Master Thesis

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Cybernetics

Prototype of the Technical Part of the Device Suitable for the Rehabilitation of the Upper Limbs

Bc. Jiří Budil

Supervisor: Ing. Petr Novák, Ph.D.
Field of study: Cybernetics and Robotics
January 2024

MASTER‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name:	**Budil Jiří**	Personal ID number:	**474554**
Faculty / Institute:	**Faculty of Electrical Engineering**		
Department / Institute:	**Department of Cybernetics**		
Study program:	**Cybernetics and Robotics**		

II. Master’s thesis details

Master’s thesis title in English:

Prototype of the Technical Part of the Device Suitable for the Rehabilitation of the Upper Limbs

Master’s thesis title in Czech:

Prototyp technické části zařízení vhodného k rehabilitaci horních končetin

Guidelines:

Nowadays, there are more and more complicated fractures of the upper limbs. Their rehabilitation is complex and time-consuming. For this purpose, various, not only experimental, rehabilitation aids are being created (in the form of 3D printing) and their development is moving forward very quickly.
1) Evaluate the current state of simple (up to prototype) aids/devices intended for the rehabilitation of complicated fractures of the upper limbs (availability, ease of use, use of new technologies, replicability, price, ...).
2) Using 3D printing, design and create your own version (only) of the technical part of the prototype of a simple device suitable for some basic methods / courses of rehabilitation of upper limb fractures. Also think about the possibility of active support during movement.
3) Design and use suitable sensors for sensing the progress and possibly the results, especially during home rehabilitation (for example angle / torsion sensing, ...).
4) Create 2 to 3 sample tasks (PC/tablet/telephone) in the form of games for support/stimulation especially during home rehabilitation of the upper limbs. In this way, demonstrate the possibilities of using the technical part of the prototype rehabilitation device designed by you.
(Design and solve the created prototype only from a technical point of view. Only after verification of its technical reliability / safety can it proceed to medical testing.)

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Name and workplace of master’s thesis supervisor:

Ing. Petr Novák, Ph.D. Department of Cognitive Systems and Neurosciences CIIRC

Name and workplace of second master’s thesis supervisor or consultant:

Date of master’s thesis assignment: **04.09.2023** Deadline for master's thesis submission: **09.01.2024**

Assignment valid until: **16.02.2025**

Ing. Petr Novák, Ph.D. Supervisor’s signature	prof. Ing. Tomáš Svoboda, Ph.D. Head of department’s signature	prof. Mgr. Petr Páta, Ph.D. Dean’s signature

III. Assignment receipt

The student acknowledges that the master’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master’s thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt	Student’s signature

Acknowledgements

Firstly, I would like to thank my supervisor Ing. Petr Novák, Ph.D. , whose expertise was very valuable in formulating comments and advice, also for his guidance and goodwill.
Next, thanks belongs to the CIIRC institution for the opportunity to do a project. In addition, I would like to thank my parents for their support .

Sincerely, thank you.

Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

In Prague, 9. January 2024

Abstract

Fractures of the upper limbs require active rehabilitation in addition to rest. There is a need to regain practical strength and restore ranges that often suffer from reduction. A common solution for rehabilitation is clinics or facilities where the patient performs various exercises with the help of staff. However, an alternative is to create a cheap device with which the patient can rehabilitate himself autonomously. This master's thesis deals with the development of a device prototype that would provide such a solution.
The design deals mainly with the arm area and covers the elbow and forearm area. The physical part of the device has elements of an exoskeleton type.
The thesis contains a more detailed description of the electronics design, including an explanation of the relevant peripherals and a description of device communication. It is also expanded to include control through a multi-platform application with a rehabilitation guide. The performed experiments verify the functionality of the designed device.

Keywords: rehabilitation, upper limbs, exoskeleton, multiplatform application, embedded system, haptic feedback, torque output

Supervisor: Ing. Petr Novák, Ph.D.

Abstrakt

Zlomeniny horních končetin vyžadují kromě klidového režimu také aktivní rehabilitaci. Je potřeba znovu získat praktickou sílu a obnovit rozsahy, které často utrpí snížení. Běžným řešením rehabilitace jsou kliniky a zařízení, kde za pomoci personálu pacient provádí různé cviky. Alternativou je však vytvoření levného zařízení, se kterým může pacient rehabilitovat sám autonomně. Tato práce se zabývá vývojem prototypu zařízení, které by takovou možnost umožňovalo.
Návrh se zabývá zejména oblastí paže a pokrývá úsek lokte a předloktí. Fyzická část zařízení má prvky exoskeletonického rázu.
Práce obsahuje podrobnější popis návrhu elektroniky včetně vysvětlení příslušných periferií a popisu komunikace zařízení. Dále je rozšířeno o ovládání skrz multiplatformní applikaci s rehabilitačním průvodcem. Provedené experimenty ověřují funkčnost navrženého zařízení.

Klíčová slova: rehabilitace, horní končetiny, exoskeleton, multiplatformní aplikace, vestavěný systém, silová zpětná vazba, měření momentu síly

Překlad názvu: Prototyp technické části zařízení vhodného k rehabilitaci horních končetin

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Chapter 1

Introduction

Fractures of the upper limbs require active rehabilitation in addition to rest. There is a need to regain practical strength and restore ranges that often suffer from reduction. The classic approach is rehabilitation with assistance where the injured person is helped by a physiotherapist or other trained person. However, this approach has the disadvantage that it is dependent on another person and there are many more people who would need an assistant than physiotherapists or assistants themselves. However, this provides ideal opportunity for automation in this sector. In the case of the use of machines and robotic components for rehabilitation, it will certainly be necessary to find suitable sensory systems and at the same time find actuators for controlling and streamlining the course of rehabilitation. Such a machine actually already shares attributes with an exoskeleton device. However, for this case, only a sub-part of the exoskeleton is sufficient.

Therefore, information about such projects will help us in designing our own device. according to [9], idea of exoskeletons appeared for the first time 1960s. It's aim was to help US army. Twenty years later, there was another attempt. A gadget, that should help people working in industry sector with heavy lifting. And over time, there appeared to be another use for them, which is medical support and rehabilitation of disabled or heavily injured. Upper limb exoskeletons should be designed to copy human arm and it's mechanical properties as much as possible. Yet that is a very difficult task. Human arm has 7 degrees of freedom a and very complex system of tendons and muscles in every joint. Exoskeletons actions can be performed by multiple types of actuators. For example Electrical, hydraulic and pneumatic. When designing such exoskeleton, all advantages and disadvantages should be taken into account. Electric actuator offer smaller dimensions precise control on the other hand hydraulic ones have higher power delivery.

1.1 Types of exoskeletons

If we divide exoskeletons according to load capacity and method of use, we can divide them into 3 basic types:

- Body-fitting exoskeleton
- Exoskeleton beyond the human figure
- Remote controlled exoskeleton

This work further focuses on the first type of exoskeletons. We can further divide it into exoskeletons for rehabilitation and industrial exoskeletons as loaders. It is characterized by the fact that the exoskeleton surrounds the person and its end members are connected to the user's end limbs. It's the type of skeletons that appeared in the movies: Iron Man, Edge of Tomorrow. Of the real exoskeletons, they are exoskeletons from the following companies: HAL Cyberdyne, Sarcos Guardian XO, Exomed Exoheaver, Raytheon XOS 2, rehabilitation Ekso Bionics EksoNR.

Representative of the rehabilitation exoskeleton is OpenWrist system described in [11]. It is basically a subsystem of an exoskeleton, which is focused mainly on the wrist part. But a fairly sophisticated apparatus covering solutions for all fingers is also included. The author's knowledge was based on previous prototype RiceWrist-S which is introduced in [10] article. OpenWrist has twice as much torque and other additional features. The authors also developed it in way that it could be compatible with the Maestro exoskeleton system [18]. Maestro covers additional body parts closer to body.

The second type of exoskeleton is characterized by the fact that the user is suspended in the central unit of the exoskeleton and, with his movements, controls massive arms that are outside his movement envelope. A typical representative of this type appeared in the movie Avatar. A real existing representative could not be found. This type probably doesn't exist in full version yet. Respectively, walking such a massive device is a difficult problem in terms of implementation and safety.

The third type of exoskeleton is not exactly an exoskeleton in the true sense of the word. There are two devices. The first device detects the movement of the user. The user wears VR glasses and has his hands placed in the controllers. These controllers are basically gloves on pliable robotic arms. This provides haptic feedback to the user. The second device is a machine/exoskeleton equipped with support arms that copy the movements of the user. It has a stereo camera above it that transmits the image to the user's 3D glasses. This second device can be of any size with any load capacity. Since the user controls the robot remotely, it is an ideal system for working with hazardous materials. It will definitely find use when working with nuclear or chemical waste. A real representative of this type is the Sarcos Guardian GT.

1.2 Principles of sensing intentions for motion

In this section, two types of sensing attitudes will be introduced.

1.2.1 Torque measurement

The exoskeleton can be controlled by measuring forces and moments of force. An example will be explained on the elbow joint on which the skeleton structure is mounted. The skeleton joint is driven by a servo motor. If the arm muscle is contracting, I can measure the force it is resting on the skeletal structure. Based on this force, it is possible to control the servomotor and regulate the acting force to 0. This is manifested by turning the skeleton joint to the desired position. The exoskeleton will therefore copy the movement of the limb.

However, for the exoskeleton to function properly, the condition of separating the forces acting from the outside world and the user's forces must be met. In principle, there must not be a situation where forces from the outside world are transferred to the measured location, via the rest of the limb. Likewise, it is not possible to measure forces directly in the servomotor. The application of force from the outside world would be perceived by the sensors in the same way as the user's force.

This principle has some disadvantages. Its usability is worse for physically handicapped users. This is because the user must always exert a certain amount of force to control. Which could be borderline for some users. At the same time, it is necessary to take into account the imperfection of the transmission of forces between the limb and the sensor. We need to sense the force (moment of force) in both directions. Due to the softness of the tissue and due to the necessary gentleness of attachment, dead zones may appear during regulation. On the other hand, there is a certain advantage in terms of rehabilitation. The user has to try and the exoskeleton will help him.

1.2.2 Measurement based myo

The basis of this technology is the sensing of biological signals. The user wears electrodes that can record muscle contractions. A big advantage is that it is not necessary to pay as much attention to the separation of forces as in the previous case. Even if some external force acts on a part of the limb, it will not affect the steering of the skeleton. It only reacts to signals in the user's muscle. It is even possible to take this sensing technology to a higher level and sense impulses directly from the nerves. In this way, even paralyzed users can control the exoskeleton. This approach is used, for example, by the Japanese company HAL cyberdyne.
A disadvantage can be the greater technological complexity in the processing and evaluation of the biological signal. It is also necessary to stick the electrodes with each use. Which could, from a practical point of view, be an obstacle to mass expansion in the field of construction and other work in a "dirty" environment.

1.3 Control

In this section, two different types of control are described.

