

## Locomotion unit for mobile robots

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**Abstract.** The first part of the paper presents a short introduction into the hybrid robots field and a classification for the wheel-leg hybrid robots. The second part presents the design and functionality of the locomotion unit proposed by the authors and the last part details the development paths proposed by the authors for this locomotion unit.

### 1. Introduction

In recent years there has been great progress in the mobile robotics field towards replacing human operators especially when performing dangerous tasks such as: demining, rescuing operations following earthquakes or other catastrophic events, fire extinguishing, exploring unknown environments etc.

For this purpose, robotics specialists have created locomotion systems that allow the robots to efficiently travel across different locomotion surfaces. These mobile robots combine wheels, tracks and legs for achieving locomotion and they are called hybrid robots.

By combining wheels, tracks and legs, four categories of hybrid locomotion systems can be obtained: legs-wheels (L-W), legs-tracks (L-T), wheels-tracks (W-T) and legs-wheels-tracks (L-W-T) [1].

The wheel-leg hybrid robots are classified in the three categories presented in figure 1 [2], [3]. These categories are:

- legged mechanism with a wheel attached at its foot end, also known as articulated wheel (figure 1a),
- independent wheel and leg modules mounted on the body of the mobile robot (figure 1b),
- wheeled legs – reconfigurable or transformable wheel modules which can be transformed into leg modules and vice versa (figure 1c).

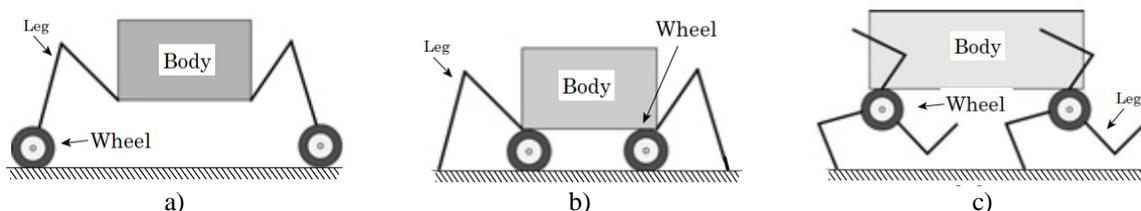


Figure 1. Wheel-leg hybrid robot categories [2], [3].

The locomotion system proposed by the authors consists of several locomotion units, and the robots obtained by using them fall into the wheel-leg hybrid robot category (figure 1c). These robots combine the advantages of both wheels and legs.

The solution proposed by the authors in this paper is not a new one. The speciality literature reports several achievements regarding this type of locomotion unit which is referred to as a Tri-Star wheel [4], [5], [6], [7], [8], [9], [10], [11], [12], [13].

The proposed locomotion unit has the following features:

- the frame consists of two steel brackets, connected with bolts, that have ten gears inside of them, which form the transmission from the main axle to three external wheels.
- reconfigurability is a possibility by changing the external wheels and the transmission according to certain needs.

In the next part the paper is structured as follows: the second section presents the structure of the locomotion unit, the third section presents the functionality of the unit, the fourth section details future development paths and the conclusions are presented in the fifth and final section.

## 2. The structure of the locomotion unit

The locomotion unit proposed by the authors was developed in two constructive versions. The first version is a drive unit and the second is an idle unit.

### 2.1. The first constructive version

The locomotion unit (TRI-STAR wheel) proposed by the authors is in fact a wheel with three legs (spokes) placed at 120 degree angles with a conventional wheel attached to the end of each leg. Inside each leg of the wheel there is a geared transmission with cylindrical gears with straight teeth.

The main components of the locomotion unit are (figure 2): unit frame – pc; sun gear – 1; primary planet gears – 2, 2', 2''; secondary planet gears – 3, 3', 3''; tertiary planet gears – 4, 4', 4''; conventional wheels – w.

