

Design of the small mobile robot Epi.q-2

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SUMMARY. Epi.q-2 is a transport robotic device able to move in structured or unstructured environments. Using a locomotion system that mixes wheeled and legged locomotion, the Epi.q-2 can face different grounds: it can move on flat, inclined, undulating or uneven terrain, it can go up stairs or climb over obstacles.

1 INTRODUCTION

Observing all over the world the robotics evolution, the recorded tendency is a diversification in three main branches: industrial robotics, service robotics and research robotics, each one with its own evolution. The scientific literature presents for robots moving on ground a further categorization, on the basis of the locomotion systems, into three main classes: rolling, crawling and walking robots, even though there are also robots that jump, slither and so on. Clearly each robot class has advantages and drawbacks, therefore some robots, called *hybrid robots*, try to join the advantages of different robot classes and, at the same time, to reduce the disadvantages. For this reason a “wheel-leg” hybrid solution has been chosen for the design of the Epi.q-2, the mini-robot presented in this paper.

The scientific literature presents several solutions for robots moving on structured and unstructured grounds; some smart reference prototypes for the Epi.q-2 are collected here.

The Spacecat [1], developed by the Ecole Polytechnique Fédérale de Lausanne, is characterized by its “Stepping Triple Wheels” locomotion unit. Two independent sets of three wheels are supported by two frames. These frames can independently rotate with respect to the main central body (payload frame), allowing the robot to climb over obstacles or steps.

The MSRox [2], developed by the Tarbiat Modarres University, is characterized by its “Star-Wheels” locomotion unit. Each locomotion unit is composed by a set of three wheels supported by a frame, and the four locomotion units are assembled on a central body. The robot can advance on a ground, when only the wheels rotation is driven, or climb over an obstacle, when only the locomotion unit is driven; these two motions are actuated independently.

The Whogs [3], developed by the Case Western Reserve University, is characterized by its three spokes locomotion unit. In this mini vehicle, cockroach inspired, wheels are replaced by three spokes locomotion units, so that the robot can move faster than legged robots and can climb higher steps than wheeled ones of similar size.

This paper describes a new robot that can passively change the functioning mode, according to local friction and dynamic conditions, from rolling on wheels to stepping on legs, showing a great

ability in moving in structured and unstructured environments. Section 2 describes the Epi.q-2 design. Section 3 presents the locomotion unit and an analysis of the different kinds of locomotion. Section 4 shows the locomotion unit dimensioning approach. Section 5 deals with the executive locomotion unit design and section 6 presents the conclusions.

2 EPI.Q-2 DESIGN

Epi.q-2 is a transport robotic device able to move in structured and unstructured environments. It is a research prototype that can be efficaciously adopted in several application fields: monitoring, surveillance and intervention tasks in restricted spaces or in potentially dangerous environments, like in presence of radiations, toxic gases or explosives.

The Epi.q-2, using a locomotion system that mixes wheeled and legged locomotion, can be classified as a hybrid robot. It can passively change functioning mode according to local friction and dynamic conditions, from rolling on wheels to stepping on legs. The robot shows a great ability in advancing on flat or uneven terrain, in stairs climbing and in overcoming obstacles.

Epi.q-2 is the evolution of Epi.q-1 robot series, presented in [4]. Differently from the first versions, the locomotion units employ a new mechanism, still based on an epicyclic gearing, that is simpler and more compact than Epi.q-1, without the capability of changing legs configuration.



Figure 1: Epi.q-1 in open field.

3 LOCOMOTION ANALYSIS

3.1 *Locomotion unit description*

The locomotion unit design starts from the idea that different motions can be obtained using one transmission system, simply locking or unlocking some degrees of freedom along the kinematic chain. Therefore a particular epicyclic gearing was adopted as transmission system for the locomotion unit, where the two degrees of freedom are the rotation of the three wheels and the rotation of the planet carrier.