1.3.1 Control type: base - end point

This approach is based on the assumption that the purpose of the exoskeleton is to get the ends of the limbs into the intended positions, regardless of the exact configuration of the exoskeleton's arms. In such a case, some base is determined where the exoskeleton is firmly attached to the user. It is most often in the lumbar region. The exoskeleton has an arm system with enough degrees of freedom to adjust to match wrist and ankle positions[7]. At the same time, the exoskeleton tries to approximately copy the user's limbs with its arms.
The advantage of this solution is universality in terms of user dimensions. Exoskeleton does not need to adjust the length of individual arms for a specific person. Thanks to this, the problem of various clearances, deviations

and inaccurate adjustments of exoskeleton parameters for a given person is eliminated. On the other hand, in each movement configuration, the arms will be folded differently and will therefore occupy a different space. As a result, it is not entirely easy to fit this type of exoskeleton with a protective frame or armor, because these elements could collide with the user in some positions. Given that the exoskeleton is designed specifically to handle heavy objects, this can be a safety disadvantage. This type of solution therefore has potential especially when working with blunt, heavy objects that are not inherently dangerous to humans.
Alternatively, there would be a possibility to design the structure of the exoskeleton for specific types of human body, so that the user's limb system closely copies. Then, protective elements could also be applied to the skeleton.

Types of sensing

This type of exoskeleton can be controlled both by measuring forces and by means of electrodes. In the case of forces, the solution here is significantly simpler. It is necessary for the end member (e.g. the wrist) to be able to sense forces in all 3 directions and likewise all 3 moments of forces. Thanks to this, the exoskeleton is put together in the appropriate position. However, it is probably advisable to add a control sensor (remote) in the middle of the arm chain. This will make the configuration as similar as possible to the configuration of the user's limbs.

Several transformations must be made when using electrodes. The system must know the exact position of a particular limb and at the same time the chain of limbs behind it. Thanks to this, they have to calculate exactly how the force will be transferred to the end member in the chain of the user's limbs. And exactly in which direction this end member will act against the skeleton. After evaluation, the system will give an impulse to the motors and adjust the configuration of the exoskeleton to suit the user.

1.3.2 Control type: limb - limb in isolation

This approach is already outlined in the chapter on force measurement control. This is a case where I will measure the moment of force between two parts of the limb or sense a biological signal on the relevant muscle. It is therefore the control of one isolated joint. This way, for example, the ankle, knee, hip can be solved isolated[12]. It is not strictly necessary to know how the rest of the system behaves for individual controls. So it's a fairly naive approach, and it almost seems like it can't possibly work. However, it should be emphasized that the exoskeleton is not controlled by itself, and has one more feedback that takes into account the entire system. That feedback is the person himself. It is obvious that during use there will be various deviations from the ideal position that corresponds to the user's limb, and it might seem that there may be a chain of deviations at each other joint. However, the person himself knows what is right and the exoskeleton forces him to take appropriate actions.

The advantage is the simplicity of management. The disadvantage is the fact that it is necessary to ensure that the lengths of the individual arms correspond exactly to the person's figure. At the same time, there is definitely a need to have more joints globally compared to control type: base end point. It is necessary to ensure the same number of degrees of freedom between the individual joints, which corresponds to the degrees of freedom of the respective human joints. This type of exoskeleton is described in [15]. To be more precise, a rehabilitation device focused on the elbow joint and forearm was designed. The authors used metallic parts for the main structure, but they managed to build it relatively lightweight. By its parameters, relatively corresponds to the area of the hand we will focus on.

1.4 Conclusion

A reasearch was carried out in the field of already existing solutions. Furthermore, it was found out how the individual types differ and on what principles they work. How are sensors and control handled. It was also found that the type of solution is highly influenced by the specific application and the appropriate solution is selected accordingly.

The part of the exoskeleton supporting the arm and wrist muscles was selected as the subject of investigation. An isolated control method was selected. So each limb is supported by the next one. At the same time, it will use a principle relying on force measurement.

However, this case is a bit special. These two joints cannot be measured separately. This problem will be more clarified and solved in later chapters.

It turned out that 3D printing rarely appears in current solutions. However, this technology gives many advantages such as easy replicability, customization, or very fast component repair. However, it also has disadvantages related to material limitations. These will be discussed during the design. However, the biggest advantage is the price. If the device could be manufactured using 3D printing, it is then possible to spread it to the general public. It could be purchased by any person, not just by clinics.

In such a case, it also makes sense to implement games that would help keep the user with the rehabilitation machine. Thanks to the increased motivation, the user would spend a longer time rehabilitating and thus the overall recovery time would be shortened So there is an exiting yet unexploited opportunities.

Chapter 2

Aim of Thesis

This chapter explains the several points of aim of this thesis, describes the steps that will be taken, and limit itself to the topics that not will be covered.

2.1 Aim

Firstly, we gathered information about the current state of the art of rehabilitation techniques. Therefore, the main effort will be to create device that will solve requirements for rehabilitation itself, and will be designed in a way that corresponds with availability for general public and meet other requirements mentioned in the assignment. First steps will lead to build a proposal of device design. It is important to write down all requirements and build a conceptual diagram. The best solution should be chosen based on properties of mechanical parts. The device will be apparently constructed from two main parts. Base part will be attached to environment together with upper arm and second part will move along. Second part will be designed and constructed as the first one, thus expected higher complexity which could affect final design of the base part.

After preparing physical design, electronics will be next to resolve. According to assignment of thesis the STM32 family microcontroler will be used. When electronics will be matched with hardware, the application will be programmed to control the device. Finally, the device will be tested and ways of using it will be shown.

2.2 Not aiming

The thesis is trying to find solution just in a manner of possible technical solutions. The author is not equipped with rigorous anatomy knowledge and thesis does not even attempt to cover all the anatomical pitfalls. Thesis and device itself can serve as an example of the possibilities of a low-cost rehabilitation facility. Communicating and presenting of ideas and solutions between the technical and medical fields is often difficult and misunderstandings occur. Therefore, it may be best to first build the first prototype and then evaluate it in reality. In the future, it is necessary to invite several experts from the field of physiotherapy and let them evaluate the equipment and discuss possible extensions or modifications with them. But this is not, and even should not be, within the scope of this work.

Chapter 3

Proposal of device design

The goal is to build a low-cost-prototype, inexpensive device that would facilitate the rehabilitation of the disabled. It is focused just on the wrist area and the elbow area. For proper design, it is necessary to understand current problems and needs at first.

3.1 Problems

Some negative influences often enter the course of rehabilitation. The following lines describe them:

1. A disabled person often has a problem with motivation to rehabilitate. Here are the two most common causes:
    a. The exercises intended for the disabled are too monotonous, stereotyped and the disabled do not see any added value in them apart from the rehabilitation itself. However, if the disabled individual connects to a device that will record his movements, he can, for example, play games through it.
    b. Carrying out a certain movement is too much effort for the affected person. This represents a kind of comfort barrier that the disabled must constantly overcome. The solution could be to make the disabled person's movement easier, i.e. to help him physically. That

is, add some action that will correspond with his movement. If we were to implement this idea to perfection, the disabled person would be able to perform normal activities and at the same time, rehabilitate.

The rehabilitation itself can be performed with varying effectiveness. For better efficiency, it would be appropriate to increase the difficulty of the movements as the limb is improving. More precisely, characteristics of enlarging difficulty should be appropriate to performance characteristics of limb improvement. This property is achievable by measuring and controlling the force feedback. Therefore, the idea is to build a cheap universal device to solve the above-mentioned points.

3.1.1 Requirements

From the gathered information, it is needed to build an apparatus that will allow the following:

1. Measurement of the moment of force in the forearm axis.
2. Measurement of the absolute angle of rotation in the forearm axis.
3. Generate a moment of force in the forearm axis.
4. Measurement of the moment of force in the elbow axis
5. Measurement of the absolute angle of rotation in the elbow axis
6. Generate a moment of force in the elbow axis.

Those points are a measurement and action properties. There are different words and labels for the parts of the arm and it could be very easy to confuse the parts. Therefore, nomenclature will be introduced to help separate these parts from each other. It is displayed at fig. 3.1. Figure displayed part that is called arm. The part closest to body is called the **upper arm** (brachium in latin). The joint that connect upper arm and the other parts away from the body is called **elbow** (cubitus in latin). The part behind the **elbow** is called **forearm** (antebrachium in latin). Last part is called **hand** (manus in latin). **Hand** could be divided to **palm** (palma manus in latin), which covers the bottom side of the **hand**. Next, it includes **back of the hand**(dorsum manus in latin) and **fingers of the hand** (digiti manus). All names were written and emphasized in **bold**, because they mean some very specific technical term. So it should be clear that when this word is mentioned, particular part of the body is meant. These terms will be used often in following chapters.

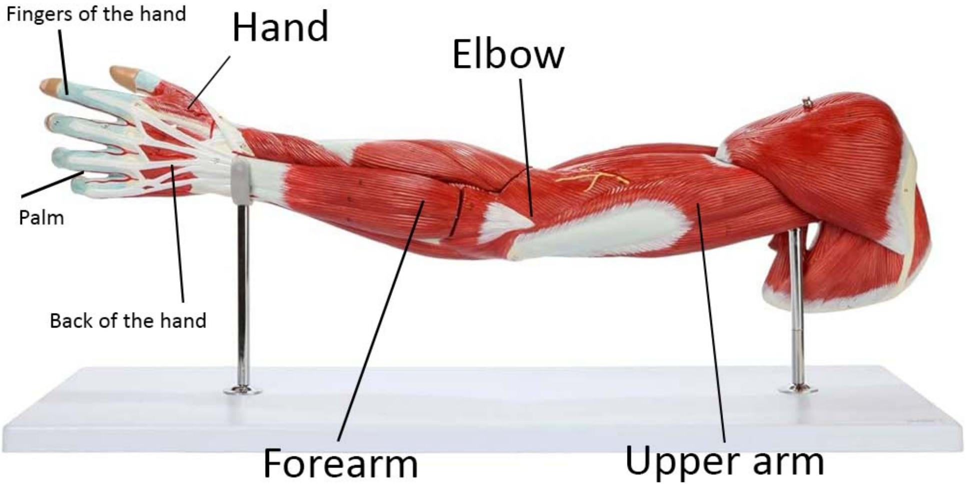


Figure 3.1: Nomenclature of the arm

Technical requirements are listed in the following table:

1. Usage of 3D print technology
2. Usage of low cost sensors
3. Ensure practicality and easy usage
4. Add some basic safety features
5. Use STM32 family micro-controller to control the device

3.1.2 Solution

According to these points, a conceptual diagram was created 3.2.

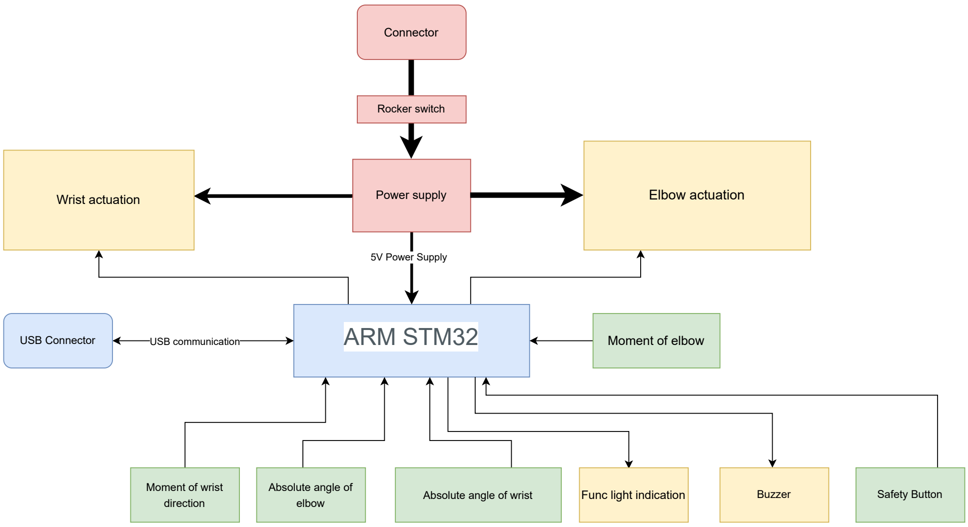


Figure 3.2: Conceptual diagram

Chapter 4

Mechanical construction

4.1 Materials

The advantage of commercial 3D printing of plastic components lies in the accuracy, which is in the order of tenths of a millimeter, and in replicability as well. 3D-printed components are also relatively light in proportion to the size of the component. At the same time, it is also relatively rigid. However, it should be emphasized that the rigidness depends on the thickness of the material. In cases when a very small but simultaneously rigid component is needed, this technology is not the best. In most cases, there is no possibility to choose a sufficiently large wall thickness.

