1. Mikołaj DROZDOWICZ[1], 2. Zbigniew WATRAL[1],3. Andrzej MICHALSKI[2]

Military University of Technology (1), Warsaw University of Technology (2)
ORCID: 2. 0000-0001-6185-5414; 3.0000-0001-5634-9584

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Simple demonstrator of the artificial hand movement system

Abstract: *The designed and manufactured demonstrator shows the technical possibilities of reproducing the biomechanics of the hand using not very complicated technical tools and with low financial outlays. In the first stage of the project, an anatomical analysis of the human hand without injuries or genetic changes was performed to appropriately select conventional substitutes for the anatomical structures present in it. The data obtained in this way served as the basis for the development and construction of the demonstrator actuator system. It includes a real model of the artificial hand with an electronic system that allows wireless Bluetooth communication and control of servomechanisms. Then, a high-level control system was designed to allow control over the artificial hand. This system was designed to be intuitive to use and at the same time allow for all possible combinations of finger movements. The production technique in 3D-FDM printing technology (Fused Deposition Modelling) was selected to make the demonstrator's construction, using PLA (polylactic acid) material. Such a choice is a compromise between costs, production time and precision, and advancement of the artificial hand demonstrator. The constructed demonstrator was tested using a comparative method. Representative functional positions of the human hand were forced in the artificial hand demonstrator, and the quality of the obtained reproduction was assessed by the organoleptic method.*

Streszczenie. *Zaprojektowany i wykonany demonstrator pokazuje techniczne możliwości odtworzenia biomechaniki ręki przy użyciu niezbyt skomplikowanych narzędzi technicznych i przy niewielkich nakładach finansowych. W pierwszym etapie projektu przeprowadzono analizę anatomiczną dłoni ludzkiej bez uszkodzeń i zmian genetycznych w celu odpowiedniego doboru konwencjonalnych zamienników występujących w niej struktur anatomicznych. Uzyskane w ten sposób dane posłużyły jako podstawa do opracowania i budowy układu wykonawczego demonstratora, który zawiera prawdziwy model sztucznej dłoni wraz z układem elektronicznym umożliwiającym bezprzewodową komunikację Bluetooth oraz sterowanie serwomechanizmami. Następnie zaprojektowano układ sterowania umożliwiający kontrolę nad sztuczną ręką. System ten został zaprojektowany tak, aby był intuicyjny w obsłudze a jednocześnie pozwalał na wszelkie możliwe kombinacje ruchów palców. Do wykonania konstrukcji demonstratora wybrano technikę produkcji w technologii druku 3D-FDM (Fused Deposition Modeling) z wykorzystaniem materiału PLA (Polylactic Acid). Taki wybór to kompromis pomiędzy kosztami, czasem produkcji oraz precyzją i zaawansowaniem demonstratora sztucznej dłoni. Zbudowany demonstrator został przetestowany metodą porównawczą. W demonstratorze sztucznej dłoni wymuszono reprezentatywne pozycje funkcjonalne dłoni ludzkiej a jakość uzyskanego odwzorowania oceniano metodą organoleptyczną. (**Prosty demonstrator systemu ruchu sztucznej ręki**)*

Keywords: demonstrator, artificial hand, 3D printing, executive system, control system.
Słowa kluczowe: demonstrator, sztuczna ręka, druk 3D, układ wykonawczy, układ sterowania.

Introduction

In the recent years, advances in the fields of robotics and biomechanics have led to significant progress in the development of bionic limbs that mimic the complex arrangements of their biological counterparts. However, accurate reading of nerve impulses in the case of amputated limbs to reproduce the intended movements remains a challenge. The issue of upper limb rehabilitation and the construction of an artificial hand is still an area of very dynamic development in the last few years. Research is conducted in two basic directions. The first direction of research is focused on the development of devices supporting the process of rehabilitation of the hand or entire forearm. The second direction concerns the construction of intelligent prosthetics of the hand or of the entire arm. The demonstrator developed and presented in the article uses commonly used solutions in its concept, but does not pretend to compete with commercial solutions.

The article is organized in a classic way; after a short introduction and presentation of problems related to the purposefulness of building this type of demonstrator, a very short version of the analysis of the state of knowledge in this area is presented. Of course, the discussed issues have been very intensively developed for several decades and have many publications, the citation and critical analysis of which would require a separate review-type article. The concept of the article adopted by the authors, which is not strictly a scientific article but only a kind of technical report describing the constructed model of the demonstrator, assumed from the beginning a very synthetic reference to the current state of knowledge. The next part of the article concerns the adopted strategy for designing the demonstrator. A general strategy for designing this type of structure is presented, assuming in advance that in the case of the constructed demonstrator not all points of the typical strategy will be implemented. The next point of the article discusses in detail the anatomical analysis of the hand, the results of which were used in the described project. The following part focuses on presenting the general concept of our project in the context of mechanical and electronic solutions. The next parts concern the presentation of all the demonstrator's executive elements with a full description of the functions performed. The next part of the article concerns the microprocessor controller used to control the full functionality of the demonstrator. The sixth chapter is devoted to a discussion of a whole series of tests and an attempt to assess the functionality of the constructed demonstrator in the context of the assumptions adopted at the beginning. The article ends with a summary and presentation of the further development path of the demonstrator.

State of the art

In the area of rehabilitation applications, there is a very rich bibliography that shows the latest research trends. Considering only the last two years, you can find dozens of publications on this issue. The synthetic review of the literature presented below is, for obvious reasons, very limited but nonetheless shows the main trends that can be observed in this area. In the paper [1] a soft pneumatic glove actuated by elliptical bending bellows is presented, which allows the effectiveness of finger and ankle rehabilitation exercises to be increased in patients with hand dysfunction. The applied actuators of guided bending bellows are made of thermoplastic elastomer, which allows one to obtain the necessary tightness of the developed glove. By appropriate pressure control, it is possible to obtain a good anisotropic kinematic bending efficiency. The designed soft rehabilitation gloves can be used for the daily rehabilitation training of hand dysfunctions to improve the range of motion of the finger joint. Comparing the proposed gloves with ordinary soft gloves from the robot exoskeleton, which are often used in the case of rehabilitation of hand dysfunctions, the developed soft powered gloves have the advantage of increasing the rehabilitation force, range of motion of fingers, and coordination of many actions, applied by means of bending actuators. The aforementioned exoskeletons are, on the one hand, a very attractive direction for the development of rehabilitation methods, and, on the other hand, they are used to support difficult physical work. The authors of [2] focused on the use of assistive and rehabilitation exoskeletons as a new option for people with limited mobility. The main goal of the aforementioned article was to identify gaps and inconsistencies in state-of-the-art assistive and rehabilitation devices. This article provides an interesting review of the literature that discusses the mechanisms, actuators, and detection procedures used in passive shoulder supports and active soft robot actuator gloves. Passive shoulder supports are an excellent option for carrying heavy loads because they allow for an even load distribution at the shoulder joint. This, in turn, reduces stress and strain around the surrounding muscles. On the other hand, the active soft robot actuator glove is well suited to provide support and assistance by imitating the characteristics of human muscles. A special case of the need for intensive rehabilitation is patients who undergo therapy after a stroke. One of the most difficult elements of stroke therapy is regaining mobility of the hand. In [3], a novel approach to robotic-assisted hand movement therapy was presented. The authors used machine learning to determine and describe hand movement patterns in healthy individuals using electromyographic signals from the flexion and extension muscles of the forearm. Time and frequency characteristics were used as parameters in machine learning algorithms to recognize seven hand gestures and track rehabilitation progress. Eight EMG sensors were used to capture each contraction of the arm muscles during one of the seven activities. The developed system was able to reconstruct the kinematics of hand movement and simulate the behavior of each movement pattern. The analysis showed that the gesture categories overlap significantly in the feature space. The correlation of the calculated joint trajectories based on EMG and the monitored hand movement was on average 0.96. Furthermore, statistical studies conducted in different machine learning configurations showed a 92% accuracy in measuring the precision of finger movement patterns. A similar problem of rehabilitation of stroke patients was the subject of research described in [4]. The authors presented a rehabilitation glove for everyday use. The proposed motorized glove was designed to provide effective and comfortable rehabilitation for patients with paresis. The glove can exercise each finger separately and all fingers together, using the assistive force generated by actuators controlled by sEMG signals. The motorized glove is worn on the affected hand to provide assistive force during rehabilitation training. The main advantage of the constructed glove is its ability to perform classified hand gestures obtained from the uninjured hand by integrating four sEMG sensors and a deep learning algorithm. Classified hand gestures can be used as a control command for a motorized, worn glove placed on the diseased hand, allowing it to mimic the movements of the uninjured hand. The problem of exoskeletons dedicated to upper limb rehabilitation is addressed in [5]. This article presents the design and tests of a portable rehabilitation robot used in the rehabilitation of the hand-elbow complex. The proposed solution allows the wrist and elbow joints to move and reproduce the full gripping action. The tests carried out show that the developed exoskeleton meets the requirements for rehabilitation training of the hand and upper extremities and has a certain ability to support users in daily life.

