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Field: Mechanical Engineering

PhD THESIS
– ABSTRACT –

Studies and research on mobile robots for search and rescue

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CONTENT

INTRODUCTION

The field of search and rescue robots is a relatively new domain, first introduced in the 1980s [1]. Although in the year 2023, the use of search and rescue robots is becoming increasingly widespread in emergency situations, this field remains challenging in terms of mobility, communication, control, sensors, autonomy, and human-robot interaction [2].

For example, search and rescue in collapsed buildings is a difficult and sometimes dangerous activity for rescuers because the debris left behind in the aftermath of building collapses can collapse further, jeopardizing the safety or even the lives of the rescuers. In these conditions, mobile search and rescue robots (USAR - Urban Search and Rescue Robot) can be a solution to assist rescuers in completing the search and rescue task within collapsed buildings [3].

Since rescuing victims after disasters is under extreme time pressure, the greatest challenge is to make search and rescue operations with robots more efficient, in order to find more survivors or provide faster and clearer information for rescuers [3].

Among the general characteristics of search and rescue robots (RCS), the following are mentioned [1]:

- High adaptability to different operating environments, including environments with high temperatures and pressures that rescuers cannot reach;
- The ability to move in rough terrain (among ruins) to detect signs of life;
- Compact size and versatility;
- Equipped with functional sensors and detection equipment, such as infrared detectors and video cameras to search for survivors;
- Use low-energy consumption batteries and have a long operating time.

The motivation behind choosing this topic is to contribute to the rescue of survivors following accidents or disasters, with the belief that robots can aid in achieving this objective.

Considering the importance of the field dealing with the rescue of victims in various disasters and understanding the fundamental issues of search and rescue robots, the purpose of researching in this domain is fully justified.

In addition to the specific elements of search and rescue robotics, the proposed robots also contain hybrid locomotion systems composed of a traditional wheel, TriSTAR unit, and Whegs unit. A significant advantage of the proposed TriSTAR locomotion unit in the PhD thesis is its ability to move on stairs and overcome other obstacles. While robots with this type of locomotion unit may have limitations in various operating environments, it is believed that it can be a viable solution in the locomotion systems of search and rescue robots.

Furthermore, the PhD thesis is structured as follows: in the first chapter, the current state of research in the field of search and rescue robotics is presented; the second chapter describes the peculiarities and characteristics of search and rescue robots. The third chapter presents the study of locomotion systems and the selection of the optimal system for the proposed search and rescue robot. Chapter four outlines the modeling and development of hybrid locomotion systems for search and rescue, while chapter five focuses on the modeling and development of the search and rescue robot with the STAR locomotion system. Chapter six details the modeling of a search and rescue robot with a hybrid locomotion system composed of a traditional wheel and the TriSTAR unit. Finally, in chapter seven, the thesis concludes with a summary of findings and outlines future research directions.

1. CURRENT STATE OF RESEARCH IN THE FIELD OF MOBILE ROBOTS FOR SEARCH AND RESCUE

In the specialized literature, it has been identified that an important category of mobile robots is represented by search and rescue robots.

Search and rescue involve the activities of finding and extracting survivors.

These robots assist rescuers in disaster scenarios by providing real-time video footage and other necessary information about the situation or by extracting victims from the risk area.

It can be observed from the study of the specialized literature that sometimes the applications of search and rescue robots are similar to military operations. However, it is essential to note that certain tasks are unique to search and rescue robots. An example would be the interaction between humans and robots, which is treated quite differently in search and rescue robots compared to military robots.

In the field of search and rescue, several characteristics must be considered as decisive factors in the design or use of a robot. These characteristics are defined based on the type of search and rescue, which can take place in *urban, rural, mountain, or aquatic environments (Fig. 1.4)*.

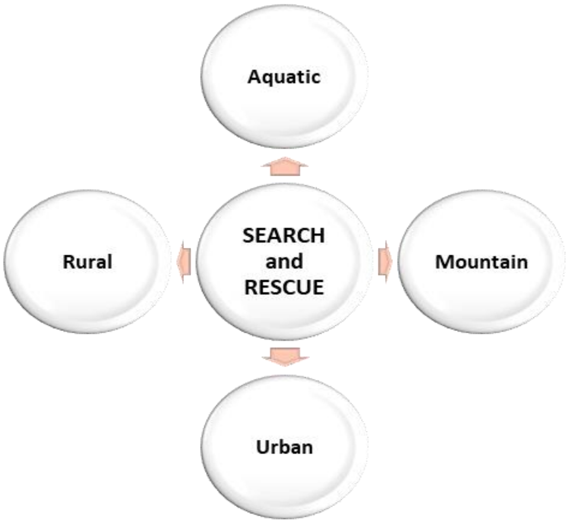


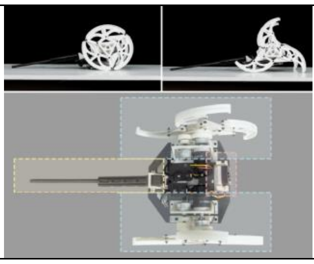
Fig. 1.4 Different environments for search and rescue [17]

A decisive factor in choosing the types of robots to be used in the environments mentioned above is the type of disaster, which can be natural or human-induced. Natural disasters usually affect very large areas, while those caused by humans are isolated and typically occur in a specific area.

Considering that this field deals with rescuing victims of various disasters and understanding the fundamental issues of search and rescue robots, the purpose of research in this domain is fully justified.

Upon studying various interventions, it can be stated that ground mobility remains a major challenge, and proper testing is crucial. Some mobile robots may have good mobility on certain surfaces but may appear unsuitable for other types of surfaces.

In the specialized literature, there are documented research efforts regarding mobility in harsh and challenging environments, leading to the continuous development of robots (Fig. 1.25) designed to cope with the conditions encountered in this field.



a) [43]

b) [44]

c) [45]

d) [46]

Fig. 1.25 Ground robots developed in recent years for search and rescue

In the future, search and rescue robots are expected to be increasingly used by rescue teams to enhance the safety of both rescuers and individuals whose lives are in danger.

In Romania, robots are also being acquired for large-scale fires to reduce risks for firefighters [36].

The PhD thesis aims to research the field of mobile robots for search and rescue and make contributions to the development of such robots with various locomotion systems.

The following secondary objectives are subordinated to this main goal:

- researching the current state of the field;
- identifying the characteristics and features of these robots;
- identifying a locomotion system for the proposed search and rescue robots;
- modeling, simulating, and creating search and rescue robots using hybrid locomotion systems (TriSTAR and Whegs);
- experimentally researching the proposed robots;
- investigating possibilities for improving these robots;
- disseminating the research results.

2. FEATURES AND CHARACTERISTICS OF SEARCH AND RESCUE ROBOTS

In this chapter, the features and characteristics of search and rescue robots were highlighted. These robots transition from an intriguing idea to an integral part of emergency response. While aerial and ground robots have garnered the most interest, especially in disaster response, it can be asserted that aquatic robots (both surface and underwater) have proven to be useful in emergency situations as well.

The main tasks of search and rescue robots include *search, reconnaissance, mapping, debris removal, structure inspections, medical assessment, extrication, and providing logistical assistance.*

Search and rescue robotics is undoubtedly a challenging field, with numerous issues, and robots present challenges in all major subsystems (mobility, communication, control, sensors, and power), as well as in human-robot interaction or evaluation criteria, which still require research, development, and testing to realistically assess robot performance. Due to the high demands of disaster environments, special attention has been given to testing and testing grounds to evaluate robot performance.