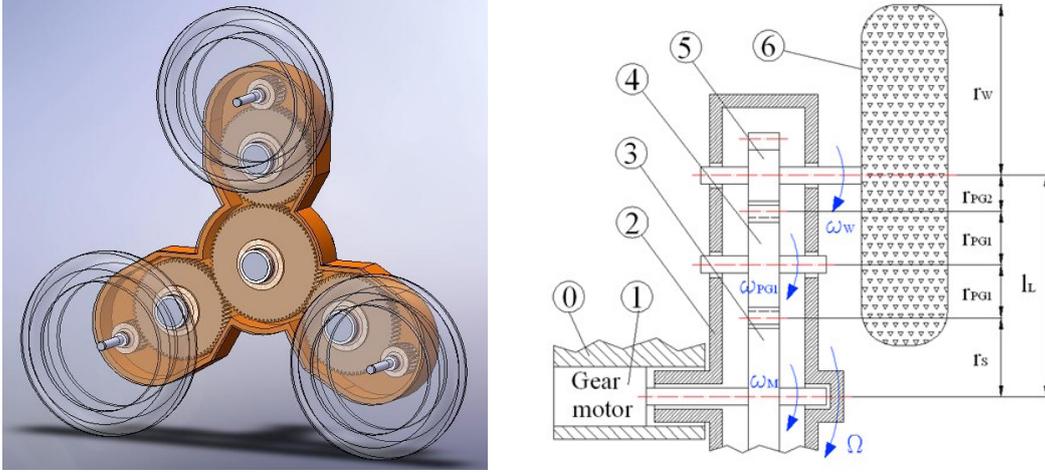


Figure 2: Robot locomotion unit.

The locomotion unit, joined to the robot chassis (0), consists of the following elements: gear motor (1), planet carrier (2), solar gear (3), first planet gear (4), second planet gear (5) and wheel (6) (see Figure 2).

Table I: Nomenclature.

Nomenclature	Symbol or subscript	Radius	Absolute rotation speed	Element number
Robot chassis				0
Gear motor	M		ω_M	1
Planet carrier			Ω	2
Solar gear	s	r_s	$\omega_s = \omega_M$	3
First planet gear	$PG1$	r_{PG1}	ω_{PG1}	4
Second planet gear	$PG2$	r_{PG2}	$\omega_{PG2} = \omega_w$	5
Wheel	w	r_w	ω_w	6

As it will be explained in the following, the robot can passively modify its locomotion from the *advancing mode*, when it moves on wheels, to the *automatic climbing mode*, when it climbs over obstacles.

Each locomotion mode needs two kinematic relations, which allow a description of the mechanical gearing functioning. One kinematic relation is valid for all operating conditions, since it represents the meshing condition of the epicyclic gearing:

$$\frac{\omega_w - \Omega}{\omega_M - \Omega} = \left(-\frac{r_s}{r_{PG1}} \right) \cdot \left(-\frac{r_{PG1}}{r_{PG2}} \right) = (-k_1) \cdot (-k_2) = k_e \quad (1)$$

A second kinematic relation, which describes the physical constraint introduced by local friction and dynamic conditions, is necessary to univocally determine the robot kinematics; it will be discussed in the following.

3.2 Advancing mode

In advancing mode, the planet carrier is mechanically free to rotate around its axis, but the robot weight and the contact forces between bottom wheels and ground constrain the locomotion unit angular position.

When the robot is moving on flat ground, the contact between the two bottom wheels and the ground hinders the planet carrier rotation:

$$\Omega = 0 \quad (2)$$

With this hypothesis, combining equations (1) and (2), the gear ratio i_A for the advancing mode can be expressed as:

$$i_A = \frac{\omega_W}{\omega_M} = k_e \quad (3)$$

therefore the linear velocity v_A (see Figure 3, left) in the advancing mode is:

$$v_A = \omega_W \cdot r_W = \omega_M \cdot i_A \cdot r_W = \omega_M \cdot k_e \cdot r_W \quad (4)$$