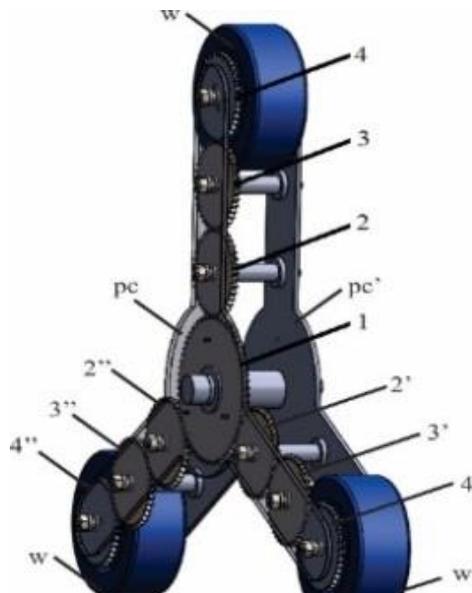


Figure 2. Locomotion unit.

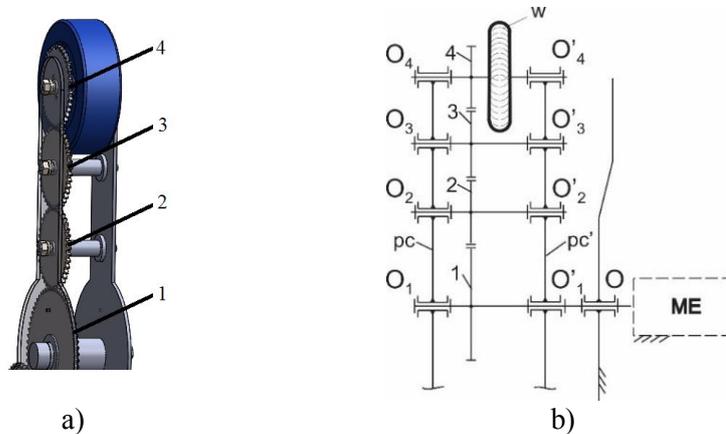
Due to the planetary mechanism used, the three external wheels ( $w$ ) will rotate with the same angular speed. The tertiary planet gears (4, 4', 4'') are connected to the external conventional wheels ( $w$ ). The frame of the unit consists of two steel star shaped brackets connected with bolts.

The ten gears, which transmit the movement from the central axle to the three external wheels ( $w$ ), are placed inside the described frame. The 3D model and a photo of the locomotion unit is presented in figure 3.



**Figure 3.** The 3D model a) and a photo b) of the locomotion unit.

The 3D model and the kinematic diagram of a leg are presented in figure 4.

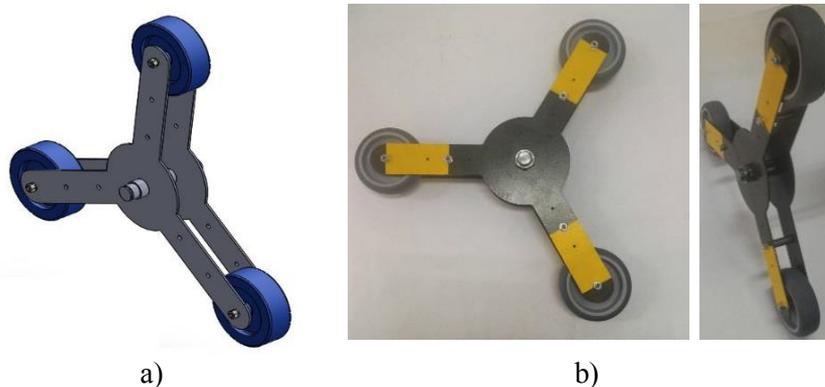


**Figure 4.** The 3D model a) and the structural diagram b) of a leg from the locomotion unit.

The locomotion unit is fixed to the robot's frame using a rotation coupling (O) which has its axis parallel with the axis of the transmission gears and the axis of the conventional wheels (w) (figure 4b).

*2.2. The second constructive version*

The second model proposed by the authors is presented in figure 5. This version functions without the use of gears and it will function mounted on a robot only in combination with the first version, which will act as a drive unit.



**Figure 5.** The 3D model of the locomotion unit V2.

The external wheels can be easily changed for this constructive version, according to the needs required by a certain task.