Wireless communications remain a major issue in this field, given signal and communication problems.

Easily transportable systems by a single person and easy to implement are popular due to their reduced logistic burden, but the size of the platforms emphasizes the need for miniaturized sensors and processors, which raises their costs.

Although tracked mobile ground robots were initially used in search and rescue operations, due to encountered issues, robotics experts continued to investigate other locomotion systems, such as hybrid locomotion systems for the ground.

Contributions

The peculiarities and characteristics of search and rescue robots are identified.

A classification of search and rescue robots is presented based on the operating environment (type / size / locomotion system).

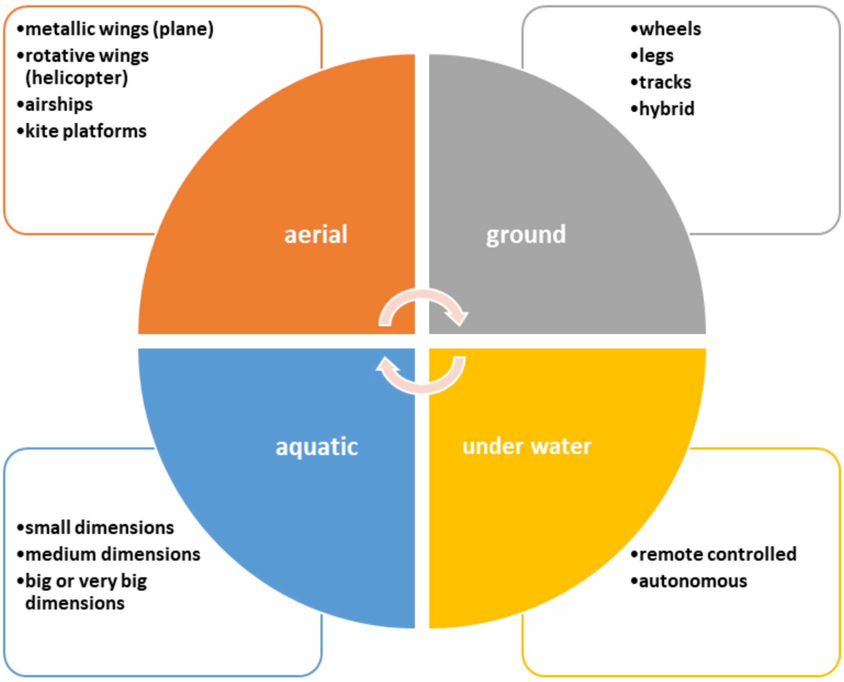


Fig. 2.1 The classification of types of search and rescue robots based on the operating environment

3. STUDIES AND RESEARCH REGARDING THE CHOICE OF LOCOMOTION SYSTEM FOR THE PROPOSED SEARCH AND RESCUE ROBOT

In this chapter, a rigorous study is presented on existing locomotion systems in the field of mobile robotics, particularly focusing on locomotion systems used in search and rescue [68-78].

The purpose of this analysis was to identify an optimal locomotion system for the search and rescue robot developed in the research.

From the conducted study, it can be concluded that:

- wheeled locomotion is optimal for fast and efficient movement but is limited to smooth surfaces;
- legged locomotion has high adaptability for complex environments, but mechanical design and control are challenging;
- the disadvantages of wheels and legs can be mitigated or even eliminated by developing a hybrid leg-wheel locomotion system. Mobile robots with combined locomotion systems are much more flexible and efficient in various applications, not only in search and rescue.

In the field of search and rescue robotics, there is an increasing number of mobile robots with hybrid locomotion systems that bring together the advantages of multiple locomotion systems described in this chapter.

One major advantage of hybrid robots is that they not only combine locomotion systems but also integrate the benefits of each, addressing the 6 key characteristics. This means that the advantages of one system complement the disadvantages of the second or third type of locomotion in the combination.

As mentioned in this chapter, the 6 key characteristics are: *obstacle traversal capability, energy efficiency, mechanical complexity, control system complexity, technological availability, and maximum speed.*

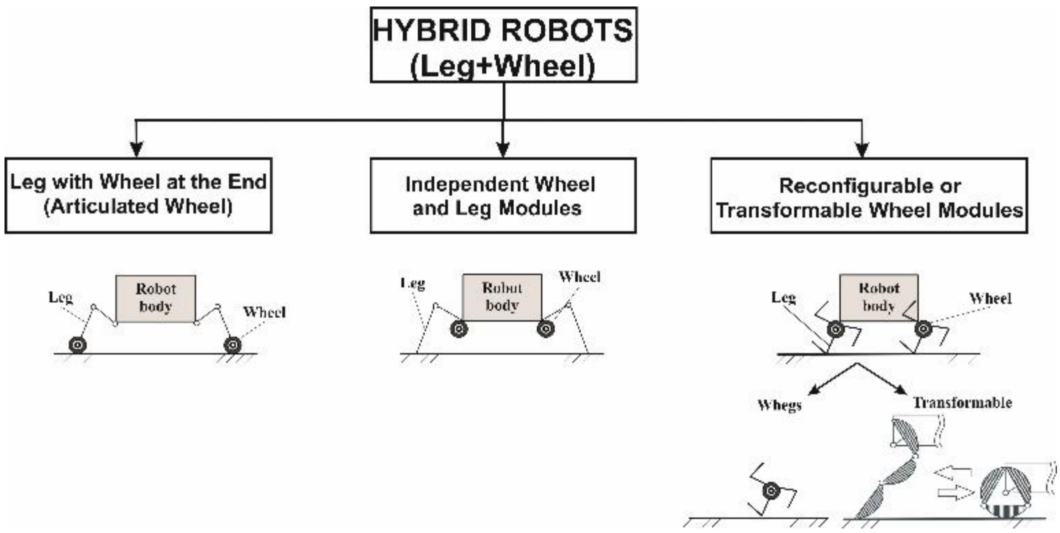
Each system is technologically impressive and designed to be the best for the environment it is intended for and specific tasks it needs to perform.

For the system to fulfill the necessary tasks, it must meet the requirements of the search and rescue field and the specific task it is meant to accomplish.

Robots with hybrid leg-wheel locomotion systems combine the energy efficiency of wheels with the operational flexibility of legs. The leg-wheel locomotion system (L-W) can also be classified as follows (Fig. 3.9, a, b, c) [105]:

- a leg mechanism with a wheel attached to the end of the leg, known as an articulated wheel (Fig. 3.9 a);
- independent wheel and leg modules on the mobile robots body (Fig. 3.9 b);
- reconfigurable or transformable wheel modules that can be transfomed into leg modules and vice versa (Fig. 3.9 c) [106].

Following the study of the specialized literature, it was concluded that the third combination of legs and wheels (Fig. 3.9c) is the most efficient and also one of the best options for the proposed search and rescue robot.



a) *b)* *c)*

Fig. 3.9 Categories of hybrid wheel-leg robots [106]

Contributions

The peculiarities and characteristics of locomotion systems applicable to search and rescue robots are identified.

A classification and comparison of locomotion systems are presented based on the advantages and disadvantages they have for the field of search and rescue.

