IOSUD - Polytechnic University of Timisoara
Doctoral School of Engineering Studies

DEVELOPMENT OF MODULAR DEVICES USED IN MEDICAL ROBOTICS

Ph.D. Thesis – Abstract

for obtaining the scientific title of doctor at
Polytechnic University of Timisoara
in the doctoral field of mechanical engineering

author ing. Ana Maria STOIAN (SCURT)
scientific supervisor Prof.univ.dr.ing. Inocențiu MANIU

Month 09 year 2024

CHAPTER 1 – INTRODUCTION

This first chapter provides a breakdown of the emergence and development of robotics science. The word "robot" was first introduced by Czech writer Karel Čapek in his 1920 play "R.U.R." (Rossum's Universal Robots). Brother of Čapek,
Josef Čapek, actually suggested the term "robot". The word "robot" comes from the Czech word "robota", which means "work". In Čapek's play, robots are artificial beings created to serve humans, but eventually rebel against their creators, leading to catastrophic consequences. The play explores themes of industrialization, capitalism, and the ethics of creating artificial life.[1][2][3]

Since then, the term "robot" has become widely used to refer to mechanical systems, machines usually designed to perform tasks traditionally performed by humans. It has become a staple in science fiction, film, and popular culture to describe different forms of artificial intelligence and automation.

Robotics is a technical field that deals with the study, design and construction of specialized control systems for the acquisition and processing of information, with the aim of replacing human activities or simply designing human-like beings in different ways that perform repetitive tasks.

In general, robots are recognized as automated systems that act and react by imitating the behavior and physiognomy of "intelligent beings".

Robotics is an interdisciplinary field and includes a variety of disciplines, for example: automation, computer science, technology, mechanism theory, industrial engineering, electronics, mathematics, physics, computer science, systems theory, logistics.

The section also addresses the evolution of industrial robotic systems and robots in the medical field, highlighting advances in robot driving technology and their importance in both manufacturing and medicine where the evolution of robots has seen significant advances, transforming the way various medical conditions are diagnosed, treated and managed.

The chapter continues by presenting statistics on the annual installations of industrial robots in different regions and fields of activity. A significant increase in installations is observed in 2021. The COVID-19 pandemic has significantly influenced the deployment of robots, with some countries accelerating their adoption, while others have seen negative developments.

This section provides a comprehensive overview of the evolution and impact of robots and robotics in different fields and regions.

Also in the first chapter, a classification of the anatomy, physiology and biomechanics of the upper limb joint is offered, as well as its conditions and recovery methods.

The upper limb is an important part of the human body, comprising three main systems: bone, joint, and muscle, which work together to allow for a wide range of motion. The anatomy of the arm can be divided into three main segments: the arm (the part between the shoulder and the elbow), the forearm (the part between the elbow and the wrist), and the hand. (Figure 1) [4].

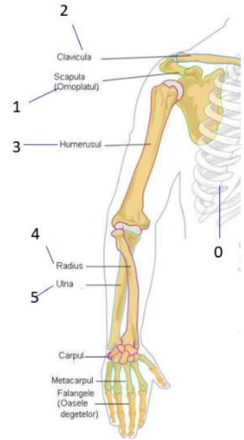


Figure 1. Anatomy of the human upper limb [5]

The RRR serial robot is an excellent example of how robotic engineering can mimic biological structures to create versatile and efficient machines. It can bring significant benefits in various areas by replicating the natural movements of the upper human arm [6].

The humero-ulna-radial joint (elbow) and the movements performed are presented below.

The humero-ulnar-radial joint, also known as the elbow joint, is a complex joint made up of three joints (humero-ulnar, humero-radial, radio-ulnar proximal) connected within the same joint capsule, which connects the upper arm (humerus) with the bones of the forearm (ulna and radius) [7].

The elbow joint allows only one movement, namely the flexion-extension movement (Figure 2) in the sagittal plane. This movement is performed around a fixed point located inside the joint capsule, called the center of rotation. [8]. The flexion movement consists of bringing the forearm closer to the arm, having an amplitude of about 150°. Due to the position of the humeral trochlea, the axis of the forearm does not coincide with that of the arm. For this reason, in the final phase of the movement, the hand is not directed towards the shoulder, but towards the chest [9].

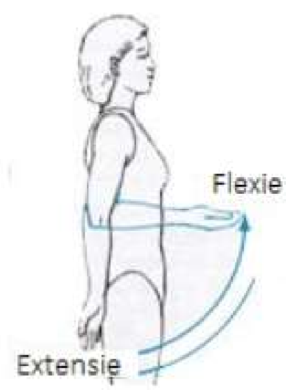


Figure 2. Flexion-extension movements [10]

Next comes the ulna-radial joint (forearm) and the movements made by it.

The ulna-radial joint is an important joint of the forearm, formed between the ulna (ulna) and the radius. It allows pronation and supination movements of the forearm, essential for the functionality of the hand in various daily activities, the amplitude being 120-140°. Pronation is the rotational movement of the forearm in which the palm is oriented downwards or posteriorly (dorsal), in this movement, the radius will have a rotational movement over the ulna, and the amplitude of movement will be about 85°. Supination is the rotational movement of the forearm in which the palm is oriented upwards or anteriorly (ventral), in which case the radius and ulna are parallel, the muscles involved including the supinator muscle and biceps brachii, and the amplitude of movement being approximately 90° [11].

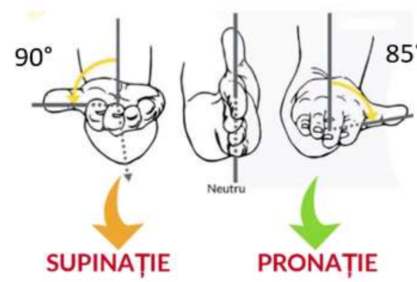


Figure 3. Forearm movement [11]

In the subchapter "Conditions and methods of recovery", various causes are presented that lead to immediate instability of the upper limb, which leads to a reduction or even blockage of its mobility. In the case of people who have suffered a vascular attack, it is very important that they start mobilizing their upper limb as soon as possible so as not to risk muscle atrophy.

The treatment of fractures varies depending on their anatomical-clinical type. The options considered are either applying a cast on the limb for a period of about 6-8 weeks, following the recovery of the joint, or surgical treatment is indicated, and after surgery, it is necessary to cast the limb.

The treatment of sprains varies depending on their severity.

Mobilization of the upper limb joints can be performed in three ways: passive (movements performed by the therapist), active (movements performed by the patient) and active with resistance. Passive movements involve the therapist performing push-ups, extensions, pronations, supinations, and circumductions. The active movements are the same, but they are performed by the patient. Active resistance movements are performed by the patient, while the physical therapist applies an opposite force to counteract the movements of dorsal flexion, plantar flexion and lateral flexion. [12],[13].

Recovery exercises will focus on the following aspects: toning the muscles that support the upper limb and increasing the flexibility of these muscles. The rehabilitation of the tendons and ligaments of the related muscle groups is also considered. The duration of the rehabilitation program is variable, between 4 and 6 weeks, or more, depending on the injury suffered. The exercises should be done gradually, because healing is different from one patient to another. Therefore, medical recovery aims to treat dysfunctions and regulate the functional level of an individual, with the help of various diagnostic and treatment methods [13].

CHAPTER 2 - CURRENT STATE OF RESEARCH ON ROBOTIC SYSTEMS USED IN THE MEDICAL FIELD

This chapter focuses on the analysis and presentation of the development of robots in the medical field in recent decades.

Throughout this chapter, by analyzing ideas from recent research and applications, a comprehensive analysis of cutting-edge technologies is presented, examining the development in different areas of medical robotics.

Currently, robotics represents one of humanity's most remarkable achievements and one of the most significant attempts to create artificial entities capable of communicating and experiencing emotions. According to recent research, the scientific community's interest in the field of medical robotics is growing, and the main focus is on developing new smart and versatile devices used in a variety of specialized fields and applications.

A concrete example is their application in the medical field, in minimally invasive surgery or in medical rehabilitation processes.