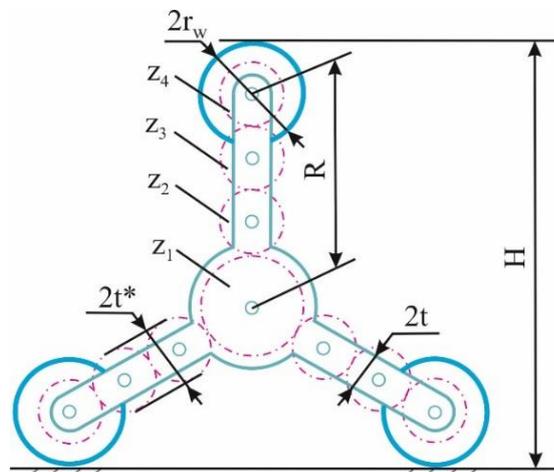
### 2.3. The parameters of the locomotion unit

The parameters used in the structure of the locomotion unit are (figure 6):

- the radius of the locomotion unit  $R$ , which is the distance from the centre of the unit to the centre of the external wheels  $w$ ,  $R = 200$  mm;
- the radius of the external wheels  $r_w = 100$  mm;
- the width of the support that fixes the external wheels onto the locomotion unit  $2t = 45$  mm.

Figure 6 shows that due to the external diameters ( $d_a$ ) of the gears 2 and 3, the width that needs to be used in the calculations is greater than  $2t$ , this being  $2t^* = 63$  mm.

The thickness of the supports that make the legs of the locomotion unit is of 2 mm. The gears are made of polyethylene and they have the number of teeth  $z_1 = 67$ ,  $z_2 = z_3 = z_4 = 40$  and the module  $m = 1,5$  mm. The weight of the locomotion unit is of 2,740 kg and the height  $H = 400$  mm.



**Figure 6.** The design parameters of the locomotion unit.

The radius of the locomotion unit  $R$  (which is also the axial distance between the axes of the gears 1 and 4) is dependent on the module of the gears and their number of teeth,  $R = f(m, z_1, z_2, z_3, z_4)$  and it can be determined with the equation:

$$R = m \left( \frac{z_1}{2} + z_2 + z_3 + \frac{z_4}{2} \right) \quad (1)$$

and the height of the unit  $H$  is:

$$H = 3 \frac{R}{2} + 2r_w \quad (2)$$

### 3. The functioning principle of the locomotion unit

Each locomotion drive unit has two rotation axes: one for the rotation of the wheels  $w$ , for when the unit travels onto flat surfaces or ascending slopes, and the other for the rotation of the whole unit, for when the unit has to climb steps or overpass obstacles.

It is known that the geometry of such a locomotion unit allows the commutation between wheeled locomotion (advancing mode) figure 7c and legged locomotion (automatic climbing mode) figure 7d [10], [11].

- When travelling on a flat surface

The movement is transmitted from the motor ME through the gears 1, 2, 3, 4 to the wheels noted  $w$  (figure 4b) placed at the extremities of the locomotion unit (figure 7c).

