University POLITEHNICA of Bucharest

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DOCTORAL THESIS

Cercetări privind optimizarea sistemelor mobile pentru persoane cu dizabilități

Researches on the optimization of mobile systems for disabled people

* Thesis summary *

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Foreword

The main purpose of the doctoral thesis is to optimize a manually operated mobile system for people with disabilities, aiming to increase autonomy, adding a function of overcoming low / medium height obstacles and one of maintaining the horizontality of the base while crossing obstacles, by by means of a bar mechanism. All this was obtained as a result of a research-development process that led to the development of an actuation system attachable to the manual wheelchair for people with disabilities and to the design of one to keep the horizontality of the base.

The doctoral program consisted of preparing, presenting and taking exams and scientific reports, deepening the study, analyzing new product development methodologies and optimizing an autonomous mobile system for transporting people with disabilities, transforming a manual wheelchair into a powered chair. (having equal autonomy to electrically operated wheelchairs, able to overcome obstacles and keep the base horizontal, at a competitive price), the realization and publication of scientific papers, as well as the elaboration of this doctoral thesis on optimizing mobile systems for people with disabilities.

First of all, I would like to extend my deepest thanks to Prof.univ.dr.ing. Cristian DOICIN, for the scientific guidance and coordination of the activity of completing the doctoral program, full confidence and total availability granted during these years. In particular, I would like to thank my father, Cătălin GHEORGHIȚĂ, who supported and encouraged me, giving me advice for the practical aspects of the issue. I also want to express my gratitude and appreciation for the teachers with whom I interacted constructively, both during my doctoral and master's studies and, implicitly, my bachelor's degree. I thank them for their constructive interventions and guidance, and I assure them that their support has greatly guided me in shaping my academic career. I especially want to thank my family who supported, encouraged and supported me throughout this period. Their confidence that I can achieve this personal and professional goal was my main support in the difficult times of the research process.

Working on the publication of this thesis, I exceeded my limits, set new professional goals and discovered both the sacrifices and the gratifications that research work brings with it. In obtaining these results, we benefited from the support of the scientific director, as well as of the professors from the doctoral activity guidance commissions. I would like to express my sincere thanks to Prof. Dr. Eng. Nicolae IONESCU, Prof. Univ. dr. eng. Marian GHEORGHE, Prof. univ. dr. eng. Tom SAVU from the POLITEHNICA University of Bucharest, for the constructive comments and recommendations within the evaluation commissions of the doctoral exams and scientific reports, as well as all the professors who guided and trained me professionally within the TCM department of the Faculty of Industrial and Robotic Engineering. I would like to sincerely thank all the members of the doctoral committee, both for the patience with which they analyzed this paper, and for the suggestions and constructive observations that will represent the foundation of my future academic projects.

Vlad Gheorghita

Introduction

The chosen research topic deals with a topical issue, whose approach has made it possible to obtain an innovative solution to a problem often encountered in people with locomotor problems or disabilities who cannot operate manually, using both arms, a wheelchair. In addition, the approach has paved the way for further research and will be able to lead to better results in the future, in order to solve other practical problems of people using wheelchairs.

* * *

The first part of the thesis includes 3 chapters and highlights the current state of research on the development of mobile systems for people with disabilities. In Chapter 1, entitled METHODOLOGIES REGARDING THE DEVELOPMENT OF A NEW PRODUCT, based on the critical study of the bibliography, research in the field of new product development is analyzed. In Chapter 2, entitled DEVELOPMENT OF AUTONOMOUS MOBILE SYSTEMS, an analysis is made of the aspects related to manual or electric wheelchairs and the ways in which they offer solutions to overcome obstacles to the wheelchair. The evolution of wheelchairs, their fields of application and future development trends are presented. Chapter 3 presents conclusions on the current state of research.

The second part of the doctoral thesis comprises 5 chapters (4-8), as presented below. Chapter 4, which presents the research directions of the doctoral thesis, own research, original contributions, results and interpretations. Chapter 5, called CONTRIBUTIONS REGARDING THE OPTIMIZATION OF A DRIVING SYSTEM ATTACHABLE TO A WHEELCHAIR, presents both the justification and timeliness of the topic, stating the main and secondary objectives, and analysis and developments for the doctoral thesis. In the 6th chapter, entitled CONTRIBUTIONS REGARDING THE CONSTRUCTIVE DESIGN OF A DRIVE SYSTEM ATTACHABLE TO A MANUAL WHEELCHAIR, the stages of the constructive design of the assembly are presented, the parts that were manufactured and those purchased, but also multiple simulations made in Ansys in order to state the positive or negative aspects resulting from this complex process. Chapter 7, called CONTRIBUTIONS REGARDING THE DETAILED DESIGN OF AN ATTACHABLE SYSTEM, improves the development process by choosing component materials, making 3D models using dedicated CAD software applications, 3D printing, finite element analysis and environmental impact analysis. . In the 8th chapter, FINAL CONCLUSIONS AND MAIN CONTRIBUTIONS TO THE DEVELOPMENT OF THE AUTONOMOUS SYSTEM, the observations resulting from the research are summarized, the developments brought by the author are highlighted and the future research directions are established.

In the final part of the thesis we resumed the original contributions of the paper and highlighted the general conclusions of each chapter, but this time elaborating aspects such as relevance, complexity and timeliness of the issue addressed. The bibliography includes works in the field of research and consists of 91 titles. The works of the author are also presented, which deal with problems related to the objective of the thesis. The annex includes the identification of patents in the specialized literature.

Chapter 1. Methodologies for developing a new product

1.1. Introduction

The particular methodologies used in process or product development have the potential to stimulate the obtaining of creative and inventive solutions to problems, to ensure the consideration of each of the elements necessary for a successful development, to ensure that all the consequences of the development of a product or process over its lifetime are taken into account [O1]. In a broader sense, the development of new products is described as the transformation of a market opportunity into a product available for sale [U3]. A process is a sequence of steps that transforms a set of inputs into a set of outputs [P1]. The process of developing a product is described by all the activities that a company goes through to design, design and market a new product. The process begins with a planning stage followed by the research and development component [U3]. The end result of the development process is the product, ready to be sold. The inputs of the development process are represented by objectives, strategic opportunities, available technologies, product platforms and production systems. The process ends when all the information needed to support production and sales has been created and communicated [U3].

1.2. Models of a product development process

In the literature are proposed several models of the product development process [C2, P1, U1, U2, V1]. This diversity is due to the multidimensional aspect of the process that makes it possible to represent it in different forms. Within existing methodologies, there are often three important steps: (1) defining the problem, resulting from analyzing the requirements imposed by customers; (2) conceptual design, the result of which is the proposal of concepts; (3) detailed design, which provides a description of the concepts.

1.2.1. Pahl and Beitz's model

According to the systematic approach described by Pahl & Beitz [P2], the aim is to implement a methodology for all stages of technical systems development. The method, developed in the early 1970s, is based on problem solving and has been called SAPB (Systematic Approach to Engineering Design). This model derives from the VDI (The Association of German Engineers) directives and is representative for the European school of design, but also with the highest level of acceptance at European level.

1.2.2. VDI 2221 Directives

The VDI 2221 directives, proposed by the German Society of Engineers, suggest a systematic approach in which the design process is divided into 7 stages. These directives describe all the steps to be followed during the design process, but do not indicate what means can be used to make decisions. The VDI 2222 Directive defines an individual approach and methods for the conceptual design of technical products and is therefore suitable for the development of new products. This Directive proposes a generic approach to the design of technical systems and products, emphasizing the general applicability of the approach in the fields of mechanics, fine mechanics, control, software and process engineering [V1].

1.2.3. Ulrich and Eppinger model

Karl Ulrich and Steven Eppinger describe the development process as a succession of six stages (Fig. 1.5). This evolution of the product corresponds to a parallel evolution of the definition of the production process. Each stage corresponds to the performance of activities previously established by the members of the development team [U3].

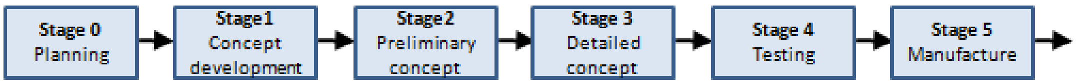


Fig. 1.5. The development process in the vision of Ulrich and Eppinger [U3]

1.2.4. Cavalluci model

In his doctoral thesis “Contributions to the elaboration of a methodological integration strategy”, Denis Cavalluci considers the conception process as a succession of 4 stages, as described in Fig 1.6.

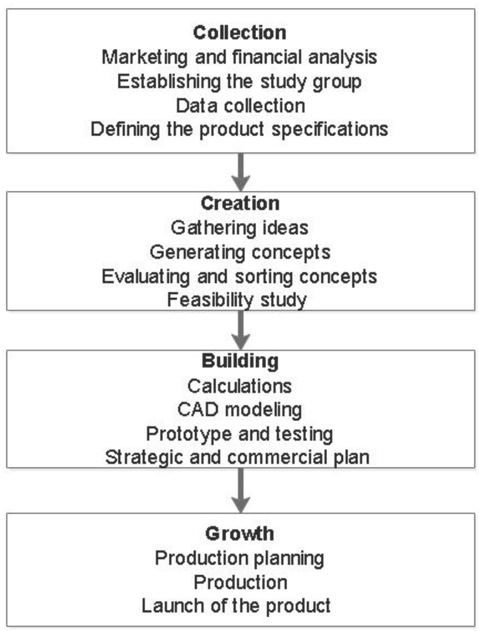


Fig. 1.6. The development process in the vision of Cavalluci [D3]

1.2.5. Ullman model

A design process applies to systems, subsystems, assemblies and components. It is used for new, innovative products and for changes to existing products. Even if a product is developed or just modified, there are steps that must be followed for all projects. The life cycle phases of a product of interest to the designer need to be improved. For each phase, there are a number of activities that need to be completed. The design process model proposed by David Ullman consists of 5 stages. Each of these stages involves the accomplishment of some tasks, and the success of the accomplishment of one is approved by an analysis of the conception [U1].

1.2.6. Cross model

There is a wide range of rational design methods that cover all aspects of the design process from clarifying the problem to design details. The selected set is detailed below, with the steps in the design process and the relevant methods for these steps [C2].

1.2.7. Product development procedure applied

Following the analysis of all the previous methods, it is found that professors Ulrich and Eppinger propose a methodology whose stages include all the others, for which reason it was selected to be used in the doctoral approach.