Medical rehabilitation is an essential area in restoring the physical capacities of patients who have suffered injuries that affect different parts of the human body, injuries that may be due to accidents, surgery, neurological diseases or other medical conditions that limit mobility and the ability to perform daily activities.

The main goal of medical rehabilitation is to restore motor function, relieve pain and improve the patient's quality of life, this complex process involving a multidisciplinary approach to physical therapies and advanced technologies such as active orthoses and possibly advanced robotic assistance equipment. By accurately assessing each patient's individual needs and implementing a personalized treatment plan, medical rehabilitation specialists can facilitate the patient's effective recovery and reintegration into daily and professional activities.

In this chapter, the methods and technologies used in upper limb rehabilitation are exposed, as well as specific therapeutic approaches for various conditions to achieve the best possible results.

To cover the need for exercise, several upper limb rehabilitation mechanisms have been developed.

Medical rehabilitation involves the use of various devices to improve the functionality and quality of life of patients with physical disabilities. Prostheses, active orthoses, and exoskeletons are all used for this purpose, but each has unique features and specific applicabilities, with the main differences being as follows:

- *Dentures* are artificial devices that replace a missing body part, such as a limb amputated due to an accident, illness, or birth defect, to restore the appearance and restore mobility and functionality to the lost limb. They can be passive (strictly cosmetic) or active (functional), using mechanical, myoelectric, or electronic components to mimic natural movements.
- External exoskeletons, rigid or semi-rigid, mechanisms that are attached to the human body and serve to strengthen and improve the person's movements, requiring their own system of action. Exoskeletons are often used to amplify strength or mobility in certain activities, such as walking or lifting heavy objects.
- Electrically operated orthoses are transforming the way we approach the requirements for mobility and rehabilitation. These advanced devices use robotic technology and sensors to provide dynamic assistance to those with movement impairments, surpassing the capabilities of traditional, passive devices. Millions of people around the world face mobility problems due to injuries, neurological conditions, and degenerative diseases. Traditional solutions often provide limited support, leading to restricted movement and prolonged rehabilitation. Electrically

operated orthoses offer a more efficient alternative by providing real-time adaptive assistance that can significantly improve mobility and speed recovery.
Some examples are set out below:

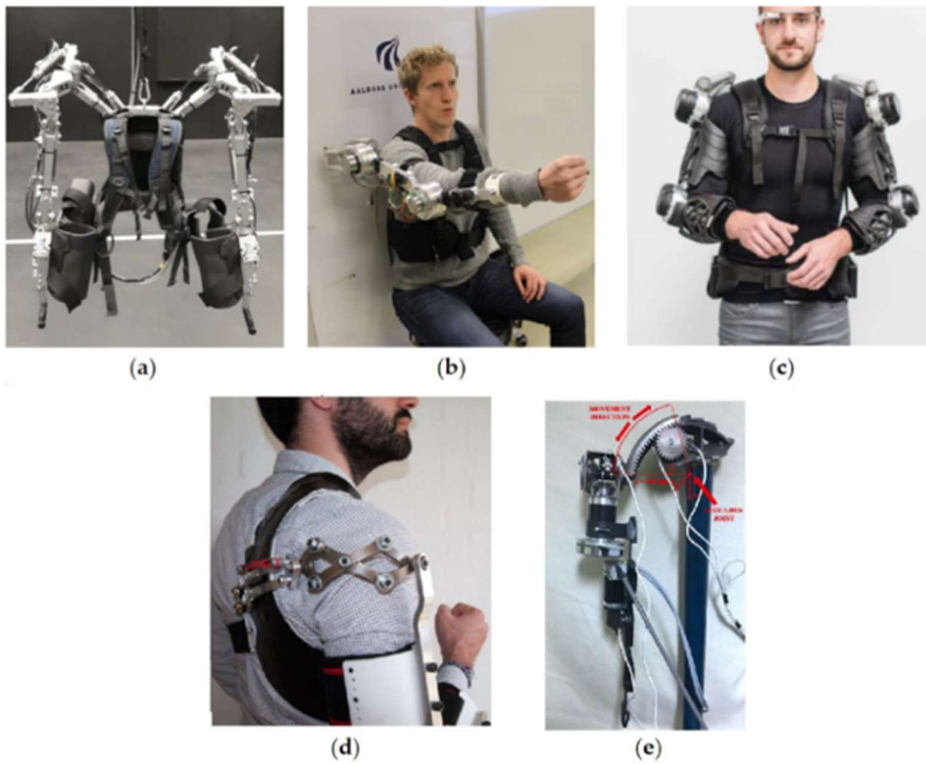


Figure 4. Proposed orthoses for comparison [14]

a) - Exoskeleton for the upper limb Inferno. Republished with permission from ref. [47]. Copyright 2018 IEEE;
b) - UB-AXO from Aalborg University. Republished with permission from ref. [48]. Copyright 2017 IEEE;
c) - Stuttgart Exo-Jacket. Republished with permission from ref. [49]. Copyright 2017 IEEE;
d) - compact scissor ties with 3 degrees of freedom for an exoskeleton for the upper limb. Republished with permission from ref. [50]. Copyright 2019 Elsevier;
e) - set of sliding links for an exoskeleton for abduction-adduction of the upper limb. Republished from ref. [15],[14].

CHAPTER 3 - THESIS OBJECTIVES

The aim of this paper is to optimally design and make experimental models of modular devices used in medical robotics.
In relation to the applications presented in the previous chapter, "The current state of research on robotic systems used in the medical field", I have opted for the study, design and practical implementation of two modules that are part of the category of those used in the field of medical recovery.

From these, I will choose the upper limb orthoses for the humero-ulna-radial joint and the ulna-radial joint, and I will develop a study to choose the optimal solution, design in a CAD

(Computer Aided Design) environment of the necessary components, 3D print (Three-dimensional) them and assemble them so as to obtain the desired product.

Another objective will be to create the command and control system and to obtain both experimental measurements and a qualitative study of the upper limb orthosis.

CHAPTER 4 – STRUCTURAL SYNTHESIS OF UPPER LIMB ORTHOSIS MECHANISMS

The upper limb orthosis proposed to be developed contains 2 independent modules that ensure: flexion-extension movement of the humero-ulnar-radial joint (elbow joint), and supination-pronation movement of the ulna-radial joint.

For each independent movement at the level of an orthosis module, the potential mechanisms that allow the desired movements to be performed are to be determined following a structural synthesis.

The structural synthesis of the actuation mechanism of the humero-ulnar-radial joint will take into account the mechanisms with elementary bars (4 elements) and the mechanisms with bars and gears (5 elements), which ensure an oscillating movement (rotation) with an angle of oscillation in accordance with the usual movement of the elbow joint.

- Structural synthesis of elementary bar mechanisms

Busbar mechanisms, which are subject to structural synthesis, must ensure a transformation of the translational motion into a rotational motion (oscillation), under the conditions in which a linear drive motor element is used.

Taking into account the Franz von Reuleaux method, which successively considers a binary element as a fixed element, an element as a motor element and an element as a driven element of the RRRT kinematic chain, all possible variants of busbar mechanisms containing the combination of the two binary elements of type RR and the two of type RT result. Figure 5 shows the kinematic schemes of the mechanisms resulting from the RRRT kinematic chain.

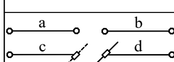
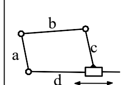
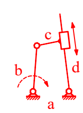
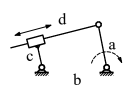
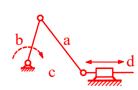
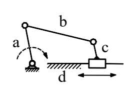
Lantul cinematic RRRT					
		Elementul fix a	Elementul fix b	Elementul fix c	Elementul fix d
1		 RTRR(a)	 RTRR(b)	 TRRR(c)	 TRRR(d)

Figure 5. Mechanisms of the RRRT powertrain [16],[17],[18]

The abbreviation of the mechanisms in Fig. 4.1 successively describes the type of kinematic couplings, the motor element is underlined, this being a translation coupling T, according to the initial considerations and the fixed element of the kinematic chain indicated in parentheses ( ). The kinematic couplings of the mechanisms are abbreviated as follows: R – rotational coupling and T – translational coupling.