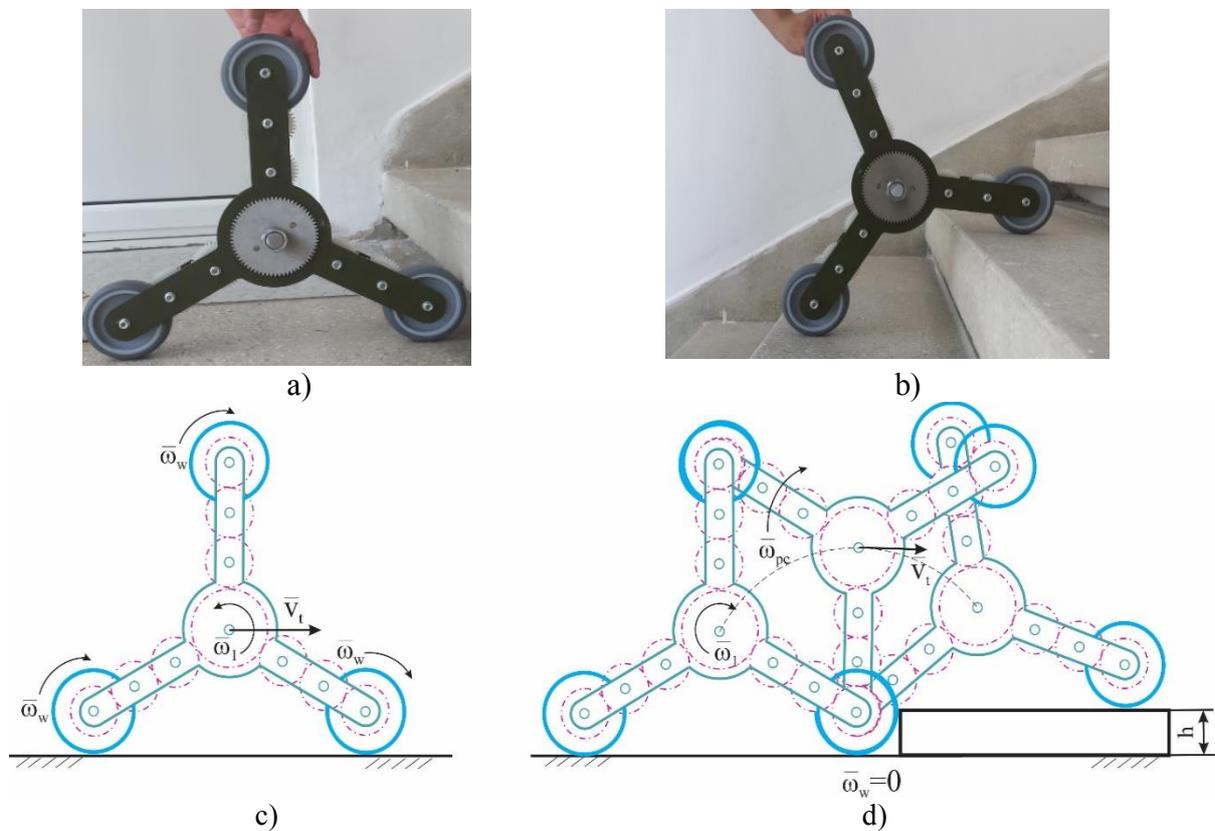
The gear ratio is (figure 4b):

$$i = \frac{n_{ME}}{n_w} = \frac{\omega_{ME}}{\omega_w} = i_{12}i_{23}i_{34} = -\frac{z_4}{z_1} \tag{3}$$

from which we obtain the rpm of the external wheels  $n_w$ :

$$n_w = -\frac{z_1}{z_4} n_{ME} \tag{4}$$

in this equation  $n_{ME}$  represents the rpm of the drive motor.



**Figure 7.** The movement of the locomotion unit  
 a), b) photo c) advancing mode d) automatic climbing mode.

The translation speed of the locomotion unit  $v_t$  is:

$$v_t = \omega_w r_w = -\frac{z_1}{z_4} \omega_{ME} r_w \tag{5}$$

where

- $\omega_w$  - the angular speed of the external wheels
- $\omega_{ME}$  - the angular speed of the drive motor
- $r_w$  - the radius of the external wheels.

- *When travelling over obstacles/steps*

Considering  $\omega_{pc}$  – the angular speed of the locomotion unit’s legs and  $\omega_i$  – the angular speeds of the gears,  $i = 1, \dots, 4$ , by using Willis’ equation we get (figure 7d):

$$\frac{\omega_1 - \omega_{pc}}{\omega_w - \omega_{pc}} = \left(-\frac{z_2}{z_1}\right) \left(-\frac{z_3}{z_2}\right) \left(-\frac{z_4}{z_3}\right) = -\frac{z_4}{z_1} \quad (6)$$

Because the wheel is blocked when passing obstacles  $\omega_w = 0$  we get:

$$\frac{\omega_1}{\omega_{pc}} = \frac{\omega_{ME}}{\omega_{pc}} = +\frac{z_4}{z_1} + 1 \quad (7)$$

Even though the planetary mechanism used in the structure of the locomotion unit has two degrees of freedom, from equation (7) we can conclude that for driving the unit only one motor is needed. Nonetheless, a great enough torque is needed in order for the entire unit to rotate around the axis of the wheel that is in contact with the step or the obstacle (Figure 7d) that needs to be overpassed.