A new issue visible in published articles is related to the rehabilitation of people after COVID-19. A severe course of this disease can lead to significant muscle loss and deterioration of patients' motor functions. Article [6] presents a hand exoskeleton used for rehabilitation purposes and to evaluate the effectiveness of the procedures performed. Studies carried out on a selected group of patients confirmed the effectiveness of the structure developed for upper limb motor rehabilitation in people after a severe case of COVID-19. Similar studies are presented in [7]. Hand disorders that persist after the SARS-CoV-2 pandemic can limit the range of wrist movement. Modern telemedicine allows one to transfer previous rehabilitation exercises from health centers to the patient's home. The described studies focused on the possibility of self-assessment of the range of wrist movement by the patient using a designed goniometer template. The template presented in the article was designed to measure flexion - extension and radial - ulnar abduction movements. The studies conducted by the authors confirmed that the developed method provides a reliable and cost-effective alternative to remote evaluation of range of motion, improving telemedicine practices in hand rehabilitation. A similar issue was presented in [8]. The authors developed a system that supports arm movements in rehabilitation therapies and movement exercises. An interesting solution in the presented work was to place sensors on a rotating crank to validate and monitor the effectiveness of arm exercises. In [9], the possibility of counting finger and wrist movements during the day was presented using a non-invasive, wearable sensor that can be used for rehabilitation after stroke, carpal tunnel syndrome, or hand surgery. The developed sensor allows for the identification of the occurrence of flexion - extension movements of the fingers and wrists based on vibrations detected by an inertial seismograph system worn on the wrist. A convolutional neural network with spectrograms was used to analyze the results obtained, which is trained using velocity and acceleration spectrograms generated by finger and wrist movements. The results obtained showed that such an approach requires further work and is difficult to disseminate at the current stage of design development. In [10], an intelligent hand-assisted diagnostic system was presented, the aim of which is to achieve a comprehensive assessment of hand function using information fusion technology. The authors developed a one-way vision algorithm that allows the developed system to perceive and analyze the morphology and posture of the patient's hand movement in real time. The developed visual perception can provide objective data and capture continuous changes in the patient's hand movement, thus providing more detailed information for the evaluation of the applied treatment procedures.

In the area of advanced hand prosthesis construction, most of the work is focused on the construction of such prostheses that will ensure the recovery of at least minimally basic biological functions of the hand. An example of this type of work is the research presented in [11] focused on the development of a signal processing technique that uses spectral characteristics and an artificial neural network to classify 17 arbitrary movements identified by a set of several electromyographic (EMG) sensors. The main goal of the presented solution is to show that it is possible to identify a relatively large number of hand movements on the basis of a set of inexpensive EMG sensors. Work [12] focused on the use of soft robotic systems, such as actuators and grippers, to ensure intensive human-robot interaction, especially in the case of human-exoskeleton applications. Human exoskeletons are usually used to assist and rehabilitate patients with motor disabilities and neurological disorders. The result of the conducted research was the development of a fully functional soft exoskeleton system for the robotic hand, using innovative compressed air-driven actuators. The developed system consists of a control glove that copies the movement of the healthy hand and transmits the finger configuration to the exoskeleton used on the diseased hand. The effectiveness of the constructed exoskeleton system was investigated through an experimental validation procedure involving healthy participants and patients, which assessed the performance of the system, including safety, ergonomics, and comfort of use. A similar problem related to improving daily life with hand dysfunction was presented in [13]. The aim of the conducted research was to offer a new three-fingered gripper to assist in daily activities, which can both grip and pinch with adaptive force, enabling the handling of a wide range of objects from the scope of daily activities. The developed gripper is designed to handle 90 essential daily objects of different shapes, sizes, weights, and textures. The designed gripper is characterized by a simple structure, which facilitates trouble-free production using 3D printing technology without compromising its operational efficiency. As part of the evaluation of the developed gripper, the authors conducted load and usability tests. The results showed that users picked up and placed 75 items out of 90 everyday objects. The gripper held and manipulated objects ranging in size from 25 mm to 80 mm and up to 2.9 kg.

When conducting a subjective review of the literature, it is difficult not to mention the solutions used in the iCub robot, where the applied hand solutions are closest in their concept to the construction developed [22]. Of course, the level of advancement and implementation of individual elements definitely exceed our solutions.

A very short overview of the latest solutions related to hand rehabilitation problems shows that this is still a current topic and an area of interest for many teams around the world. Most of the solutions presented were characterized by a relatively high degree of complexity and, consequently, a high price.

The main goal of the authors of the article was to develop a demonstrator of the hand that would be a relatively simple design and would allow its use in home rehabilitation procedures. The demonstrator should provide the ability to reproduce basic hand functions while maintaining the highest possible accuracy.

An additional condition that had to be met by the developed demonstrator was the possibility of using it in the didactic process of students of electronics faculties. This condition concerned both the process of designing the demonstrator structure and the preparation of the appropriate software. The mechanical structures, software, and electronic systems used had to be characterized by low costs and the possibility of simple modification of the solutions used in the stage of subsequent development procedures.

Anatomical analysis of the human hand

Human movements can be classified as voluntary and involuntary. Voluntary movements include purposeful actions, such as precise manipulation of objects, such as writing. In the case of these movements, a brain structure, the cerebral cortex, generates signals directed to the appropriate muscles, allowing precise control over their activity, resulting in the movement of the limbs. Involuntary movements, on the other hand, are initiated by spinal reflexes or the autonomic nervous system. They include reactive actions to stimuli that do not require conscious involvement of the person. Examples of such movements include shivering caused by cold or instinctively releasing a hot object from the hand. To reconstruct voluntary movement of the fingers, a detailed analysis of the anatomy and biomechanics of a healthy human hand is necessary. The anatomy of the human hand is shown in Figure 1.