The conceptual design stage of the development process requires better coordination between product functions. Rarely does the whole process take place sequentially, ie completing one activity and then starting the next. In practice, activities may overlap and their repetition is often necessary. At almost any stage, new information can become available and take a step back to repeat a past activity. The conceptual development process includes the activities presented in Fig. 1.9:

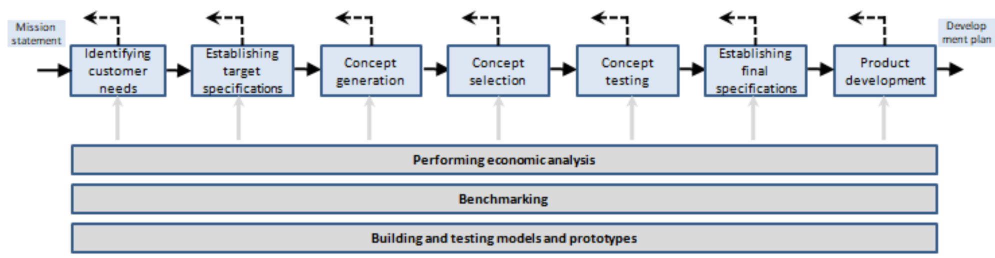


Fig. 1.9. Concept development stage activities [U3]

Chapter 2. Development of autonomous mobile systems

2.1. History of mobile systems

Wheelchairs have evolved very little in the last 1000 years. Most of the design changes have occurred in recent decades. The first wheelchair is known to be designed to provide mobility and has been called a "wheelchair" (Fig. 2.1.b). It was invented in 1595, especially for King Philip II of Spain. The chair had small wheels attached to the end of the legs of a normal chair and included a foot platform and an adjustable backrest. However, he could not be self-propelled, another person's openwork being necessary for travel.

Fig. 2.1.a The first wheelchairs [W9]

Fig. 2.1.b Wheelchair for Filip II [W9]

There are two types of wheelchairs, which are differentiated according to the mode of operation used for travel [A1]:

- manually operated wheelchair;
- electrically operated wheelchair.

2.2. Mobile systems for overcoming obstacles

The wheelchair powered by the electric motor requires navigation controls, such as an armrest-mounted joystick, which is usually the most commonly used control. On the other hand, for users who cannot operate a manual joystick, head switches, chin-operated joysticks or other specialized means of control that allow the independent operation of the wheelchair may be used. Motorized wheelchairs are useful for those who cannot propel it manually or who need to travel a long distance, which makes it difficult to operate manually.

2.3. Equipments for continuous overcoming of obstacles

The main property of equipment for the continuous overcoming of obstacles is that they have a single set of assistive devices through which the chair achieves a continuous movement. According to the movement mechanisms there are two categories: equipment with planetary mechanism and equipment with track mechanism.

2.3.1. Planetary mechanism equipments

The planetary mechanism consists of small wheels that are evenly distributed on a "Y" or "+" shaped connecting element. The small wheels can rotate around their own axles, but they can also make a revolutionary movement around the main shaft. Each small wheel rotates around its own axis when the wheelchair moves on the ground, and each small wheel rotates around the central axis when the wheelchair goes up or down stairs. This type of equipment can avoid overloading and can move smoothly, but has a low range.

2.3.2. Tracked equipments

By comparing planetary geared equipment with tracked equipment, the latter use a continuous mode of motion and have a high efficiency of motion transmission. The movement of the center of gravity of the wheelchair with tracked mechanism is always performed parallel to the connecting line of the obstacle edges, when the wheelchair goes up and down. The wheelchairs work smoothly, but there are also quite big disadvantages, namely high strength and lack of flexibility when moving on the ground. High pressure will be exerted on the edges of the stairs when the track mechanism accesses them, which could lead to their deterioration. Due to its reliability, the crawler mechanism is used more often in climbing stairs.

2.3.3. Wheel group equipments

Among the characteristics of a wheelchair for climbing obstacles we can list: the ability to overcome obstacles; matching all types of stairs; operation similar to that of electric wheelchairs; low mass; the need for assistance for a person to travel; ensuring a lower level of comfort for users when performing an orbital movement such as climbing stairs.

2.4. Equipments for intermittent overcoming of obstacles

The main feature of the wheelchairs for intermittent overcoming obstacles is the presence of two support devices, one with a lifting role and another with a supporting role. Both assistive devices are used for the function of ascending and descending stairs. The first wheelchairs used this method, as did the first stair lift developed in 1892. These chairs operate intermittently to perform their function, have low transmission efficiency and have some difficulty maintaining balance.

2.4.1. Mobile systems with leg mechanism

The Tokyo Institute of Technology began research on four-legged stepping gear as early as the 1970s, which led to the development of the TITAN series, typical obstacle access systems and which were developed successively.

2.4.2. Combined autonomous mobile wheel foot systems

Based on the characteristics of a mobile system, the simplicity of the mechanism and the efficiency of wheel and track type movement, adaptability to different surfaces and compaction of the construction, many combined systems have been developed to improve locomotion performance [G1]. Tracked systems have many negative aspects such as damage to the edges of the stairs or the danger of slipping, and leg systems do not offer improvements in safety and reliability when accessing the stairs. Using wheel or foot mechanisms in mobile systems eliminates many negative points.

2.5. Auxiliary obstacle overcoming equipments

This type of equipment is based on an assistive device, such as wheelchair accessories or a stair lift, to perform the function of accessing obstacles. Wheelchair accessories rest on another device mounted on the wheelchair and require an assistant to help perform the obstacle overcoming function.

2.6. Existing mobility solutions

Due to the different design specifications, wheelchairs can be classified into 4 categories. Each of these types of wheelchairs is specialized for either internal or external environments. The self-propelled wheelchair is specialized for the internal environment, and the scooter mobility solution is specialized for the external environment. The following table shows the comparative advantages of the different types of wheelchair.

Table 2.2. Comparisons between different types of wheelchairs and their characteristics [L2]

Model	**Interior wheelchair** 	**Electric wheelchair a)** 	**Electric wheelchair b)** 	**Scooter** 	**Power attachment system** 
Dimension	4	2	2	1	4
Mass	4	1	1	2	3
Return radius	4	2	3	1	4
Stability	2	3	3	4	2
Speed	1	3	3	4	3
Price	4	1	1	1	1

where: 1 = poor, 2 = medium, 3 = good, 4 = excellent.

In conclusion, there is no ideal configuration that maximizes stability, maneuverability and control simultaneously. Each mobile system application imposes unique constraints on the design issue, and the designer's task is to choose the most appropriate configuration possible from this compromise space.

2.7. Patents for power systems attached to mobile systems

Patents are a rich and easy-to-obtain source of detailed technical information containing drawings and explanations of many products. The main disadvantage of a patent is that the protection extends for a limited period from the filing of the patent application, so that there may be a royalty involved in its use. However, patents are useful to see which concepts are already protected and which should be avoided or licensed. Concepts contained in foreign patents, without worldwide coverage and in expired patents may be used without payment of royalties. Patent searches have been carried out to determine the key problems of the system that led to the solution of the problem [P1] and are presented in the Annex. The external influences of similar mobility solutions help to develop the product.

The general remarks are that power supply systems can be represented by:

• an attachment system on the front wheels (No. 3912032);
• friction drive unit placed on the rear wheels (No. WO2017131292A1);
• a system placed behind the wheelchair (No. 1136052).

Capitolul 3. Conclusions on the current state of research on the development of mobile systems for people with disabilities

From the analysis of the current state of research - development of mobile systems for people with disabilities, the following can be deduced:

• There will always be several ways to solve problems and a solution to a problem will be a local optimum (see § 1.1).

• The methodology for a design problem must take into account the needs and requirements of the user and the need solved by product development (see § 1.1).

• A process is a sequence of steps that transforms a set of inputs into a set of outputs (see § 1.1).

• Several models of the product development process are proposed. Within the existing methodologies, there are three important steps: defining the problem resulting from analyzing the requirements imposed by customers, conceptual design, the result of which is the proposal of concepts and detailed design, which provides a description of the concept (see § 1.2).

• Following the analysis of the literature in the field of methodologies for the development of an existing product or the design of a new product, the stages and activities that will be completed in order to develop an autonomous mobile system for transporting people with disabilities wheelchair manually in an electrically operated wheelchair.

The methodology to be used for product development involves the following steps: planning, concept development, system-level design, detailed design, testing and improvement, zero production (see § 1.2.7).

• The conceptual development process includes the activities: identifying customer needs, establishing target specifications, generating the concept, selecting the concept, testing the concept, establishing the final specifications, project planning, economic analysis, benchmarking of competing products, modeling and prototyping (see § 1.2.7).

• In order to achieve the design objectives, the requirements of the users must be detailed and clarified: safety in use, low risk of user mistakes, reliability, ease of use, robustness, resistance to external mechanical stresses, ease of assembly and disassembly, size reduction, use of elements standardized.

• From a constructive point of view, wheelchairs have evolved very little in the last 1000 years, most of the design changes have occurred in recent decades. The result was a less bulky product, but not easy to transport (see § 2.1).

• Electric wheelchairs do not allow the use of manual propulsion (see § 2.6).

• Wheelchairs available with their own energy source provide assistance, using combinations of the following functions: avoiding obstacles and collisions, maneuvering in narrow places, navigating by following a road and landmarks. However, these products are not accessible to everyone due to the high price (see § 2.6).

• Wheelchairs use different ways to transmit power (see § 2.7).

• There is no ideal configuration that maximizes stability, maneuverability and control at the same time.

• A key design principle resulting from taking into account the achievement of all set objectives is to increase the mobility of wheelchair users.

Chapter 4. Directions, main objective and research and development methodology of the mobile system for people with disabilities

4.1. The main objective of the research - development activity

Based on the critical bibliographic analysis on research on improving the performance of autonomous mobile systems, by presenting the current state of use of autonomous mobile systems, by classifying them according to different criteria and by analyzing patented models, is determined as the main objective of the doctoral activity: optimizing a autonomous mobile system by developing a module that can be attached to it, offering new functions: increased mobility and stability, ability to overcome obstacles of low height and keep the horizontality of the base.

4.2. Research - development directions

From the analysis of the current state, the following research and development directions are established regarding the optimization of a wheelchair manually by developing a module attachable to it, which would give it additional functions:

• Generating as wide a set of concepts as possible to meet the specifications of the mobile system;

• Development of constructive variants that allow a mobile system to overcome the obstacles encountered during travel;

• 3D modeling / simulation of mechanisms adaptable to the mobile system leading to increased mobility and the ability to overcome low-altitude obstacles;

• Detailed design of all components of previously modeled systems, attachable depending on the location on the wheelchair;

• Use of a control system adaptable to a standard manual wheelchair;

• Topologicy optimization of some components within the mobile system;

• Realization of components designed by rapid prototyping and product testing;

• Carrying out analyzes and optimizations to minimize the impact that the product has on the environment (including by using a small amount of material);

• Validation of simulation results by analytical methods implemented numerically in software programs such as Matlab, LabVIEW and Ansys.