The suitable structural solutions are indicated in red in Figure 5, which are RTRR(a) and TRRR(c), which are correspondingly similar to the RTRR(b) and TRRR(d) structures.

- Structural synthesis of bars and gears

Mechanisms with bars and gears must also provide a transformation of the translational movement into a rotational movement (oscillation) with an oscillation angle of 120° and use a drive with a linear motor [16],[17],[18].

Using the Franz von Reuleaux method, the geared mechanisms of the TRRR(RRd) and RTRR(RdR) powertrain are obtained. Figure 6 shows the kinematic schemes of the mechanisms resulting from the TRRR(RRd) and RTRR(RdR) kinematic chain.

The abbreviation of the mechanisms in Figure 6 is identical to the previous one, containing in parentheses ( ) the kinematic chain linked in parallel with the elementary structure. The additional kinematic couplings of the mechanisms are abbreviated as: Rd – upper planar coupling formed between the tooth profiles of the gears.

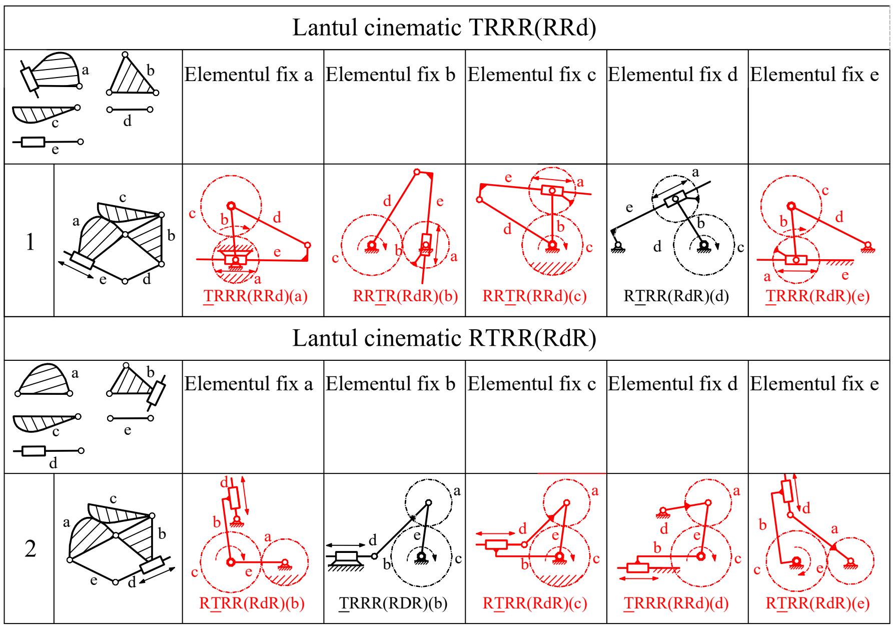


Figure 6. Mechanisms of the RRRT(RRd) kinematic chain [16],[17],[18].

Structural synthesis of the mechanism of action of the ulna-radial joint The mechanism of action of the forearm will ensure its orientation and will contain the ulna-radial joint that ensures the supination-pronation movement. The actuation mechanism used in the case of supination-pronation movement ensures a rotational movement, under the conditions in which a single rotating motor element is used.

Following the analysis, it was determined that the kinematic chain resulting from the combination of these elements is of the RRRd type (ordinary gear with gears).

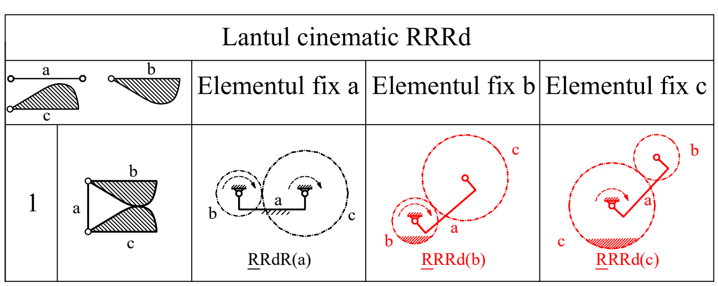


Figure 7. Mechanisms of the RRRd kinematic chain [16],[17],[18].

CHAPTER 5 – KINEMATIC-POSITIONAL ANALYSIS OF THE UPPER LIMB ORTHOSIS

In this chapter, the kinematic analysis of the mechanisms of the upper limb orthosis will be performed separately for each of the 2 independent modules related to the humero-ulnar-radial joint (elbow joint) and the ulna-radial joint.

The studies presented above show that the mechanisms with bars and gears with linear action allow to achieve a very large oscillation angle of the output element of the actuation mechanism of a humero-ulnar-radial orthosis (approx. 150°). Compared to basic bar mechanisms, they provide a favourable transmission angle for a large oscillation angle due to the increased movement of the output element by means of the cycloidal gear step. It is also observed that the transmission function of order 0 is approximately linear in a wide range of the motor parameter (linear stroke). Due to the advantages of linear drive bar and gear mechanisms over the corresponding elementary bar mechanisms, only these mechanisms will be studied for use in the operation of a humeroulnar-ulnar-radial orthosis.

The supination-pronation movement of the ulna-radial joint is to be performed by means of an ordinary mechanism with two-stage gears presented in chapter 4.2, which allows a high amplitude oscillation movement (approx. 180°).

CHAPTER 6 – SYNTHESIS OF UPPER LIMB ORTHOSIS MECHANISMS

The synthesis of the upper limb orthosis mechanisms will be performed separately for each of the 2 independent modules related to the humero-ulnar-radial joint (elbow joint) and the ulna-radial joint.

Synthesis of the mechanisms of action of the humero-ulnar-radial joint

The mechanisms that will be further considered for the actuation of the humero-ulnar-radial joint are the mechanisms with bars and gears having the basic crank-piston mechanism and oscillating slide.

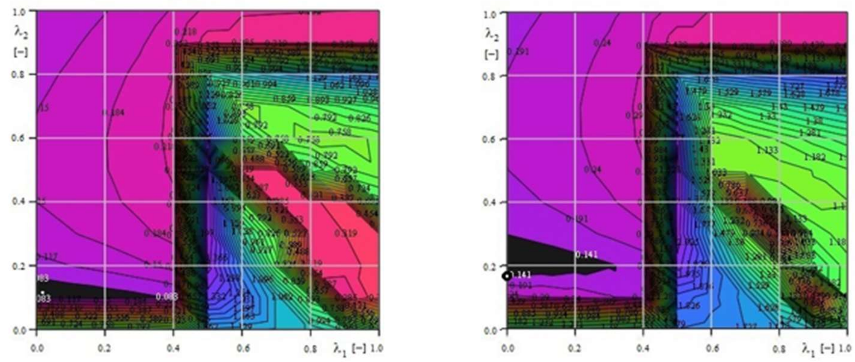
Using the calculation relations of the optimal synthesis method described in 6.1, in the case of the bar and gear mechanism with the oscillating slide mechanism as the basic mechanism, an analysis of the values of the normed lengths of the elements of the bar and gear mechanisms will be performed, depending on the maximum normalized stroke and the inverse of the transmission ratio.