When designing, it is also very important to take into account the orientation of the component during printing. Within the plane of the layer, the printed component has much more strength than the layers between themselves. For that reason, it is sometimes advisable to assemble the component from several sub-components so that the mechanically stressed parts have the correct orientation during printing. At the same time, it is necessary to consider the physical limitations given by the width of the nozzle. With a standard width of 0.4 mm, it is impossible to print walls with a thickness lower than 0.4 and at the same time, print the walls in the range of 0.4-0.8 (open interval). The disadvantage lies in the long printing time for larger prints.

These properties show that 3D printing is best suited for sophisticated elaborate components with lengths of roughly 1.5 cm to units of cm. It is ideal for various couplings, gears, holders, tailor-made boxes, custom sliders. However, it does not make sense to use 3D-printed technology to create an entire device that should cover the length of one arm. It is therefore ideal to combine

3D printed components with other materials. Construction materials were selected from commonly available sources. Due to the smallest possible weight, aluminium proved to be a suitable material. The best construction material was an aluminum profile 10x10mm, 1mm thick anodized 4.1a, which met the rigidity requirements and was light enough.

4.2 Forearm part

The following section will be devoted to the actual design and production of the first part of the device, which will be attached in parallel to the **forearm part** of the arm.

4.2.1 Attachment of forearm part

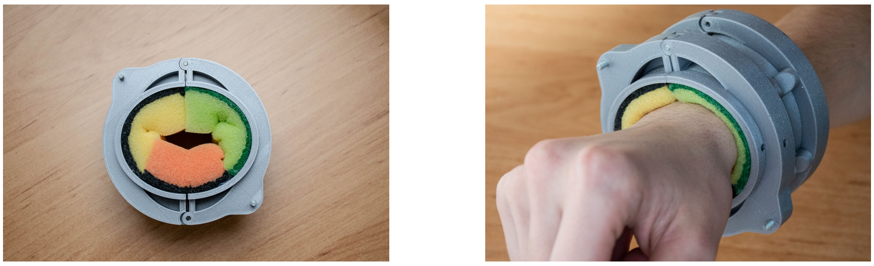
Firstly, it was necessary to figure out how to attach the limb. The ideal part of the body turned out to be the forearm just before the wrist. In this part, you can almost always palpate the bone from the sides, regardless of body fat or muscle mass. Limb should be firmly secured if this part is pinched from the sides. Furthermore, this grip can be improved by adding a flexible element between the forearm and the holder. Thanks to this, a more reliable attachment and greater universality are ensured. The first version of the holder can be seen in the picture 4.1b. Holder will be marked with the abbreviation **HolderF-arm** as **Holder of the forearm version 1** for greater clarity. As the flexible element the kitchen sponges were used 4.3a.

(a) : aluminum profile 10x10mm **(b) :** HolderF-arm

Figure 4.1: component and first holder

4.2.2 Sensing of forearm part

Furthermore, angle and torsion sensing needed to be solved. From these two tasks, torque sensing places much greater demands that must be complied with. Firstly, to clarify the task, there is the demand to measure the torque of the **Hand** that could be generated relative to the **elbow**. In that case, the torque axis passes through the **elbow** joint and the **Hand**. The case is illustrated in figure 4.3b for better clearance. The axis will be marked as the **forearm axis**.



(a) : HolderF-arm upgraded with flexible element

(b) : HolderF-arm with human forearm inside

Figure 4.2: HolderF-arm

(a) : Disassembled HolderF-arm

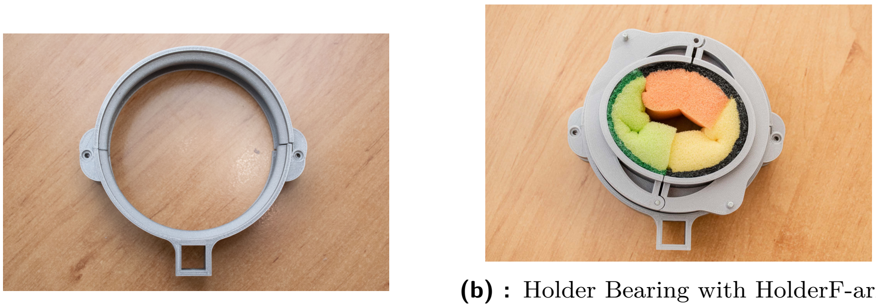
(b) : Forearm axis

Figure 4.3: Disassembled holder and axis

The torque is defined as follows:

$$\vec{T} = \vec{F} \times \vec{r} \tag{4.1}$$

Where the $\vec{T}$ means Torque vector, $\vec{F}$ means Force vector and $\vec{r}$ means the distance from the axis expressed by a position vector[3]. Let's suppose that we already have the main structure of forearm, which is moving in parallel with the forearm. This structure is firmly attached to the elbow joint. This structure will be marked as **mStructF-arm**. The torque needed must be measured between that main structure and **HolderF-arm**. But that probably would mean that **HolderF-arm** will have to be frozen in one position during torque measurement. Fortunately, the solution could be to use active support. We could design a ring that would embrace the inner **HolderF-arm**. This ring will be marked as **Holder Bearing** 4.4a.



(a) : Holder Bearing

(b) : Holder Bearing with HolderF-arm inside

Figure 4.4: Holders

HolderF-arm would be connected to other component which will be marked by **DRC** as **Drive ring component**. This component will be driven along the **forearm axis** 4.3b. The drive would be provided by motor or servo-motor. This modification will allow one to exercise in various positions and simultaneously measure the torque.

At this moment, two challenges arose. The drive motor cannot be placed along the **forearm axis** 4.3b, which means some mechanical transmission has to be implemented. The second challenge is to find a suitable torque sensor.

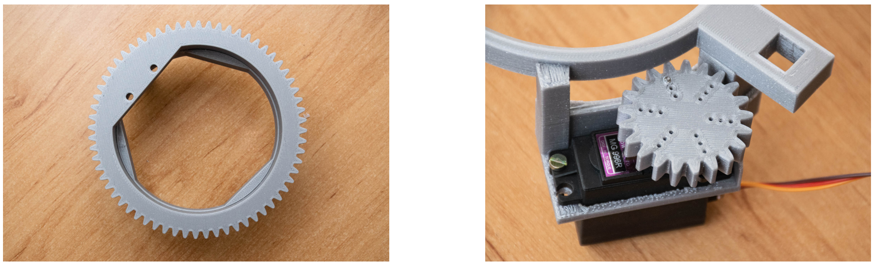
4.2.3 Drive

There are assumptions from biology that the average **Hand** can turn relative to the **elbow** at a maximum interval of 170°[9]. Therefore, it will be assumed that **DRC** needs to be able to rotate relative to the main structure in interval 200°with some added margin. If there would be a possibility to connect the motor directly along the **forearm axis** to the **DRC**, the best solution would probably be to choose a servo motor. Servo motors have the advantage of position feedback. This mean that a position is set and the motor itself ensures the correct position. But the disadvantage is that servo motors has limited range of rotation. Most commonly limited to 90°. Some of them are limited up to 180°and even some that are limited up to 270°exist.

However, servo-motors with a range that exceeds 360 °cannot be considered cheap and widely available components if they even exist.

If there was a possibility to connect the servo motor directly, it would not be a problem to use a servo motor with range up to 270°. But some mechanical transmission has to be implemented. Gear transition could be used. Tooth gears were added at the **DRC**(see fig. 4.5a). There was an effort to keep the teeth as small as possible but at the same time maintain a sufficient number of perimeters during printing. The perimeter is the boundary line forming the shell of the printed part. Due to the optimization of the rigidness properties of 3D printing, a gear module of 1.75mm was chosen. The whole gear ring has a pitch size of $d = 112$mm and 64 teeth. A servo motor AX12A with 300°interval is probably the servomotor with the greatest operational interval we could afford. But even so, this servo-motor is quite expensive. In that case we need to convert 300°to 200°. That leads to 1:0.662 ratio. Which means, second gear need 43 teeths at minimum. Such gear would have a pitch size of $d = 74.14$mm.

According to calculated pitch size, such size of driving gear was considered as too big and impractical. Choosing a motor with continuous rotation allow to use a smaller gear at the expense of position feedback. And it will be a better strategy. For that reason, the MG996R with continuous rotation servo motor was chosen 4.5b. This motor is basically a standard MG996R, which was modified, and an internal stop was removed. Servo motor can now turn continuously, but the position feedback is removed. On the other hand the secondary gear could be designed much smaller, precisely just with 21 teeth 4.6a. To summarize final parameters, the table follows.



(a) : DRC (Drive ring component)

(b) : MG996R with gear

Figure 4.5:

gear	pitch diameter	module	number of teeth	angle of pressure
driven	112mm	1.75mm	64	20°
driving	36.75mm	1.75mm	21	20°

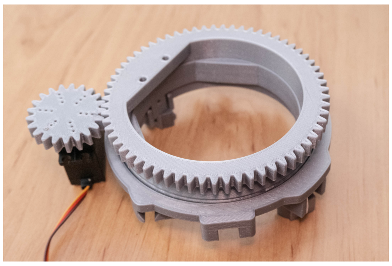
Table 4.1: table of gears parameters

The size of the individual wheels is given by the formula:

$$d_r = m \cdot t \tag{4.2}$$

$$\tag{4.3}$$

where d_r is the pitch diameter, m is the module of gear, t is the number of teeth,



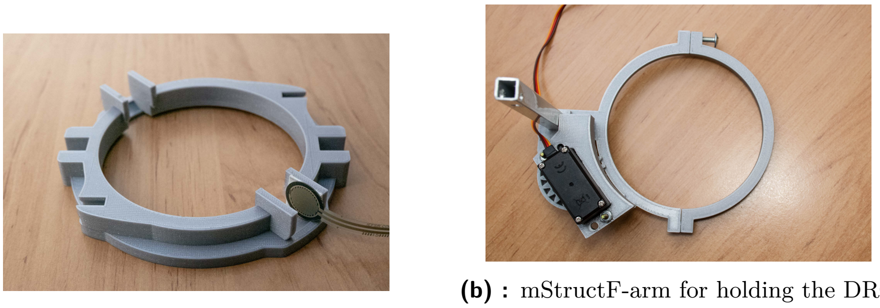
(a) : Gear assembly

Figure 4.6: Gears

4.2.4 Torque sensor

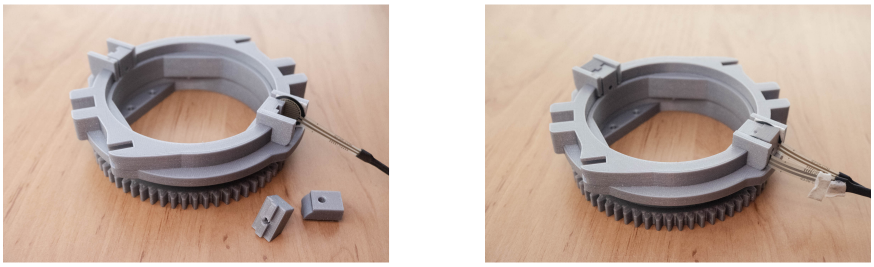
Commonly available torque sensors are usually designed to be placed in the axis of rotation. However, this is no option in this case. Therefore there is needed other solution. Torque could be measured by the force applied on the lever with known length according to 4.3.
Force measurement can be implemented in many ways. The advantage of a strain gauge element is the ability to measure the force in both directions. It is relatively accurate, and scalable - from 0.6kg, 1kg, 2kg, 3kg, up to 5kg and 6kg. On the other hand, these sensors are quite big for this particular application. The usual size of one such sensor is 12.7mm x 12.7mm x 80mm.