If the geared transmissions, from the gear 1 to the wheel  $w$ , have an uneven number of gears, the rotation directions of the drive motor shaft and of the wheels  $w$  will be the same. If an even number of gears is used, the drive motor shaft and the wheels  $w$  will have opposite rotation directions.

From equation (7) we can conclude that when travelling over obstacles, in this instance (due to the even number of gears used in the transmission), after stopping the external wheels  $w$ , in order to overpass the obstacle/step, the rotation direction of the drive motor shaft will need to be reversed.

#### 4. Development directions

Regarding the constructive solution presented in the third section of the paper ( $R = 200$  mm,  $r_w = 100$  mm,  $2t^* = 63$  mm), in order to avoid collision between the external wheels support and the step, the latter has to have a height of  $h \leq 50$  mm. This limitation is due to the small radius of the external wheels. However, the external wheels can be easily changed so that the unit can adapt to different situations. For example, in order to overpass steps with a height  $h = 200$  mm and a width of  $w = 280$  mm, the wheels  $w$  have to be changed, therefore obtaining the configuration presented in table 1. These values have been obtained by using the equations presented in [8].

**Table 1.** The locomotion unit parameters for  $h = 200$  mm and  $w = 280$ mm

Parameters [8]	Calculated	Chosen
$R$	198,66 mm	200 mm
$R = \sqrt{\frac{w^2 + h^2}{3}}$		
$2t^* = d_a$	63 mm	63 mm
$d_{a2} = m(z_2 + 2)$		
$r_{w \min}$	86,32 mm	$173 \text{ mm} \leq 2 r_w \leq 344 \text{ mm}$
$r_{w \min} = \frac{6Rt + h(3w - \sqrt{3}h)}{(3 - \sqrt{3})h + (3 + \sqrt{3})w}$		
$r_{w \max}$	172,04 mm	
$r_{w \max} = \sqrt{\frac{w^2 + h^2}{2}}$		

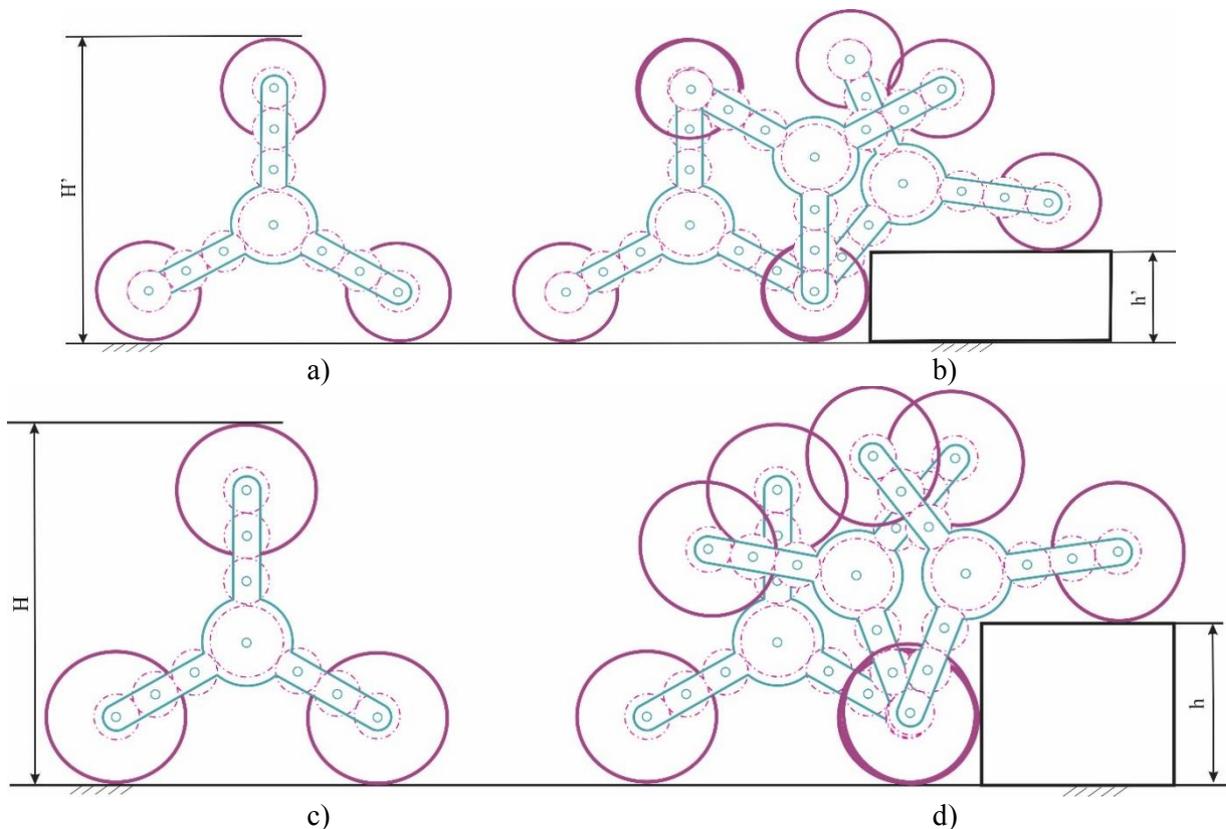
In the above equations,  $r_{w\ min}$  si  $r_{w\ max}$  represent the minimum and maximum radius of the wheels  $w$ , which help avoiding the collision between the wheel supports and the step, and  $d_{a2}$ ,  $d_{a3}$  represent the external diameter of the gears 2 and 3.