3.3 Automatic climbing mode

When the robot is moving forward and it bumps against a step or an obstacle, the planet carrier rotation starts, if the local friction between the front wheel and the obstacle is sufficient to block the wheel. When this condition occurs, the front wheel and the second planet gear rotation are hindered and consequently the planet carrier rotation starts, so the locomotion unit rotates around the stopped wheel and the robot climbs over the obstacle (Figure 3, right):

$$\omega_W = \omega_{PG2} = 0 \quad (5)$$

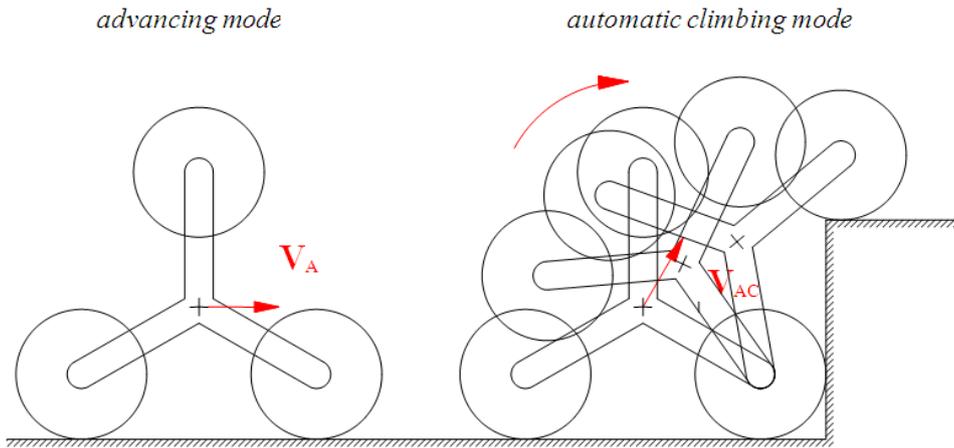


Figure 3: Locomotion unit during step climbing operation.

The gear ratio i_{AC} for the automatic climbing mode, combining equations (1) and (5), can be expressed as:

$$i_{AC} = \frac{\Omega}{\omega_M} = \frac{k_e}{k_e - 1} \quad (6)$$

therefore the angular velocity of the planet carrier is:

$$\Omega = \omega_M \cdot i_{AC} = \omega_M \cdot \frac{k_e}{k_e - 1} \quad (7)$$

and consequently the linear velocity v_{AC} (Figure 3) of the locomotion unit axis is:

$$v_{AC} = \Omega \cdot l_L = \omega_M \cdot i_{AC} \cdot l_L = \omega_M \cdot \frac{k_e}{k_e - 1} \cdot l_L \quad (8)$$

where l_L is the length of the locomotion unit leg.

The planet carrier geometry is designed to reduce the risk of interferences between obstacles and locomotion units; nevertheless this condition can happen sometimes, especially in the automatic climbing mode. In this case we experimentally verified that the robot gets anyhow over the obstacle with a slightly irregular motion that combines advancing and automatic climbing modes.

The automatic climbing mode can also be triggered off by the robot acceleration or by the ground slope, if these exceed limit values, as explained in [4].

4 LOCOMOTION UNIT DIMENSIONING

After the selection of the locomotion unit kinematic chain, it is necessary to identify gears and wheels dimensions as well as the planet carrier geometry.

The locomotion unit dimensioning starts from this consideration: when the robot bumps against an obstacle the locomotion unit gear motor still continues to rotate in the same direction, because the robot is not equipped with sensors for obstacles detection. Therefore the locomotion units work properly only if the gear ratios are suitable both for advancing mode and for automatic climbing mode. Equations (3) and (6) allow us to identify the following condition:

$$k_e > 1 \quad (9)$$

and so it is necessary to use an odd number of gears, with a ratio between the solar gear radius and the external planet gear radius bigger than one. A second condition is that the transition between advancing and automatic climbing mode has to preserve the robot motion continuity. The α coefficient identifies the ratio between the locomotion unit axis speeds in automatic climbing mode and advancing mode; it can be expressed as follows:

$$\alpha = \frac{v_{AC}}{v_A} = \frac{1}{k_e - 1} \cdot \frac{l_L}{r_W} \quad (10)$$

If the α coefficient is not far from the unit value, there is a soft transition from advancing to automatic climbing mode, even though v_A and v_{AC} have different directions.