Another option is to use FSR sensors. These sensors are compact and small. Printed on laminate in the shape of a flat cylinder with a diameter of around 20 mm and a thickness of up to 1mm. Unfortunately, sensor gives the information only about mechanical pressure/ force in one direction. Therefore, two of them are needed to measure the force in both directions. Thanks to small size, FSR sensors were chosen for this application. Sensors were installed between **DRC** and **HolderF-arm** by FSR attaching component(**FSR-AC**). Attachment is displayed in figure 4.8a.



(a) : Attachment of FSR sensors **(b) :** mStructF-arm for holding the DRC (without DRC on picture)

Figure 4.7: Couplings



(a) : Disassembled attachment of FSR **(b) :** Fully assembled FSR attachment

Figure 4.8: FSR Attachment system assembly

4.2.5 Modification due to complexity

This description was given by the assumption that it is needed to solve just the part of **forearm**. But it is needed to measure the torque in **elbow** (torque in axis which is perpendicular to **forearm** and **upper arm**). Lets suppose that **Holder Bearing** will be attached through force sensing element to **mStructF-arm** 4.9. In case of sensing torque in elbow, torque would be blocked by **DRC** attachment. Therefore, it was necessary to create special joint between **HolderF-arm** and **DRC** (more precisely **FSR-AC**). Joint should transmit torsion, but at the same time allow the slight displacement

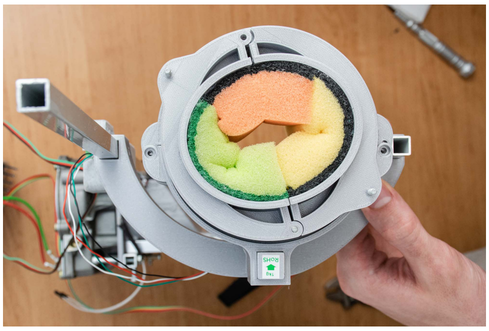


Figure 4.9: Force sensing element and **Holder Bearing**

in directions perpendicular to the axis of rotation 4.11.

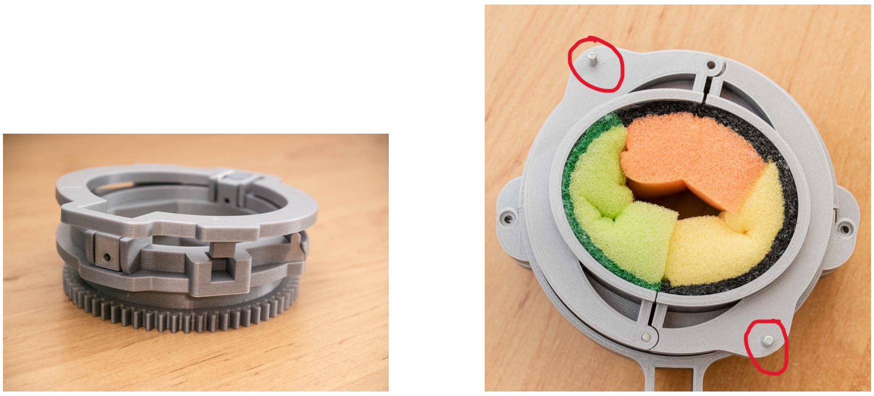
(a) : Displacement in vertical direction, upper side

(b) : Displacement in vertical direction, bottom side)

Figure 4.11: Displacement

4.2.6

Thanks to that special joint, it will be ensured, that torque of the elbow will not be blocked by any other component, and measurement will be valid. Special joint was designed by two perpendicular sliders that are implemented between **DRC** and **HolderF-arm**. One of the sliders was created fully by 3D printed mechanisms 4.12a, the other one was created by combining two elongated holes and the two metric bolts attached at the **HolderF-arm** 4.12b.



(a) : 3D printed parts on both sides

(b) : Elongated holes and bolds

Figure 4.12: Sliders for special joint

4.2.7 Angle sensing

As the best sensor of angle sensing, was AS5600 chosen. Reasons are written in more detail in Chapter 5 (5.6). Sensor works as magnetic rotary encoder. Sensor has to be attached at one part in the axis of rotation. On the other part is attached magnet, also in the axis of rotation. There is demand to measure the angle between **HolderF-arm / DRC** and the **mStructF-arm**. But sensor could be installed in those due to its requirements of axes. Therefore, sensor was attached at **mStructF-arm** 4.13a and the magnet was attached at driving gear that drives **DRC** 4.15b.

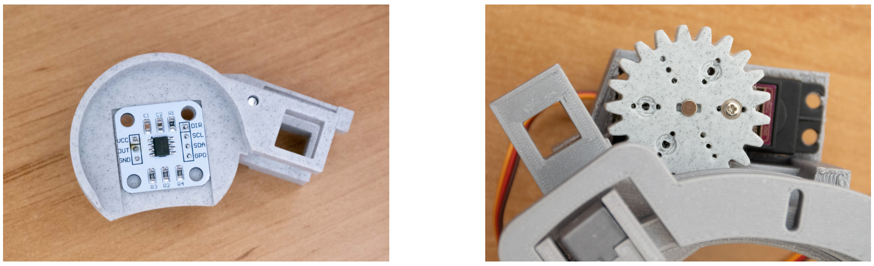

(a) : Attachment of AS5600 **(b) :** Gear with magnet attached

Figure 4.13: AS5600 physical implementation

However, it is necessarily to take in account the gear ratio 21:64. From the assumption of rotation 200°of **DRC** it leads to rotation of 1.69 of turns at driving gear. Respectively, to turn 200°with bigger gear means to turn 609°with smaller gear. Therefore, sensor gives two same values for different angles at the **DRC**. Fortunately, this problem could be solved, by adding the micro-switch at the **mStructF-arm** which will be triggered by the protrusion from **DRC**. This protrusion has to be installed in a way that micro-switch will be triggered on half of interval of rotation of **DRC**. For better understanding, it is recommended to see figures 4.15. Micro-switch was also covered by a cap to prevent accidental triggering by hand 4.15a.

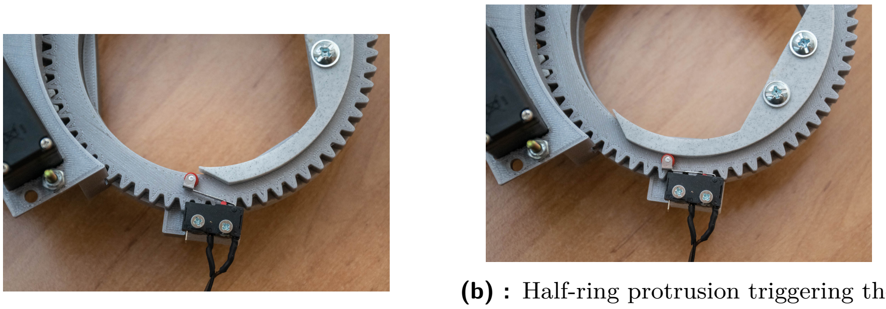
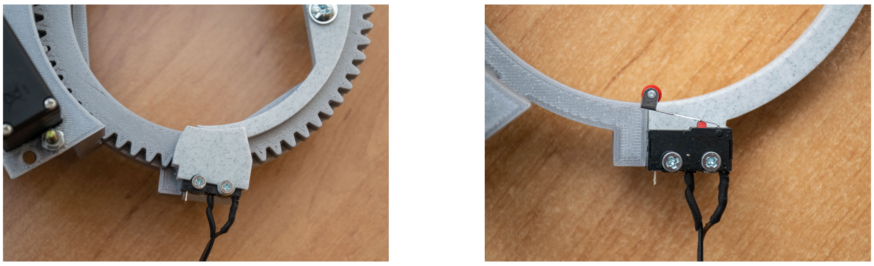

(a) : Micro-switch attachment **(b) :** Half-ring protrusion triggering the micro-switch

Figure 4.14: Angular distinguish solution



(a) : Micro-switch attachment covered with cap

(b) : Switch itself attached to the mStructF-arm thru ring

Figure 4.15: Angular distinguish solution detailed

4.3 Upper arm part

Let's suppose that body part of **upper arm** will be pinned to **the base structure**. **The base structure** will be be attached to environment (e.g. to some table, board etc.). **Base structure** will also carry electronics. Secondly, the joint ensuring the rotation in elbow axis has to be built. Firstly, type of drive has to be resolved.

4.3.1 Joint and Drive

Requirements in term of torque are much bigger in compare to wrist part. This drive has to be strong enough to lift whole forearm part of the device when it is in a horizontal position (maximum torque against drive created by gravitational force) and plus some margin for potential case of lifting some object. Whole forearm part has weight 530 g and center of balance is around 25 cm from the elbow joint. That means that $T_{fp} = 0.53 \cdot 0.25 = 0.1325 N \cdot m^{-1}$ when forearm part is in horizontal position. It was also chosen that in motion-support mode device should be able to lift a cup of water at minimum. In that case, center of the cup will be placed around 35cm from the center of the elbow joint. Lets assume that this cup could have weight 1kg. Then, cup of tea could generate up to $T_{cup} = 0.35 \cdot 1 = 0.35 N \cdot m^{-1}$ in case of static positions. When the torques are summed, $T_{all} = T_{fp} + T_{cup} = 0.4825 N \cdot m^{-1}$. This torque is present in static case without any other additional dynamics. In real situations, dynamics forces will be present for sure. It will be reasonable to add margin to cover them. Therefore, the value was multiplied by 3 and rounded. Required minimal momentum for this purpose will be then $T_{req} = 1.5 N \cdot m^{-1}$. The first assumption was the use of a servo motor due to its position feedback. However, such high value torque is not something common in list of hobby servomotors. Instead, industrial servomotors had to be used. But such servomotors are really expensive, unnecessarily robust and heavy. Thus, it make sense to look for other solutions.

Second idea was to implement standard joints on both sides of the elbow, as two bearings, to be more precise. Then, the drive would be attached on the bottom side of the elbow in the form of a linear motor or piston. This solution will ensure sufficient Force/Torque for sure. On the other hand, it will require mechanical levers and other moving parts sticking out to the sides. This turns out to be not practical and it even could be dangerous, especially when considering rehabilitation device.

Third idea turns out to be the best from the mentioned. There is a possibility to use a big DC motor 24V with a gearbox. Such motors are really common in various devices. They are quite cheap or easy to obtain from an old device. The particular motor used in this device was taken from an old garage opener 4.16.