Table 2 presents other values which help avoiding collision, values obtained from different configurations ( $h$ ,  $w$ ) of the steps and different parameters of the locomotion unit.

**Table 2.** Locomotion unit parametric values for various steps configurations ( $h$ ,  $w$ )

$h[mm]$	$w[mm]$	$R[mm]$	$r_{min}[mm]$	$r_{max}[mm]$	$2t[mm]$	$2t^*[mm]$
155	300	194,95	83,36	168,83	45	63
<b>160</b>	<b>300</b>	<b>196,299</b>	<b>84,29</b>	<b>170</b>	<b>45</b>	<b>63</b>
165	300	197,67	85,15	171,19	45	63
170	280	189,21	83,40	163,78	45	63
<b>170</b>	<b>300</b>	<b>199,08</b>	<b>85,96</b>	<b>172,04</b>	<b>45</b>	<b>63</b>
175	300	200,52	86,72	173,65	45	63
180	280	192,18	84,60	166,43	45	63
180	300	201,99	87,42	175,92	45	63

When designing the steps, a connection equation is used between the *width*  $w$  and the *height*  $h$  of one step. Thus, according to the generally used equation:  $2h + w = 620 \div 640$  mm, for a step with a width  $w = 300$  mm we get the values for the minimum optimal height  $h = 160$  mm and maximum optimal height  $h = 170$  mm.

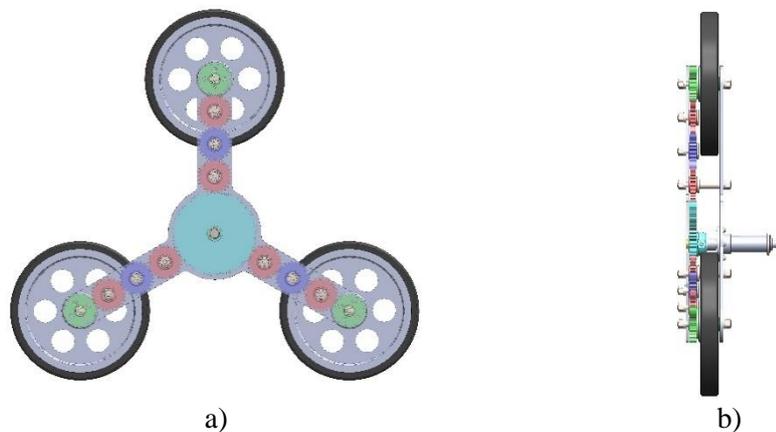


**Figure 8.** The locomotion unit with different radius external wheels a), c) on a flat surface b), d) over steps.

For stairs with steps smaller than 160 mm ( $h < 160$  mm) or larger than 180 mm ( $h > 180$  mm), the equation  $3h + w = 800 \div 850$  mm is used. For stairs situated indoors which are used by children (preschools, schools), the equation  $2h + w = 580 \div 600$  mm is used. According to the height of the steps  $h$ , the stairs can be with low steps  $h < 165$  mm, with medium steps (standard)  $165 \text{ mm} \leq h \leq 175$  mm, with high steps  $175 \text{ mm} < h \leq 225$  mm or abrupt  $226 \text{ mm} < h \leq 300$  mm.