A third condition is a geometrical constraint for the locomotion unit (see Figure 2):

$$l_L = r_s + 2r_{PG1} + r_{PG2} \quad (11)$$

Locomotion units with different climbing abilities can be obtained varying the l_L/r_W parameter, as shown in Figure 4: considering locomotion units with similar overall dimensions, if the l_L/r_W value increases, the robot can climb over higher obstacles and it is more oriented to stepping on legs locomotion; if the l_L/r_W value decreases, the gearing is more protected by the wheels and the locomotion unit is more suitable for locomotion on wheels. The lower limit value for the l_L/r_W parameter is:

$$\frac{l_L}{r_W} = \frac{1}{\cos 30^\circ} \quad (12)$$

which occurs when the wheels are in interference limit condition.

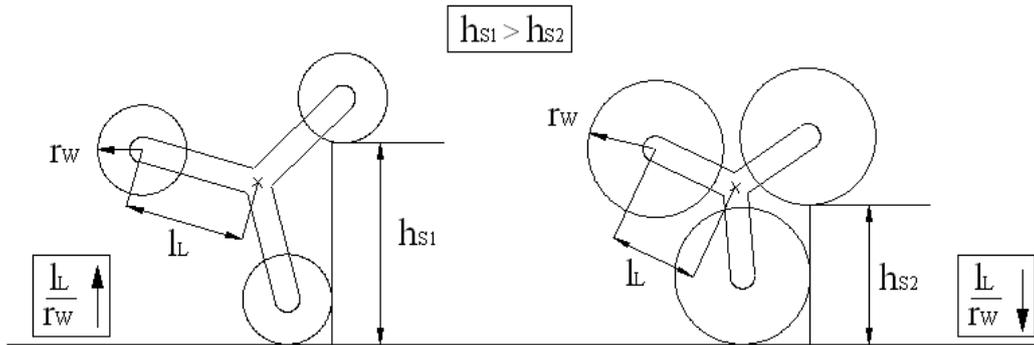


Figure 4: Locomotion unit dimensioning with different l_L/r_W ratios.

Once the l_L/r_W value is chosen and an acceptable value for the α coefficient is assumed, equation (10) allows to identify a first attempt value for the k_e gearing ratio:

$$k_e = \frac{1}{\alpha} \cdot \frac{l_L}{r_W} + 1 \quad (13)$$

Also when l_L , r_W and k_e are fixed, there are infinite solutions for selecting the radii of the gears, as shown in Figure 5.

A consideration on the locomotion unit overall dimensions can help this final choice: as shown in Figure 5, when the solar gear (3) and the first planet gear (4) have approximately the same dimension, the locomotion unit has a geometry that reduces the interference with the obstacles.

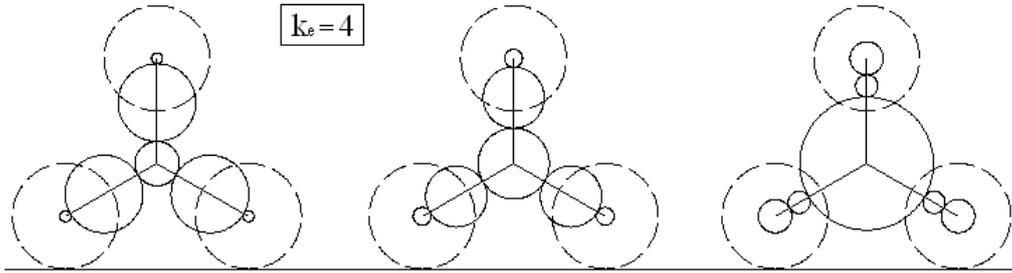


Figure 5: Three possible locomotion unit geometries with equal values of l_L , r_W and k_e .