Optimal synthesis of the linear drive bar and gear mechanism with the crank-piston mechanism as the basic mechanism

Table 6.1. Linear actuator strokes and characteristic length norms

Parameters								
$s_{\max}$	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
λ_1	0.026	0.000	0.027	0.010	0.028	0.028	0.000	0.000
λ_2	0.108	0.163	0.218	0.268	0.332	0.390	0.450	0.512

The level charts corresponding to the various values of the parameter indicated in Table 6.1 are shown in Figure 6. 1$s_{\max}$

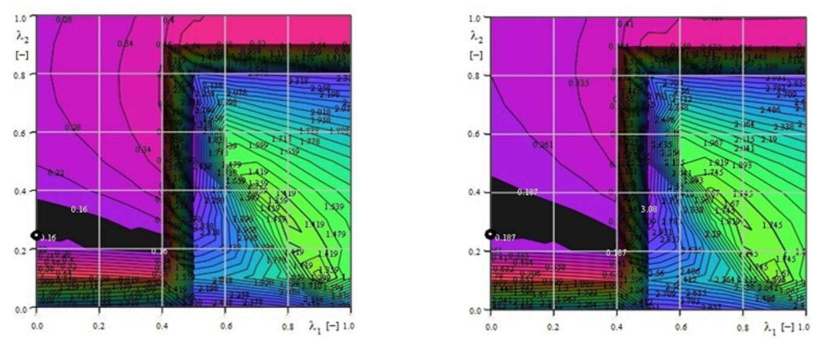


a) $s_{\max} = 0.2$, $\lambda_1 = -0.026$ $\lambda_2 = 0.108$ b) $s_{\max} = 0.3$, $\lambda_1 = 0.000$ $\lambda_2 = 0.163$

Figure 6.1 Level diagrams corresponding to the different maximum standard strokes of the bar and gear mechanism with the crank-piston mechanism as the basic mechanism

The variation of the inverse transmission ratio of the gear gear and the normed values of the lengths characteristic of the bar and gear mechanism with the piston crank mechanism as the basic mechanism are given in the table. The maximum standard stroke of the linear actuator has been chosen and the minimum transmission angle has been chosen. The norming was made according to the length of the fixed element $.6s_{max} = 0.5\mu_{\min} = 30° l_{1x} = 1$

Parametrii						
ρ	0.4	0.6	0.8	1.0	1.2	1.4
λ_1	0.000	0.000	0.000	0.010	0.027	0.027
λ_2	0.256	0.265	0.264	0.268	0.274	0.274



a) $\rho = 0.4$, $\lambda_1 = 0.000$ $\lambda_2 = 0.256$ b) $\rho = 0.6$, $\lambda_1 = 0.000$ $\lambda_2 = 0.265$

Figure 6.2 Level diagrams corresponding to the different reverse transmission ratios of the bar and gear mechanism with the crank-piston mechanism as the basic mechanism

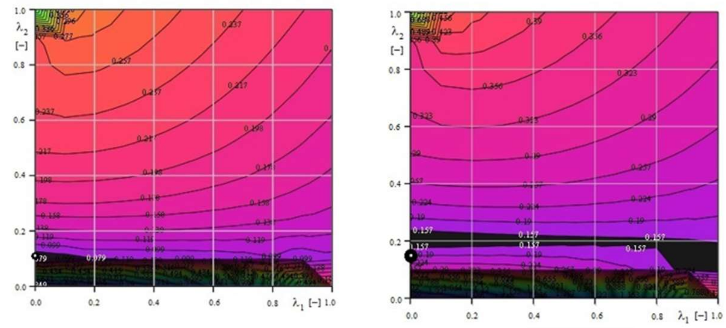
Optimal synthesis of the linear drive bar and gear mechanism with the oscillating slide mechanism as the basic mechanism

The normed lengths of the elements of the sliding mechanism – the eccentricity of the slide and the length of the crank, are dependent on the maximum normalized stroke and the inverse of the transmission ratio. The variation of the standard strokes of the linear actuator and the standard values of the lengths characteristic of the bar and gear mechanism with the oscillating slide mechanism as the basic mechanism are given in Table 6.3. The inverse of the gear gear transmission ratio was also chosen as the minimum transmission angle. The standardization was made according to the length of the fixed element.$s_{\max}\rho\rho = 1\mu_{\min} = 30° l_{1x} = 1$

Table 6. 3. Normalized strokes of the linear actuator and normed values of characteristic lengths

Parameters								
$s_{\max}$	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
λ_1	-0.017	-0.001	0.016	0.001	0.017	0.004	0.044	0.034
λ_2	0.100	0.149	0.198	0.248	0.296	0.338	0.390	0.440

The level diagrams corresponding to the various values of the parameter indicated in Table 6.3 are shown in Fig. 6.3$s_{\max}$



a) $s_{\max} = 0.2,\ \lambda_1 = -0.017\ \lambda_2 = 0.100$ b) $s_{\max} = 0.3,\ \lambda_1 = -0.001\ \lambda_2 = 0.149$

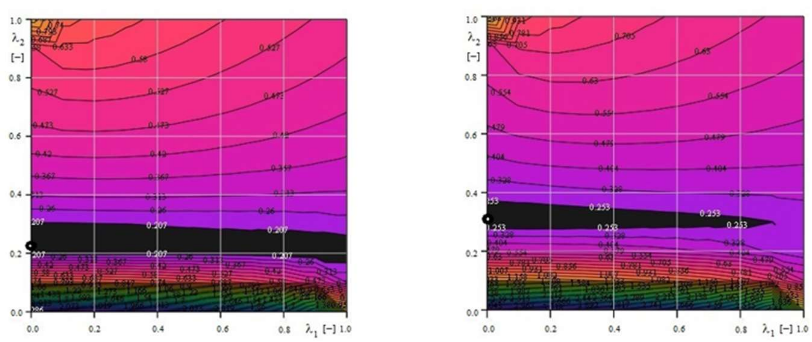
Figure 6.3 Level diagrams corresponding to the various maximum standard strokes of the bar and gear mechanism with the oscillating slide mechanism as the basic mechanism

The variation of the inverse transmission ratio of the gear gear and the normed values of the lengths characteristic of the bar and gear mechanism with the oscillating slide mechanism as the basic mechanism are given in Table 6.4. The maximum standard stroke of the linear actuator has been chosen and the minimum transmission angle has been chosen. The standardization was made according to the length of the fixed element.$s_{max} = 0.5\mu_{\min} = 30° l_{1x} = 1$

Parametrii						
ρ	0.4	0.6	0.8	1.0	1.2	1.4
λ_1	-0.002	0.005	0.013	0.006	0.009	-0.002
λ_2	0.237	0.243	0.245	0.248	0.250	0.252

Table 6.4 Inverse gear transmission ratio and normed values of characteristic lengths

The level charts corresponding to the various values of the parameter ρ indicated in Table 6.4 are shown in Fig. 6.4



a) $\rho = 0.4,\ \lambda_1 = -0.002\ \lambda_2 = 0.237$ b) $\rho = 0.6,\ \lambda_1 = 0.005\ \lambda_2 = 0.243$

Figure 6.4 Level diagrams corresponding to the different reverse transmission ratios of the bar and gear mechanism with the oscillating slide mechanism as the basic mechanism

Synthesis of the actuation mechanism of the ulna-radial joint

For the synthesis of the actuation mechanism of the cubito-radial joint, it is necessary to impose the inner radius (diameter) of the wheel ring 3 (r), in order to ensure the fixation of the forearm in order to achieve the supination-pronation movement, the thickness of the ring of the gear 3 (b), the vertical position of the motor coupling – the axis of rotation of the rotary motor on the fixed gear ring 1 (t) respectively the number of teeth of the satellite wheels 4, 4', 4" (z_4=z_4'=z_4") [19],[20],[21],[22]. Thus, the division radius of the 4, 4', 4" satellite wheels and the division radius of the gear ring (3) will be calculated, the radius of the drive gear (1) will be determined, where the vertical position of the drive coupling of the rotary motor on the fixed gear ring (t) is chosen according to the characteristic dimensions of the rotary motor used. The dividing radius of the fixed toothed ring (1) is also geometric. Knowing the dividing radii of the gears will determine the number of teeth of each gear. It should be specified that element (3) contains two gears with the same division radius , but with modules () and implicitly different numbers of teeth ().$r_3 m_1 \neq m_2 z_3, \neq z_3$

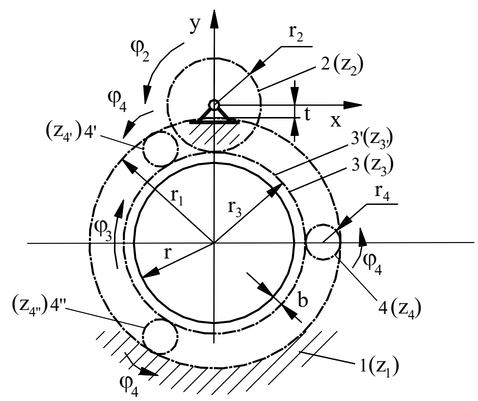


Figure 6.5 Geometric synthesis of the gear mechanism used to drive the cubit-radial joint

CHAPTER 7 – DESIGNING THE MECHANISMS FOR THE UPPER LIMB

For the design of the two modules of the prosthesis of the upper limb, the dimensional synthesis of the linear drive bar and gear mechanism will be performed, with the oscillating slide mechanism as the basic mechanism for the humero-ulna-radial joint (elbow joint) and the toothed wheel mechanism for the ulna-radial joint.