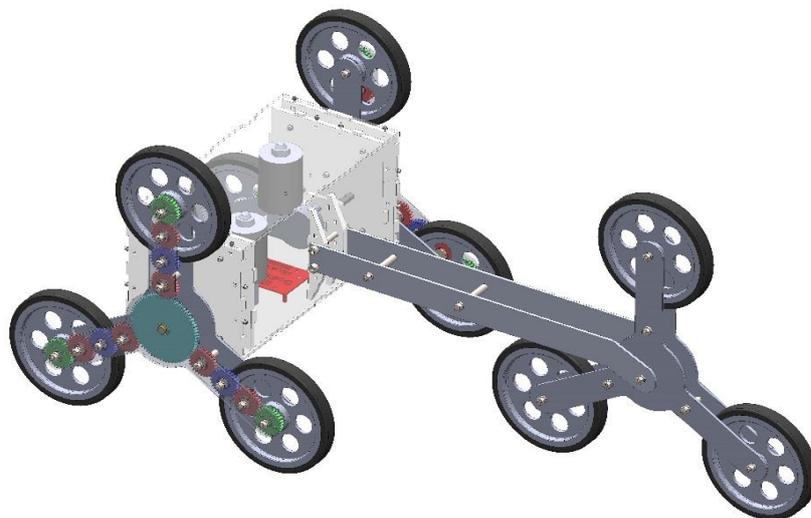
For the proposed locomotion unit, for the same value of the parameter  $R$  and the same width  $2t^*$ , it can be concluded that by increasing the radius of the external wheels  $r_w$ , the possibility of overpassing higher obstacles/steps also increases (figure 8). That means, of course, that the unit height  $H$  also increases, according to equation (2).

The authors *recommend using an uneven number of gears for transmitting the movement from the drive motor shaft to the wheels  $w$*  (for example:  $z_1 = 71$ ,  $z_2 = z_3 = z_4 = z_5 = 28$  and  $m = 1,5$  mm,  $R = 200$  mm,  $t = 45$  mm), (figure 9). Thus, the rotation direction of the drive motor will not have to be inverted when the wheels  $w$  are in contact with the step/obstacle, therefore the act of overpassing the obstacle will be done automatically and continuously (automatic climbing mode).



**Figure 9.** The new design of the locomotion unit.

In this case, the angular speeds  $\omega_1, \omega_w$  and  $\omega_1, \omega_{pc}$  will have the same rotation direction. The locomotion unit proposed by the authors offers a promising solution for search and rescue robots. By using this locomotion unit, the authors want to develop a mobile robot whose 3D model will be presented next. The authors also want to improve the structure of the locomotion unit.