After the geometrical dimensioning of the locomotion unit, it is necessary an in-depth dynamic analysis to evaluate the conditions for the locomotion transition. This analysis, that considers the whole robot, the friction and the bearings and gearings efficiency, can help for example to evaluate the limit acceleration or slope values that trigger off the automatic climbing mode, as described in [4]. Moreover it is necessary to verify that the automatic climbing mode starts with torque values lower than the one needed for the slipping conditions.

The process here described is an iteration process and so, if the results are not satisfactory, it is necessary to modify some parameters and start again the procedure.

5 LOCOMOTION UNIT EXECUTIVE DESIGN

The core of the locomotion unit is the planet carrier; it consists of two aluminium alloy 2011 shells, one flat and one carved (see Figure 6). The two shells are connected by means of M3 screws.

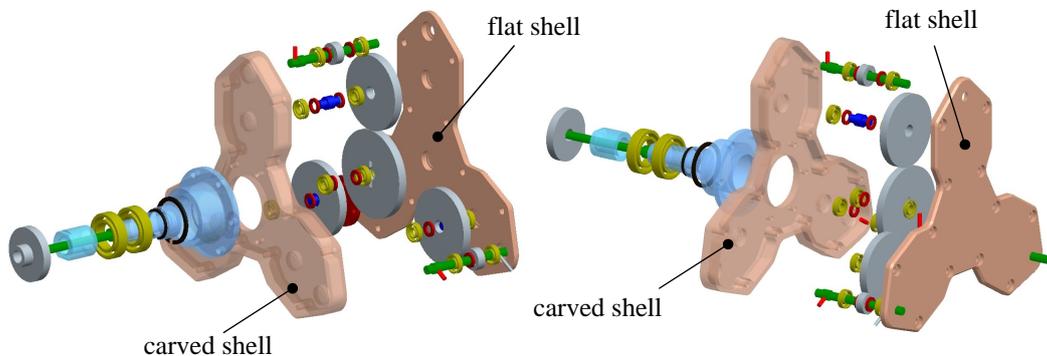


Figure 6: Executive design of the locomotion unit.

The planet carrier is screwed to a brass hub, which hosts two sealed ball bearings (inner diameter 12 mm, outer diameter 21 mm, width 5 mm). These are axially fixed to a hollow shaft by means of headless Seeger rings (Figure 7). Inside the hollow shaft, the main shaft driving the solar gear (diameter 41 mm, 82 teeth, 4 mm thickness) is housed. The first and the second planet gears are, respectively, with 35 mm diameter (70 teeth) and 10 mm diameter (20 teeth).

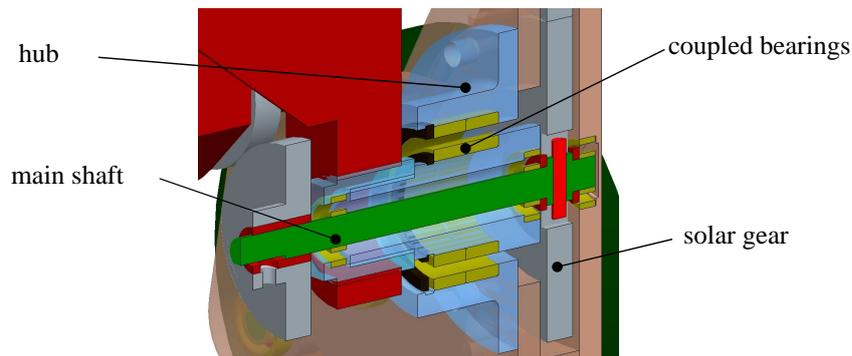


Figure 7: Detail of the central part of the locomotion unit.

The solar gear receives power from a motoreducer which is offset located to lower the overall width of the vehicle (see Figure 8). The transfer of motion from the motoreducer to the main shaft is performed by a straight gear (21/24 teeth) which grants a slight speed reduction (0.875); the gears might be inverted to test experimentally a slight speed increase (1.14).