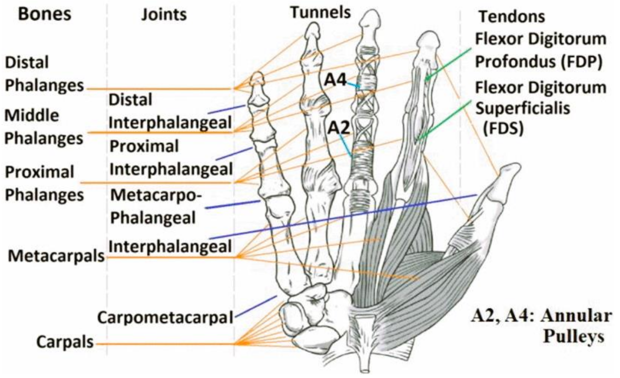


Fig. 1. Anatomical structures of the human hand [14]

Finger movement is a highly complex process that involves a number of anatomical structures working in harmony. The primary initiator of movement in the finger is a muscle that tenses or relaxes in response to impulses received from the nervous system. However, full finger movement requires the integrated action of many anatomical structures: muscles, tendons, joints, ligaments, and the nervous system. The muscles responsible for finger movement are located in the forearm and the hand. They are connected to the fingers by tendons, which transfer the force of muscle contraction to the bones, and the points of attachment of these tissues, known as attachments, are surrounded by ligaments. As the tendon moves, the fingers can bend or straighten. When the flexor muscles are released, the fingers return to a neutral position through the action of the antagonist extensor muscles or the elastic ligaments between the phalanges. A combination of both mechanisms is also possible. As a result of the elasticity of the ligaments, the fingers can maintain their neutral position even when the muscles responsible for movement are completely relaxed. The interphalangeal and interosseous joints contain joint capsules that contain synovial fluid. This fluid is crucial to ensure the proper lubrication of the articular cartilage, which is important for reducing friction, allowing smooth and precise movements. Arcil cartilage, together with ligaments, allows fingers to move with the necessary smoothness. The complex interaction between muscles, tendons, ligaments, joints, and the nervous system constitutes a complex and flexible mechanism. The cooperation of these elements is fundamental to the correct functionality of the human hand, allowing for a wide range of precise and varied movements. The movement analysis will be performed on the example of possible movements of one selected finger - 2 (index finger) as shown in Fig. 2.

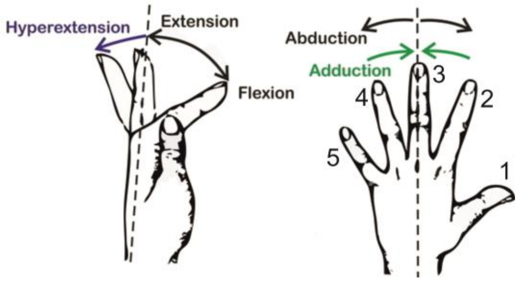


Fig. 2. Possible finger movements analyzed [15]

The acquired information will then be applied to fingers 3, 4 and 5, as they represent an iteration of similar anatomical structures. The exception is the thumb, which, due to its unique anatomical structure and the difference in the range and number of movements performed, requires a separate analysis [16].

Analysis of the anatomy of human hand movements indicated the anatomical structures that needed to be replicated using mechanical substitutes, so that the movements of the artificial fingers from the second to the fifth remained as close to real ones as possible using selected production techniques:

1. **Bones:** Will be replaced with rigid geometric figures of similar dimensions and functions. Then, these figures will be printed on an FDM machine, using PLA material.
2. **Skin:** Similar to bones, it will be printed from PLA.
3. **Nervous system:** Its equivalents will be wires and a microcontroller of the low-level control system.
4. **Brain:** It will be the microcontroller of the high-level control system.
5. **Two-axis joints:** They will be replaced with their mechanical equivalents, ball joints.
6. **Hinge joints:** Will be replaced with a mechanism containing two bearings and an axle.
7. **Muscles:** Their equivalents will be servomechanisms with the possibility of 180 degrees of rotation.
8. **Tendons and ligaments:** The connection of the servomechanisms to the bones will be made using narrow knotted ropes. The selected jewelry, steel, seven-string coated cords. This solution provides resistance to friction while providing adequate durability.
9. **Channels**: The friction of cables against bone structures will be reduced by insulating sleeves for electric cables made of fiberglass, placed in appropriate holes**.**

For fingers 2-5, three joints are required, two hinge joints, and one ball joint. Muscles responsible for adduction and abduction of the proximal phalanx from the axis of the hand are also needed. This function can be performed by one servo mechanism rotating in two directions. Extension and flexion of the three phalanges can be performed by two mechanisms because the middle and distal phalanges move together. It is also necessary to precisely determine the lengths of the bone elements and the ranges of movements that occur in the joints during the design stage of artificial finger models.

In the case of the demonstrator project, the interosseous movements will not be reproduced. Like the other bones, the metacarpal part of fingers 2-5 will be printed on an FDM machine as a rigid block, thus preventing interosseous movements.

Design methodology

The presented work carried out focuses on the most precise reproduction of the positions of the fingers of an artificial hand. The constructed demonstrator of the artificial hand will not fulfill the function of a prosthesis but rather an attempt to reconstruct a fragment of the human body for diagnostic purposes or to build a humanoid.

However, the design stage was carried out in accordance with the guidelines for the production of bionic upper limb prostheses. The prosthetic part production process of the human body usually follows a scheme based on carefully planned stages and procedures. A more general formulation of this process is presented below.

1. **Anatomical analysis and design** - includes detailed identification of biological structures and assessment of their functionality. The model is then designed on this basis, taking into account the unique anatomical features of the unit tested and the individual needs of the patient.
2. **Selection of materials and production techniques:** After initial approval of the design, the selection of production techniques and appropriate materials is made, which will ensure not only the durability and functionality of the prosthesis but also the biological compatibility with the patient's tissues.
3. **Prototype production and testing:** At the stage of prototype production, rigorous quality control procedures are applied, including accuracy measurements, strength tests, and assessment of biological compatibility. The prototype is subject to a series of clinical tests, which allow for the assessment of the functionality, ergonomics, and comfort of use of the prosthesis.
4. **Adjustment** - based on the test results, any adjustments to the prototype are made, taking into account the patient's opinions and specialists' recommendations.
5. **Series production and documentation** After approval of the prototype, the production of a series of prostheses is started, in accordance with the established quality and technical standards.
6. **Monitoring** - during the use of the prosthesis, continuous support is provided to the patient, enabling individual adjustments if necessary, and providing technical assistance.