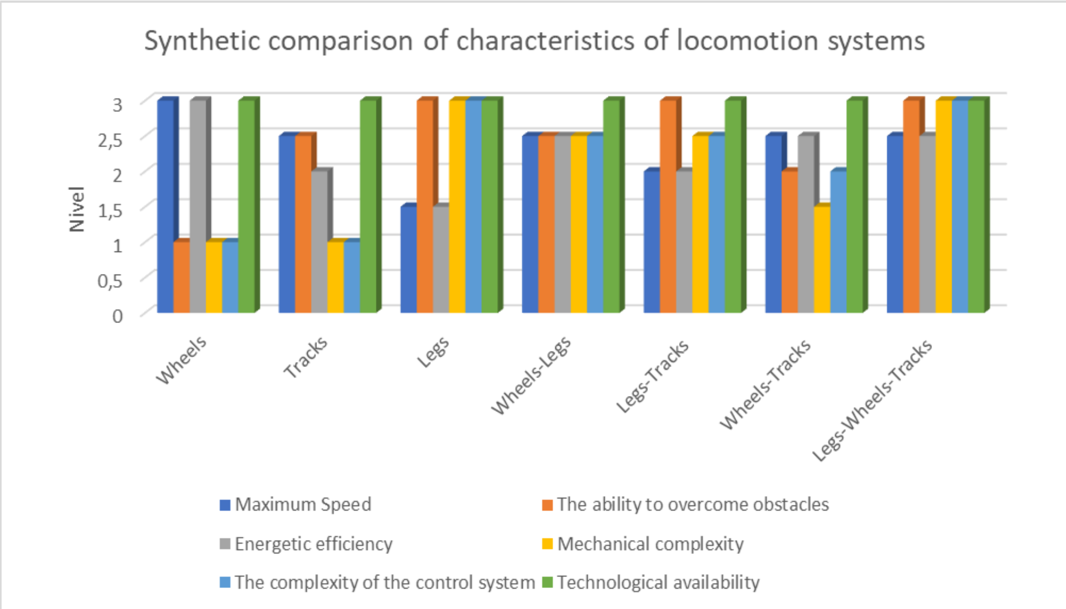


Fig 3.22 Comparison of Locomotion Systems [68]

4. CONTRIBUTIONS TO MODELING AND DEVELOPMENT OF HYBRID LOCOMOTION SYSTEMS FOR SEARCH AND RESCUE ROBOTS

In this chapter, the 3D modeling, prototyping, and experimental testing of hybrid locomotion systems with leg-wheel-type locomotion units for search and rescue robots are presented.

The proposed locomotion unit (star wheel) is a wheel with 3 legs (spokes) at the end of which there are 3 conventional wheels. The 3 legs are arranged at 120 degrees.

Inside these legs, there are 3 transmissions with cylindrical gear wheels with straight teeth [115].

The main components of the locomotion unit are (Fig. 4.1):

- satellite gear carrier „pc";
- solar gear wheel– 1;
- three primary satellite wheels- 2, 2', 2'';
- three secondary satellite wheels- 3, 3', 3'';
- three tertiary satellite wheels - 4, 4', 4'';
- three conventional wheels W [115].

Due to the planetary mechanism used in its structure, the 3 external wheels - W will rotate at the same angular velocity.

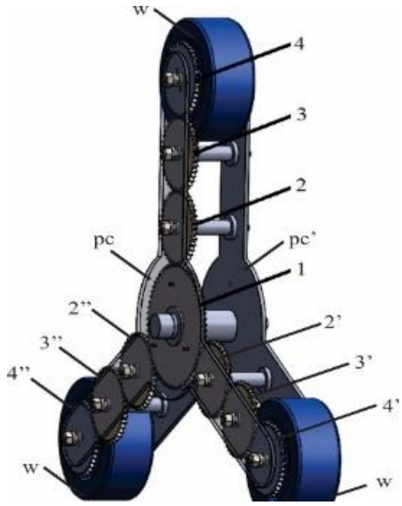


Fig. 4.1 The developed TriSTAR locomotion unit [115]

The three planetary gear wheels (4, 4', 4'') are connected to the external conventional wheels marked with W. The body of the locomotion unit consists of 2 star-shaped steel frames, which are connected by screws.

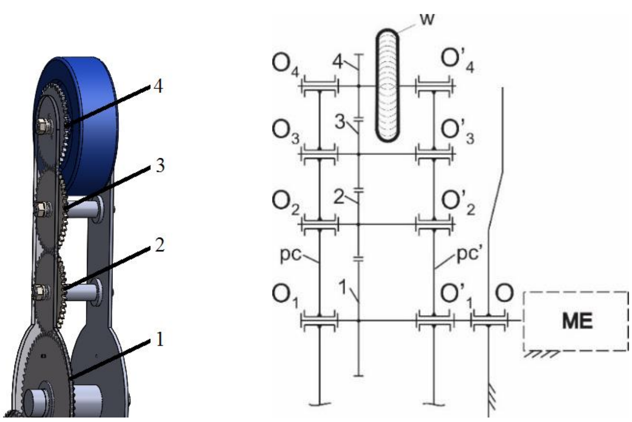
Inside these frames, the 10 gear wheels are arranged to transmit the movement from the main axis to the three external wheels W.

Figure 4.2 presents the 3D model and photograph of the locomotion unit.


a) *b)*

Fig. 4.2 The first constructive variant of the developed locomotion unit [115]

The 3D model of a 'leg' of the locomotion unit and its kinematic diagram are presented in Figure 4.3.



a) *b)*

Fig. 4.3 3D Model a) and the structural diagram of a 'leg' of the locomotion unit b)

The locomotion unit connects to the robot chassis through a rotation joint (O), with the axis parallel to the rotation axes of the gear wheels and the axes of the conventional wheels W (Fig. 4.3b).

The parameters used in the structure of the locomotion unit are (Fig. 4.5):

- the radius of the locomotion unit R, the distance between the center of the locomotion unit and the center of the external wheels W, R = 200 mm;
- the radius of the external wheels, r_W = 100 mm;
- The width of the support fixing the external wheels to the locomotion unit, 2t = 45 mm.

From Figure 4.5, it can be observed that due to the external diameters (head diameters - d_a) of gear wheels 2 and 3, the width used in calculations is greater than 2t, which is 2t* = 63 mm.

The thickness of the supports forming the legs of the locomotion unit is 2 mm. The gear wheels are made of polyethylene and have tooth numbers z_1= 67, $z_2 = z_3 = z_4 = 40$ and the module m =1,5 mm. The weight of the locomotion unit is 2.740 kg, and the height H = 400 mm.

