improvements in its functionality, gripping capability, and gesture performance. The thumb in the human hand is responsible for about 40% of gripping dexterity [59]. With an additional, separate motor, the thumb could move more independently and precisely, which is key to executing complex tasks.

- Future models could be integrated with additional sensors such as tactile, temperature, and pressure sensors, as well as more complex control algorithms. This will give the hands the ability to "sense" the environment and make autonomous decisions, thereby improving their dexterity and applicability.

- 3D printing technology enables the manufacture of personalized prosthetics at a much lower cost than traditional methods. In the future, robotic hands could be produced that are designed according to the individual needs and anatomy of each user. Additionally, new 3D printing materials that are stronger, more flexible, and lighter could be explored. A new layer imitating natural human skin could be added to the surface of the hand, similar to [60], which would be important in the case of a prosthetic.

Contributions of the Dissertation

Considering the work on the dissertation and the results obtained from the conducted research and presented in the dissertation thesis, the following contributions can be formulated:

Scientific and Applied Contributions

1. A novel approach for creating assembled 3D printed fingers for a humanoid hand was developed. An innovative design was proposed that allows the fingers to be printed as a single object with movable joints using FDM (Fused Deposition Modeling) printing technology. This was achieved through a combination of factors such as: the position and orientation of the finger on the 3D printer's build platform; the shape of the joints; the clearance between the finger links; and the printing processes. The approach enables the creation of fully functional fingers that can be printed in an assembled state.

2. The geometric and kinematic characteristics of humanoid hand fingers were investigated. This includes the reachability zones of the fingertip of a humanoid hand with dependent movements, as well as the distribution of the manipulability coefficient within those zones.

Applied Contributions

3. A prototype of a humanoid hand with modular fingers was created. The modular fingers are printed fully assembled on an FDM 3D printer, and the modularity is evident not only in the mechanical components but also in the hardware elements and the developed software. This applied contribution simplifies the assembly of the finger and the overall assembly of the hand. Modular fingers allow for easy replacement in case of damage, uniformity in control and setup, and other advantages.

4. Hardware and software for the control and setup of the 3D printed modular humanoid hand were developed.

5. Software for reproducing signs from the sign language alphabet was created and applied to the 3D printed humanoid hand.

6. Experiments were performed that confirm the functionality of the 3D printed hand. The experiments include object gripping and sign language reproduction.

Publications Related to the Dissertation

P*1.* Ivan Chavdarov, **Ivaylo Georgiev,** Lyubomira Miteva, Roumen Trifonov, and Galya Pavlova. 2021. Analysis of the kinematic characteristics of a 3D printed finger of robotic humanoid hand. In Proceedings of the 22nd International Conference on Computer Systems and Technologies (CompSysTech '21). Association for Computing Machinery, New York, NY, USA, 145–150. https://doi.org/10.1145/3472410.3472434

P*2.* V. Nikolov, **I. Georgiev** and I. Chavdarov, "Hardware and software of a 3D printed humanoid hand," *2023 XXXII International Scientific Conference Electronics (ET)*, Sozopol, Bulgaria, 2023, pp. 1-6, doi: 10.1109/ET59121.2023.10278809.

P*3.* Chavdarov, **I. Georgiev,** B. Naydenov and V. Nikolov, "Design of a 3D Printed Humanoid Robotic Hand," *2023 International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, Split, Croatia, 2023, pp. 1-6, doi: 10.23919/SoftCOM58365.2023.10271644.

P*4.* I. Chavdarov, B. Naydenov, V. Nikolov and **I. Georgiev,** "Modular Design, Communication and Control Systems of a 3D-printed Humanoid Robotic Hand," in Journal of Communications Software and Systems, vol. 20, no. 2, pp. 146-156, March 2024, doi: https://doi.org/10.24138/jcomss-2023-0168

P*5*. **I. Georgiev**, V. Nikolov, I. Chavdarov and B. Naydenov, "Grasp planning and sign language gestures with 3D printed humanoid hand," 2024 XXXIII International Scientific Conference Electronics (ET), Sozopol, Bulgaria, 2024, pp. 1-5, doi: 10.1109/ET63133.2024.10721540.

Summary

This summary outlines a project focused on the design and management of a humanoid, 3D-printed robotic hand. The project combines principles from mechanical engineering, robotics, and additive manufacturing to create a functional and cost-effective prototype. The design process begins with conceptualizing the hand's structure, aiming to replicate the dexterity and range of motion of a human hand. This involves using CAD (Computer-Aided Design) software to model the hand's components, including the palm, fingers, and joints. The material choice is crucial, with PLA (polylactic acid) being common option for 3D printing due to its strength and printability. Once the digital design is finalized, the components are fabricated using 3D printing technology. This method is selected for its ability to produce complex geometries quickly and affordably, allowing for rapid prototyping and iteration. An innovative idea described in the dissertation is that the fingers are 3D printed assembled through a combination of factors such as: placement and orientation of the finger on the 3D printer's build platform; the shape of the joints; the space between the finger joints; the printing processes. The main hardware components that make up the modular finger are a potentiometer, a DC motor, a motor driver, a microcontroller, and an I2C communication module. A command to move the finger is sent from the computer through the communication module. The message is transmitted via I2C protocol to the microcontroller for the corresponding finger. The microcontroller processes the received request and sends a signal to the motor driver to perform the movement. The potentiometer serves as a feedback loop for the exact positioning of the finger. Several programs are created to control the fingers of the hand. One of the developed programs reproduces gestures from the American sign language. A number of experiments are performed to confirm the functionality of the hand. These experiments include grasping specially designed 3D printed objects such as prisms, spheres, and cylinders; grasping objects such as cardboard coffee cup, working tools; reproduction of sign language gestures.