The demonstrator project will not meet the requirements for serial production, which is why the designer's attention was focused on the first four of the above-mentioned points. In the presented study, the main emphasis was placed on the analysis of the technical possibilities of reproducing the biomechanics of the hand and the selection of materials and production techniques, which fills the first two points of the above-mentioned scheme of action. Points 3 and 4 were appropriately emphasized in the remaining chapters of the study. As part of the reproduction of hand movement, it is necessary to transform anatomical structures into their artificial equivalents using available technologies. The project used FDM 3D printing technology, which is particularly useful due to the possibility of rapid prototyping and testing of concepts without the need to engage additional laboratory machines, as is the case with SLA (Stereolithography) technology. The main advantage of FDM is its cost effectiveness and ease of use. However, it should be mentioned that the selected technology has limitations, such as low printing resolution, which is about 0.4 mm, and the possibility of delamination of models under the influence of external forces. PLA was used as the printing material, which is the most popular material in FDM printing due to its ease of use and widespread availability. The disadvantages of PLA are its brittleness and tendency to deform when exposed to temperatures above 70°C; however, in the context of this project, these inconveniences should not negatively affect the demonstrator being built.

The project takes into account potential limitations resulting from the use of cheaper materials and less advanced production methods, which will result in the stiffness of the entire structure. It is possible to use an alternative to PLA, the FLEX material, a flexible filament that allows the production of flexible models. However, printing with FLEX would require modification of the FDM device itself, which is associated with higher costs and an extended production time. Due to its flexibility, this material causes problems with introducing the filament into the nozzle of a standard printer, resulting in FLEX entanglement and interruption of the print.

The decision to choose FDM technology and PLA material is a compromise between costs, production time, and precision and advancement of the final artificial hand.

In this design, these choices were anticipated to be adequate for experimental purposes, with the caveat that the design would have limited movement capabilities compared to the natural hand.

Demonstrator Design Concept

After anatomical analysis, it was determined that in the artificial hand each of the five fingers will be made up of two hinge joints and one ball joint. For effective manipulation of these three joints, it is necessary to use four servomechanisms. This is due to the fact that two joints are single-axis, while one is biaxial. The specific application of this configuration concerns only the thumb, whose last phalanx has the ability to move independently relative to the neighbouring one. In the case of the remaining fingers 2-5, it is possible to reduce the number of implemented mechanisms, because the movement of the distal phalanx is dependent on the movement of the middle phalanx. In such a situation, one servo mechanism is quite sufficient to coordinate the joint movement of these units. The basis of the constructed artificial finger is three elements, performing functions analogous to the anatomical bones of the hand. These bodies, called artificial phalanges "P", were connected by single-axis and biaxial joints, as shown in Figure 3.

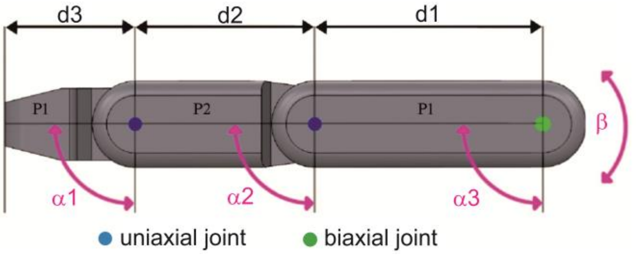


Fig. 3. Finger model of an artificial hand

The lengths of the individual segments are marked as *d* and the angular ranges of joint movement are marked as *α*, and *β*. In the design stage, it is crucial to correctly determine the location of the attachment points of the synthetic cables that will act as anatomical tendons. In the case of a real hand, the tendons and ligaments, which are soft tissues, are flexible and elastic. In the reconstruction process, they will be replaced by rigid counterparts that run along the phalanges. This fact, in turn, will have a significant impact on the distribution of forces acting on the components during movement, which will certainly affect the optimal target location of the cable connections. The design stage began with a general block diagram of the demonstrator shown in Fig. 4.

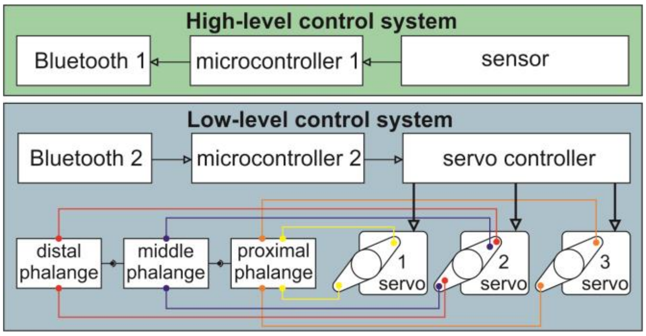


Fig. 4. Block diagram of an artificial hand using one finger as an example

The block diagram in Fig. 4 shows the structure of the connections of the control system with only three servos of one finger moving its phalanges. The servos of the other fingers of the artificial hand are connected in the same way to the PCA 9865 chip. The key to the developed finger model will be the use of a properly designed high-level control system and a low-level control system, which will enable effective control of the mechanisms of all fingers of the artificial hand. The low-level control system of the demonstrator project includes a real model of the artificial hand with an electronic system that enables wireless Bluetooth communication and servomechanism control. The high-level control system is responsible for generating and sending signals, which will then be interpreted by the low-level control system.

The construction of the actuator system began with the inner layers of the fingers and metacarpus, which form the actual skeleton of the structure. Information on the dimensions of individual phalanges and metacarpus bones was taken from research published in the article [17]. In the process of designing CAD models, the maximum limit values of the dimensions obtained in the aforementioned study were used, rounding them to the nearest decimal place. This approach ensures the largest margin of error during the 3D printing process, while contributing to the increased strength of the final model.

In the process of constructing the artificial hand, printed models were used, the structure of which can be divided into two main groups: the inner layer and the outer layer. The inner layer performs functions analogous to the bones in the human hand. This layer provides a mechanical and structural base for the fingers. It is responsible for the stability of the structure and redirecting the cables to their target attachment points, which is crucial for proper finger manipulation. The outer layer simulates the skin, designed to limit unwanted bilateral bending movements of the finger in the hinge joint and to give the appropriate shape to a fragment of the human hand. Both of these layers are visible in Fig. 5. The joint (highlighted in brown) visible in Fig. 5 acts as a ball joint for the proximal phalanx, allowing biaxial movement of this segment. The uniaxial joint will be implemented by using a mechanism consisting of a screw, a nut, and two bearings placed in specially hollowed out places of the phalanges. This solution allows for a smooth connection of adjacent phalanges while ensuring stability and the possibility of movement in one plane.

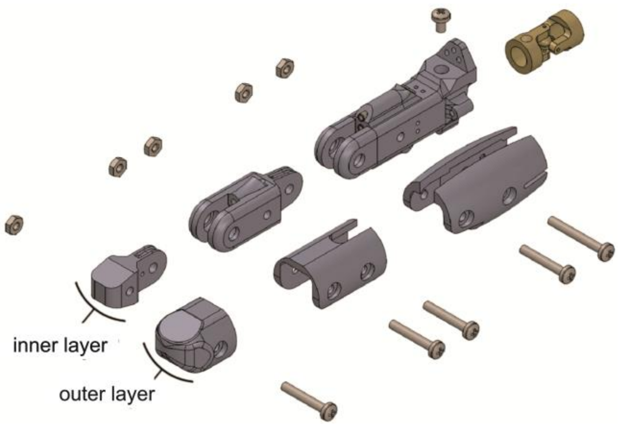


Fig. 5. Finger components: inner layer, outer layer, screws and nuts, joint

The finger design stage itself began with the development of appropriate elements that would enable movement of the phalanges through the links. The mechanism of straightening the bent distal phalanx, crucial for the functionality of the entire hand, is shown in Fig. 6.