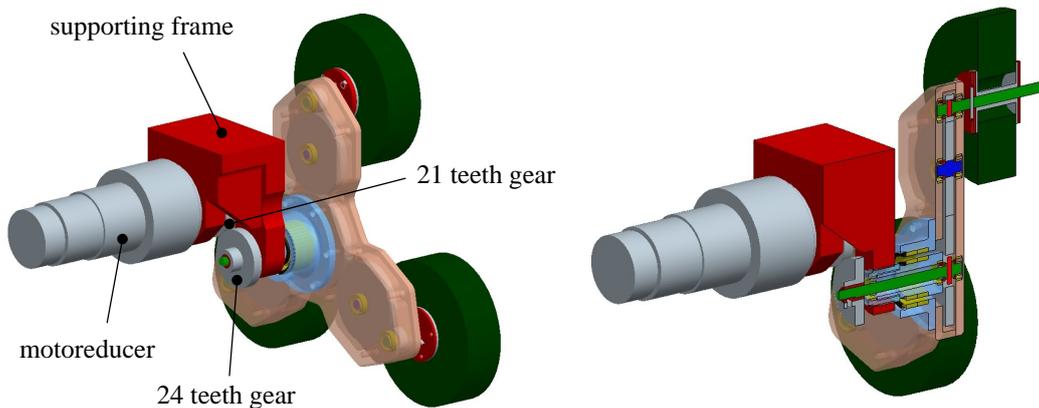


Figure 8: Connection of motoreducer and locomotion unit.

In order to avoid costly and time-consuming machining, it was not used the classical mounting of gears by keys; moreover, for the same reason and due to the very small diameters, shoulders on shafts were limited as much as possible. The axial positioning of the gears exploits the use of washers (Figure 9): first the gear is mounted on the major diameter region of the shaft; then washers are pushed on both sides of the shaft shoulders and the bearings too (inner diameter 4 mm, outer diameter 9 mm, width 2.5 mm); everything is packed by screwing the shells of the planet carrier together (the design axial clearance is 0.5 mm). Cylindrical pins passing through the shaft are used to constrain the rotation of the gears with respect to the shafts: the exceeding ends engage in the slots realized in the gears (Figure 9). Intermediate planet gears do not need torsional fixing since they are idle.

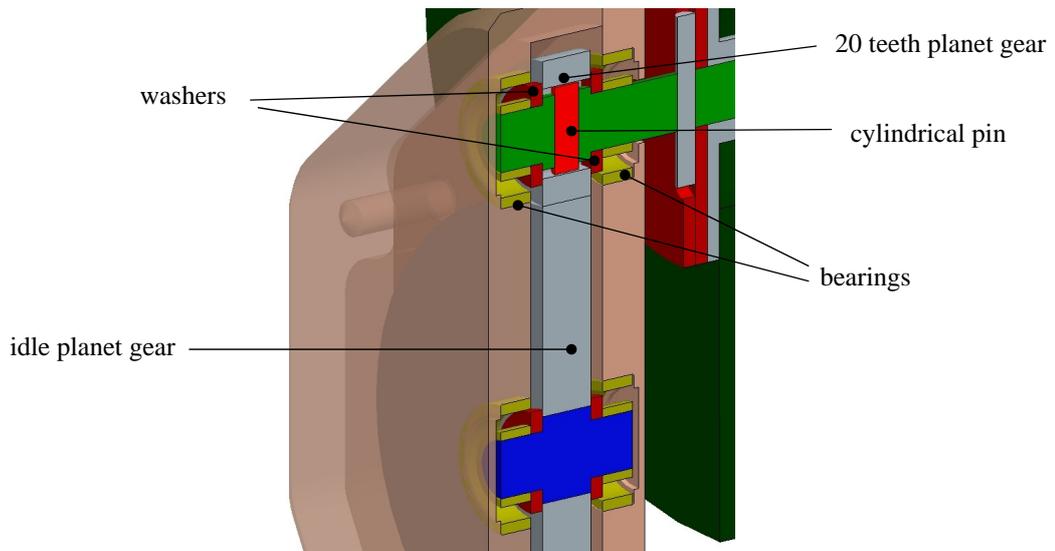


Figure 9: Torsional fixing of the planet gears.