Design of the actuator for the humero-ulna-radial joint

According to the studies presented in chapters 5 and 6, the mechanism with bars and gears with linear actuation with oscillating slide as the basic mechanism was chosen as the mechanism for actuating the humero-ulnitar-radial joint, due to the smaller size compared to the mechanism with bars and gears with linear actuation with the piston crank mechanism as the basic mechanism [23].

The initial parameters required for the design of the mechanism design are indicated in Table 7.1:

Parametrii		
Inversul raportului de transmitere	ρ	1.3
Cursa maximă normată a actuatorului	s_{max}	0.6
Unghiul de oscilaţie a roţii conduse	χ_{max}	120°
Unghiul de transmitere minim	μ_{min}	50°

The normed lengths of the eccentricity and of the crank result according to the optimal synthesis method presented in chapter 7. The level chart corresponding to the values required in Table 7.1 is shown in Fig. 7.1.

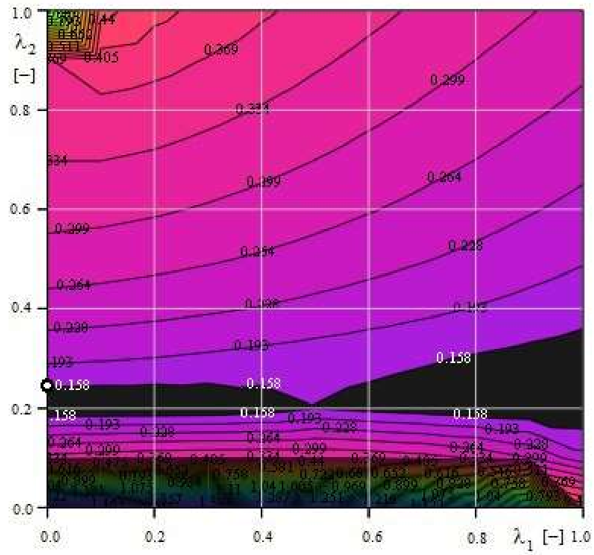


Figure 7. 1. The level diagram corresponding to the optimal synthesis of the gear mechanism used to drive the humeroulnar-radial joint

The optimum normed values of the eccentricity and crank result from the level diagram for the initial normed values () :$\lambda_1^{(0)} = 0.01,\ \lambda_2^{(0)} = 0.01$

$$\lambda_1 = 0.000, \quad \lambda_2 = 0.162. \qquad (7.1)$$

Thus, the geometric constructive parameters of the linear drive bar and gear mechanism with the oscillating slide mechanism as the basic mechanism are indicated in Table 7.2:

Parametrii		
Lungimea elementului fix	l_{1x}	212 mm
Lungimea excentricităţii	l_2	0 mm
Lungimea manivelei	l_4	34.5 mm
Cursa iniţială	s_0	177.5 mm

Following the kinematic analysis of the bar and gear mechanism with linear drive having the oscillating slide mechanism as the basic mechanism presented in the head. 6. the transmission function of order 0 and order 1 from Figure 7.2 and Figure 7.3 are obtained.

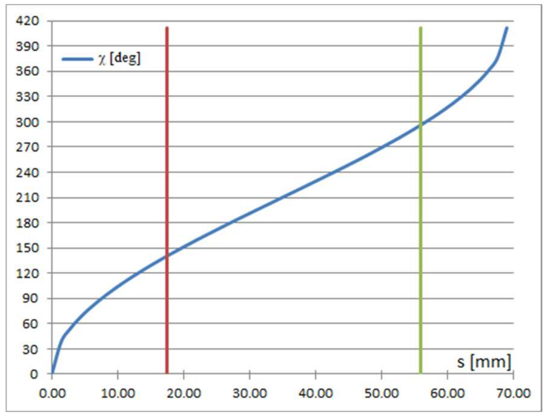


Figure 7. 2. Transmission function of order 0 of the actuation mechanism of the humero-ulnar-radial joint

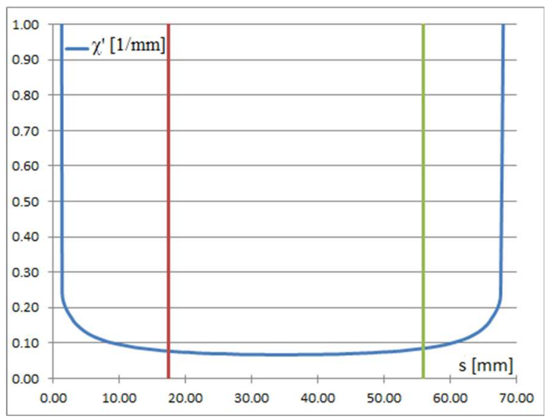


Figure 7. 3. Transmission function of order 1 of the actuation mechanism of the humero-ulnar-radial joint

The variation of the transmission angle is shown in Figure 7.4 which falls within the previously established piston stroke range for values greater than ().μ$\mu_{min} = 56.6°\mu_{max} = 123.4° = 180° - \mu_{min}$

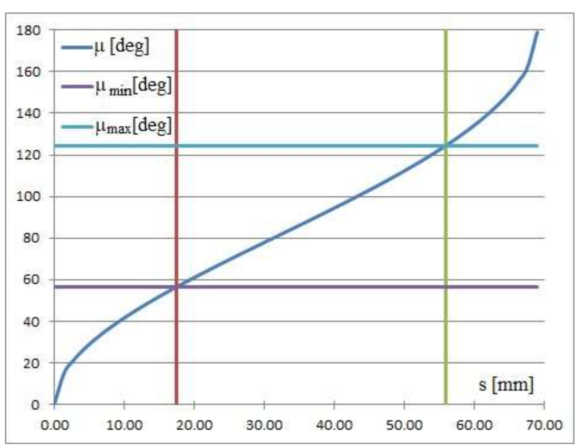


Figure 7. 4. Transmission angle of the basic actuation mechanism of the humero-ulnar-radial joint

In order to design the drive, a kinetostatic analysis of the linear drive bar and gear mechanism will be performed, having as basic mechanism an oscillating slide mechanism, shown in Figure 7.5 [17],[23].