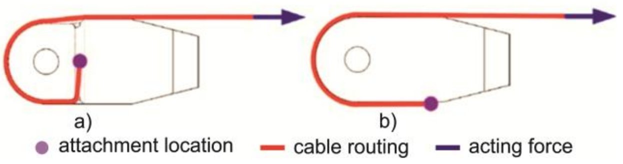


Fig. 6. The mechanism of straightening the maximally bent distal phalanx of the finger (a - spool mechanism, b - anatomically correct attachment site)

The cords run along the phalanges, which is why the chosen method of bending and straightening is based on double-sided winding of two cords on one spool. This approach creates an optimal distribution of forces that act on the phalanx regardless of its position. The use of anatomically correct attachment points would cause problems during finger straightening, which is why an innovative solution was chosen. In each block that replaces the phalanx, additional holes with specific functions were drilled, as shown in Figure 7.

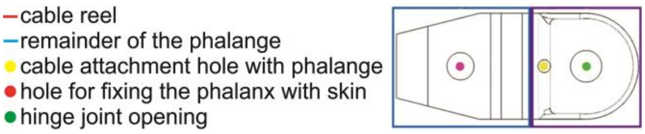


Fig. 7. Construction of the distal phalanx model

The connected models of the internal layers of the three phalanges with hinge joints and the cable courses are shown in Fig. 8.

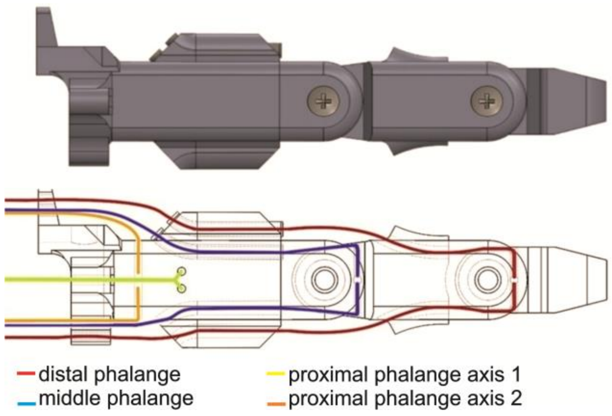


Fig. 8. The course of the lines along the folded phalanges and examples of covers that reduce the friction of the lines against the models.

The construction and design of the described finger serve as a blueprint for all fingers of the artificial hand. The lengths of the individual phalanx segments, shown in Figure 3, are the basis for their appropriate scaling and modification for the constructed fingers. An example of the appearance of finger 2 – the index finger is shown in Figure 9. As mentioned above, the ranges of motion of the joints in the constructed finger are currently limited by the outer layer of the model. This limitation is intended only to prevent the unnatural movement of hyperextension.

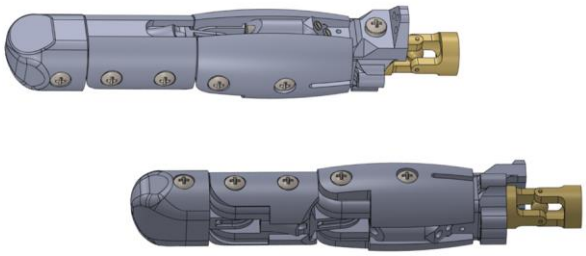


Fig. 9. Example of index finger positioning

The precise ranges of motion of each joint need to be determined, but will be implemented in the program code of the executive low-level control system by adjusting the values of the servo motion ranges. Actual values of the angular ranges of the hand joints often do not match the theoretical values specified in the anatomical atlases [18]. For this reason, the angular ranges of joint motion were taken from the article [19].

The inner layer of the artificial hand model performs functions analogous to those of the metacarpal bones. To obtain the appropriate hand shape, the inner layer of this model was designed according to the dimensions given in [20], taking into account the neutral and relaxed position of the hand, shown in Fig. 10.

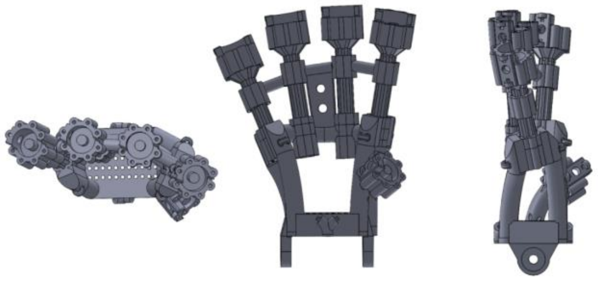


Fig. 10. The inner layer of the metacarpal model visible from three side

The functions of the metacarpus are to shape the hand to enable gripping and to redirect cables from the fingers to the servos. These units will be permanently placed at the top of the "tower" model shown in Figure 11.

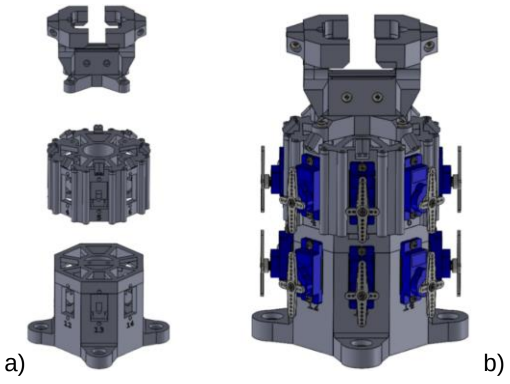


Fig. 11. Tower elements a) and its assembly b)

The tower is a model designed on the basis of an octahedron to minimize the space occupied by 16 servos and divided into several smaller parts to facilitate printing in FDM technology. The base in the artificial hand design shown in Fig. 12 serves as a stable base for the entire structure and also integrates the electronic system elements.

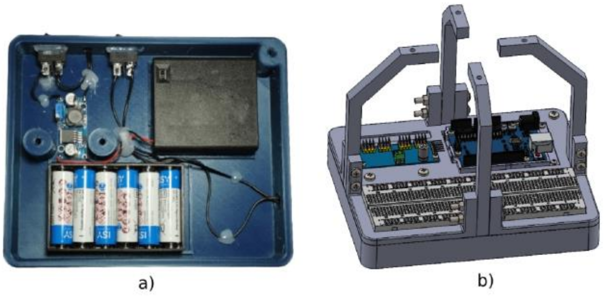


Fig. 12. Model of the base. The interior of the lower part a) visualization of the upper part b)

In its lower part, there are two separate power sources; in the upper part, there are the remaining elements of the electronic system of the demonstrator's executive part (Fig. 12a). The low-level control system was designed to control the servos using a signal received from the high-level control system. Three models combined into one: the hand, the tower, and the stand, which together constitute the assembly of the low-level control system, are shown in Fig. 13.