4.3. Research - development methodology

The research-development methodology is conceived as a logical succession of stages for the actions that will be taken to achieve the main objective of the doctoral activity, as well as for possible future developments. The aim is to ensure open-mindedness for the widest possible searchfor solutions and to avoid errors by generating concepts for the developed system. The methodological references are as follows:

(1) Defining the general objective, sub-objectives and their importance, ensuring the motivation and tools to solve the topic;

(2) Systematic analysis of mobile systems, with or without additional electrical drive;

(3) Clarification of the operating limit conditions, establishment of the list of requirements, specifications and functions of the developed product, as the mode of attachment to a manually operated mobile system;

(4) Conceptual product design;

(5) Modeling / simulation of product operation;

(6) Detailed design of the chosen variant;

(7) Manufacture of components of the developed system;

(8) System testing.

Chapter 5. Contributions on optimizing a drive system attachable to a manual wheelchair

5.1. Process and design objectives

The design process involves a systematic approach, which designers can follow, regardless of their specialty. In this process, progress is made from qualitative to quantitative, each stage being much more concrete than the previous one [P4]. Defining the essential problems in the most abstract way possible, for setting the main objectives and constraints, allows finding solutions, because an abstract formulation encourages a more thorough research of unconventional solutions.

The design methodology used tries to narrow down the options, starting from a. Initially large area of problems, represented by solutions and unclear use and economic and environmental needs.

As more information is obtained, the design process begins to narrow and information is filtered to guide the project to a final solution. The central objective in the design of any mobility aid device must be safety. Ease of handling is essential for users with mobility impairments, people with disabilities or the elderly and will be central to the acceptability of the final solution. Operation in barrier-free areas must be similar to that of a standard electrically operated wheelchair.

The next objective is to achieve a mechanism that does not exceed the physical dimensions of existing products. This goal is achieved in the design, and some exaggerated dimensions of the prototype may be due to the use of mechanical components that are not available on an appropriate scale.

Another goal is a structure based on the use of small components. This can be achieved due to the availability of a range of small linear actuators, the purpose of which is not to add to the initial mass of the product. In practice, the addition of any function will lead to an increase in mass.

5.2. Product specifications

In order to ensure a functional and technical advantage of the product, its characteristics are determined on the basis of the analysis of competing products [H2]. The conceptual design is based on the specifications established for the wheelchair, the main features being presented below. Most of these were established following discussions with people who frequently use such mobile systems and with specialist doctors. Some of the features were indicated by the author, based on the analysis of existing products.

5.3. Determining the functions of the product

A technical system can initially be modeled as a "black box" [P1] with energy inputs, material, signal and outputs from the system. Usually, when modeling the black box, the energy is represented by a thin line, the material flows with a thick line and the control flows and feedback signals within the system with a dotted line. The technical system therefore supposes a functional relationship between inputs and outputs.

In Fig. 5.2. the black box for the product to be developed is presented.

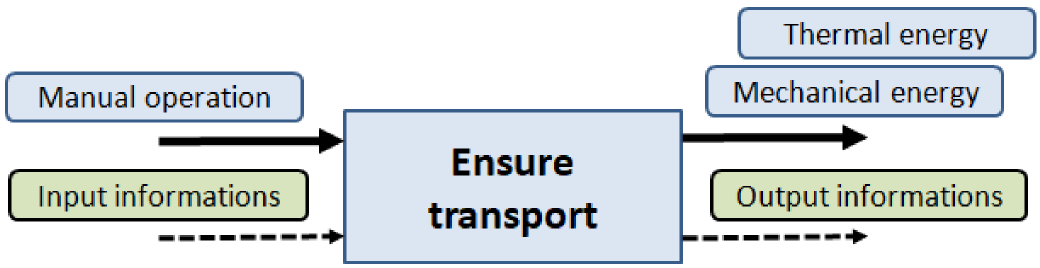


Fig. 5.2. Black box for a mobile system for transporting people with disabilities

A product is a set of components. Functional decomposition is the technique that identifies the critical functions for the product and the attributes that describe the functions with the input and output flows defined as material, information and energy [P1]

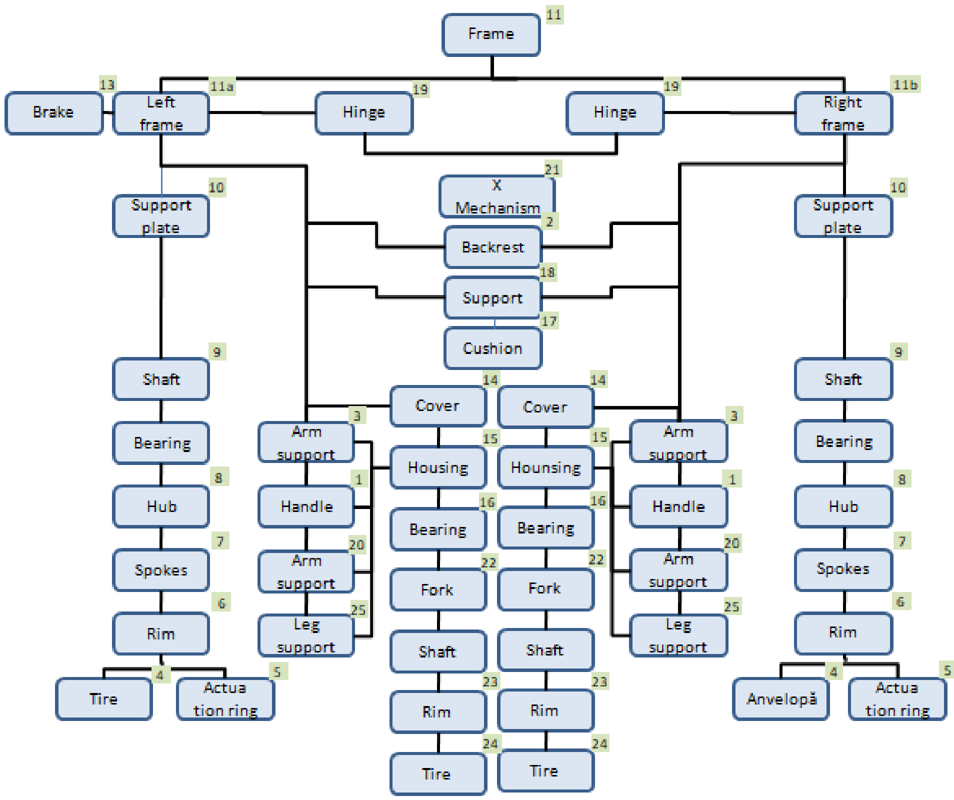


Fig. 5.3 b.
Components of a manual wheelchair

A complete functional analysis involves [U1]: identification of product components and their functions; description of the functional interactions of the components with each of the others; clarifying the best solution to meet customer needs by describing the functional requirements of the component; use of functional descriptions for the generation and selection of sets of technological components that meet the basic functional requirements.

The following steps [P1] are used to identify the functions:

• expressing functions intuitively;

• identification of functions by analyzing the relationship of the product with the environment;

• identification of functions based on the study of the component elements of a reference product;

• identification of restrictions based on the analysis of the norms in force.

Following the functional analysis performed on the elements of the wheelchairs operated manually in terms of functions and interactions, the components of the wheelchair were determined, the functions and interactions between them, it was identified which components perform each function and detailed how to perform customer needs by describing the product or component.

The 'black box' model of existing systems to be redesigned breaks down the existing system into subsystems, which are then transposed into sub-functions. The combination of subfunctions is a solution that achieves the desired overall function.

The next step in the functional breakdown is to divide the flows in the black box into secondary functions for a more accurate description of the general function of the product, that of transport. Each subfunction can be further divided into simpler subfunctions. For a mobile system, its functions can be defined according to Fig. 5.5.

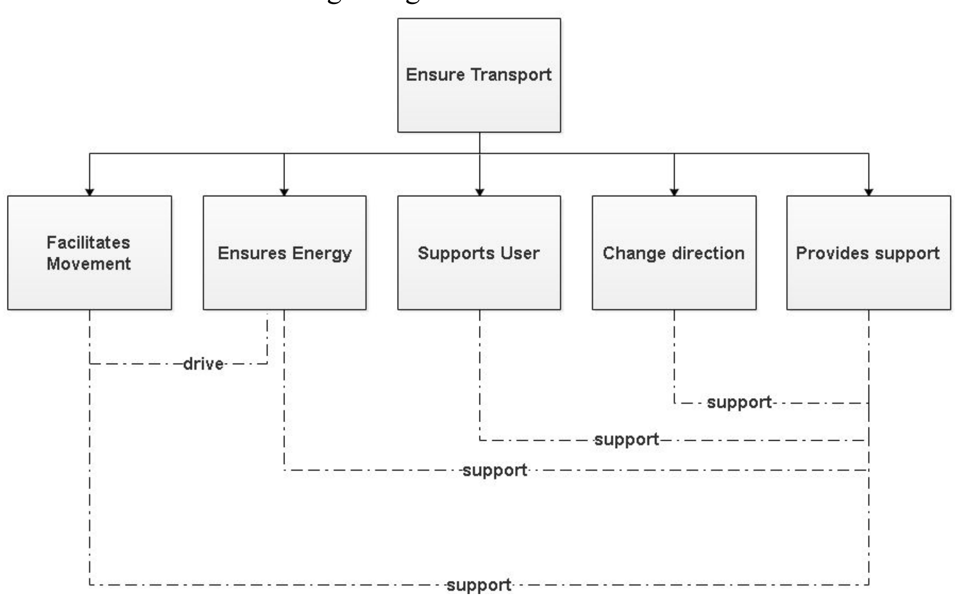


Fig. 5.5. Functions of the autonomous mobile system

The end result is a diagram containing the function and subfunctions related to the flow of materials, energy and signal. The aim is to describe the functional elements of the product without assuming a technological working principle specific to the product concept [P1].

Needs breakdown is used for products where shape is the main issue, not working principles or technology [P1]. After the problem is completely decomposed, the subproblems that are critical for the success of the product and which are the ones likely to benefit from new solutions according to Fig. 5.6.