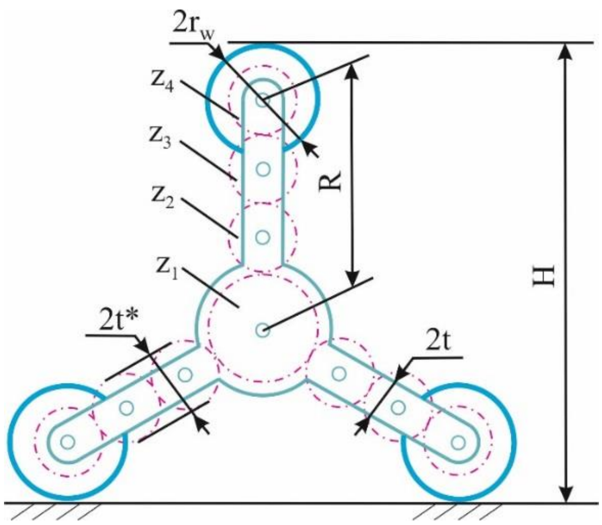
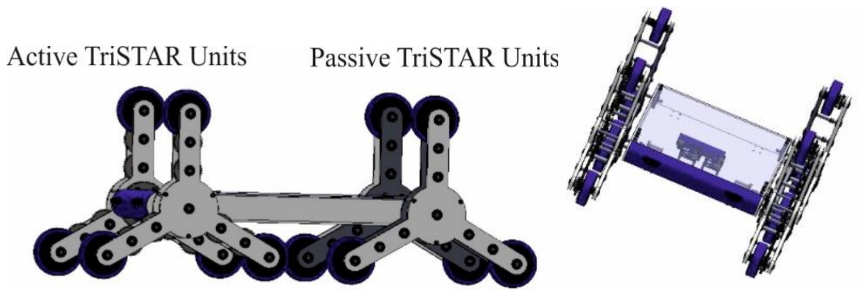


Fig. 4.5 Design parameters of the locomotion unit [108]

The first proposed design variant is a mobile robot with 4 TriSTAR locomotion units, of which 2 are active and 2 are passive (Fig. 4.9). The robot's dimensions are 872 mm x 620 mm x 400 mm (Length x Width x Height), and it can be used for rough terrains or buildings affected by disasters, with the significant advantage of overcoming various obstacles and stairs of certain dimensions.

The designed robot was proposed to be equipped with proximity sensors, smoke sensor, LED lights, Arduino control board, and a battery. However, during the prototype development, more attention was focused on the locomotion system, aiming for successful use in the search and rescue field [119].



a) *b)*

Fig. 4.9 The first design variant – 3D model [119]

The wheels of the locomotion unit can be easily changed, allowing the unit to adapt to different situations in which it will be used.

For example, to climb stairs with a step height h = 200 mm and step width w = 280 mm, the W wheels need to be changed, resulting in the configuration presented in Table 4.1. These values were obtained using the relationships presented in [118].

Table 4.1 Parameters of the locomotion unit

Parameters [118]	Calculated	Chosen
R $R = \sqrt{\frac{w^2+h^2}{3}}$	198,66 mm	200 mm
$2t^* = d_a$ $d_{a2} = m(z_2+2)$	63 mm	63 mm
$r_{W\,min}$ $r_{W\,min} = \frac{6Rt + h(3w - \sqrt{3}h)}{(3-\sqrt{3})h + (3+\sqrt{3})w}$	86,32 mm	$173\ mm \leq 2\ r_w \leq 344\ mm$
$r_{W\,max}$ $r_{W\,max} = \sqrt{\frac{w^2+h^2}{2}}$	172,04 mm	

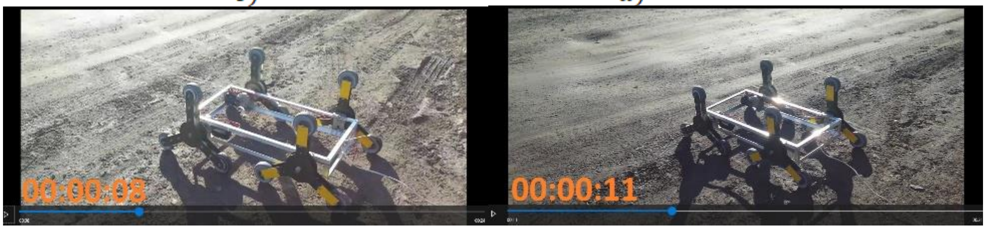
In order to test the proposed locomotion units, the prototype shown in Figure 4.11 was built. It uses two Topran model 108792 DC motors with reducers for actuation [119, 121].

Fig. 4.11 Prototip experimental [119]

The purpose of the experimental tests presented in the first part of this chapter was to validate an optimal locomotion system for the search and rescue robot developed in the research.

a) *b)*

c) *d)*



e) *f)*

g) *h)*

Fig. 4.12 Images from the testing of the experimental prototype overcoming an obstacle [119]

In the second part, various types of Whegs locomotion units are proposed and implemented. Additionally, several such robots are analyzed, and finally, a search and rescue robot with Whegs units is proposed, developed and tested.

Fig. 4.15-Fig.4.16 3D models and pictures of the Whegs locomotion units and the developed robot [120]

Fig. 4.20 Images obtained from recording with the video camera on the robot [120]

The conclusions drawn from the experimental tests are as follows:

- the operating environment of the search and rescue robot is challenging and harsh, requiring a versatile locomotion system that can adapt to different types of terrain;
- a locomotion system for search and rescue can be either the TriSTAR or Whegs system;
- the TriSTAR and Whegs systems, being hybrid locomotion systems, successfully combine the advantages of both legged and wheeled systems;
- the system proposed in the first part (with TriSTAR units) uses gear transmissions made of polyamide, but for increased durability and lifespan, it is recommended to choose a tougher material, though not too heavy;
- to prevent wheel blockage due to debris or mud entering between the axles or gear wheels, it is recommended to enclose the transmission system of the TriSTAR locomotion unit;
- if the robot is expected to overcome obstacles such as stairs, the wheels must be calculated specifically for these dimensions; otherwise, the robot will remain stuck on stairs without being able to move further;
- to avoid technical issues such as short circuits or damage to electronic components, it is recommended to seal the structure;
- a potential improvement could be using battery power, but the drawback would be the increased weight of the structure and limited energy autonomy. On the other hand, a wired power supply, although limiting the mobility of the robot due to the power cable, provides unlimited energy.

For the efficient operation of the TriSTAR unit, it is proposed to use an odd number of interlinked gear wheels in the transmission system or with a positive transmission ratio.

The Whegs locomotion system, equipped on the second robot, demonstrated good performance in laboratory conditions.

The robot can function even if overturned due to the positioning of the Whegs locomotion systems on the robot's chassis.

By designing and implementing two hybrid locomotion systems: the TriSTAR and Whegs systems, the practical confirmation of the comparative analysis conducted in Chapter 3 was achieved. Both systems belong to the category of hybrid systems composed of legged and wheeled locomotion systems, and during experimental tests, some advantages and disadvantages of this category of locomotion systems were confirmed.

The studies conducted have led to new solutions in the modeling and development of the proposed search and rescue robot, which will be presented in the next chapter.

Contributions

The design and implementation of two hybrid locomotion systems, the TriSTAR and Whegs systems, were undertaken.

Additionally, the development of two search and rescue robots equipped with hybrid locomotion units was carried out. These robots were then tested in various operating environments.

Experimental tests were performed on diverse types of terrain, aiming to identify solutions for improving the proposed locomotion systems.

5. CONTRIBUTIONS TO THE MODELING AND DEVELOPMENT OF MOBILE ROBOTS FOR SEARCH AND RESCUE WITH STAR LOCOMOTION SYSTEM

This chapter presented the improvements identified through experimental tests in Chapter 4. These improvements were leveraged in Chapter 5 through the modeling and development of constructive variants, for which various simulations were conducted using Matlab and Solidworks programs.

In the designed and developed STAR models within the research, the gear transmissions from the first toothed wheel to the external wheels w have an odd number of interlocking gears. The rotation direction of the drive motor axis and that of the external wheels w are identical.