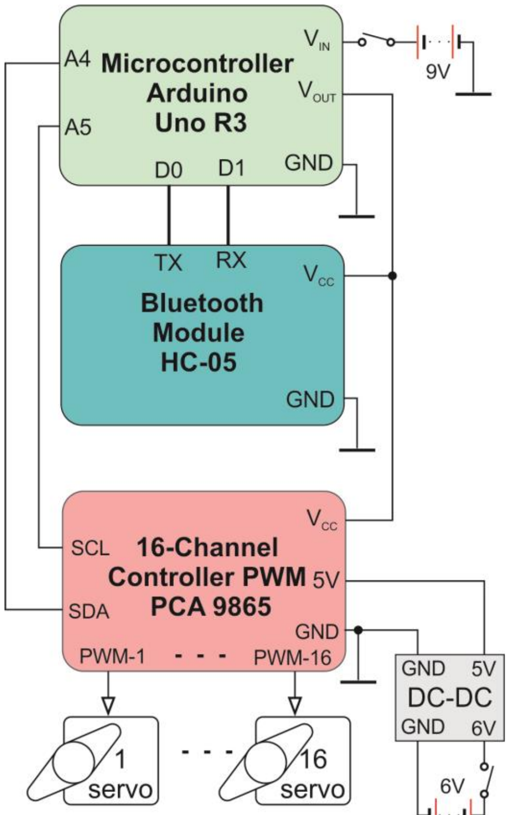


Fig 13. Schematic diagram of the electronic part of the low-level control system

Due to the limited current efficiency of the VOUT output of the Arduino microcontroller, it became necessary to use an additional module responsible only for controlling the servos. The PCA9685 controller was connected to the 5V output voltage of the Arduino Uno board, which allows the controller system to be powered. However, this module requires an additional independent 5V power source redirected directly to the servos. For this purpose, a DC-DC converter was used, which also ensures protection of the high-level control system and servos against too high input voltage. Thanks to this additional 5V power supply, it was possible to implement the HC-05 Bluetooth module in the Arduino system, providing wireless communication between the high-level control system and the low-level control system. A huge advantage of this module is the ability to work in two modes - slave (receiver) and master (transmitter). Therefore, you can buy two identical modules, connect them to two different executive and high-level control systems, and then configure each in a separate mode. It should also be noted that the PCA9685 controller requires an additional voltage source with a specific value of 5V. In the described case, four AA cells were used as the second power supply, which theoretically should give a voltage of 6V. However, these cells are often overloaded and the actual voltage value of four batteries of cells connected in series was 6.4V. In such a case, it was necessary to reduce the voltage to the 5V recommended by the manufacturer.

In Fig.14, 3 areas are marked, indicating 3 main parts that together constitute the low level control system. Area 1 is the artificial hand, area 2 is the tower that contains the servomechanisms, and area 3 contains the base with the electronic system placed on it.

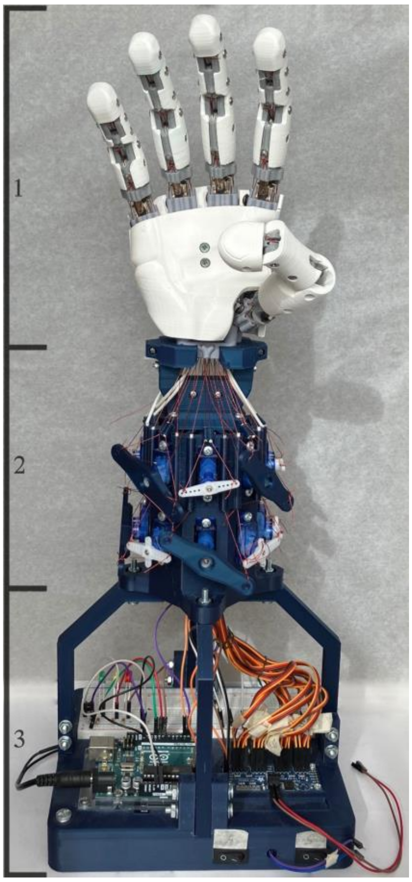


Fig 14. View of the assembled actuator

The high-level control system should provide precise control over 16 servos divided into five groups, corresponding to fingers. To achieve this goal, 16 encoders can be used, which will control the servos assigned to them by transmitting a PWM (Pulse Width Modulation) signal. This will provide rotation in both directions with different angular values, allowing us to precisely achieve the target position of each mechanism, simulating both contraction and relaxation of different intensity. However, such a solution will make it difficult for the user of the system to move more than two encoders at the same time, which would be cumbersome. As a result, only a small part of the actuator's potential would be used at a given moment. For example, it would not be possible to bend all fingers at the same time in one smooth movement. Furthermore, Bluetooth transmission of multiple PWM signals could cause various types of interference. Independent PWM signals can interfere with each other, losing stability, because Bluetooth modules operate on specific limited bands. If too many PWM signals are sent at once, some of them may fill all the available space, and the rest will be ignored or limited. These errors can cause delays in response or complete loss of transmitted data, leading to confusion of target units of received information. This is a serious hazard, because the servos can damage the hand model if they exceed their specified range of motion, which is perfectly possible in the case of PWM interference.

It was necessary to find a solution in which the aforementioned error would not occur and the stability of the system would be maintained. Such requirements are met by a high-level control system that only sends information about the logical state of the elements responsible for controlling the servos. The low-level control system then interprets the received information and locally converts it into the appropriate PWM signal. The greatest user convenience is provided by one encoder responsible for the possibility of movement in two directions. In such a case, however, there is no distinction between active and inactive executive units. Therefore, it is necessary to introduce a matrix consisting of five switches, guaranteeing the selection of currently regulated fingers and three buttons, allowing for any combination of simultaneous operation of 15 servos. The second row of the matrix was additionally equipped with a fourth button, which was required to operate the unique thumb of the fourth servo. Ultimately, one encoder and a matrix of five switches and four buttons allow control of all 16 servos located in two rows of the "tower" model (Fig. 11). The schematic diagram and of the high-level control system are shown in Fig.15.’

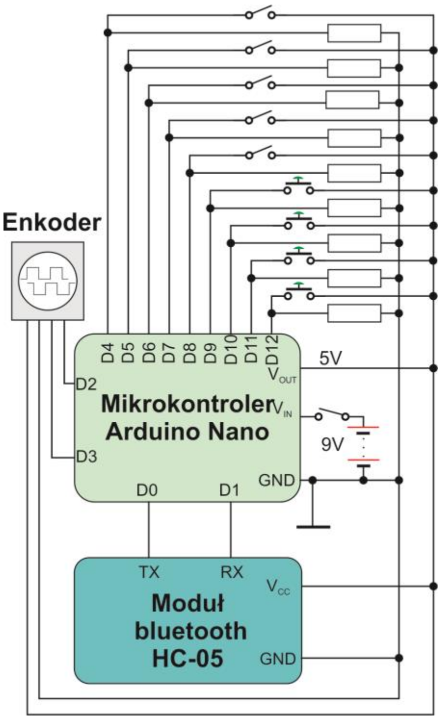


Fig. 15. Schematic diagram of the high-level control system.

This matrix requires the connection of nine 1 kΩ load resistors at each element to ensure a low logical state when the button or switch is in the neutral position. When the button is pressed or the switch is switched, the ground connection is closed, which causes the microcontroller to read the change in the state of the given pin. A view of the assembled system is shown in Figure 16.