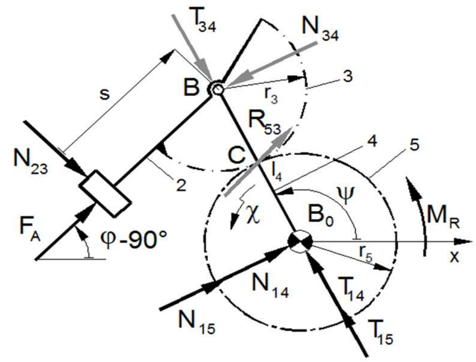


Figure 7. 5. Kinetostatic analysis of the basic mechanism of action of the humero-ulnar-radial joint

The driving force of the linear motor results from the equilibrium equations of the kinematic chain. Accepting the weight of the forearm G=15 N and the length of the arm of the weight of the forearm b=100 mm, it is possible to determine the variation of the actuation force necessary to actuate the humero-ulnar-radial joint (Figure 7.6). It can be seen that the maximum value required to be developed by the linear motor is F_max=79 N.F_A

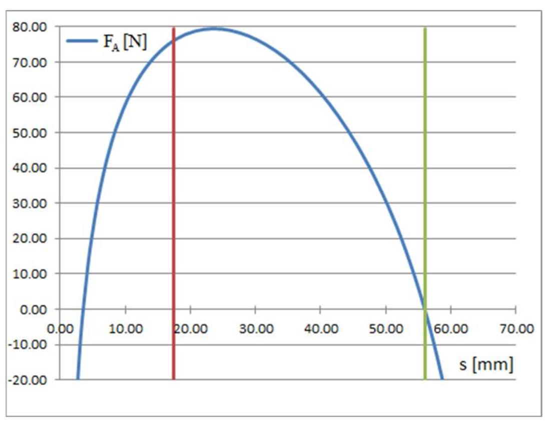


Figure 7. 6. The actuating force of the actuation mechanism of the humero-ulnar-radial joint

Design of the actuator of the ulna-radial joint

According to the method of synthesis of the gear mechanism used for the actuation of the ulna-radial joint presented in chap. 6.2 The following shall be required: the inner radius (diameter) of the wheel ring 3 , the thickness of the gear ring 3), the vertical position of the drive coupling on the fixed gear ring 1) respectively the number of teeth of the satellite wheels 4, 4', 4" . These values are presented in the $(r)(b(t(z_4 = z_{4'} = z_{4''})$Table 7. 1.

Table 7. 1. Initial parameters required for the design of the actuation mechanism of the cubito-radial joint

Parameters		
Inner Spoke of Wheel Ring 3	r	80 mm
Gear ring thickness 3	b	8 mm
Vertical position of the drive coupling on the gear ring 1	t	30 mm
Number of teeth of satellite wheels 4, 4', 4"	$z_4 = z_{4'} = z_{4''}$	12 teeth
Cycloidal step module with gears	m_1	1 mm
Ordinary gear module with gears	m_2	2 mm

With these values, the division radii of the gears (6.20)-(6.21) and the number of their teeth will be determined according to the relations (6.15)-(6.19) of the doctoral thesis. The corresponding values are given in Table 7.4.

Table 7. 2. Constructive parameters of the cubit-radial joint drive mechanism

Parameters		
Gear dividing radius 4, 4', 4''	$r_4 = r_{4'} = r_{4''}$	12 mm
Gear dividing radius 3	r_3	96 mm
Number of teeth of the gear 3 $()m_1 = 2$	z_3	48 teeth
Number of teeth of the gear 3' $()m_2 = 1$	$z_{3'}$	96 teeth
Gear dividing radius 2	r_2	30 mm
Number of teeth of the gear: 2 $()m_1 = 2$	z_2	30 teeth
Sprocket Dividing Radius 1	r_1	120 mm
Number of teeth of the sprocket 1 $()m_1 = 1$	z_1	120 teeth

In subchapter 7.3 the constructive solutions of the upper limb orthosis will be determined.
The CAD design of the upper limb orthosis was made using "Creo Parametric 2.0", a program designed for computer-aided mechanical design.

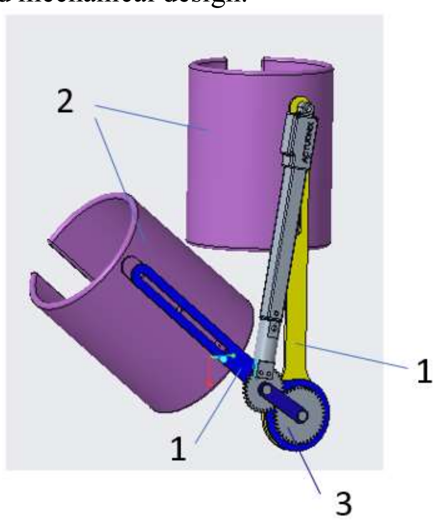


Figure 7. 7. Humeral-ulna-radial joint - overview

Initially, the support components of the upper limb orthosis were graphically modeled, namely the rails and sleeves (Figure 7. 7 – elements 1 and 2).
This was followed by the construction of the gears and the connecting element between them – the satellite arm (Figure 7. 7 – element 3).

The CAD assembly of the upper limb orthosis of the ulna-radial joint module is shown in Figure 7. 8, and in Figure 7. 9 is shown the exploded view of the module, the components being recorded in Table 7. 5.

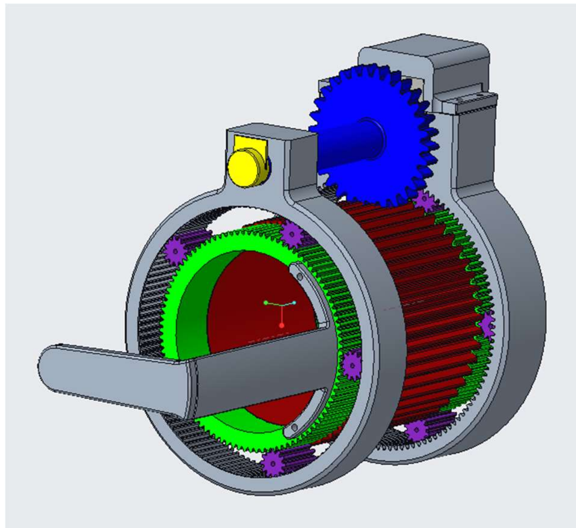


Figure 7. 8 Cubito-radial joint module

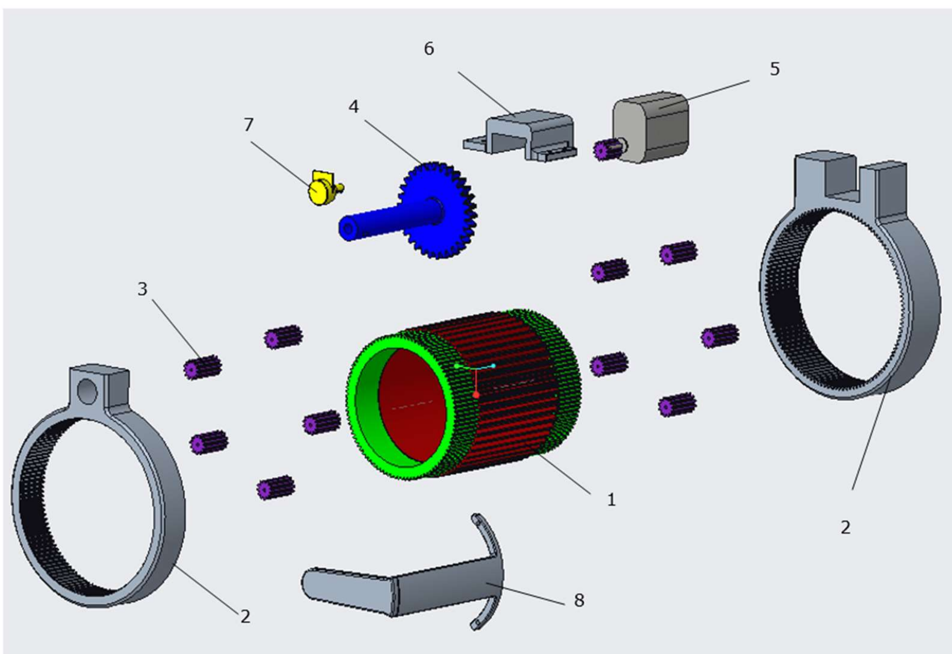


Figure 7. 9. Modulus of the cubit-radial joint - exploded vision

Table 7. 5. List of components in the cubit-radial joint module (forearm)

No.	No. of pieces	Part Name
1	1	Ring that covers the forearm with external teeth having two different modules
2	2	Fixed toothed ring with inner teeth
3	10	Satellite wheels
4	1	Gear shaft
5	1	Motor DC

6	1	Lid
7	1	Position potentiometer
8	1	Adjustable handle

Chapter 7.4 presents the practical realization of the upper limb orthosis.

For the practical realization of the upper limb orthosis, the following components were used:

1. Medical orthosis, purchased commercially
2. Cubicle-radial articulation module, made by the 3D printing method
3. Linear Actuator
4. DC motor for driving the forearm module
5. Arduino Uno Board
6. 16-bit analog-to-digital converter
7. Motor driver L298 N
8. Current Sensor
9. Position Potentiator
10. Connecting elements.