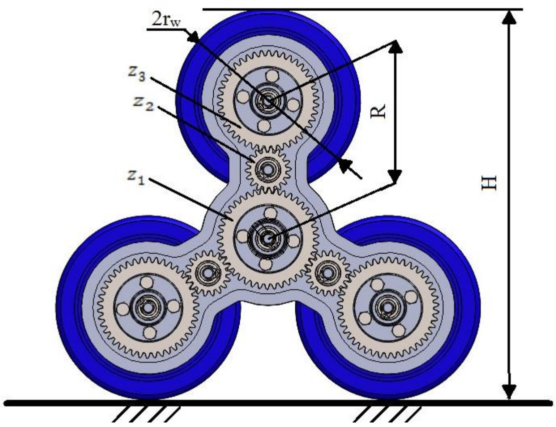


Fig. 5.4 The design parameters of the new locomotion unit

The proposed and implemented locomotion system has the significant advantage of using a reduced number of motors, which lowers energy consumption and the overall size of the robot.

Another improvement suggested after testing the experimental prototype is the use of a casing for the gearbox and the repositioning of the wheel outside the planetary mechanism. This means that there is the possibility of having a sealed locomotion system, preventing debris or other foreign objects from reaching and blocking or damaging the gear transmission.

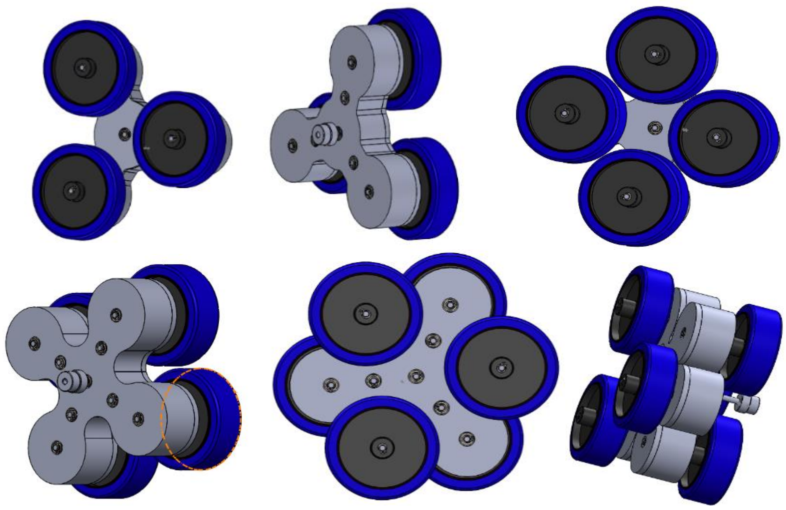


Fig. 5.7 - Fig. 5.9 3D models of the STAR locomotion units

The proposed locomotion unit structure is a very good solution when the robot needs to have the ability to move both on flat surfaces and on rough terrain and stairs.

Figure 5.10 shows proposed design variants of search and rescue robots with the previously presented locomotion systems [122].

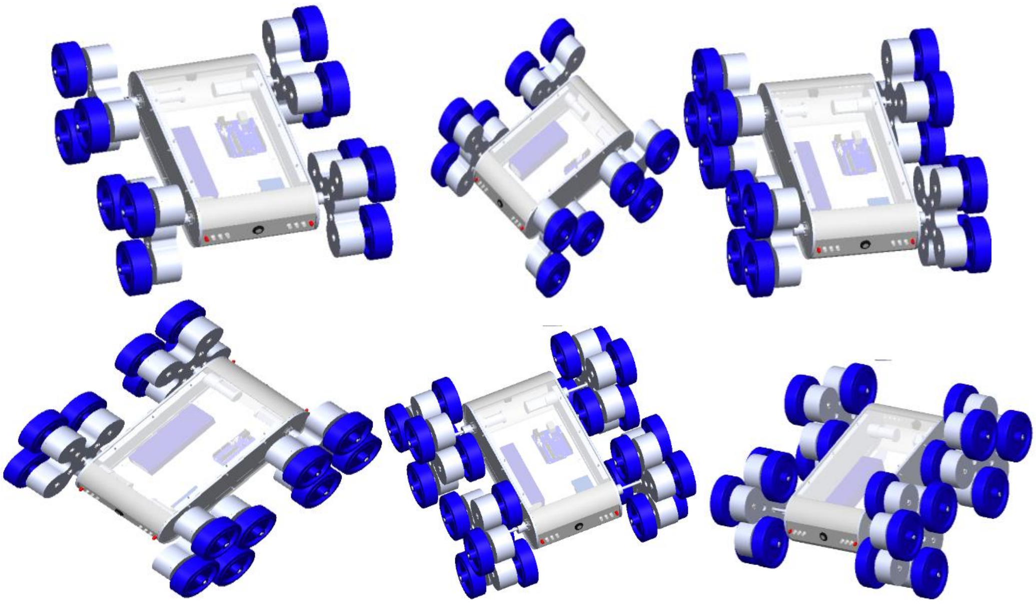


Fig. 5.10-Fig. 5.12 3D models of the search and rescue robots with STAR locomotion units

During simulations, it was observed that we cannot say there are bad or good hybrid systems, but rather those optimal for certain types of terrain. It was also noticed that, in addition to the locomotion systems, the structure of the robot is crucial. Neglecting ground clearance could result in the robot remaining in the air or getting stuck when encountering an obstacle.

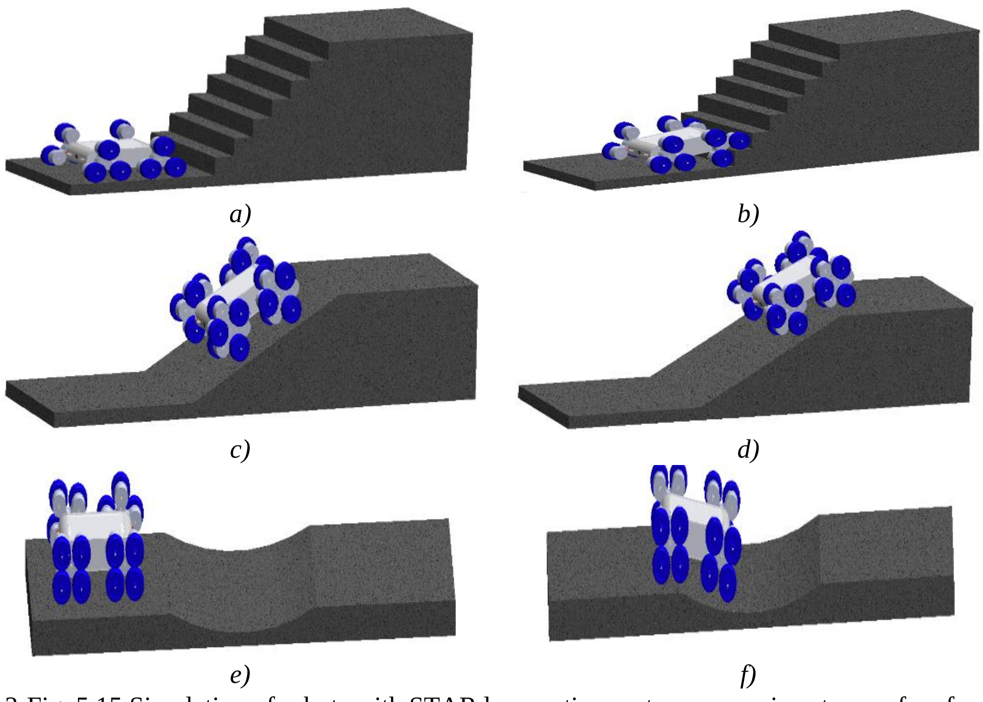


Fig. 5.13-Fig. 5.15 Simulation of robots with STAR locomotion systems on various types of surfaces [122]

Contributions

In this chapter, the modeling of multiple locomotion units that can be used in the case of hybrid mobile robots for search and rescue actions is presented, along with the proposed search and rescue robot.