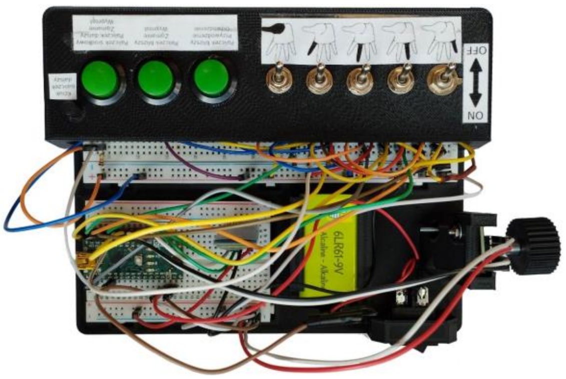


Fig. 16. View of the high-level control system

The described system is able to send information about logical states for later interpretation by the low-level control system. However, to optimize Bluetooth transmission, the most efficient way would be to send bit information. However, in the case of short signals, it is possible to transmit information in any way without negatively affecting the data. The chosen solution will be to transmit a string of characters in the form of a 10-element string table, although the matrix values are declared as Boolean. To avoid continuous activation, the high-level control system starts transmitting when it detects the rotation of the encoder knob, sending a table in which the first element is information about the direction of rotation of the knob. The next three elements are the states of the three main buttons, the next five are the states of the switches, and the last element of the table is the state of the additional, rarely used by default thumb button. In the case of no movement of the stick, the system remains at rest, assuming that the user is adjusting subsequent combinations containing movements different from the previous ones.

Testing of an artificial hand

The examination of the capabilities of the artificial hand demonstrator was performed by assigning specific reference static positions of the fingers of the human hand. The static grips of human hands, described in the publication [21], were used as reference for functional position tests for the artificial hand. The obtained research results in the form of photographs are presented in Fig. 17. In the vast majority of cases, the artificial hand was able to reproduce the 11 unique functional positions selected. The greatest differences resulted from the simplification of the thumb saddle joint, which resulted in the inability to perform the abduction and opposition movements. This is clearly visible in Example 9 from Fig. 17, where finger 1 is unable to touch finger 4. Furthermore, differences were observed that result from the deviation of the finger axes of the artificial hand from the real finger axes [21], as shown in Example 11. At the design stage, the use of anatomically correct axes was considered, but due to the lack of movement of the metacarpal bones, this operation turned out to be impossible. The natural axes run as shown in Example 11, precisely due to the possibility of deformation of the palm surface.

In the case of the artificial hand, the axes were selected so that they run along the metacarpal bones, allowing the widest range of movement of the finger. The artificial hand is less able to hold heavier objects (e.g. a screwdriver, example 8) than objects that require finger precision (e.g. a needle, example 1). This is due to the use of a rigid material as a skin substitute, which deprives the outer surface of the ability to deform in order to provide a stable position while holding the weight. As a result, objects usually slip out of the fingers.

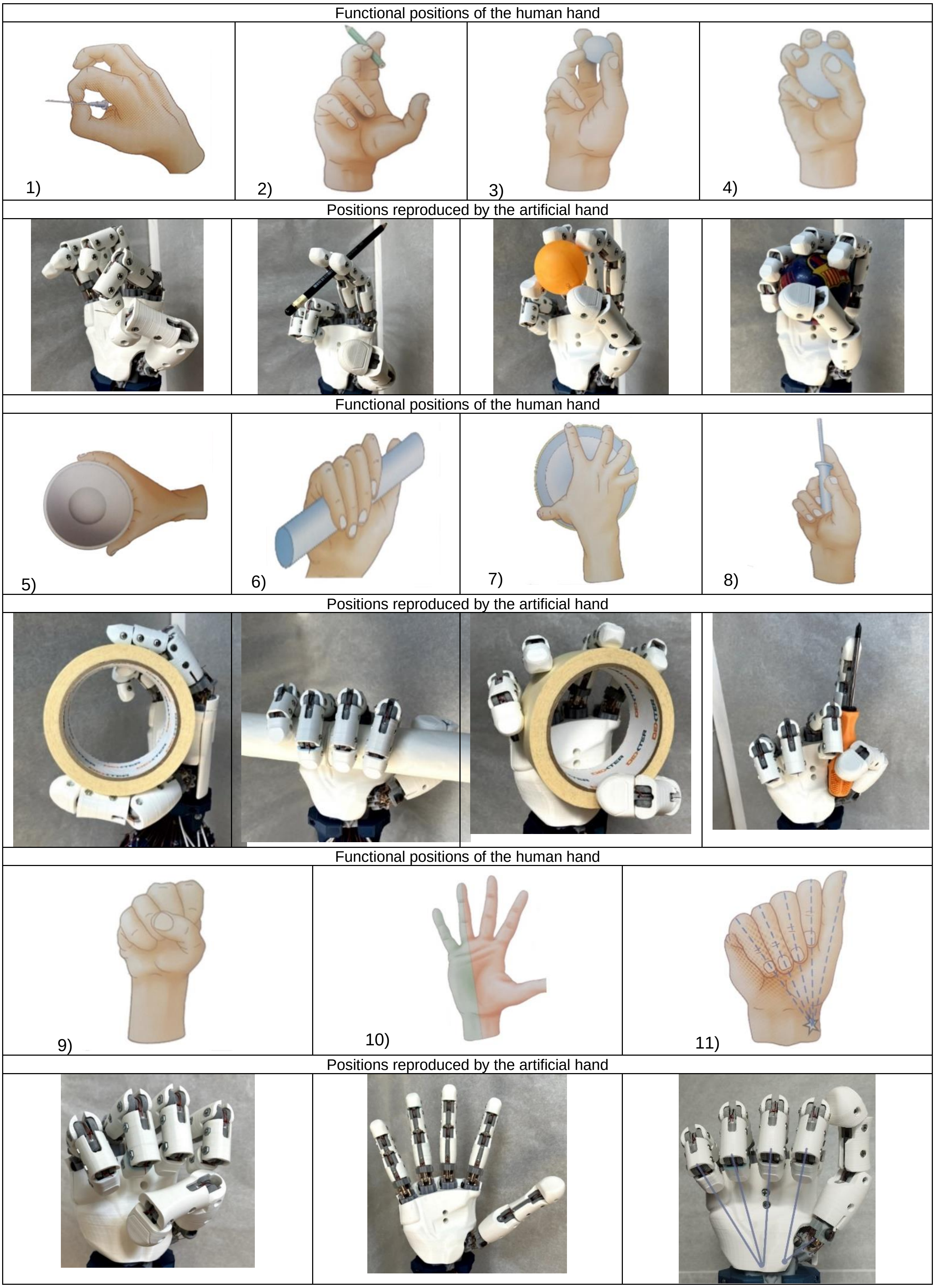
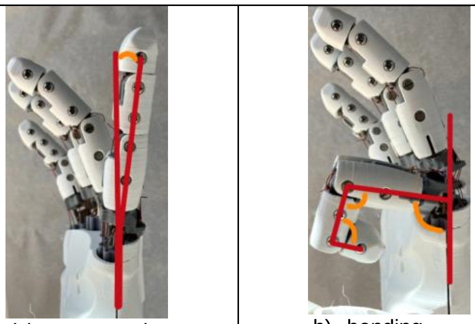
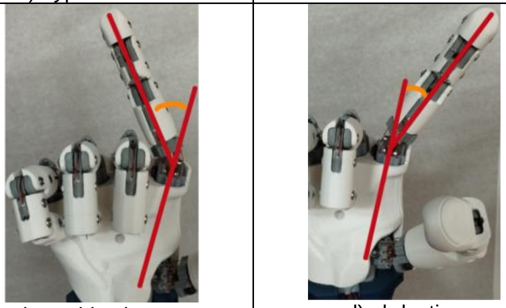


Fig. 17. Comparison of static positions of the fingers of the human hand with the position obtained by the demonstrator

The demonstrator test also included testing the range of motion of the artificial hand by measuring the angles between the most and least deflected positions of individual fingers. Since fingers 2-5 are identical in construction, measurements were made only on finger 2. The method for marking the angular values during the tests is shown in Fig. 18.



a) hyperextension b) bending



c) adduction d) abduction

Fig. 18. Movement ranges of the 2 fingers

The adduction and abduction movements were decidedly unnatural, with a range of about 100°. Therefore, the range of motion of the servomechanisms responsible for these movements was reduced by 40% in the low-level control system program code. Similarly, the ranges of motion of the thumb were measured, and the values obtained were compared with theoretical data. The missing values were supplemented with information from the anatomical textbook [18]. All results are presented in Table 1.