The upper limb orthosis, with the two modules developed for performing the flexion-extension movement of the arm, as well as the module for performing the pronation-supination movement of the forearm, is shown below, mounted on the upper limb (Figure 7.10 and Figure 7.11).

Figure 7. 10. Flexion-extension movement of the arm

Figure 7. 11. Pronation-supination movement of the forearm

In order to obtain the movements necessary for the rehabilitation of the upper limb, flexion-extension of the arm and pronation-supination of the forearm, the assembly presented in the connection diagram (Figure 7. 12) was performed, where 1. Arduino Uno Development Board, 2. 16-bit analog-to-digital converter, 3. Motor driver L298 N, 4. Current sensors (2), 5. Electric motors (Actuonix L12-P series linear actuator, for elbow mode actuation and 12V DC motor, for forearm module actuation), 6. Position potentiators, 7. Power supply.

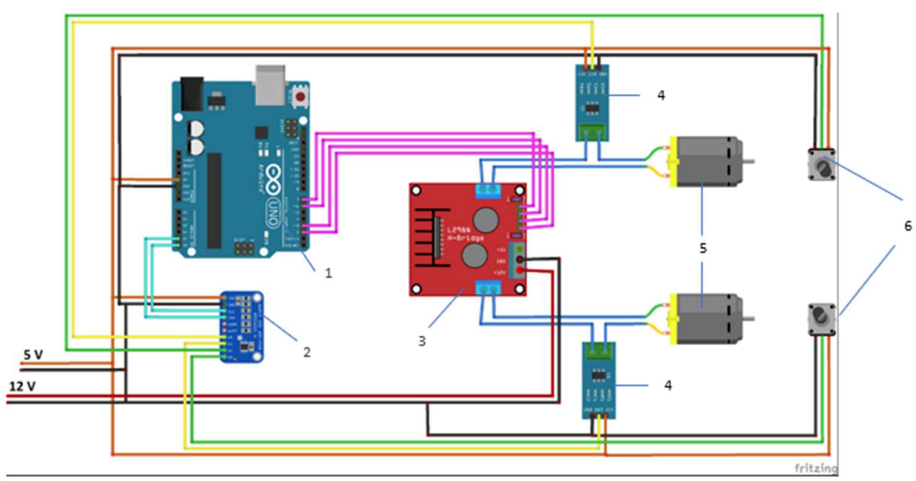


Figure 7. 12. Connection Diagram

The power supply of the assembly was made from a DC power supply, According to the specifications of the linear actuator, the expansion and retraction of the piston can be achieved by reversing the polarity of the motor pins using an electronic system. This was solved by using an H-bridge module, which is powered by the Arduino board and an external 12V source. The module allows both pin polarity reversal and voltage control, making it ideal for situations where the motor requires a voltage of 12V, while the Arduino board operates at 5V. The same system is used for the forearm module, demonstrating the modularity of the system.

In order to achieve the rehabilitation system, we will try to reproduce the repetitive movements performed by a physiotherapist. The method implemented in the control part of the system mainly takes into account the hardware architecture of the developed system. This may include information related to:

- position, through the potentiometers on the axes
- Resistant moment through current sensors on actuators

this type of information is also available to the physiotherapist.

Taking into account the architecture of the system, the controller to be programmed is an Arduino UNO, and the logic of the developed program focuses on 3 major components:

1. Position sensor reading in the 2 axes
2. Actuation of axis 1 corresponding to the elbow joint (humero-ulnar-radial)
3. Actuation of axis 2 corresponding to the forearm joint (pronation-supination)

CHAPTER 8 – EXPERIMENTAL RESEARCH AND RESULTS OBTAINED ON THE COMPONENT MODULES OF THE UPPER LIMB ORTHOSIS

To make experimental measurements on the modules made, the Arduino programming environment and an Arduino UNO development board were used.

Measurements of the intensity of the supply current of the electric drive motors were made with the help of sensors to determine the resistant moments in the orthosis modules.

The system was also measured and calibrated to establish the dependence between the potentiometer indication and the actual position of the output element of the actuator.

Integration of the above-mentioned information (moment and position) into an automatic adjustment system to limit the movement of the modules made.

As an overview in Figure 8. 1 and Figure 8. 2 you can see the results obtained from the measurements, positioned next to each other.

It is verified that the peaks resulting in the electric current measurement graphs, peaks representing the change of direction of the motors, correspond to the peaks obtained from the potentiometer indication, in terms of the effective position of the output element of the drive mechanism.

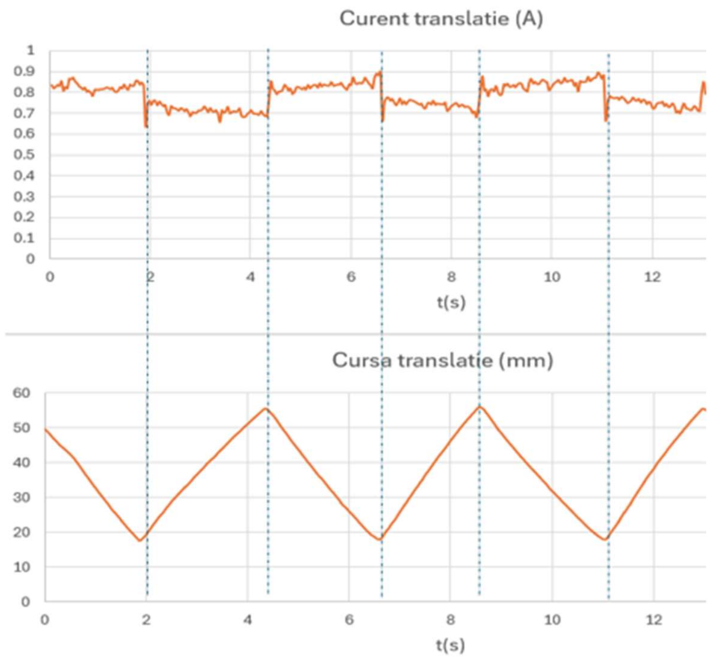


Figure 8. 1. The variation of the electric current and the translation stroke of the motor as a function of time for the module that drives the humero-ulna-radial joint.

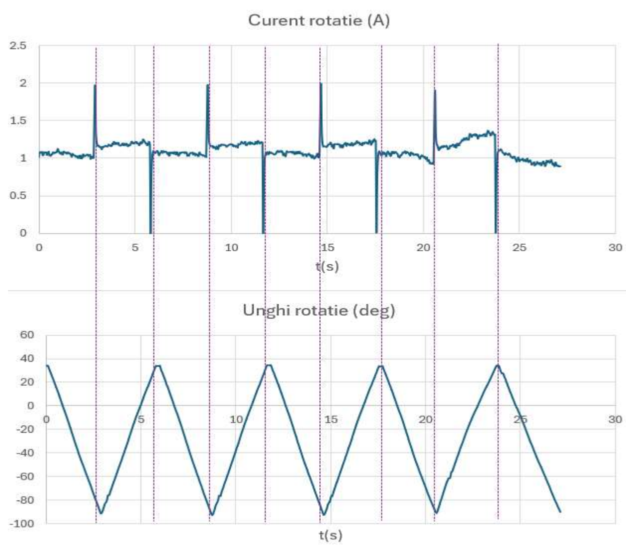


Figure 8. 2. The variation of the electric current and the angle of rotation of the motor as a function of time, for the module that drives the cubit-radial joint.

A qualitative questionnaire on the upper limb orthosis was also carried out. Thus, we performed tests on 5 subjects, to whom we provided a feedback questionnaire at the end of the use of the orthosis.

The subjects were clinically healthy, ranging in age from 24 to 40 years.

It can be concluded that the users were largely satisfied with the use of the upper limb orthosis, they considered it useful, effective, reliable and easy to put on the upper limb, but they considered that they needed authorized assistance to use the system.