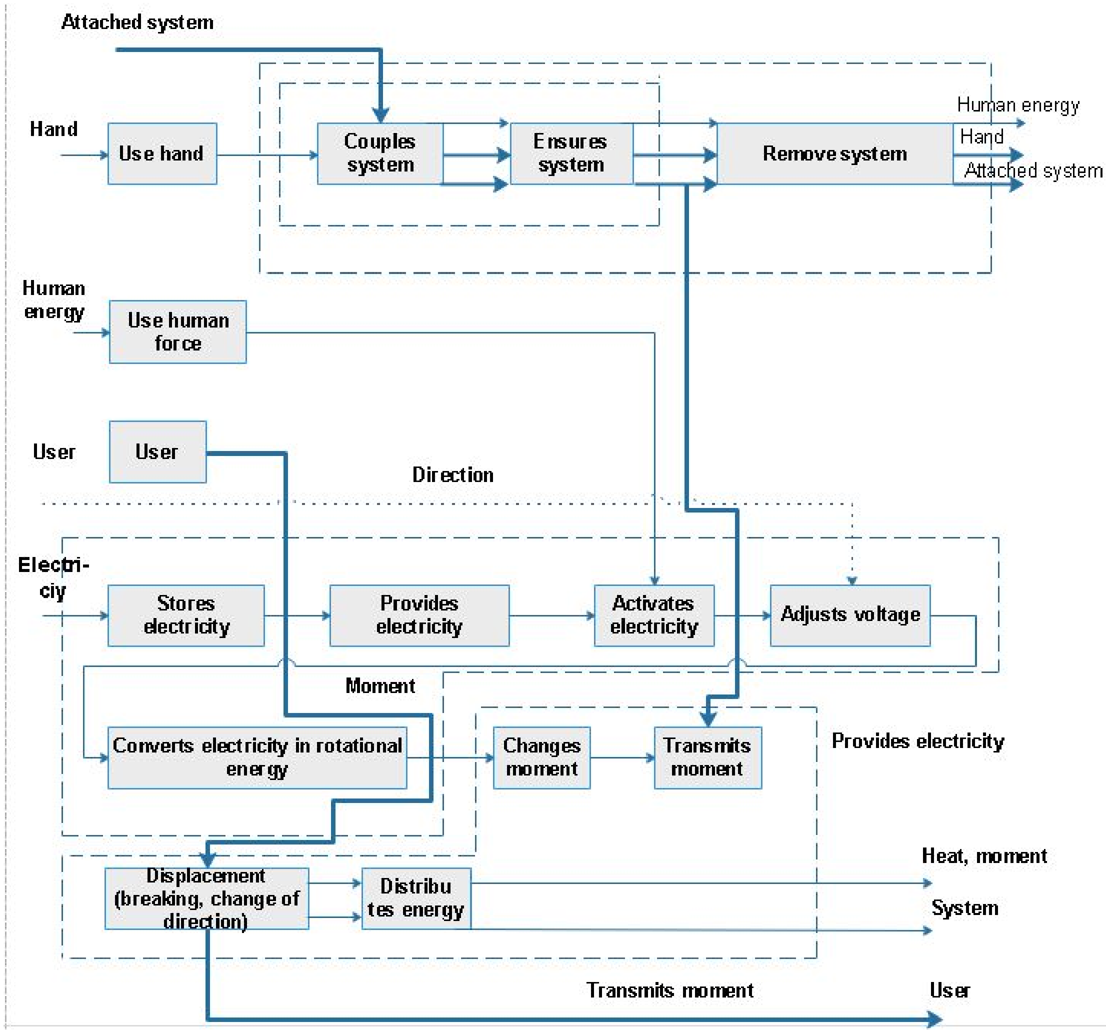


Fig. 5.6. Functional structure of the attachment system [G10]

Following the analysis of the scheme shown in Fig. 5.6 it follows that the optimal constructive solution that can meet the assumed optimization characteristics (increasing mobility, overcoming obstacles and maintaining the horizontality of the platform along the whole route) is a system attachable to the usual wheelchair, which brings increased autonomy due to electric drive, keeping the mass low. and the possibility of folding - characteristic of manually operated chairs. Next, the development process will focus on making this new product attachable to a standard wheelchair.

5.4. Wheel impact analysis with a fixed obstacle

5.4.1. Geometric modeling of the impact with an obstacle

The movement of the wheel when overcoming an obstacle can be divided into two components, exemplified in Fig. 5.7: impact at point C of contact with the obstacle and then passing over the obstacle encountered. When the contact takes place at point C, the wheel pivots over the obstacle at that point and the friction F between the wheel and the ground disappears.

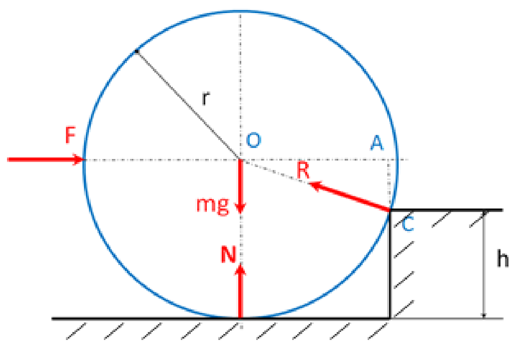
During and immediately after impact, an unknown impulse force R acts on the wheel for a short period of time: $\Delta t \cong 0$.

When the wheel is about to pivot around the obstacle, the net torque is 0, so that the minimum force required to lift the wheel on the obstacle is given by the relation:

$$F = m \cdot g \cdot \left(\frac{\sqrt{2 \cdot r \cdot h - h^2}}{r - h}\right) \text{ [N]} \tag{5.1}$$

$$\tau_w = m \cdot g \cdot \sqrt{2 \cdot r \cdot h - h^2}$$

$$\tau_F = -F \cdot (r - h)$$



where:
m = mass [kg];
g = gravitational acceleration [m / s^2];
r = wheel radius [m];
h = obstacle height [m];
τ_w = moment determined by weight [N • m];
F = force required to overcome the obstacle [N];
τ_F = moment determined by the applied force [N • m].

Fig. 5.7. Impact stress diagram

5.4.2. Analysis of variants of maintaining the horizontal position during the crossing of the obstacle

5.4.2.1. Application for the analysis and synthesis of 6-bar mechanisms

The wheelchair can have several modules: lifting at another person and controlling the direction. One of the design objectives for the wheelchair product to become modular is to perform the function of maintaining the user's horizontality, so that analyzes have been performed to define a mechanism that will be the most important in performing this task. Secondary mechanisms were analyzed, including the addition of stability bars, wheelbase extension and automatic braking.

In order to modify the configuration of some components of the mechanism in order to fit the overall dimensions of the wheelchairs while maintaining the horizontality of the user's seating platform, the performance of a 6-bar mechanism was analyzed, according to performing such a function. It is necessary to establish the criteria that the mechanism must meet, the most important being the support of a weight. When overcoming an obstacle, the platform of a wheelchair changes its horizontal position, which causes the center of gravity to change, making the chair unstable. The maintenance of the horizontal position of the seating platform is achieved by means of a mechanism that is mounted on the sides of the wheelchair. Changing the position of the platform when overcoming an obstacle will be done with a separate drive system whose horizontal position varies by an angle θ determined by the initial and final value of the input quantity (Fig. 5.8).

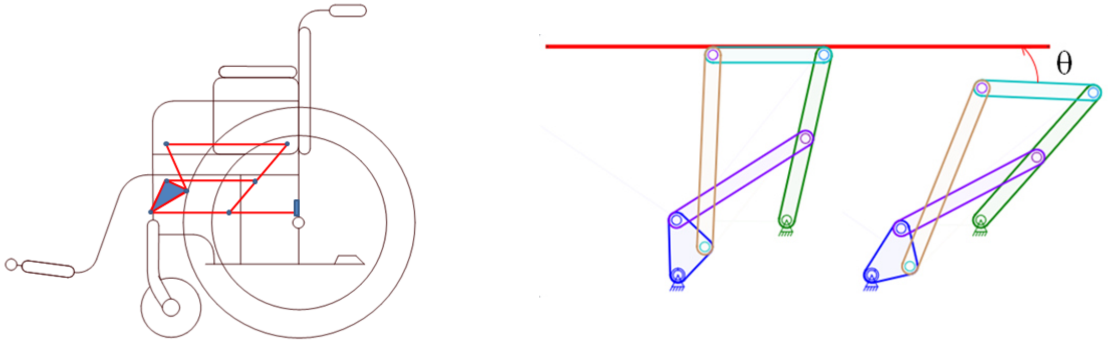


Fig. 5.8. The position of the mechanism

For such a mechanism it is necessary to analyze its position to determine the influence of joint angles on the horizontal position of the element attachable to the seating platform. Such an analysis can be done for a 6-bar mechanism [A3].

Solving the problem was done using a Matlab application that generates random lengths for the mechanism bars using a set of values for the angle θ_2. Some constant quantities consider θ_2, θ_3, θ_4, θ_5 și θ_6 (initialized with the value zero), θ_0 (15˚) between the element R1 and the vertical were considered, and for the horizontal variation of the platform a domain (± 15˚). To find the lengths of the mechanism arms that satisfy an acceptable error requires a large number of iterations.

5.4.2.2. Application for kinematic analysis of 6-bar mechanisms

In plane mechanisms, kinematic analysis can be performed either analytically or graphically. Analytical kinematics is based on the design of the equations of vector loops of a mechanism on the axes of a fixed Cartesian system. This projection transforms a vector equation into two algebraic equations. For a given value of the position or orientation of the input elements, the algebraic equations are solved for the position, respectively the orientation of the remaining connections. The first and second time-derived derivatives of algebraic position equations provide equations for the velocity and acceleration of the mechanism [H1].

Using the Matlab R2015a environment, an application was made with which speed and acceleration were analyzed (Fig. 5.18). The graphs show the existence of a difference between the values of speed and acceleration for the two points P3 and P5 from which the landing platform is attached. By modifying the lengths of the elements of the mechanism, a combination was found that would lead to approximately equal values for the parameters of points P3 and P5.

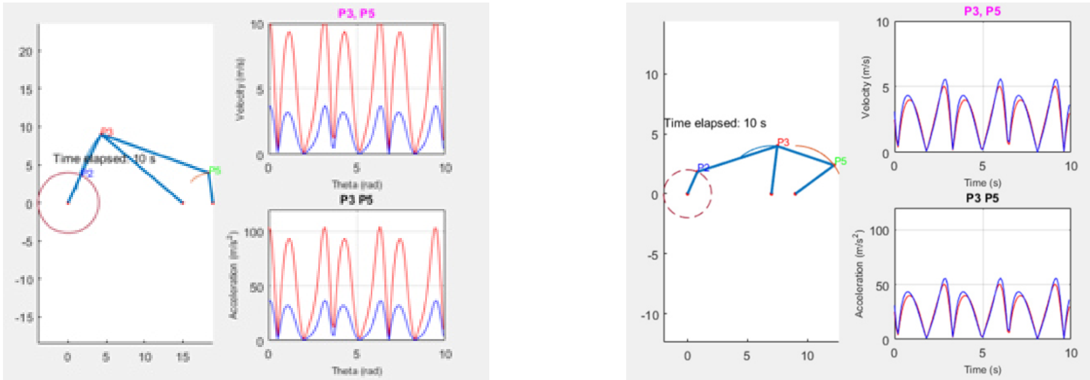


Fig. 5.18. Graphical representation of speed and acceleration

5.4.3. Matrix approach for the study of product modules

An approach for developing a new product can be a modular design that divides the product into independently created modules and then used in different systems [B1], as already considered in the previous section. The design of the electric actuator attached to the wheelchair was done using the modeling method proposed by Mocho [M5], which uses the matrix approach and establishes the following activities and steps for product development and modeling: requirements modeling, function modeling, component modeling, feature modeling tested, analysis of requirements and functions, analysis of functions and components, analysis of components and technical characteristics, analysis of requirements and components, analysis of requirements and assembly, analysis of function and assembly. Matrices provide a means of modeling the relationships between the fields of system design and analysis using mathematical functions. Based on the proposed algorithm, a Matlab software application was developed to solve the structure of a wheelchair manually.