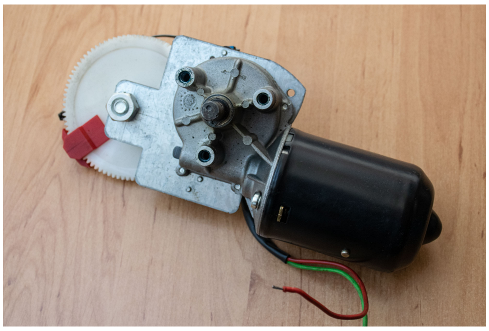
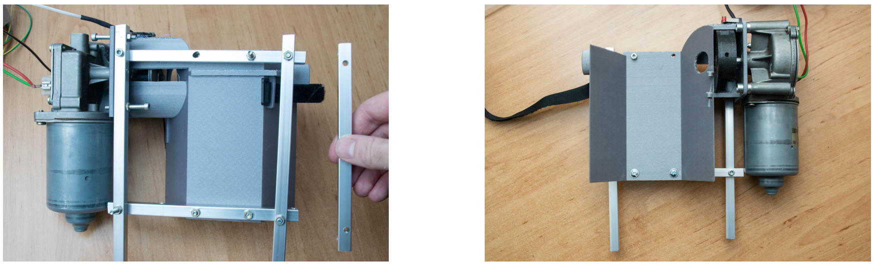


Figure 4.16: DC motor

This motor was originally powered and controlled via original PCB of the garage opener. But this particular PCB was 20cm by 15cm which was too big for this purpose. PCB has also included own power supply which convert 230V AC to 24V DC via massive transformer and then rectified by Graetz bridge. This solution is not even suitable for this project because this values are not considered as a safe voltage. Thus it was decided that it will be better to supply motor directly from prefabricated DC power supply. Such as those which are used for powering laptops. Connecting 12V DC power supply and H-bridge should lead to full control over DC motor. According to tests which were made with this particular motor, it turned out that at least power supply of 4 Amperes is needed. It is known that other servomotor could take up to 1.3A at 5V in its maximum consumption. There is assumption that micro-controller consumption will be up 100mA at 5V. When consumption of these two is summed and presence of step-down is taken into account, it could be told that power supply with 5A should be enough to power whole device. Therefore power supply 12V DC 5.417A from Delta Electronics was chosen.

4.3.2 Shape

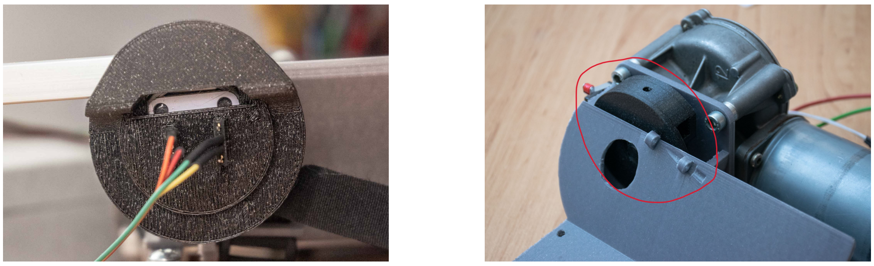
Now, way of assembly has to be resolved. DC motor was modeled in CAD software. Also steal bearing was added into design. Dimensions and shape of human upper arm was measured and approximated. Thanks to gathered information, supporting shape was designed. In figure 4.17b can be seen as a shape similar to trough. During design, the thickness of flexible padding was taken into account. The final form of printed component can be seen in figure 4.17b. Printed component itself was not rigid enough, so it was reinforced with aluminium profiles from the bottom side 4.17a. Connections were made by M4 bolts. Elbow joint is than created by steal bearing on left side and by shaft of the motor on the right side. Attachment to **mStructF-arm** was achieved by two 3D printed (black) components on each sides 4.18.



(a) : Base component from bottom

(b) : 3D printed base component

Figure 4.17: Base component



(a) : Left coupling (bearing)

(b) : Right coupling (motor shaft)

Figure 4.18: 3D printed couplings

4.3.3 Additional features

Main 3D printed part has also features determined for attachment of Velcro strap. This velcro strap is used for pinning the elbow part to the **Base structure** from up just at the point of joint flexion 4.20a. Next, the trough part was covered with flexible padding 4.21b. Aluminium profiles parallel to upper arm were prolonged at 23 cm instead of original 16 cm cause end of the profile serves now as the holder for second pinning 4.21a. Two components were printed in way that could be slid on profiles and holding second strap. Second strap was created combining fabric elastic band and Velcro strap 4.20b. Elastic element was added because upper arm is pinned specifically around the biceps which means that the strap must be able to change its length while one exercising.

(a) : Front Velcro strap pinning left **(b) :** Front Velcro strap pinning right

Figure 4.19: Straps

(a) : Biceps Velcro strap pinning unfolded **(b) :** Biceps Velcro strap

Figure 4.20: Straps

(a) : Holder of biceps Velcro strap **(b) :** Flexible padding

Figure 4.21: Attachment and padding

4.3.4 Angle of elbow

Due to the selection of drive, there is no position (angular) feedback of the motor yet. From the range of available sensors AS5600 was used because of its good results in previous case. Component connecting steal bearing and the **mStructF-arm** was modified 4.22a. Sensor AS5600 was mounted in this component and the magnet was inserted inside the bearing where was mounted in prolonged cylinder 4.22b. It is worth mentioning that the front parts of the both AS5600 are covered with transparent adhesive tape. It will not affect the measurement, but at the same time it can protect the chip in the event of an accidental short circuit caused by the connection of some terminals through a conductive magnet.

(a) : Modified component **(b) :** Magnet inside and sensor mounted

Figure 4.22: AS5600 assembly

Chapter 5

Control Unit Design

5.1 Introduction

When we take in account previous remarks and requirements, we can conclude to following list of specifications.

1. 12V PWM (5A) output to control motor at elbow
2. 5V PWM output to control servomotor
3. Measurement of force from strain gauge
4. Measurement of force from FSR sensors
5. Measurement of the absolute angle of rotation at the elbow
6. Measurement of the absolute angle of rotation at wrist

This list will lead to more particular specifications for the controller. It is also clear that external H-bridge will have to be used. According to high current demand, up to 5A, model BTS7960B 5.6 was chosen. The model is designed to handle 43A, so it has sufficient current margin for project purposes. According to datasheet, two PWM signals are needed to control H-bridge in both directions. From the information gathered, the following pin specifications were built.

1. 2x PWM pins - H-Bridge
2. 1x PWM pin - servomotor
3. 1x GPI + 1x GPO pins - Tensometr
4. 2x AD convertor pins - FSR
5. 2x2=4 pins with I2C support - angle measurement
6. 1 GPIO pin - angle at servo - distinguish position
7. 2 GPIO pins - buzzer and LED
8. 1 GPIO pin -safety switch

As the core of the Electronics, the development board BlackPill was chosen. The BlackPill is equipped with microcontroller STM32F411. This Microcontroler was chosen due its low cost and simultaneously meets the requirements for evolving device. This microcontroller also has the opportunity to power from external source that means device is not fully dependent on PC or other control platform. Microcontroler comes from ARM family and board is programmable via SWDIO connector.

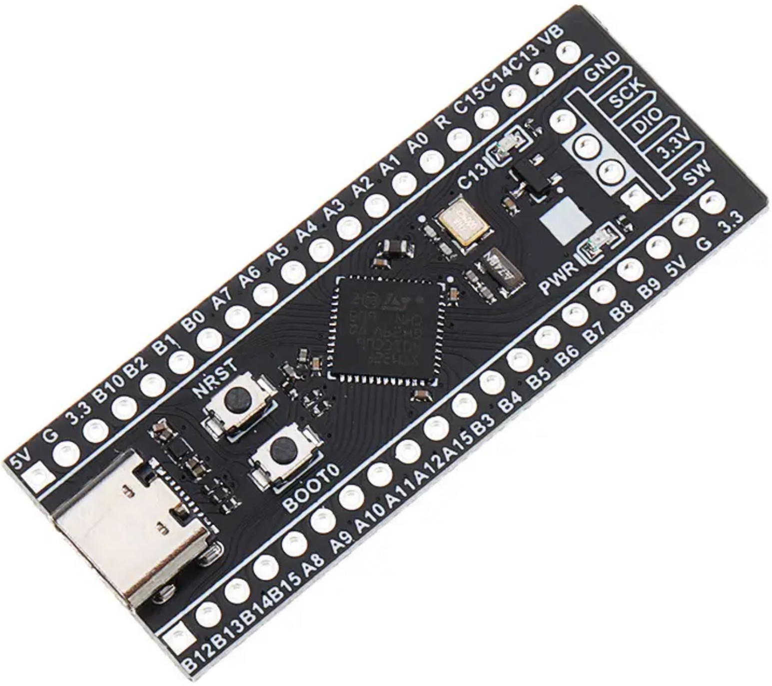


Figure 5.1: Blackpill development board

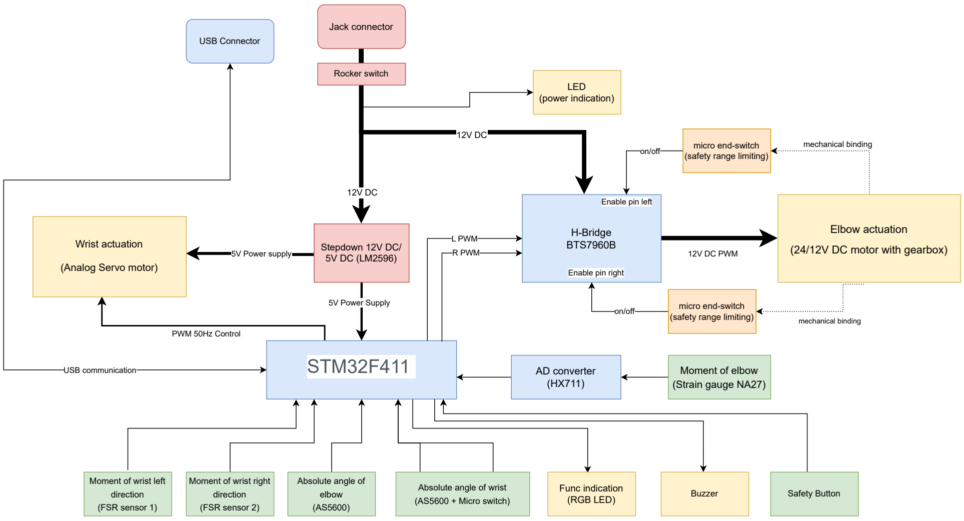


Figure 5.2: Block Diagram

5.1.1 Programming connector

To upload a program from the computer to selected MCU, some intermediate device is needed. In the case of the STM32 series, it is an ST-link. It can be purchased as a standalone device but is also built-in in the NUCLEO development boards. ST-Link serves as a translator which converts program information that comes via USB, and after conversion send them via SWDIO to board. In Figure 5.3, the St-link is highlighted by a red frame.

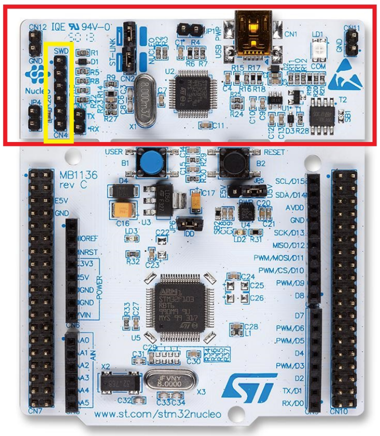


Figure 5.3: ST-link included in NUCLEO board

There is a 6-pin SWD programming connector in the front part of the

NUCLEO development board. It includes VDD, SWCLK, GND, SWDIO, NRST in this order. The sixth pin is SWDO, which is used for feedback communication. However, this pin is not supported by selected STM32F411 and is not even needed for the application. SWD programing connector is highlighted by yellow frame in figure 5.3.
As a programming connector 5-pin header connector with a pitch of 2.54 mm will be used.