CHAPTER 9 – FINAL CONCLUSIONS. PERSONAL CONTRIBUTIONS. FURTHER RESEARCH PERSPECTIVES

The paper presents the development of modular devices to be used in medical robotics, more precisely in the field of medical recovery.

I chose the research of this topic as a continuation of my dissertation, where I studied tools used in the medical field, considering that it can bring added value in the field of medical recovery.

The methods currently used on patients who require upper limb recovery for various reasons (stroke, injuries, accident, etc.) are simple, require travel to a rehabilitation center, require the permanent presence of a physiotherapist, which means a smaller number of patients who can benefit from this service and of course the overload of the medical staff.

In addition, the SARS-COV19 pandemic has shown us how important it is to have remote medical services, therapies and care available.

The integration of robotic systems in rehabilitation therapies represents a promising direction for improving recovery outcomes and increasing the accessibility of advanced therapies.

To this end, we have carried out an optimal design, which included the realization of a structural synthesis of the mechanisms that are part of an upper limb orthosis, the realization of a kinematic-positional analysis of the upper limb orthosis mechanisms taking into account both crank-piston type mechanisms, oscillating slide mechanisms, bar and gear mechanisms, as well as the realization of an optimal synthesis of the upper limb orthosis mechanisms for the variant of the upper limb orthosis bars and gears with linear drive, having in the first phase the crank-piston mechanism as the basic mechanism and later the oscillating slide mechanism as the basic mechanism.

The experimental part included the development of a module for the humero-ulna-radial joint (elbow joint), having as an actuation mechanism the mechanism with bars and gears with linear actuation and a module for the ulna-radial joint for achieving the pronation-supination movement of the forearm, based on a mechanism with two-stage gears, the first ordinary step, with external cylindrical gears and a second cycloidal stage with satellite gears.

For the practical realization of some component elements of the two modules, we opted for the technology of 3D printing of the parts for several reasons.

First of all, it allows the creation of customized products according to the needs and preferences of the user in a very short time and with low costs, while giving design freedom and allowing the creation of various complex geometries.

This was followed by the integration of the two modules on an existing commercial support, in order to obtain a complex, electrically operated modular orthosis.

For the experimental research part, we obtained results from measurements with the help of sensors of the supply current intensity of the electric drive motors, in order to determinate the resistant moments in the orthosis modules. We measured and calibrated the system to establish the dependence between the potentiometer indication and the actual position of the output element of the actuator. Last but not least, we have integrated the above-mentioned information (moment and position) into an automatic adjustment system to limit the movement of the modules made.

Also in the experimental research part, we conducted a qualitative questionnaire on the ease, reliability and comfort of using such equipment by various users.

As a result, I was able to develop an electrically operated upper limb orthosis that would be affordable and that could be used in the absence of a medical rehabilitation therapist.

Regarding personal contributions to this research, the following can be mentioned:

- Conducting extensive research on the current state of applications used in medical robotics.

- Achieving a structural synthesis of the mechanisms that make up an upper limb orthosis.
- Performing a kinematic-positional analysis of the mechanisms of the upper limb orthosis.
- Achieving an optimal synthesis of the upper limb orthosis mechanisms.
- Design and practical implementation of two modules for the humero-ulnar-radial and ulna-radial joints.
- Integration of the two modules on an existing support, purchased from the market, thus obtaining the electrically operated upper limb orthosis.
- Making a command and control algorithm for operating the orthosis.
- Conducting experimental research to determine the resistant moments and position of the orthosis modules.
- Making a quality questionnaire in order to improve and develop the product.

The following can be considered as directions of further development:

- Development and practical implementation of a module for the operation of the wrist joint.
- Development and practical implementation of a module for the operation of the shoulder joint.
- Research and development of a way to make the device portable.
- The use of the upper limb orthosis in an authorized rehabilitation center, in order to carry out long tests on patients suffering from various upper limb disorders in order to implement it on a large scale.

CHAPTER 8 – Bibliography

[1] K. Capek, Rossum's Universal Robots, translated by Paul Selver. 1923.
[2] T. R. Kurfess, Robotics and automation handbook, vol. 414. CRC press Boca Raton, FL, 2005.
[3] I. Margolius, „The robot of Prague", The Friends of Czech Heritage , 2017. https://czechfriends.net/images/RobotsMargoliusJul2017.pdf., accesat 09.04.2024
[4] Prof.univ.dr.med. Sorin Bollintineanu, s.a., Human Anatomy, Vol. II: Anatomy of Limbs and Trunk Walls, Semester I, "Victor Babes" Publishing House, Timisoara, 2021
[5] https://upload.wikimedia.org/wikipedia/commons/4/49/Human_arm_bones_diagram.svg, accessed 07.03.2024
[6] Erwin Christian Lovasz, Biomechanics of the Upper Limb, Prosthetics, Course, Year IV
[7] https://anatomie.romedic.ro/membrele-superioare, accessed 07.03.2024
[8] https://kupdf.net/download/anatomia-si-biomecanica-cotului_59f2a371e2b6f5a230930ef9_pdf, accessed 15.03.2024
[9] http://www.lectiadeortopedie.ro/notiuni-de-anatomie/articulatia-cotului, accessed 15.03.2024
[10] https://stanciucosmin.ro/planuri-de-miscare/, accessed 15.03.2024
[11] https://ro.wikipedia.org/wiki/Antebra%C8%9B, accessed 27.03.2024
[12] Cotoman, R., Kinetotherapy: the method of carrying out practical activity, "Romania de Mâine" Foundation Publishing House, Bucharest, 2005.

[13] Eng. Cristina-Magda RACU, Research on the development of new mechatronic systems for ankle joint rehabilitation, "Gheorghe Asachi" Technical University of Iaşi, 2020
[14] Francesco Durante , Terenziano Raparelli and Pierluigi Beomonte Zobel, “Development of a 4-DoF Active Upper Limb Orthosis”, Robotics 2022, 11, 122. https://doi.org/10.3390/robotics11060122
[15] Strzelczyk, P.; Tomczewski, K.; Wrobel, K. The Middleware for an Exoskeleton Assisting Upper Limb Movement. Sensors 2022, 22, 2986. https://doi.org/10.3390/s22082986., accesat 13.06.2024
[16] Lovasz E.-C., Modler K.-H., Hollmann, C, - Design of Gear Coupling Gears with Linear Drive, 47th International Scientific Colloquium, Technical University of Ilmenau, 23-26.09.2002, (2002) 316-317, exteso CD-ROM.
[17] Modler K.-H., Lovasz E.-C., Perju D., Hollmann Ch. - Geared Linkages with Linear Displacement Actuator Used as Function Generating Mechanisms, 11th World Congress in Mechanism and Machine Science, Tianjin Vol. 3 (2004) 1254-1259.
[18] Lovasz, E.-C., Modler, K.-H., Pop, C., Pop, F., Mărgineanu D.T., Maniu, I.: Type Synthesis and Analysis of Geared Linkages with Linear Actuation, Mechanika, 24(1), (2018), 108-114, IF=0,529 (Q4-2017).
[19] D. Perju, Mechanism for Precision Mechanics, vol. 1 and 2. Lito. UP Timişoara, Romania, (1990).
[20] N. Manolescu, F. Kovacs, A. Orănescu, Teoria mecanisme-lor şi a maşinilor, Ed. Didactică şi Pedagogică, Bucharest, (1972).
[21] E.-C. Lovasz, I. Cărăbaş, Principles of synthesis of mechanisms with gears and cams, Ed. Politehnica Timişoara, (2004).
[22] Cosmina-Mariana Suciu, Grigore URDĂREANU, Study on the construction of active orthotics, 2020, Polytechnic University of Timișoara
[23] Lovasz, E.-C., Sticlaru, C., Suciu, C., Gruescu C.M., Ceccarelli M., Maniu, I., Moldovan, C.E. - Novel Actuation Design of an Active Elbow Orthosis, 15th International Federation for the Promotion of Mechanism and Machine Science World Congress, IFToMM 2019, Kracow, Series: Mechanisms and Machine Science, Springer International Publishing, 73, (2019), 1527 - 1534, ISSN 2211-0984