5.5. Concept generation

The process of generating the concept begins with identifying a set of customer needs and establishing objective specifications, which will be grouped into a set of product concepts from which a final selection will be made. A good generation of the concept involves exploring the whole space of alternatives [P1].

The new attachment system will be designed to have the following features:

1. Be a cheap product.
2. To be able to attach to a wheelchair with minimal interventions.
3. Maintain the maneuverability of the wheelchair, allowing it to turn as far as possible without increasing the overall dimensions of the wheelchair.
4. Maintain the stability of the wheelchair.
5. Maintain traction on uneven surfaces.
6. Keep the portability of the wheelchair and the possibility of being transported in a car.
7. Direct the wheelchair in any direction with a simple steering and reversing mechanism.
8. Allow the device to be synchronized with almost all standard wheelchairs, with simple modifications to the extensions and mounting accessories.

The organization and combination of alternative solutions for each function is done using a morphological matrix [G14]. It consists of a table with in the first column the relevant functions of the product, and in each row the possible solutions that allow the performance of that function. Texts are used to represent possible solutions. The morphological matrix of the developed product is presented in Fig. 5.25.

	1	2	3	4	5	6
Motor	Stepper motor	DC motor	Hydraulic motor	Pneumatic motor		
Accumulator	NiCd	NiMh	$LiCoO_2$	$LiNiMnCoO_2$		
Moment transmission	Conical gears	Differential	Planetary mechanism	Worm wheel	Friction	Pinion-toothed crown
Control system	Buttons	Joystick	Vocal	Touch Screen		
Braking system	Disc brake	Roller	Brake on the tire	Brake on the rim		
Steering control	With additional motor	Wheels separately				
Motor placement	Hub	Back of the wheelchair	On the shaft	Behind the wheelchair	Under the wheelchair	
Wheel	Track	Classic wheel	Swedish wheel			

Concept A   Concept B   Concept C   Concept D   Concept E   Concept F

Fig. 5.25. Morphological matrix for the wheelchair

The generation of the concepts was done by eliminating from the beginning the types of drive motors that require power supplies that make the wheelchair difficult to operate. One solution is combined for each wheelchair function, resulting in several candidate concepts.

5.6. Concept selection

The selection of the concept will be made by going through the sorting stages that allow an initial reduction of the set of variants and evaluation with the use of more detailed filters that allow the preservation of 1-3 concepts for further development. In the step of selecting the optimal concept, the concepts resulting from the previous stage (that of generating concepts) were taken into account.

The complete concepts are presented in tabular form. It is recommended that the reference concept be a simple solution that involves low costs and is found in similar products on the market [U3]. The evaluation and selection of the concept can be done on the basis of an evaluation matrix or a more advanced methodology [W3].

Following the analysis, the concept C was reached, which will be further developed and which involves the use of the following components: DC motor, LiCoO2 battery, planetary mechanism, joystick control, tire braking, joystick steering, motor located on the wheelchair axle and classic wheels.

Chapter 6. Contributions regarding the constructive design of a drive system attachable to a manual wheelchair

Constructive design is that part of the design process in which, starting from the concept of a technical product, shapes are defined and dimensions and materials are assigned, in accordance with economic and technical criteria.

6.1. Stages of constructive design

According to one of the constructive design principles presented by Pahl & Beitz [P1], known solutions or existing components (repeating parts or standardized and standardized components) will be purchased.

The structure of the attachment system (Fig. 6.1) was divided into three subsystems (control, for power supply and for power transmission) tran for the realization of which components purchased or designed by the author were used.

6.2. Purchased subassemblies

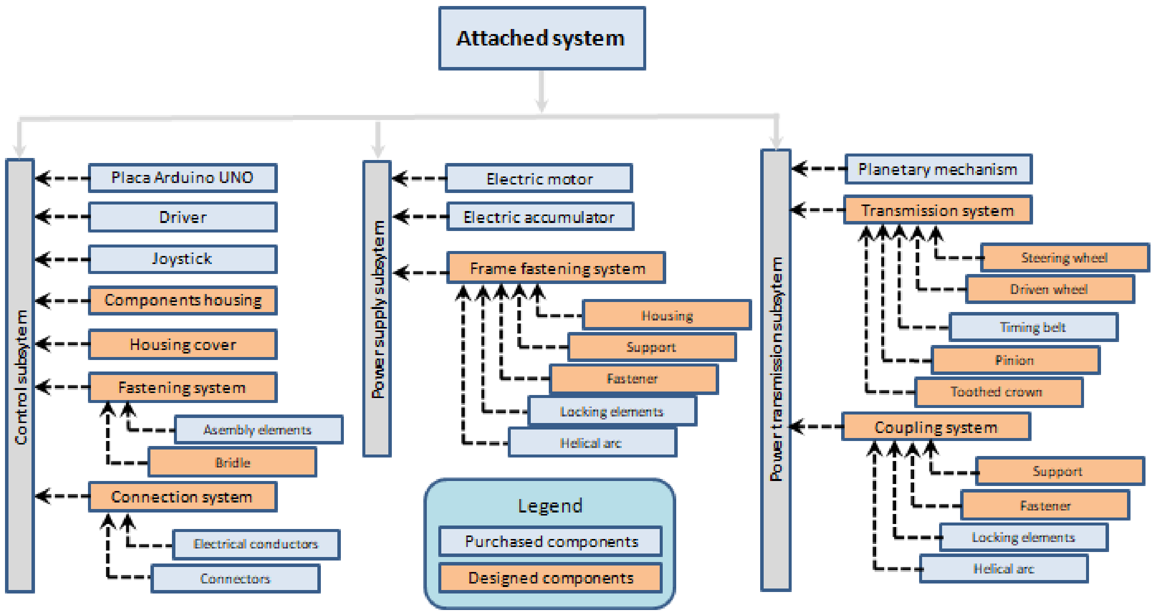


Fig. 6.1. Structure of the attached system

6.2.1. Choice of engine

The important elements for choosing the engine are torque, speed, power consumption, size. We assume, for simplicity, that there is a responsibility of the user to brake or control the speed, so that the maximum speed of a powered wheelchair does not exceed 5 km / h [W8].

6.2.2. Calculation and sizing of the belt drive

The toothed belt drive has 2 gears and a toothed belt. The dimensions of the system are determined by its mode of assembly on the wheelchair. In this sense, the size of the drive wheel, the driven wheel and the distance between the axles have the most important role in choosing the purchased belt [W21].

Thus, the choice of engine will be based on the following restrictions: to be easy to control, small and light, to be durable and easy to maintain, to have low noise in operation, to have low cost, to be able to be used in different conditions. environment, including in humid conditions. Purchased components include the engine, gearbox (planetary mechanism), control system and power supply.

6.3. Constructive design of some components of the attachable system

The attachment system for operating the manual wheelchair with two symmetrical parts has the following components (Fig. 6.4):

- Power supply subsystem (battery + motor);
- Power transmission subsystem (belt drive, planetary mechanism, wheel coupling subsystem);
- Control subsystem;

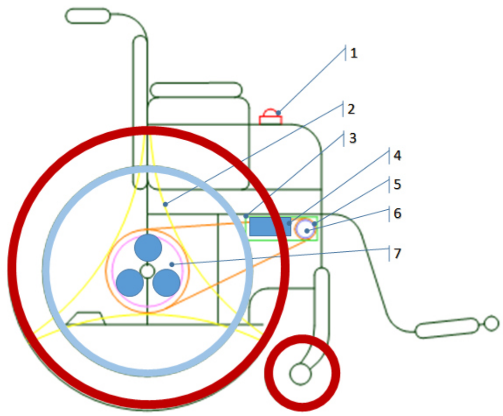


Fig. 6.4. System attached to the wheelchair manually (1- joystick, 2 - coupling device, 3 - bracket, 4 - battery, 5 - transmission with belt, 6 - electric motor, 7 - planetary mechanism)

The dimensional differences between the two systems considered for the gearbox can be seen in Fig. 6.11. The use of a two-stage planetary mechanism reduces the diameter of the ring gear from 130 mm to 50 mm and thus helps to reduce the mass of the system.

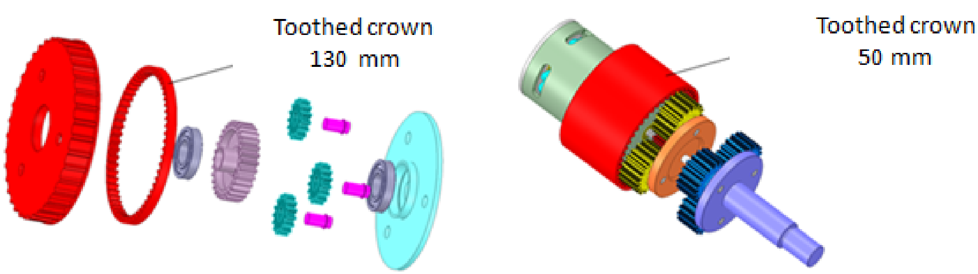


Fig. 6.11. Comparison between the mechanisms used

6.4. Choice of materials

The material selection methodology established by Ashby [A4] was applied in the case of the wheelchair attachment system for fixing the material in case of a simple component, the support in the wheel mounting system. In this case, the material is chosen for a single component, represented by the spoke of the mounting bracket on the wheel, being considered a embedded bar at one end of length L and stressed at the other end by a force F.

6.5. Determining the shape of the material index

The stages of the process of selecting a material for a particular part of the wheelchair product are defined below.

1. Defining the requirements;
    a. Establishing the landmark functions;
    b. Establishing the objective function - the optimization criterion (minimum cost, maximum profit);
    c. Establishing independent and dependent variables;
    d. Definition of restrictions: required mechanical characteristics;
2. Development of dependency relationships between independent variables and dependent variables;
3. Development of a relationship to define the objective function in correlation with the functional requirements;
4. Grouping the variables into three groups: functional requirements F, geometry G and properties of materials M;
5. Determination of the material index, expressed as a quantity M, as a criterion of excellence that optimizes the performance value.

It is easy to identify the group of materials that optimizes the maximum performance for each mode of application. All materials that are located on the right corresponding to the material index behave the same for the considered mode of application. The line on the graph isolates a search area that contains a small number of candidate materials. Boundary features can be added by narrowing the search area. The number of candidate materials can be increased or decreased by moving up the line corresponding to the material index, up or down.

Using Ashby's graphs and the form factor, we arrive at the choice of other materials for the studied component, the material index being the same because all the materials are on a straight line with the same slope.

Chapter 7. Contributions to the detailed design of a manual wheelchair attachment system

Detailed design is that part of the design process that complements the technical designs with the final instructions regarding the appearance, shape, dimensions and surface properties of each component,the final selection of materials, manufacturing processes and costs [P1].