Several locomotion units have been researched, developed, and realized for use in hybrid mobile robots for search and rescue actions.

6. MODELING A SEARCH AND RESCUE ROBOT WITH A HYBRID LOCOMOTION SYSTEM COMPRISING A CLASSIC WHEEL AND A TRISTAR UNIT

In this chapter, the 3D model, mathematical modeling, and simulation of a search and rescue robot are presented, incorporating a hybrid locomotion system consisting of a conventional wheel and TriSTAR unit.

6.1. 3D Model of the Search and Rescue Robot with a Hybrid Locomotion System Comprising a Classic Wheel and TriSTAR Unit

The 3D model of the proposed search and rescue robot, which includes a hybrid locomotion system consisting of a classic wheel and TriSTAR unit, is presented in Figure 6.1.

To the chassis, in addition to the components described earlier in Chapter 5.2.1, a modularly designed front-facing video camera module has been added to the casing.

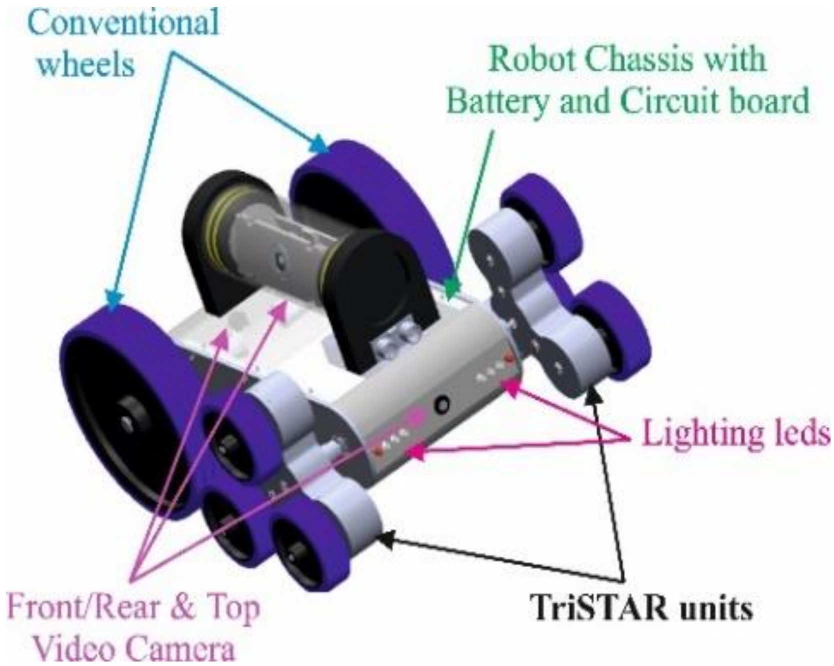


Fig. 6.1 Proposed search and rescue robot [127]

As the need for a gripper in the field of activity became evident, a robotic arm was used to extend the capabilities of the search and rescue robot, allowing it to inspect the surrounding environment, interact with survivors, move lightweight objects, and monitor areas that the robot cannot reach with the help of the video camera mounted at the end of the arm.

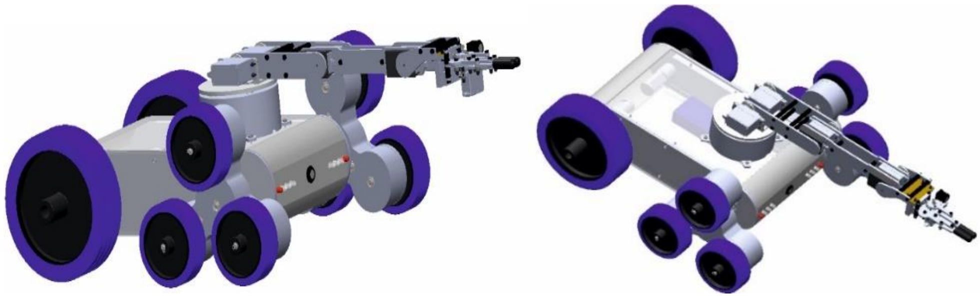


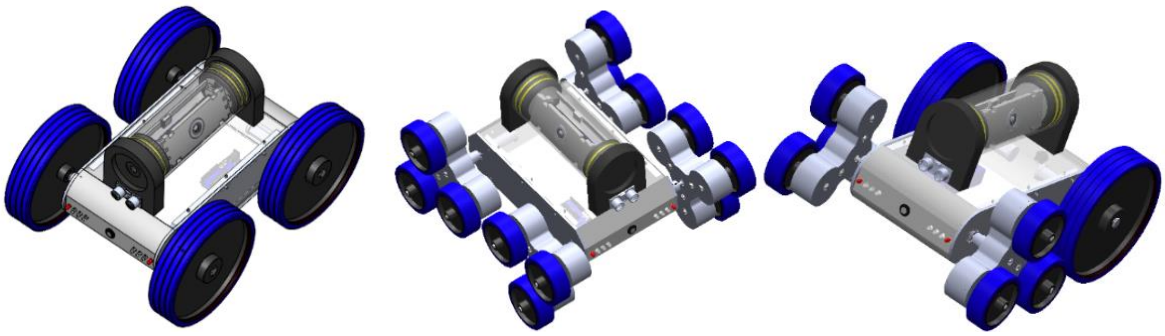
Fig 6.3 The proposed robot with a manipulation device [127]

TriSTAR locomotion units are a very good solution when the robot needs to have the ability to move both on flat surfaces and on rough terrain and stairs.

Although the locomotion unit has a complex structure, a major advantage of this system is that it uses a reduced number of motors.

In comparison with classical systems, it can be clearly concluded that hybrid systems are superior because they combine the advantages of singular systems. One drawback is their complexity and higher costs.

A solution is also to combine locomotion systems and obtain a hybrid system composed of a classic wheel and a TriSTAR unit.



a) b) c)

Fig. 6.4 3D model of the mobile search and rescue robot with the proposed locomotion systems [127]

6.2. The actuation and control of the search and rescue robot

The TriSTAR locomotion units and wheels will be powered by individual DC motors, specifically GHM-01 continuous current motors with a 30:1 reduction gearbox, running on a 12-volt power supply, and having a nominal speed of 200 rpm [127].

Each motor requires a driver, and it is mandatory to use an H-bridge for each motor to enable bidirectional control. For this purpose, the L298N motor driver will be used, which is a module containing all the necessary passive components.

The control diagram of the robot is depicted in Figure 6.7. The power supply source provides power to all power components and peripherals.

The proposed Arduino Uno development board for the robot includes a 5V regulator that powers the microcontroller.