The mounting of the traction wheels is accomplished in the following way: first, two plain washers mate the two sides of the wheel hub; a special washer with a slot is put in contact with the inner plain washer; finally all is locked by M2 screws (see Figure 10). The slot of the inside washer engages with a pin set in the shaft to transmit torque. The wheel is axially tightened by a M3 nut to the threaded end of the shaft.

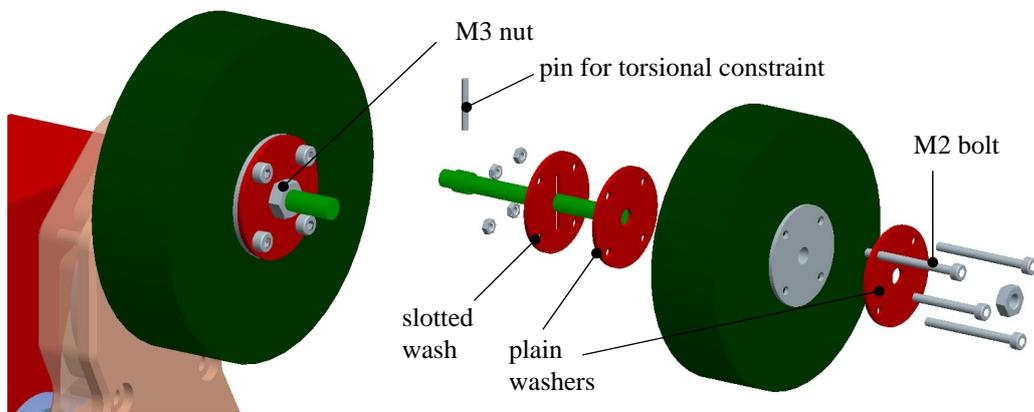


Figure 10: Torsional fixing of the wheels.

The left and right locomotion units are arranged to avoid the interference of the two motoreducers as shown in Figure 11. In this layout the motors are installed at the maximum height from the terrain to minimize the risk of collision against obstacles.

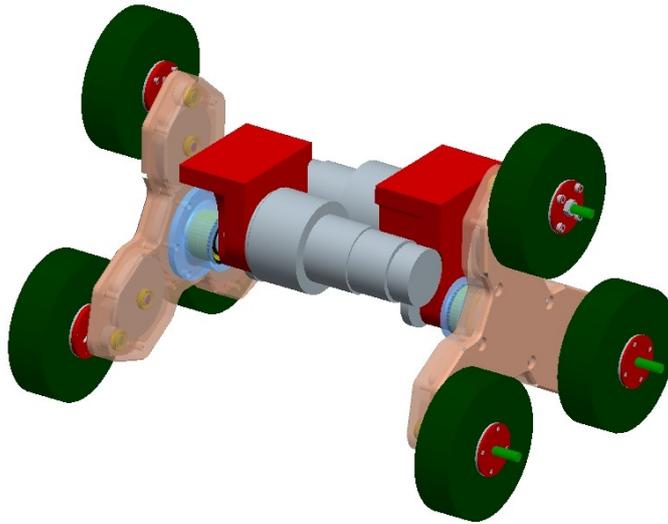


Figure 11: Mutual positioning of the two front locomotion units.

6 CONCLUSIONS

The functional and constructive designs of the Epi.q-2 mobile robot have been outlined. On the basis of the detailed design, the prototypes of the locomotion units have been built and are ready for the first experimental tests.

The first objective of the experimental campaign will be the performance comparison between the Epi.q-1 and Epi.q-2 locomotion units, using a mobile robot overall layout similar to the one of the Epi.q-1 (two motorized front locomotion units with differential steering and two passive rear ones).

Once defined the better solution for the locomotion modules, the future steps of the research will investigate the effectiveness of alternative mobile robot layouts, for example: four active modules instead of two active and two passive ones; robot frames with additional active degrees of freedom to enhance the obstacle overcoming capability.

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