An important component of the detailed design stage is the elaboration of technological and constructive documentation. These activities are supported by CAD / CAPP / CAM / CAE software applications, which allows the direct use of constructive and technological information on production planning and control of CNC machines.

7.1. Topology optimization of the system

Topology optimization is a mathematical method that improves the shape of the material in a certain design space, for a set of tasks, limiting conditions and constraints, in order to maximize system performance [B3]. The purpose of topology optimization is to find the best use of the material of a part so that the objective function (rigidity, own frequency, etc.) reaches the maximum or minimum value, subject to the given restrictions (reduction of volume or mass).

AnsysSpaceClaim 18.1a software was used to create the geometry of the component (Fig. 7.2), reducing its mass by changing the shape so that the component does not yield.

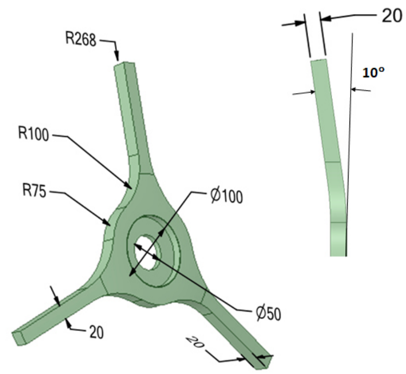


Fig. 7.2. Initial geometry of the component

Higher values of the total deformation indicate that the material should be preserved, lower values indicating the areas with material to be removed. The highlighted part is the material to be removed, the gray part is the critical material, the blackened part is the material that will be kept.

For this topology optimization, the supports and loads were placed on a volume of material and iteratively the shape of the component was changed until the mass reduction coefficient reached the value of 60% (Fig. 7.6).

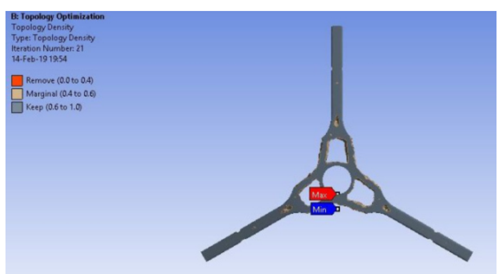


Fig. 7.6. Topology optimization

The initial profile and the profile obtained after an iteration are presented in Fig. 7.7.

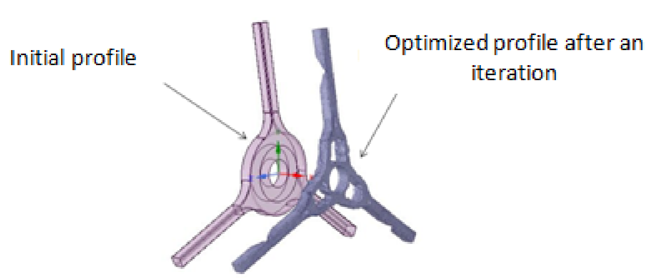


Fig. 7.7. The new form obtained after topology optimization

The volume of the initial shape of the analyzed component is $6{,}07 \cdot 10^5$ mm^3 and the volume of the final shape obtained after topology optimization is $2{,}25 \cdot 10^5$ mm^3, resulting in a reduction in mass by 55.58% in the case of the material considered, aluminum. The changes adopted led to the elimination of less requested areas and to the obtaining of a configuration of the structure corresponding to the way of request.

7.2. Eco-audit and the impact of the system on the environment

Any product is made after going through a production process. The life cycle of a product comprises a longer time interval than that of the production process, including the stages of identifying a need, conceptual design, detailed design, design of technological processes, manufacturing, operation / use, decommissioning. If the environmental impact assessment of a product is to be assessed, all stages of its life cycle must be studied. The aim is to measure the impact on the environment of the product at all stages of the life cycle and to identify all aspects of potential problems from the extraction of raw materials to production, distribution, use and disposal.

The purpose of the environmental impact assessment of a product is to determine the energy used, water consumption, the amount of CO2 released annually into the atmosphere, the carbon footprint, the recycling fraction (percentage of material that can be recovered from the mass of a component), toxicity and approximate processing energy. The eco-audit method allows the analysis of alternative design options to meet the required requirements and to reduce the environmental impact of the system attached to the wheelchair [G5].

A detailed breakdown of energy and CO2 footprint for life cycle phases (semi-manufacturing, manufacturing, transport and end of life cycle) is shown in Fig. 7.9.

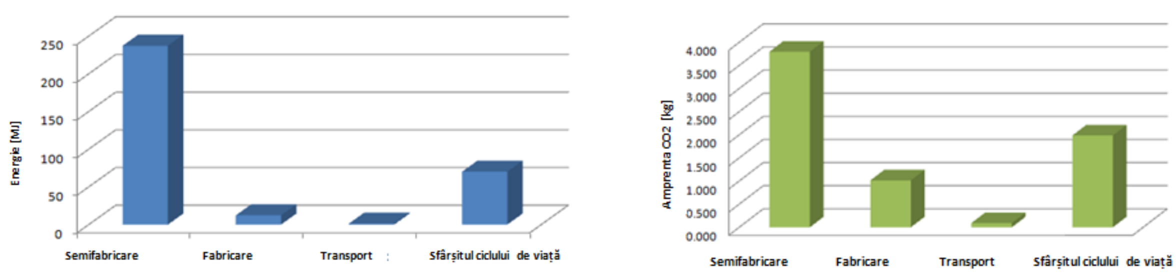


Fig. 7.9. Life cycle analysis

7.3. Detailed design of system components for an manual wheelchair

The main objective of the design process was to create an attachable system that would transform a manual wheelchair into a controlled, propelled wheelchair. The designed device can be mounted on a manually operated wheelchair used by persons who are temporarily or permanently unable to move.

The designed device seeks to eliminate the disadvantages presented and to allow the user to easily overcome, without considerable effort, obstacles and to allow the folding of the wheelchair for transport, without the need to disassemble the device before folding (Fig. 7.10).

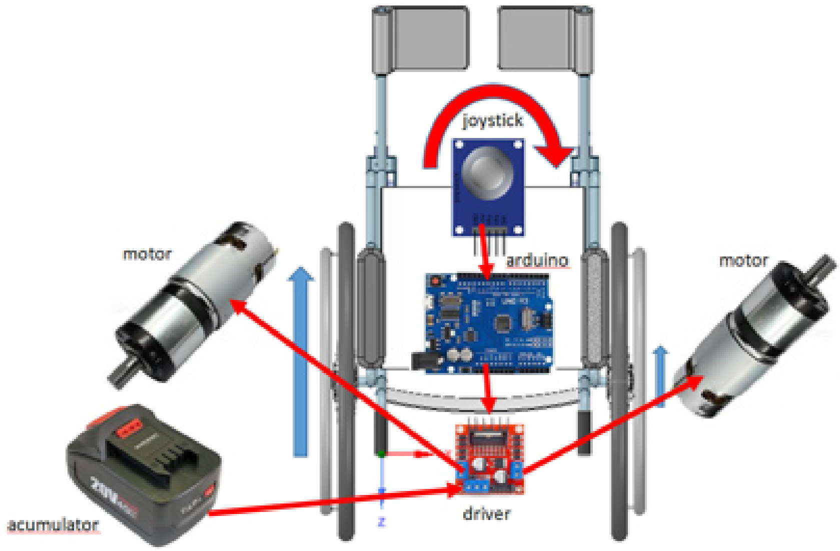


Fig. 7.10. General diagram of a control system

The system includes an electric motor, which is the input element of the actuation of a planetary gear mechanism, a coupling for transmitting motion to the sprocket gear. In the case of the wheelchair control system, the ArduinoUNO board was used.

The circuit diagram resulting with the assembled electronic components is shown in Fig. 7.13. The elements are mounted in a unit fixed on the arm of the wheelchair. To verify the operation of the Arduino, driver, joystick and motor assembly, a VI (Virtual Instrumentation) was created, a virtual instrument programmed in the LabVIEW graphical programming environment).

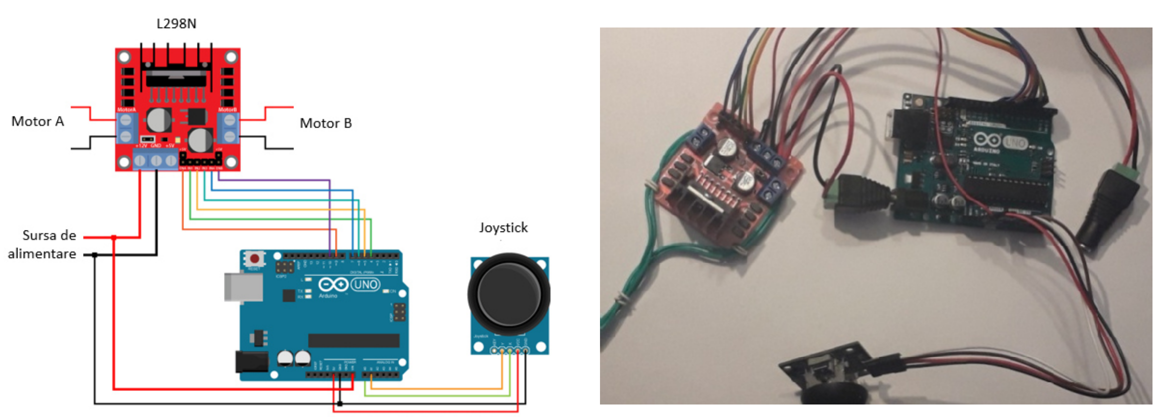


Fig. 7.13. Circuit diagram with electronic components and the real version

The virtual tool is created to simulate the operation of the entire system.

The design of the attachable system was done by choosing a wheelchair with a regular / standard design. The wheelchair of your choice has a steel frame, with footrest and the possibility of being folded. The folding mechanism of the X-wheelchair frame (Fig. 7.16) consists of two tubular elements fixed in a joint so that when the wheelchair is folded, the elements are oriented almost parallel, joining the wheels of the wheelchair.

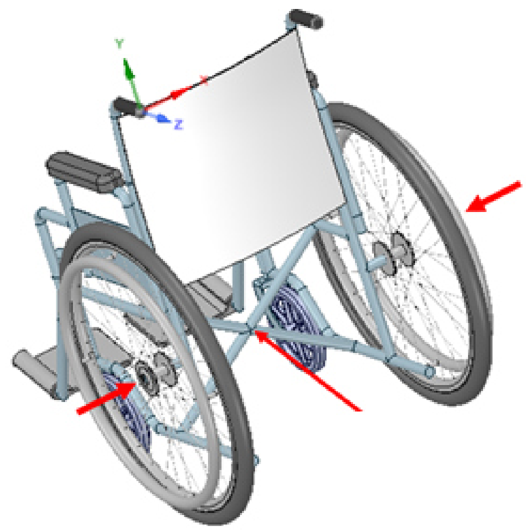


Fig. 7.16. Folding mechanism

The components of the attachment system were purchased or designed to fit the dimensions of the frame and were checked for interference during folding based on the dimensions and constraints derived from static and dynamic analysis. It is essential to have such a view of the mechanism, because in this way the dimensional requirements and constraints can be interpreted more easily, and then the general improvements are taken into account.