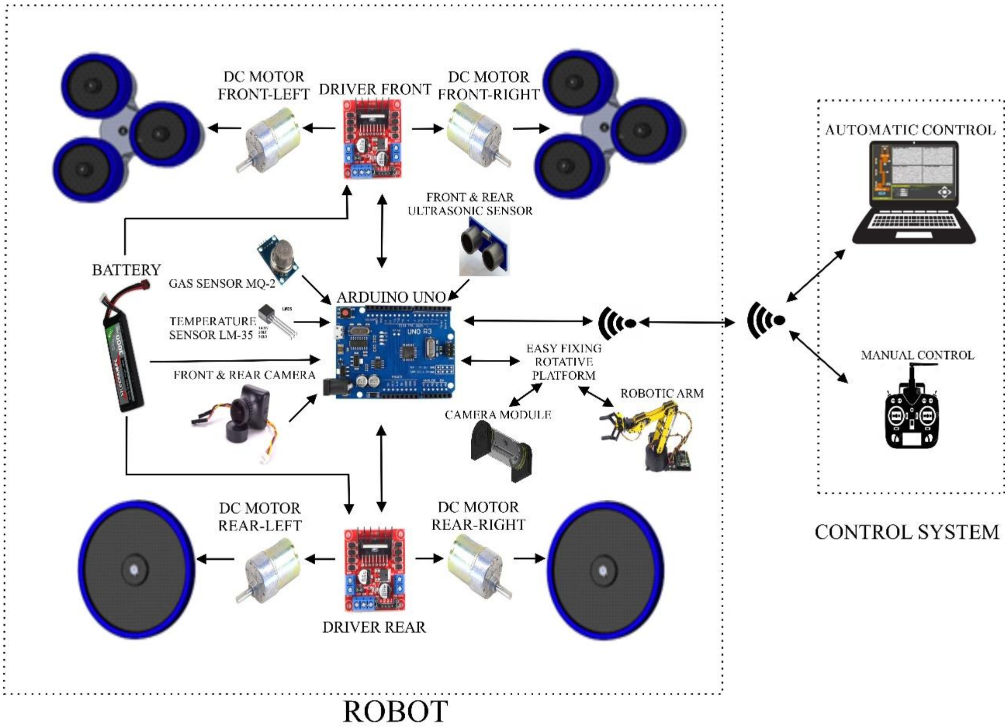


Fig. 6.7 The drive diagram of the mobile search and rescue robot [130]

6.3. The control interface of the robot

The control interface for remote control of the robot and special modules for search and rescue operations was developed in the Matlab App Designer environment.

The graphical interface includes a main window for controlling the robot's movement and real-time monitoring of the operating environment, affected by accidents and natural disasters.

The main window allows access to secondary graphical interfaces to utilize the functions of special modules (Fig. 6.10) [119].

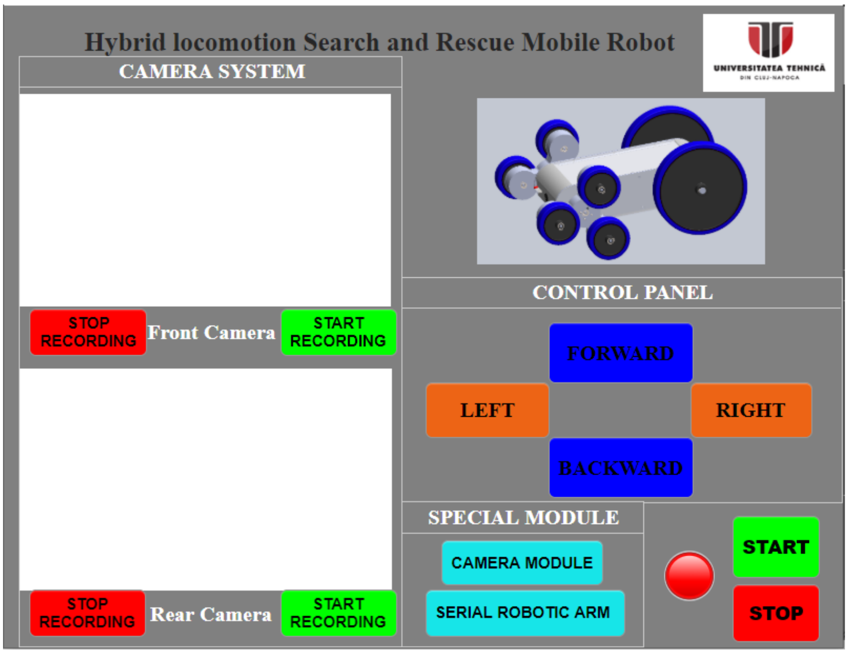


Fig. 6.10 The control interface of the search and rescue robot designed in Matlab [119]

6.4. Mathematical modeling of search and rescue robot with hybrid locomotion system composed of classic wheel and TriSTAR locomotion unit

Using Lagrange's equation, the motion equation of the mobile robot with hybrid locomotion system composed of TriSTAR units and conventional wheels will be determined [131, 132].

The Langrangian of robot L is given by the relation:

$$L = K - P \tag{18}$$

where:

K - the kinetic energy of the robot;

P - the potential energy of the robot.

Lagrange equation is [133]:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q'_i \quad \text{(i=1, 2, ... n)} \tag{19}$$

where:

q_i - the generalized coordinate,

Q` - the generalized force not derivable from a potential function.

Because the robot has to move on different type of surfaces we will consider for our study the movement on a ramp with the angle of inclination α as shown in Figure 6.13 [130].

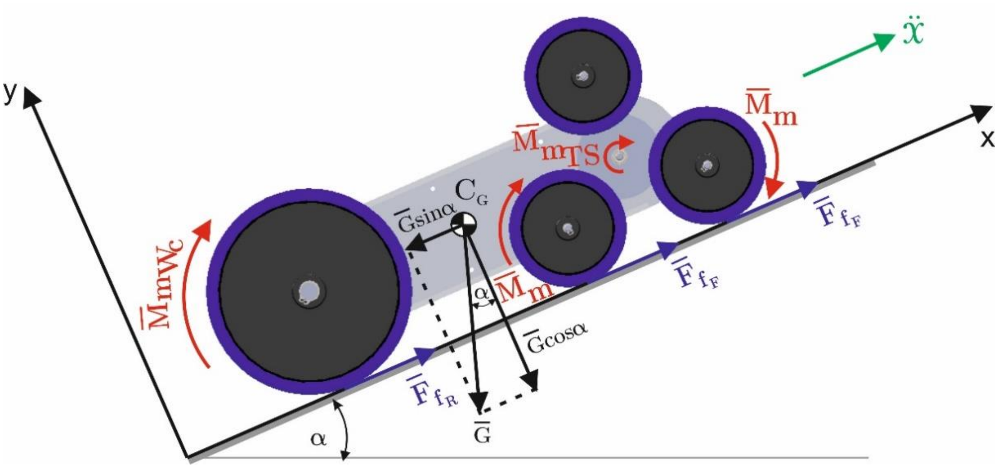


Fig. 6.13 Movement of the robot on and angled plan with α angle [130]

To describe the robot's motion a single generalized coordinate x will be considered $(\boldsymbol{q_i = x})$.

The kinetic energy K for the robot with hybrid locomotion system is determined with the equation:

$$K = \frac{1}{2}\, m_C\, \dot{x}^2 + 2\left(\frac{1}{2}\, m_{TS}\, \dot{x}^2\right) + 6\left(\frac{1}{2}\, I_w\, \omega_w^2\right) + 2\left(\frac{1}{2} m_{W_c}\, \dot{x}^2\right) + 2\left(\frac{1}{2}\, I_{W_c}\, \omega_{W_c}^2\right) \tag{20}$$

In relation (20) the kinetic energy was included in the translational motion of the robot chassis, conventional wheels and TriSTAR units and in the rotation motion of the two conventional wheels and the six wheels of the three TriSTAR locomotion units. In this relation (20) the movement of the gear wheels was neglected because the kinetic energy in their rotation motion is insignificant (the moments of inertia of the gear wheels are small) [130].