Most of the ranges of motion of the fingers of the artificial hand match the expected ranges obtained in the study conducted on human hands. The most noticeable differences occur during the hyperextension movement of fingers 2-5. However, in this case, these movements were deliberately limited in the model design stage in order to increase the durability of the printed models. This decision was possible because the hyperextension movement does not participate in any grip or functional position. Theoretically, it can be ignored, and its ranges vary greatly, and some people are almost unable to perform it at all. In the remaining cases of fingers 2-5, approximate values of the intended ranges of motion were achieved; in the case of visible excess, they were leveled out in the low-level control system program code. The structure of the thumb does not differ from the previous cases, so the values of its ranges are identical in the case of the artificial hand before the introduced restrictions. Although the appropriate ranges of motion are achieved, the thumb cannot oppose, which prevents it from touching other fingers. This is definitely the biggest problem of the entire demonstrator project. However, it can be said that the original design goal of recreating range and motion was achieved for 4 of the 5 fingers due to an underestimation of the unique anatomical structure of the thumb area and the significant difference between the saddle and ball joints.

Table 1. Summary of Joint Movement Ranges

No.	Fingers	Joint	Type of movement	The anatomical range of the hand [°]	Artificial hand range ± 2 [°]
1	2-5	Metacarpophalangeal	Extension and flexion	−102.23 ± 15	100
			Hyperextension	45 [18]	9
			Adduction and abduction	60 [18]	66
2	2-5	Distal interphalangeal	Extension and flexion	87.50 ± 16.87	82
3	2-5	Distal interphalangeal	Straighten	62.48 ± 22.25	82
4	1	Carpometacarpal	Flexion and extension	50.92 ± 21.17	50
5	1	Carpometacarpal	Adduction and abduction	30 [18]	30
6	1	Interphalangeal	Flexion and extension	59.56 ± 8.34	60
7	1	Metacarpophalangeal	Flexion and extension	57.27± 18.01	60

Summary and conclusions

This article presents the design and construction process of an artificial hand demonstrator project using FDM 3D printing technology. Analysis of the results indicates that fingers 2 to 5 have been reproduced with high precision, both anatomically and functionally. The index, middle, ring, and little fingers are characterized by an appropriate range of movements, which confirms the effectiveness of the applied mechanism of double-sided winding of lines onto a spool. The need to use this mechanism itself resulted not only from the need to replace anatomical structures with conventional equivalents, but also from the lack of soft tissue in the artificial hand, which was not taken into account at the analysis stage. Unfortunately, the reproduced movements of the thumb did not achieve the same precision. Due to the complex structure of the thumb saddle joint, it was replaced with a ball joint, which limited the range and naturalness of its movements. This problem is mainly due to the economic constraints applied during the project. The servomechanisms used were selected to minimize the space occupied and production costs. However, this proved disastrous, as the torque of 0.2 Nm was insufficient to smoothly move the uniquely constructed, heavy, and most friction-laden thumb model.

It was also noted that although finger mapping is crucial, they only constitute a part of the entire range of hand movements. Currently, there is no possibility of mapping the movements of the metacarpal bones, which play an important role in more complex positions and grips. Integration of such movements in a possible future model of the artificial hand will be necessary to achieve full functionality.

Integration of the high-level control system with the actuator also did not proceed according to the assumptions; problems with Bluetooth transmission required the use of a delay in order to ensure stability and the time required for the appropriate conversion of the signal received to a PWM signal by the actuator. Although the high-level control system provides the possibility of controlling the artificial hand, despite establishing communication with an appropriately selected transmission speed, the transmitter is still susceptible to all kinds of interference. This is most likely caused by the constant presence of other devices using a Bluetooth connection near the demonstrator, the bandwidth of the connection itself, and the quality of the cables used on the breadboard. Due to the lack of feedback in the actuator, these jams sometimes cause desynchronization and incorrect operation of the servos during prolonged use of the high-level control system, it was also noticed that the systems are unstable only in the case of operation of several servos at the same time, when one actuator unit is used, interference does not occur, or occurs very rarely. This means that another reason for interference may be interference from the PWM signal, despite the fact that preventive measures have been taken to prevent this phenomenon. In summary, the current design of the artificial hand has met the assumptions of the movement of fingers 2-5, the movements of the thumb have been limited and the movements of the metacarpus have been omitted. Therefore, the design is only a prototype for potential reconstruction. It is necessary to maintain properly functioning fingers, rebuild the area of the ball of the thumb, and equip the hand with a metacarpus with the possibility of movement. It is also necessary to redesign the cable routes for fingers 1 and 5, or in these cases, use larger and more powerful servos.

One of the interesting potential areas of application of the developed demonstrator is rehabilitation. The issue of artificial hands arises in connection with the increasingly frequent need to implement intensive hand rehabilitation after injuries or surgical operations. The workload of medical personnel in the field of rehabilitation is very high, which means that the waiting time for rehabilitation exercises under the supervision of a specialist increases every year. One way to reduce the burden on the health service is to provide patients with the possibility of performing effective rehabilitation at home. According to the authors, one way to solve this problem is to build demonstrators that provide a model for exercises performed at home. After obtaining the appropriate permits, the demonstrator will undergo a complete clinical trial procedure. After the tests have been completed, it is planned to develop a modified design that will eliminate the main problems of the demonstrator.

In summary, the developed demonstrator met the assumptions made at the beginning and the preliminary tests confirmed its usefulness both in the initial rehabilitation process and in the didactic process.

The first version of the demonstrator was created based on research conducted as part of a diploma project carried out at the Military University of Technology, Faculty of Electronics.

Autorzy: dr hab. inż. Zbigniew Watral, Wojskowa Akademia Techniczna, Instytut Systemów Elektronicznych, wydział Elektroniki, 00-908 Warszawa 46 ul. Gen. S. Kaliskiego 2, zbigniew.watral@wat.edu.pl,
prof. dr hab. inż. Andrzej Michalski, Politechnika Warszawska, Instytut Elektrotechniki Teoretycznej i Systemów Informacyjno Pomiarowych, Politechnika Warszawska, Warszawa 00-525 ul. Koszykowa 75, andrzej.michalski1@pw.edu.pl,
inż. Mikołaj Drozdowicz, Wojskowa Akademia Techniczna, Wydział Inżynierii Mechanicznej, 00-908 Warszawa 46 ul. Gen. S. Kaliskiego 2, mikołaj.drozdowicz@student.wat.edu.pl,

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