7.4. 3D modeling of the system attachable to a wheelchair

The following can be known by the 3D design of the components of the attachment system: mass, volume, center of gravity, data that can be used later in the component manufacturing process. The choice of a wheelchair frame as a base for mounting the other components gave the possibility to visualize how the components could be adapted to other frames. Because adaptability was important, the interface between the wheel and the frame must be designed to fit any design variant.

The design of the elements that facilitate the attachment or detachment of the developed device to / from the wheelchair is of critical importance for the operation of the mechanism and for the success of the product. Advanced structural analysis techniques, including the development of mechanism models required by the finite element method, were used to optimize the operational efficiency of the new attached device.

In Fig. 7.19 presents the first detailed design variant. It was decided to redesign to reduce the number of components of the device that will be attached to the wheelchair. The designed mechanical components of the attachment system have been modeled to ensure proper choices in the design process, ensuring element alignment and interference detection. The following subassemblies have been designed: coupling, attachment, transmission and mounting.

The attachment system (Fig. 7.20) ensures the mounting of the device on the frame of the wheelchair by means of a bracelet-type system, consisting of external support and internal support, positioned in the area of the wheel axle and fixed by means of screws. The adaptation to various thicknesses of the frame is made with the help of intermediate elements placed in the curved area of the two supports.

The planetary mechanism is mounted in a housing which, by construction, blocks the circular crown and prevents its rotational movement, as in Fig. 7.21. The electric motor is assembled on the planetary mechanism, the whole system being coupled to the inner support by means of elastic zones, the position being established by a guide element.

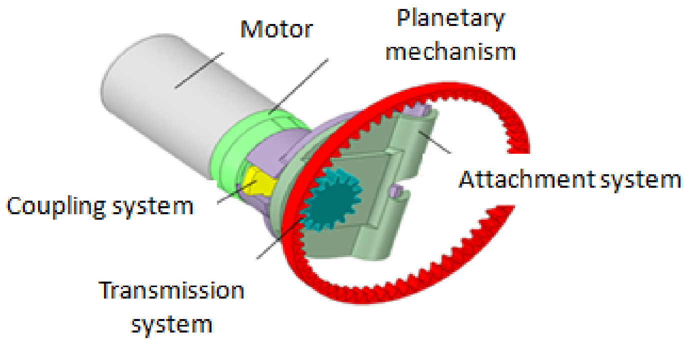


Fig. 7.19. Wheelchair accessible system

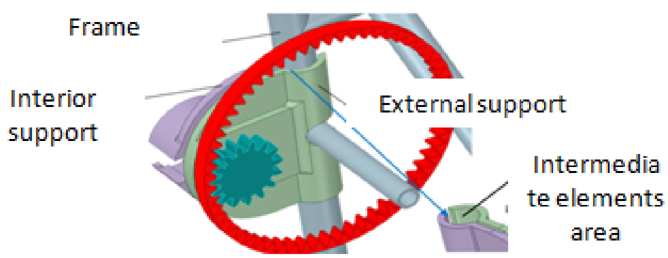


Fig. 7.20. Attachment system

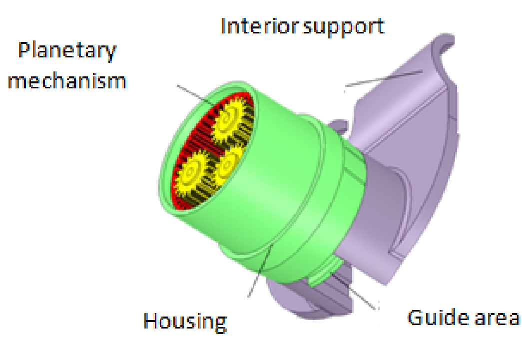


Fig. 7.21. Assembling the planetary mechanism with the attachment system

The rotational movement of the planetary mechanism is transmitted to a pinion gear - toothed ring by means of a coupling system consisting of a bush with inner hexagon and a movable actuating element which, by axial movement, stiffens the output shaft with the pinion shaft. The role of the coupling system (Fig. 7.22) is to allow the wheelchair to be switched to manual operation without disassembling the device.

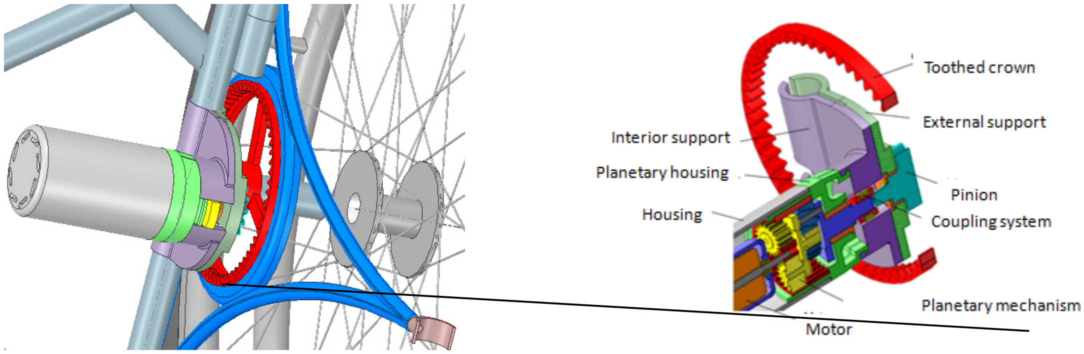


Fig. 7.22. Coupling system

The transmission of the movement to the wheels of the wheelchair is done through a pinion gear - toothed crown. The pinion is drilled in the outer support, and the toothed ring is fixed in the rim attachment system. The total gear ratio of the system is 1: 144 and is obtained from the product between the gear ratio of the planetary mechanism and that of the pinion-toothed gear.

7.5. Rapid prototyping

In order to validate the system that will manually transform the wheelchair for people with disabilities into an electric one and in order to be able to perform validation tests, a physical model was created by rapid prototyping. Further research will be carried out on ensuring the coupling on the wheel, taking over the transmission of the movement from the motor and the coupling of the elements for the electric mode. Not being able to print the coupling system on the rim of the wheelchair, another constructive solution was sought, fixing the toothed crown to the wheel spokes, according to Fig. 7.23.

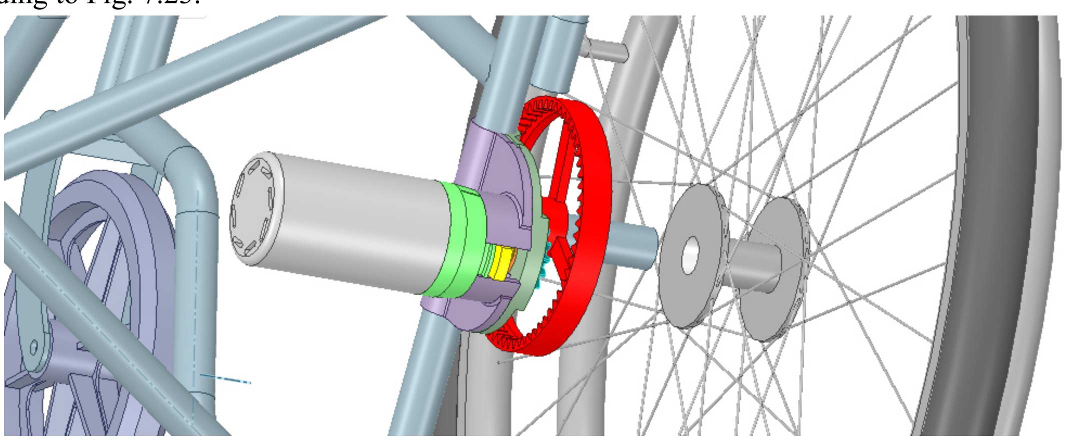


Fig. 7.23. Alternative coupling constructive solution

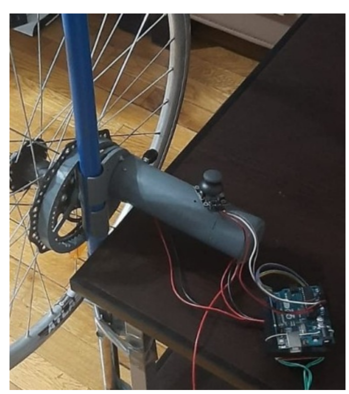
For prototyping, a cheap and versatile additive manufacturing (FA) technology was chosen, capable of using biodegradable plastics and allowing to obtain parts, possibly to be used in a prototype, FDM technology (FusedDepositionModeling).

FDM technology is characterized by simplicity and accessibility. Like all FA technologies, FDM builds objects layer by layer. The 3D mode made in a CAD application is exported in STL (StandardTessellationFile) format and then "sliced" by a special software, in layers with thicknesses of several tens of micrometers, depending on the 3D printing equipment used. Using the STL file, the physical model is made by uniformly applying, layer by layer, a plastic filament heated to the melting point.

The 3D printed components for the developed product are represented in Fig. 7.24.

Fig. 7.24. 3D printed components

Two identical modules placed on each side of the wheelchair are required to operate a wheelchair. If it is desired to maintain the possibility of folding the wheelchair, one of these modules can be placed in front of the wheel axis, so that when folding the modules will move next to each other, the direction of rotation of the two modules is established by changing connections. According to the methodology applied in the design of the attachment system using components purchased for the mechanical part (drive motor and planetary mechanism) and components manufactured by FDM 3D printing technology, the assembly of a module of the attachment system for the wheelchair was made. These components, together with the control system and the power source, were mounted and tested to determine the behavior of the developed system. The 3D printing of some system components was chosen to check the attachment mode on the frame, the transmission of the rotational movement from the engine to the toothed crown and the technical solution for attaching the crown to the wheel. To test the system, the toothed crown was mounted on the brake disc of a spoke wheel, and the wheel was loaded by attaching counterweights (Fig. 7.25).



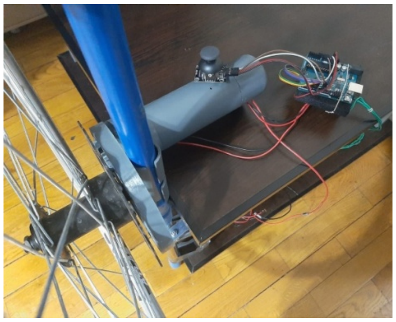



Fig. 7.25. Testing the attachment system

Following the test, taking into account that the diameter of the frame pipe varies for different models of wheelchairs (25.7 - 31.9 mm) to allow the use of the system developed on a diverse range of manual wheelchairs, it was decided to change the size of the attachment supports and the use of additional elements to compensate for the difference in diameter of the frame pipe. It was found that, from a constructive point of view, the subassembly consisting of electric motor - planetary mechanism - coupling system - pinion must allow the adjustment of the play in the pinion gear - toothed ring for proper operation. In this case, it is decided to change the configuration of the product so that the system consisting of motor, planetary mechanism and pinion is placed on a guide that allows a radial displacement and the use of anti-friction bushes for bearing sprocket and toothed crown. This solution compensates for the differences that occur due to the different construction variants of wheelchairs (Fig. 7.26).