The potential energy *P* of the robot with hybrid locomotion system is obtained with the relation:

$$P = (m_C + 2\, m_{TS} + 2\, m_{W_c})\, g\, x \sin\alpha \qquad (25)$$

Using the relation (18) Lagrangian *L* will have the expression:

$$L = \left[\frac{1}{2} m_S\, \dot{x}^2 + 2\frac{1}{2} m_{TS}\, \dot{x}^2 + 6\frac{1}{2}\left(I_r\left(\frac{\dot{x}}{r_r}\right)^2\right) + 2\frac{1}{2} m_{R_c}\, \dot{x}^2 + 2\frac{1}{2}\left(I_{R_c}\left(\frac{\dot{x}}{r_{R_c}}\right)^2\right)\right] -$$
$$-\left[(m_S + 2\, m_{TS} + 2\, m_{R_c})\, g\, x \sin\alpha\right]$$

(26)

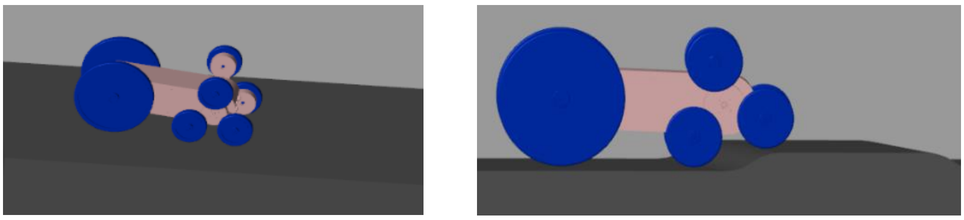
This relation (60) is the law of motion of the mobile robot. Using the relation (60) we can determine *M* if the acceleration $\ddot{x}$ of the robot is required, or imposing torque *M* we can determine the acceleration with which the robot will move [130].

$$\left[m_C + 2\, m_{TS} + 6\left[I_w\left(\frac{1}{{r_w}^2}\right)\right] + 2\, m_{W_c} + 2\left[I_{W_c}\left(\frac{1}{{r_{W_c}}^2}\right)\right]\right]\ddot{x} + (m_C + 2\, m_{TS} + 2\, m_{W_c})\, g \sin\alpha =$$
$$2\, M\left[\frac{i}{r_w} + \frac{1}{r_{W_c}}\right] - [s_F m_{R_F} + s_R m_{R_R}]g \cos\alpha =$$
$$2\, M\left[\frac{i}{r_w} + \frac{1}{r_{W_c}}\right] - [s_F m_{R_F} + s_R m_{R_R}]g \cos\alpha \qquad (60)$$

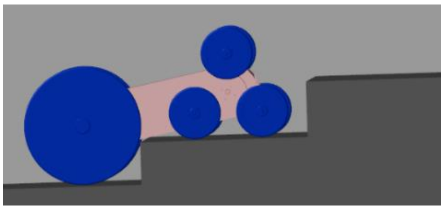
6.4.3. Simulating Robots with a Hybrid Locomotion System Composed of a Classic Wheel and TriSTAR Unit

The simplified 3D model of the proposed search and rescue mobile robot was imported from the SolidWorks design environment into the Matlab programming environment using the Simscape Multibody Link plug-in.

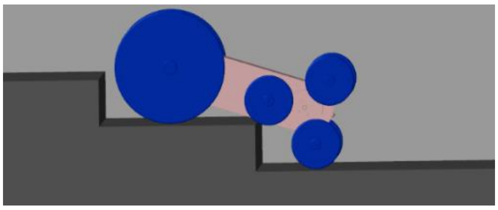
The locomotion process and the behaviour of the proposed search and rescue robot was simulated on different types of terrain and locomotion surfaces.



a) *b)*



c)



d)

Fig. 6.19 Simulation of the locomotion process for the proposed search and rescue mobile robot [119]

Contributions

Following the tests and improvement ideas, the modeling of the proposed search and rescue robot continued, designed for use in urban disasters.

To drive the search and rescue robot, a control diagram was created.

To remotely control the robot and special modules for search and rescue operations, a graphical interface was developed in the Matlab App Designer environment. The interface includes a main window for controlling the robot's movement and real-time monitoring of the operating environment affected by accidents and natural disasters. The main window allows access to secondary graphical interfaces. The secondary graphical interfaces enable the control of the functions of the special modules available on the search and rescue robot.

The mathematical modeling of the proposed search and rescue robot with a hybrid locomotion system composed of a classic wheel and a TriSTAR unit was performed.

7. FINAL CONCLUSIONS AND ORIGINAL CONTRIBUTIONS

7.1. General Conclusions

Conclusions drawn for robotics in these disasters were that ground mobility remains a major challenge, and adequate testing is crucial. Models that may succeed on certain types of surfaces appear to be unsuitable for other surface types.

The goal of the PhD thesis was to research the field of mobile robots for search and rescue and to contribute to the development of such robots with various locomotion systems.

The goal of the PhD thesis was to research the field of mobile robots for search and rescue and to contribute to the development of such robots with various locomotion systems:

- the working environment of search and rescue robots is divided into four major categories: urban, rural, mountainous, and aquatic;
- when choosing a type of search and rescue robot, two of the most important features are size and locomotion system, always correlated with the environment in which the robot must operate. Electronic components are crucial for successfully completing tasks, ensuring control, autonomy, and communication with the rescue team;
- the legged locomotion system has high adaptability to complex environments, but a major disadvantage is the difficulty in mechanical design and control.

Each system is technologically impressive, and each is designed to be the best for the specific requirements of the environment in which it is intended to perform certain tasks.

7.2. The originality and innovative contributions of the thesis

The features and characteristics of search and rescue robots were identified and systematized.

Locomotion systems were systematized and compared to choose the best option for the proposed search and rescue robots.

Whegs-type locomotion units were proposed and developed.

3D models of search and rescue robots with various hybrid locomotion systems were designed.

Two experimental robot prototypes were developed and tested using hybrid locomotion systems, namely TriSTAR and Whegs.

Various simulations were performed using Matlab and Solidworks for the proposed search and rescue robots.

After analyzing the observations obtained from the tests, improvements were made in the new designs of search and rescue robots.

Several STAR locomotion units were developed for use in the structure of search and rescue robots.

Mathematical modeling was conducted for the search and rescue robot with a hybrid locomotion system composed of a classic wheel and TriSTAR unit.

T*he directions for development are as follows:*

- Due to the robot's size and wheels, it is recommended to reduce dimensions so that the search and rescue robot can be carried in a backpack.
- To avoid technical issues such as short circuits or damage to electronic components, a good sealing of the robot's structure is recommended.
- To increase the robot's autonomy, a possible improvement would be to power it with high-performance batteries.
- Improving the proposed TriSTAR locomotion units by using an odd number of gears in the transmission system, if the gears are in series, or a mixed system of gears with a positive transmission ratio (motor and driven gear with the same rotation direction).
- Connecting and networking the robots designed for search and rescue activities.
- Search and rescue robotics remains a challenging field with many problems. Search and rescue robots have presented and continue to present challenges, and the need for improvements in all major subsystems is ongoing.

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