5.2 Forearm actuation - Servomotor

As the servomotor for the wrist actuation model, MG996R with continuous rotations was chosen. The reason why the model with continuous rotation was chosen instead of standard one, is the insufficient angle of rotation in the wrist. The requirement is to turn at least 360 deg, but unfortunately, the standard model of MG996R, even with an extended range, has a maximum angle of 180 deg. For reminder, an angle 360 deg is needed because of gearing. The forearm itself has to be able to turn 180 deg, but that means 360 deg turn for servomotor. The fact that the servo has continuous rotation means that the servo doesn't act as a proper servo. That means that position feedback was cut during modifications and now servo has no information about absolute position. By giving information with an angle, the servo sets RPM instead. The greater the position value given, the greater the rotation speed. For our purposes it is not crucial in case of control. In the case of gathering information, a separate sensor is going to be used that allows to read out the angle. Model MG996R is analog servomotor, meaning that control is

Figure 5.4: Servomotor

provided via PWM signal at 50 Hz. Position (speed rotation in this case) is proportional to the value of the duty cycle. More precisely, when the duty cycle is 1ms, the value of left rotation is at the maximum. When the duty cycle is 1.5ms, motor stops. When the duty cycle is 2ms motor turn to right at maximum speed.[17]

5.3 Elbow actuation - Motor

Motor at elbow position is supposed to be strong enough to turn with whole forearm plus construction itself. Calculations to make expert estimate of sufficient torque were made. It turns out that for smooth operating with added reasonable margin, torque about $5N \cdot m^{-1}$ According to these properties, was clear that servomotor similar as in wrist case, cannot be used. Theoretically, servomotors with such force exist and it is possible to buy them, but the are too expensive. Price should be also reasonable in this case because goal is to evolve all-available home-rehabilitation device.

But better solution it turn outs to be usage of standard 12-24V DC motor with gearbox. This particular motor was dismantled from old garage door opener. This motor was assembled to original control unit, which is however not needed for this case. Motor was originally supplied by heavy transformation which convert 230V to 24V. But only 12V will be used for this case. Thanks to metal gearbox, motor is strong enough, even with extra margin. Original control unit provides control via radio, setup of ending positions, changing rotation speed and direction, power supply. But on the other hand, it was too dimensional and heavy due to tranformator. In case of this project, regulation rotation speed and direction + resolve endpoints is needed. Therefore control unit can be easily replaced by H-bridge BTS7960B 5.6. This H-bridge has 8 pins but for a project only 6 of them are relevant

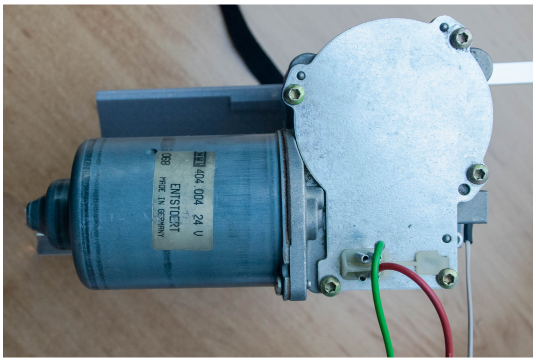


Figure 5.5: Motor

according to[4]. Two pins are determined for power supply, RPWM pin is determined for PWM control in right direction, LPWM pin is determined for PWM control in left direction. Pins R_EN and L_EN are pins for enabling each directions. These pins could be use in direct connection with end-switches. That ensures that motor will not destroy anything due to getting out of safe range. H-bridge board has also attached passive heat-sink.

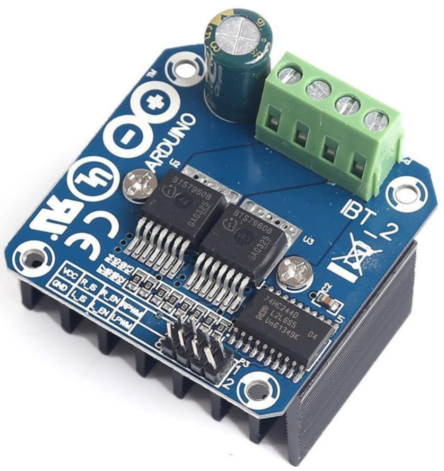
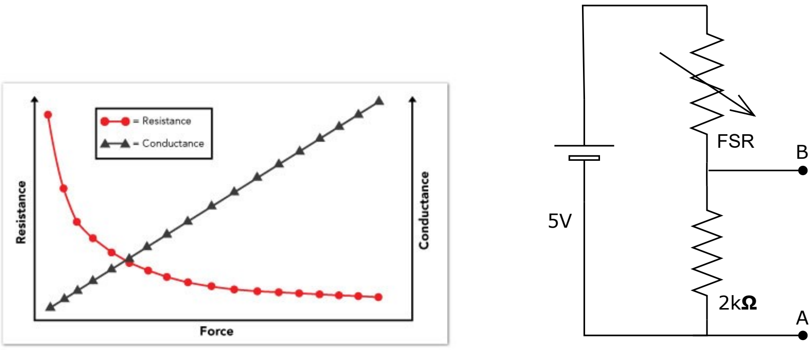


Figure 5.6: H-Bridge

5.4 Forearm moment - FSR sensors

To measure the moment of a wrist, FSR sensors were chosen. FSRs sensors allow to detect physical pressure, in way of squeezing and weight/Force. They are simple to use and low cost. The FSR is made of 2 layers separated by a spacer. When sensor is pressed, the more of active element dots touch the semiconductor and that makes the resistance go down. When the sensor is unloaded, it has a high resistance (Megaohms) that is reduced as force is applied (to Kiloohms). Characteristics of resistance reduction is exponential 5.7a. On the other hand the conductance characteristics is linear within the sensor's designated force range. FSR sensors are not very accurate in general. The accuracy is stated to be around 10 percent. But it is sufficient for this purpose. In this case, device contains two sensors which are both connected according to figure 5.7b.

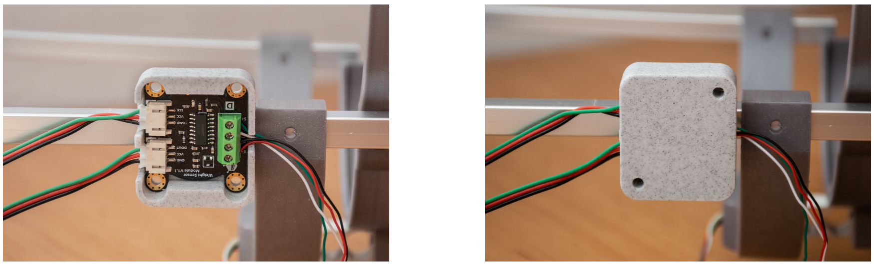


(a) : FSR characteristics **(b) :** FSR scheme

Figure 5.7: FSR properties

5.5 Elbow moment - Strain gauge

As the strain gauge to measure moment of elbow, the NA27 was chosen. The sensor is connected to weight module with AD converter HX711. Weight module has 2x3 wires in total. Each 3 wire cable contains GND and VCC. Last pin is clock for one cable and data pin for other cable. A case for weight module was 3D printed 5.8. It has added holder so it can be attached to main aluminium profile.



(a) : Case of weight module **(b) :** Case of weight module with cap

Figure 5.8: Weight module

5.6 Angle of elbow

There are several types of sensors of rotation. There are with absolute angle and also with relative angle. For this case was appropriate to use type with absolute angle. It turns out that magnetic rotary encoder could be the best solution. Type AS5600 was chosen. Sensor should be quite resistant against changing air gap between sensor and magnet and should have a range of maximum 3mm of air gap[1]. Sensor has the capability to communicate via I2C, or to send data via PWM signal. Also has a reserved pin, which gives direction information. Finally, there was a decision to use only 4 wires. Two wires for power supply and two wires for I2C.

5.7 Angle of wrist

The disadvantage of this type of sensor itself is that it has to be placed in the axis of rotation. This could be problem in case of measuring angle of wrist because we are not able to place the sensor inside hand. Therefore, the sensor is placed on the axis of the driving gear that is mounted directly on the servomotor. However, gear ratio is not 1:1. It is exactly 2:1, which means that the angle has to be recalculated. At the same time, this means that the servomotor can be in two different positions, but the sensor shows the same angle. To resolve that problem, the micro-switch connected to gear ring was added. The ring has protrusion on the half of its circumference. This protrusion triggers the micro-switch, so the problem with same angle is resolved.

5.8 Power supply

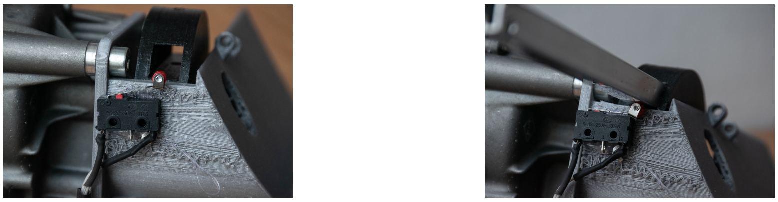
There was a question of how to power supply all electronics, especially the motors, but simultaneously stay at a safe voltage. During laboratory experiments with motors, it was found that a minimum current at 5 A is needed to run the elbow motor at 12V reliably. Therefore, there was a need to find a 12V source of at least 5A. Fortunately, such sources are produced as power sources for laptops. These sources are very often with jack connectors. That was why the electronics case had the jack as the main power source plug. The model DPS-65VB LPS from Delta Electronics was chosen. The next advantage of the solution is that in case of power supply damage, the power supply is easily replaceable.
Microcontroler and also the servo motor have to be powered. Both are designed to 5V. That means that there is a need to convert voltage from 12V to 5V.
One of the most energy-efficient way to convert voltage is a step-down converter, also known as a buck-converter. Principles of those converters are based on coil properties.

It is possible to use a linear regulator, but it is inefficient, especially with such a large voltage drop and current flowing. Therefore, step-down converter or buck-converter is more preferred solution. It is known from the documentation[14] that the consumption of STM32F411 will probably not be higher than 100mA. It is also known from datasheet of servomotor MG996R that power consumption will not be greater than 2.5A at 6V in any case.[17] According to previous information, the converter was chooses up to 3A for reliability.

The step-down converter generally works as follows: There is a switch in the main control chip, which opens/closes at a variable frequency. So it creates something like a PWM with an input voltage range. In the first phase: This PWM passes through the coil, and there is a voltage drop across it. At the same time, the block capacitors behind the coil are charged. The current returns from the load directly to the ground.
Second phase: The switch is closed, but energy is accumulated in the coil, pushing the current further and maintaining voltage. Decoupling capacitors help us to cover the current consumption. The current returns through the diode to the coil.
This process is constantly repeated and thanks to that it is possible to maintain the necessary voltage at the output of the converter. The circuit includes feedback, which determines the switching frequency. [8].
Powerlines from step-down converter was connected to pin designated to power supply servo motor and to the pin +5V. According to reference manual[13] pin 5V is connected to supply wire from USB via diode. So there are three situations. When supply is presented just via USB, nothing extraordinary happens. When supply is presented just via stepdown, everything works as well. When both power supply is presented, everything is also ok, because even in case of higher voltage from stepdown compared to voltage from computer, diode will prevent current flowing to computer. Therefore this connection could be made without damaging anything. Thus, the LM2596 DC-DC stepdown was used. It could support current up to 3A according to [16], which is clearly sufficient for powering MG996R and the microcontroler.