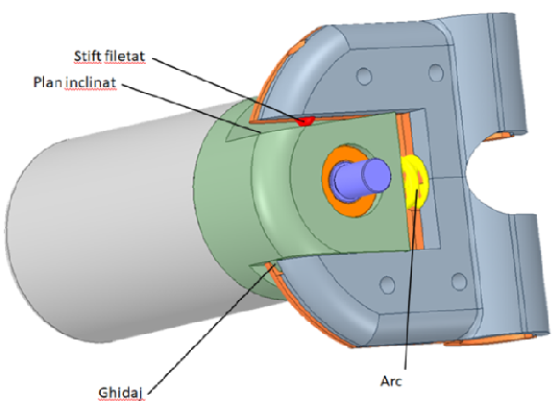


Fig. 7.26. Constructive change

The application code developed for controlling the system was tested by checking the direction and direction of travel, the manual-electric switching system, as well as the variation of the drive motor speed. The next option will include improvements to eliminate potential noise sources.

Chapter 8. Final conclusions, main contributions and directions for future development

The objective of the doctoral thesis was to conduct research on optimizing an autonomous mobile system by developing a module attachable to it, offering new functions: increased mobility and stability, ability to overcome obstacles of low height and maintain the horizontality of the base.

Following the thesis development stages, an electric drive system attachable to manual wheelchairs was designed, manufactured and tested in order to increase autonomy, increase driving energy, offer the possibility of overcoming small / medium obstacles and increase user comfort. , by maintaining the horizontal position of the base, with minimal costs. The paper contains 8 chapters and Appendices, as presented below. Part I, which presents the current state of research on the development of mobile systems for people with disabilities, includes Chapters 1, 2 and 3. The remaining chapters are part of the contributions to the development of a wheelchair-accessible drive system.

Chapter 1 analyzed the stages and activities proposed by several methodologies for the development of a new product and made in-depth comparisons between them. Chapter 2 studied assistive systems and equipment for people with disabilities. The existing mobility solutions for overcoming various obstacles, the technical modalities of realization and patents for power systems attached to wheelchairs were analyzed.

Chapter 5 defined the design process of the new product represented by a system attachable to the manual wheelchair to transform it into a mobile and autonomous one by imposing the objectives to be achieved, setting product specifications, establishing functions and subfunctions. product, identifying which components of the product make them. Different concepts were then generated using the sketches and those appropriate to the proposed objectives were selected.

Chapter 6 finalized the constructive design methodology, respecting the constraints imposed by the design by generating the morphological matrix of the product with the functions and technical solutions for their fulfillment. The types of motor and battery to be used were established, the required motor power was calculated, the technical characteristics of the belt drive were determined for a case of motion transmission, the type of planetary mechanism used was defined by establishing movement input and output elements. Several software applications were developed in Matlab and LabVIEW to facilitate the constructive design of the product by establishing its modules, kinematic and kineto-static analysis of some component mechanisms, synthesis of a 6-bar mechanism for which the dimensions of the components were determined with the purpose of maintaining the horizontality of the base.

Following the 7th chapter, the detailed design of the system attached to the wheelchair was made, which will transform it into an autonomous mobile system by choosing the optimal materials, determining the appropriate shape of the components, finite element analysis and topologicy optimization, eco-audit and environmental effects analysis and 3D printing. At the same time, the control mode of the wheelchair was defined, by creating an interface for an easy control mode of the product.

The prototype can be tested in its real-time operating environment. It was essential to develop a product that could offer comfort, stability, safety and complete mobility. The purpose of developing a wheelchair is to give the future user a complete sense of freedom and a chance to progress in life on their own. Taking into account the cost of purchased components (DC electric motor, planetary mechanism, battery, ArduinoUNO board, L298N driver, joystick, cables, connectors, etc.) and the cost of 3D printing of other parts of the system (material and labor) , the total value for the system attachable to the wheelchair manually is approximately 600 RON.

Personal contributions

Following the research presented, the author has made personal contributions to the development of a system attachable to a manual wheelchair, as shown below:

1. Carrying out a bibliographic study in which the current state of product development methodologies was critically analyzed (Chapter 1);
2. Carrying out an analysis on the evolution of mobile systems for people with disabilities and the technological advances made (Chapter 2);
3. Establish, on the basis of an analysis of existing systems, a list of requirements on the basis of which the new product has been designed (Chapter l 5);
4. Full 3D modeling of a manually operated wheelchair (Chapter 5);
5. Preparation of the constructive and functional decomposition structure for the manually operated wheelchair (Chapter 5);
6. Generation of 6 original concepts for an electric drive system attachable to the wheelchair manually (Chapter 5);
7. Development of a Matlab application for the analysis and synthesis of a 6-bar mechanism to maintain the horizontality of the base (Chapter 5);
8. Kinematic analysis of the 6-bar mechanism, determination of graphs, calculation of speeds and accelerations (Chapter 5);
9. Development of an application in Matlab for the matrix description of the modules of the developed product (Chapter 5);
10. Selection of the materials of the product components by using the appropriate material graphics for the manufacture of some components (Chapter 6);
11. Topologicy optimization of the shape of some system components using specialized software applications (SpaceClaim, Ansys) (Chapter 6);
12. Detailed design of the chosen concept, with different variants for the frame mounting system and for the wheel mounting system (Chapter 7);
13. Dimensioning of components and elaboration of constructive documentation for the manufacture of the new product (Chapter 7);
14. Carrying out an eco-audit on the environmental impact of the product manufacturing process (Chapter 7);
15. Manufacture of components designed using an additive manufacturing technology (Chapter 7);
16. Testing of the device attached to a standard manual wheelchair which has led to the adaptation of components to allow attachment to any type of wheelchair. Following this test, the efficiency of the engine used, the battery life, the stability to overcoming common obstacles and the efficiency of the control system used were verified. (Chapter 7).

Dissemination of results

The original contributions made consist in the experimental research carried out. The obtained results were capitalized in articles from ISI specialized journals, articles published in journals indexed in international databases (BDI), as well as in the volumes of scientific conferences. Some of the results obtained from the research carried out within the doctoral school were disseminated as follows:

a) Publication of 13 scientific articles (10 BDI, 3 ISI):

1. „Application of Multiobjective Methods for Optimization of Machining Process Parameters”, International Journal of Modern Manufacturing Technologies ModTech Volume 7 Number 1/2015, ISSN 2067-3604.
2. „Materials Selection for an Engineering Application using Multiple-Criteria Decision Analysis”, ICMAS 2015 International Conference on Manufacturing Systems Volume 10 Issue 3 2015, ISSN 2343-7472.
3. „Eco-audit and Environmental Impacts of Products”, ICAMAT 2015 8th International Conference on Advanced Manufacturing Technologies, 2015, ISSN:1662-7482 Vol.834, pp. 34-39, doi:10.4028/www.scientific.net/AMM.834.34.
4. „Optimization of the Mechanism from an equipment for Overcoming Obstacles with Design of Experiments”, IMANE Innovative Manufacturing Engineering & Energy International Conference, Iași, 25-26 Mai, 2017, doi:10.1051/matecconf/201711206006.
5. „Determining the Optimal Dimensions for a Mechanism from a Wheelchair using LabVIEW”, International Journal of Research – Granthaalayah Vol.6 Issue 1, 25-27 Ianuarie, 2018, doi: 10.5281/zenodo.1164122.
6. „Matlab Application for The Analysis of Existing Systems with the Purpose of Developing New Products”, 6th Conference on Modern Technologies in Industrial Engineering (ModTech), IOP Conf. Series: Materials Science and Engineering 400 (2018) 062011, 13 - 16 Iunie, 2018, doi:10.1088/1757-899X/400/6/062011, WOS:000461147400153.
7. „Applying Regression Analysis to Optimize the Length of Components of a Six Bar Mechanism”, 6th International Conference on Modern Technologies in Industrial Engineering ModTech, IOP Conf. Series: Materials Science and Engineering 400 (2018) 042024, Constanța, 13-16 Iunie, 2018, doi:10.1088/1757-899X/400/4/042024, WOS:000461147400096.
8. „Applying of a Design Methodology for a New Mobility Product”, 22nd International Conference on Innovative Manufacturing Engineering and Energy (ImanE&E), Chișinău, Moldova, 31 Mai – 2 Iunie 2018 , doi:10.1051/matecconf/201817805002.
9. „Influence of Cutting Parameters on Surface Quality when machining a CoCrWNi alloy”, 22nd International Conference on Innovative Manufacturing Engineering and Energy (ImanE&E 2018), Chișinău, Moldova, MATEC Web of Conferences 178, 01009 (2018), ISSN:2261236X, 31 Mai-2 Iunie, 2018, doi:10.1051/matecconf/201817801009.
10. „Determining the Materials and Shape of Components within a System Attached to a Wheelchair”, ICAMAT 9th International Conference on Advanced Manufacturing Technologies, București, Noiembrie, 2018, Materials Science Forum Volume 957, pp. 15-22, doi.org/10.4028/www.scientific.net/MSF.957.15.

11. „Research on the Design and Testing of a New Product Development Methodology", Proceedings of the 32nd International Business Information Management Association Conference, IBIMA 2018 - Vision 2020: Sustainable Economic Development and Application of Innovation Management from Regional expansion to Global Growth, pp. 5479-5490, Sevilla, Noiembrie, 2018.
12. „Dimensions of Customer-Based Assistive Technology Innovation: Exploring Marketing Strategy through Developing a Wheelchair for People with Disabilities in Romania", 34th International Business-Information-Management-Association Conference IBIMA, Madrid, 13-14 Noiembrie, 2019.
13. „Project Planning for the Development of an E-learning Interactive Educational Platform in Industrial Engineering-based Applications", 36th Conference IBIMA, Noiembrie, 2020.

b) Participarea la două conferințe științifice:

1. ICAMAT 2018 - ICAMAT 9th International Conference on Advanced Manufacturing Technologies, Romania.
2. IBIMA 2019 - 34th International Business-Information-Management-Association Conference, Spania.

Future directions of research

The research presented in the doctoral thesis contributes to the development of the wheelchair attachment system, and other future technical solutions can be identified and tested as future research directions:

• Identifying possible deficiencies of the prototype and improving it by implementing a more advanced control structure.

• Redesign of the planetary mechanism to reduce its size, weight and costs.

• Detailed design of the mechanism for maintaining horizontality.

• Improved attachment system - wheelchair interface to develop the interface options needed for mounting on different wheelchair frames.

• Carrying out wheelchair control via a mobile phone application and introducing a trajectory tracking controller.