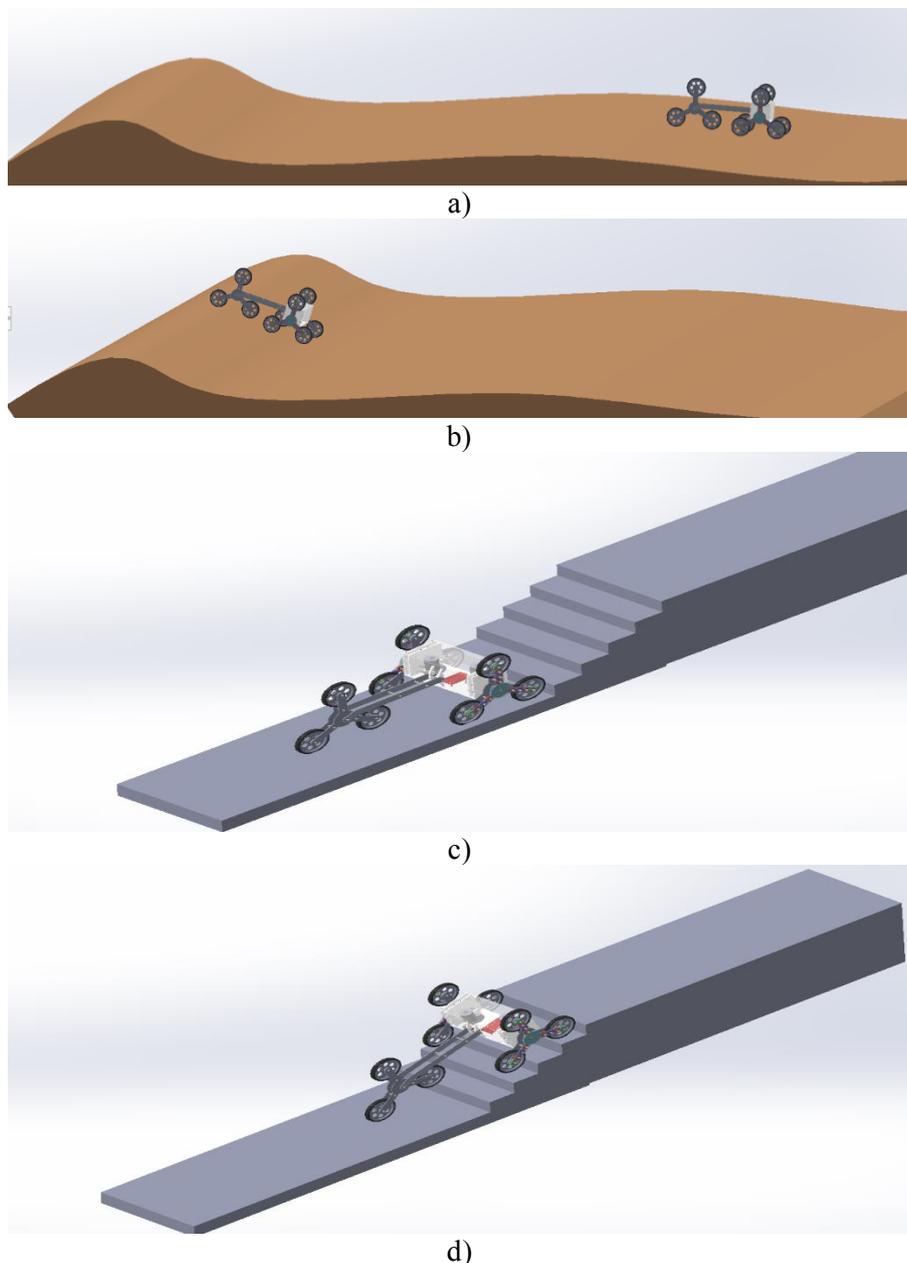
**Figure 10.** Mobile robot with two drive locomotion units.

The locomotion unit is a good solution when needing a robot that can easily move both on flat surfaces as well as over rough terrain or over steps. The locomotion system of the proposed robot (figure 10) consists of two drive locomotion units. The robot needs to be driven by two geared DC motors. For the control aspect, the authors want to use INTEL Galileo Duo development boards.

The trajectory of the robot in this configuration will depend on the rotation speed difference between the two driving motors. Thus, when the motors have the same rotation speed, the robot will travel in a straight line. Steering to the left is achieved when the right motor has a greater rotation speed than the left motor and the other way around for steering to the right.

The developed robot can be included in the hybrid robots category because it uses a locomotion system that includes the advantages of both wheels and legs. The robot will be built in the near future and tests and improvements will also be performed.

Figure 11 presents images with potential terrain types that the proposed robot can travel onto.



**Figure 11.** Images of the proposed robot on different types of terrain.

## 5. Conclusions

In order to increase flexibility, efficiency and manoeuvrability when operating in rough environments, the mobile robots must have improved locomotion systems. In this regard, the speciality literature mentions an increasing number of robots that have hybrid locomotion systems.

The paper presents the design of a locomotion unit that can be used for search and rescue hybrid robots. The structure of the locomotion unit looks to be a fit solution for cases when the robot needs to travel both on flat surfaces and on rough terrain or over steps. A great advantage of this locomotion system is the fact that it uses a small number of motors.

## 6. References

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