5.9 Protections

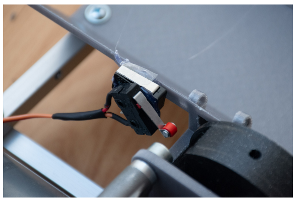
There are two micro-switches attached to the device. They serves as an end switches of the elbow joint. First switch is displayed at figure 5.9a. It ensures stopping motion when **mStructF-arm** reaches the end of the range while opening. Second end switch ensures stopping motion when **mStructF-arm** reaches upper range end while it is closing 5.10a.



(a) : Front end-switch open

(b) : Front end-switch closed

Figure 5.9: Front end-switch



(a) : Back end-switch

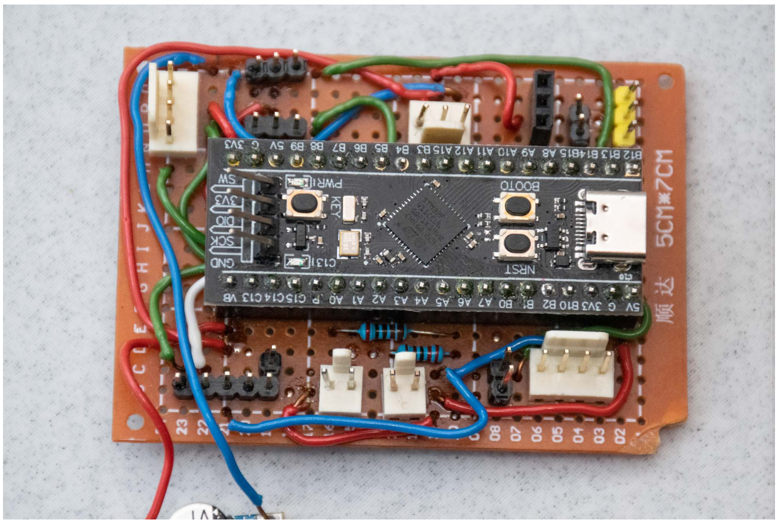
Figure 5.10: Back end-switch

5.10 Prototyping

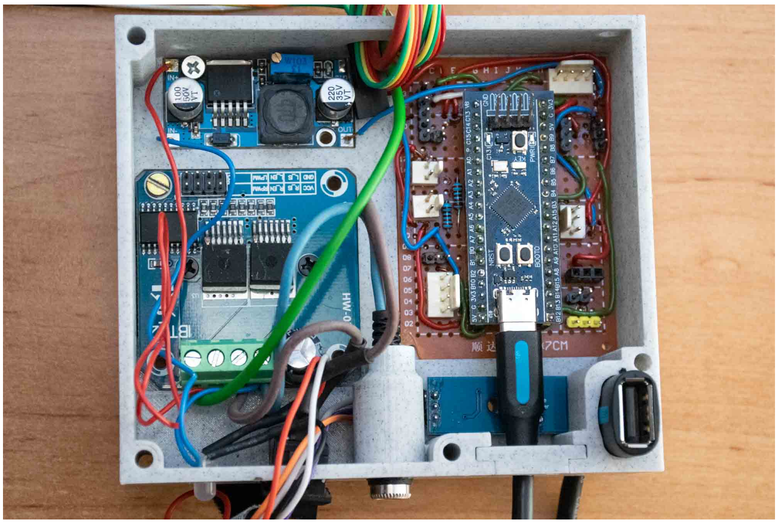
At first circuit was tested at breadboard. Engagement can be seen at figure below.Breadboard has advantage of fast prototyping, but on the other hand it is quite easy to disconnect some connections by accident. This problem should have been fixed in the final version.

5.11 Final prototyp version

As the final prototyp version circuits were transferred to soldering board. Thanks to that it will be ensured that cable cannot disconnect from the board during any manipulation. Therefore connectors with snap on protrusions were used. Next advantage is that in case of microcontroller failure, replacement is very easy. Finally, the tailor-made 3D printed case was made for electronics. The next phase could be design regular printed circuit board. However, in the current state, it is first necessary to find out if the device meets the user's expectations. PCB production could be premature and this option is a more optimal solution. If the equipment proves to be successful, PCB production is in place.

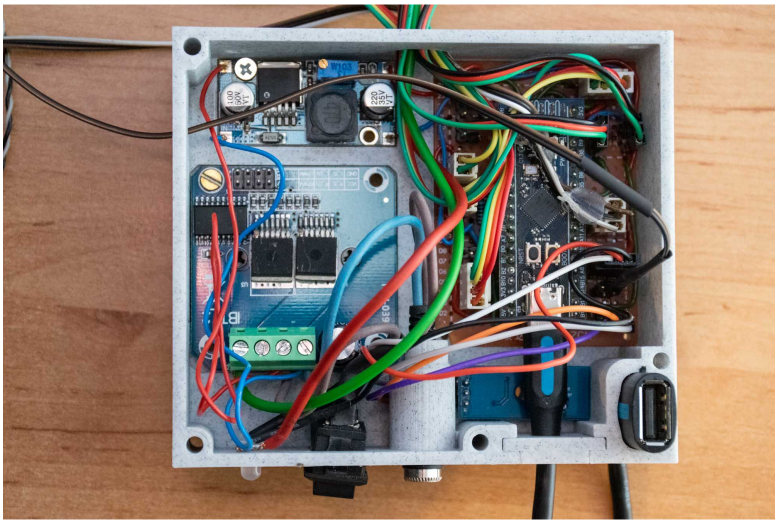


(a) : Soldering board

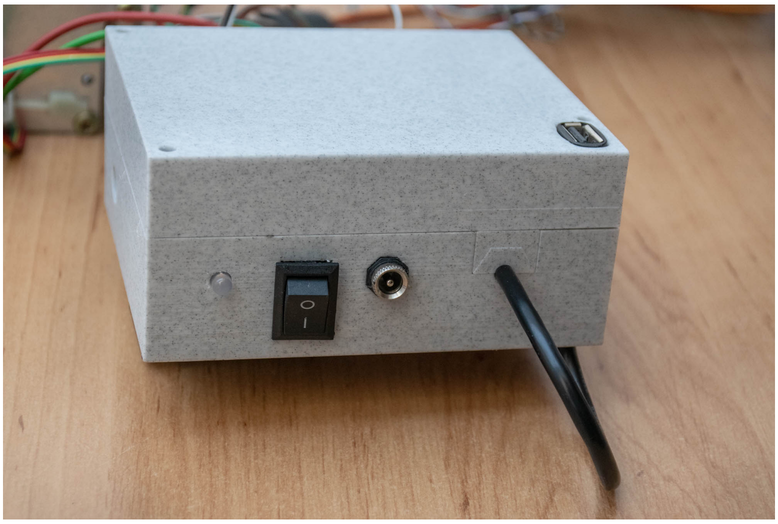


(b) : Tailor made case

Figure 5.11: Complete control electronics in printed case



(a) : Connectors plugged in



(b) : Case closed

Figure 5.12: Connectors plugged in, case closed

Chapter 6

Software and application

6.1 Introduction

The goal was to create a multiplatform application that would enable communication with the device and give to the user control over the device. Application was made with Czech interface, To gather data and provide the desired functions. It was needed for the application provide these modes. The reason was the potential possibility of testing in a czech environment.

- main screen
- Basic set-up of the device - control of actuators, display of collected data
- Games using angle data
- Games using torque data
- test screens for ensuring that all peripherals are connected

6.1.1 Properties

The main page was created so that the user can easily switch between the other modes. Contains a list of games, tests, settings. In the basic mode of controlling the device, the user has access to data from the device, but he can also control the device. Games are used here as a motivational tool for easier rehabilitation. Using games to guide the user into appropriate positions or force actions. Thanks to this, the user can actively rehabilitate.

6.1.2 PC application environment

Cross-platform application is built on .NET MAUI. The information and skills needed for the design of the application were mainly drawn from [5]. Thanks to the properties of this platform, the application can installed on almost all types of devices, to a computer, phone or tablet. Thus, support is present for operating systems: Windows, Android, iOS. The development of the application itself was carried out using Visual Studio 2022. The beforementioned modes ware programmed in the application. After switching on, a drop-down screen appears, where the user selects the COM port number and selects the appropriate mode. Then switching between modes is an option.

6.1.3 Communication protocol

A serial line is used for communication, where the following protocol is implemented:
[CMD C=<1;5> Rgb=<0;+100>;<0;+100>;<0;+100> Rot=<-100;+100> Lok=<-100;+100>]
The general range of individual values is indicated in the upper line. A specific example of a possible message is indicated here:
[CMD C=5 Rgb=1;2;3 Rot=-23 Lok=+50]

The control procedure is as follows: User change the parameter via the GUI of the application. Application will evaluate the action and send message via the serial communication to device. Device evaluate the message and undertakes wanted actions. Then send the message back to computer with new data.

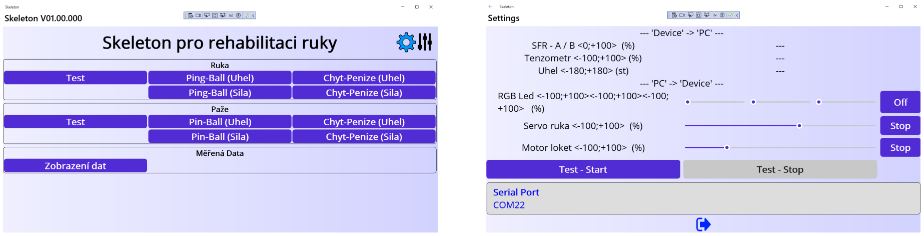
6.2 Controller Software Implementation

The basic principle has already been mentioned in the introduction. The knowledge essential for the implementation of this application into the STM32 microcontroler was obtained mainly from the [14].
The control procedure is as follows:
Micro-controller programs runs in a main loop where in set-up interval data from Laptop/tablet are received. The actuators are moved to the desired positions and the data is read from the sensors. Angle sensors sends data thru I2C to micro-controller. For weight module, special communication has been implemented for HX711. According to datasheet [2], a custom library was written and especially implemented. In case of FSR sensors the internal ADC has been used. Servo motor is type of analog servo motor which means that microcontroller has to generate PWM at 50 Hz. Then speed of this (continuous) servo motor is changed by value of duty cycle. Elbow DC motor is controlled via PWM as well. However compared to servo motor, there are two PWM for each directions due to H-bridge module. In this case PWMs has the frequency of 1kHz for quieter operation.

Chapter 7

Usecase

The device was designed in such a way that use and control were as simple as possible. Therefore the case has implemented USB-A hub and an additional cable is delivered. The mentioned cable is USB-A, type M-M. This combination allows user to transport device with the cable unplugged. So, in compact form without any cable sticking around. Also power adapter 12V with jack connector is added to the device. The following lines describe setup of the device. Firstly, the rocker switch is recommended to be turned off. The next step will lead to connecting laptop/tablet/other with the rehabilitation device. Then, connect the jack connector. When the application is launched, the main page is displayed 7.1a. It is necessary to go to the setup page and choose the right COM port. If a COM port is chosen wrongly, the error message will appear.



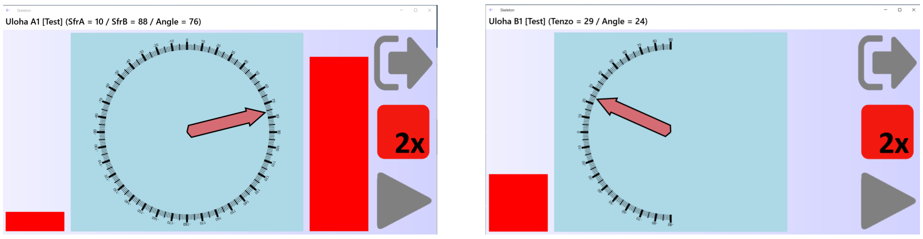
SFR - A / B <0;+100> (%) ---
Tenzometr <-100;+100> (%) ---
Uhel <-180;+180> (st) ---
RGB Led <-100;+100><-100;+100><-100;+100> (%)
Servo ruka <-100;+100> (%)
Motor loket <-100;+100> (%)
Serial Port
COM22

(a) : Main page

(b) : Elbow moving forearm up

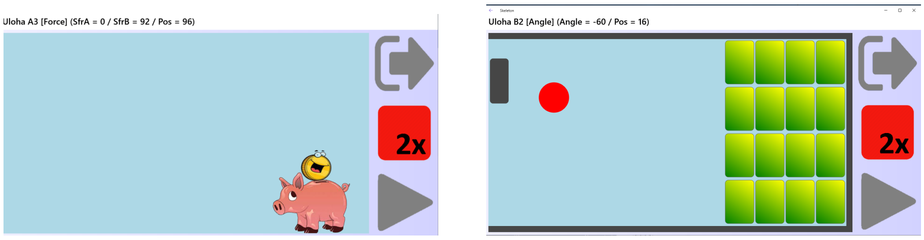
Figure 7.1: Controlling device via App running on laptop

After clicking on button *Test-Start*, the device will switch to the setup mode (fig. 7.1b), and both actuators can be controlled and moved to the desired position. Now, it is possible to switch on the rocker switch. User can set up the desired default suiting position. User can now put on himself the **HolderF-arm** which was introduced at fig. 4.2b. After suiting up, he insert his hand in the way that bolts in **HolderF-arm** will fit into the holes in **FSR-AC**. Then **Holder Bearing** (fig. 4.4a) component has to be closed to secure placement. After this procedure user can leave the set up page and use the device in full scale. It is recommend to run the tests, to confirm, that everything works well. Test screens are displayed in fig. 7.2. When is it confirmed that everything works well, it is turn for the games. Two main types of the games are implemented. First game is about catching the coin in the piggy bank. It is displayed in fig. 7.3a. Second game is based on pinball mechanics (see fig. 7.3b).



(a) : Test screen for forearm-wrist part **(b) :** Test screen for base-elbow part

Figure 7.2: Test screens

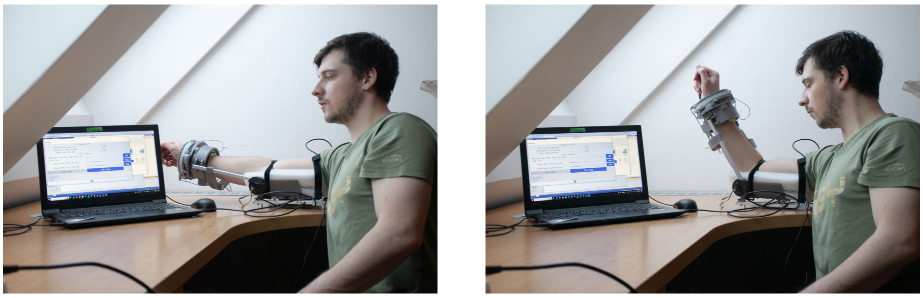


(a) : Catching coins in piggy bank **(b) :** Pinbal based game

Figure 7.3: Playing games

Although the game could be the same for angle and for torque, the behavior is a little different. Respectively, it has to be different just because of physical meaning. Torgue control is more straightforward. The position of the piggy bank corresponds to value of torque. User can also change his positions of exercising. While angle control has work in active support mode. It means that user has to generate some minimal value of moment / torque. Then the device will turn in desired direction, while torque is still present.

For a better idea and understanding, photos are attached. Fully assembled device with user can be seen. Here are several examples how the user sets up the device and then uses it. In the pictures (fig. 7.7) it can be seen the

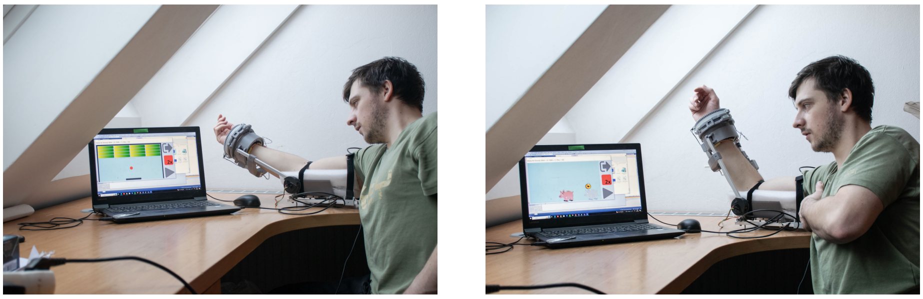


(a) : Elbow holding forearm down

(b) : Elbow moving forearm up

Figure 7.4: Controlling device via App running on laptop

device with an active light indication. The last picture shows the detail for the attachment of **HolderF-arm** lying next to.
Whole device can be seen in operation also in video which is available at the following link: [6].



(a) : Pinball

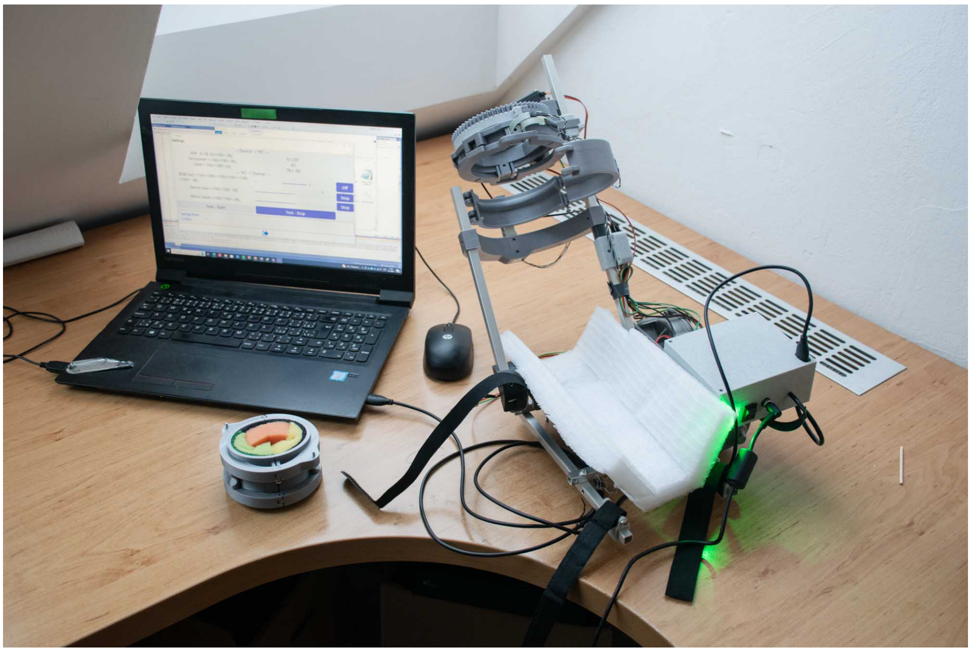
(b) : Coin game

Figure 7.5: Playing games - data from sensors are used as the controller

(a) : Test - to find out if FSR sensors are working properly

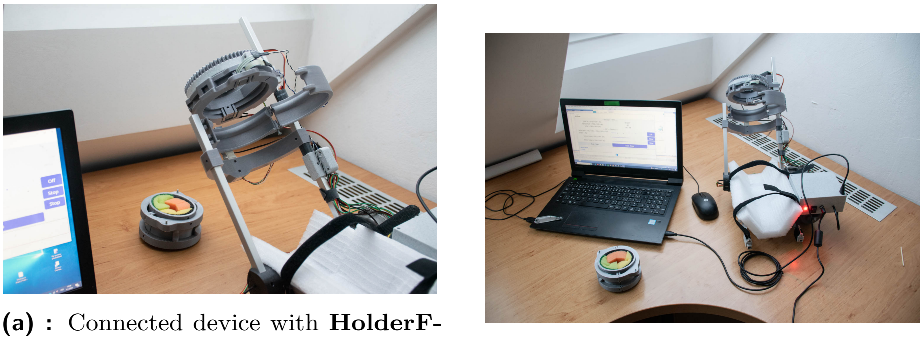
(b) : Another part is tested

Figure 7.6: Mode for testing sensors



(a) : Green indication activated

Figure 7.7: Connected device showing color indication



(a) : Connected device with **HolderF-arm** laying next to

(b) : Red indication activated

Figure 7.8: Whole device

Chapter 8

Conclusions

Research for current methods was done. It turns out that the main problem is usually the cost of devices or unavailability due to a limited number of existing devices. Also, 3D printing technologies are not often present yet. According to these and other gathered information, the functional rehabilitation system was designed. The device is compact and easy to use. Also, it could be controlled with any device due to its multi-platform support. The device is built mainly from 3D-printed parts and wide-spread aluminum profiles. Thanks to that, it is extremely easy to replicate the device. The device has implemented active support, which allows measuring the forces/moments of the limbs. Standard torque moment sensors are not suitable for this application. Therefore, it was necessary to find a way to measure the torques of the limbs with available sensors. A special ring that converts torque moment to force was designed and 3D printed. Thanks to that, force can be measured instead of torque, and FSR sensors could be used. Also, special holders and bearings were created to measure the angles of limbs.

For better control, the multiplatform application was created. The application has a custom GUI, and a communication protocol was implemented. The device itself runs on ARM STM32F411, and the firmware is synchronized with the PC application. User is able to switch between several modes of application, play games, exercise in a controlled manner, or check their improvements. The whole device was tested in real conditions, and the results were demonstrated. During the development of the device, it was necessary to overcome problems in construction design, 3D printing, programming, and electrical engineering. The output of the thesis is not a complete rehabilitation device, but a prototype of such a device on which the possibilities of maximum use of 3D printing, suitability of sensors and control applications were verified. The created prototype should serve as an initial sample for the creation of a real rehabilitation aid using all the previously mentioned advantages.

There are still some ways how to improve the device or move functionalities further. A possible improvement could be to put all the electronics together and put it all into a single PCB.
There is also opportunity to implement myo-sensors in the device. In that case, device could serve as a great platform for myo-sendors calibration. Thanks to access to information about the condition of the limbs, it would be possible to map them with data from the myo-sensor.

Appendix A

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Appendix B

List of Abbrevition

Abbrevition	Meaning
CIIRC	Czech Institute of Informatics, Robotics and Cybernetics
CTU	Czech Technical University
MCU	Microcontroller Unit
PCB	Printed Circuit Board CAD
Computer Aided Design	

Appendix C

CD Content

In Table C are listed names of all root directories on CD.

Directory name	Meaning
Thesis	The thesis in pdf format
STM32_Rehabilitation_exoskelet	control program for STM32F411
src/Skeleton-F411-USB-CDC	Visual Studio 2022 code with control application
3D_models/drawings	fusion360 files of designed system
3D_models/stl	stl files of designed system