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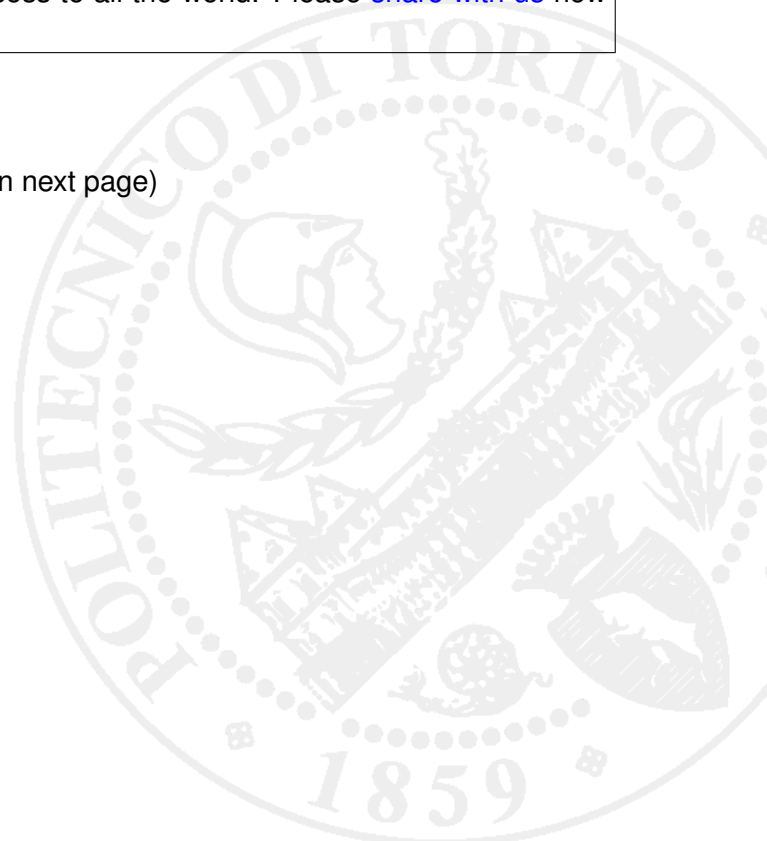
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Experimental assessment and evolution perspectives of the Epi.q mobile robot architecture

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In the last years the research interest about mobile robots and unmanned vehicles for unstructured environments has remarkably grown; the range of tasks that can be performed avoiding the direct human intervention has outstandingly widened, thanks to the technological progress in remote control system, sensing devices, electrical actuators and batteries.

For example, mobile robots moving on ground can be used in the security field for unmanned surveillance of critical assets, for inspection or intervention in case of radioactive or chemical contamination, for planetary exploration.

On the basis of the locomotion systems, it is possible to distinguish three main categories of ground mobile robots: wheeled, legged and tracked robots. In general, wheeled robots are faster and with higher energetic efficiency, while legged and tracked robots have better capability of moving on uneven terrains and overcoming obstacles. Hybrid mobile robots try to combine the advantages of different robot classes, avoiding their disadvantages.

The Epi.q mobile robot family is based on a hybrid wheeled-legged locomotion system. The three-wheeled locomotion unit is equipped with an epicyclical mechanism, which switches between wheeled locomotion and legged locomotion depending on terrain characteristics and presence of obstacles, without active control intervention; moreover, only one motor actuates each locomotion unit. For all of these reasons, the motion control of the whole robot is relatively simple, and this reduces the overall cost.

At present two different Epi.q prototypes have been realized, which have significant differences as regards the constructive features of the locomotion units, but close similarity as regards the frame architecture: two front locomotion units with differential steering, and a rear axle with two idle locomotion units [1,2]. The experimental tests on the two prototypes have shown the good overall motion performance and obstacle climbing ability of the Epi.q architecture [3]; however, these characteristics can be further improved by replacing the passive rear locomotion units with active ones. To this aim, a four-unit drive version of the Epi.q robot has been designed and is currently under construction; the two front locomotion units are independently actuated for differential steering, while the two rear ones are actuated by a differential gear.

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SUMMARY. Epi.q robots are a family of hybrid wheeled-legged mobile robots. Their three-wheeled locomotion unit is based on an epicyclical mechanism, which switches between wheeled locomotion and legged locomotion depending on terrain characteristics and presence of obstacles, without active control intervention. At present two Epi.q prototypes have been realized, very similar as regards the frame architecture: two front locomotion units with differential steering, and a rear axle with two idle locomotion units. The experimental tests on the two prototypes have shown good performance in terms of overall motion and obstacle climbing ability; however, these characteristics can be further improved by replacing the passive rear locomotion units with active ones. To this aim, a four-unit drive version of the Epi.q robot has been designed and is currently under construction.

1 INTRODUCTION

In the last years the research interest about mobile robots and unmanned vehicles for unstructured environments has remarkably grown; the range of tasks that can be performed avoiding the direct human intervention has outstandingly expanded, thanks to the technological progress in remote control system, sensing devices, electrical actuators and batteries.

For example, mobile robots moving on ground can be used in the security field for unmanned surveillance of critical assets, for inspection or intervention in case of radioactive or chemical contamination, for planetary exploration. In general, the use of mobile cameras and other sensors on mobile robots is an effective option whenever it is useful to monitor a specific zone on-demand.

On the basis of the locomotion systems, it is possible to distinguish three main categories of ground mobile robots: *wheeled*, *legged* and *tracked robots*; in the scientific literature there are also examples of mobile robots with different locomotion systems, often biologically inspired (e.g. jumping, slithering robots), but they are designed for specific environments and operative requirements. Focusing on the three main categories, wheeled robots are faster and with higher energetic efficiency [1], while legged and tracked robots have better capability of moving on uneven terrains and overcoming obstacles [2-5].

Hybrid mobile robots try to combine the advantages of different robot classes, avoiding their disadvantages; in particular, Spacecat is a hybrid legged-wheeled mobile robot developed by EPFL for space exploration [6]. It is characterized by two stepping triple wheels locomotion units, with two independently driven sets of three wheels, supported by two frames; the frames can rotate independently and allow the rover to climb obstacles; eight independent actuators are necessary to control the motion (two for the frames and six for the wheels).

The Epi.q mobile robot family [7, 8] is based on a hybrid wheeled-legged locomotion system. The three-wheeled locomotion unit is equipped with an epicyclic mechanism, which switches between wheeled locomotion and legged locomotion according to terrain characteristics and presence of obstacles, without active control intervention. Thanks to the epicyclic transmission, only one motor actuates each locomotion unit; this is the main difference with respect to Spacecat, and it remarkably reduces the control complexity, and consequently the overall cost.

At present two different Epi.q prototypes have been realized (Epi.q-1 and Epi.q-TG), which have significant differences as regards the constructive features of the locomotion units, but close similarity as regards the frame architecture and locomotion unit functions. Both robots have two front locomotion units with differential steering, and a rear axle with two idle locomotion units. The tests on the two prototypes have shown good performance in terms of overall motion and obstacle climbing ability [9]; however, these characteristics can be further improved by replacing the passive rear locomotion units with active ones. To this aim, a four-unit drive version of the Epi.q robot has been designed and is currently under construction: the two front locomotion units are independently actuated (differential steering), while the two rear ones are actuated by means of a differential gear.

In the following of the paper the main features of Epi.q mobile robots are discussed, with reference to Epi.q-TG; moreover the experimental campaign is described and the mechanical architecture of the four-unit drive version is outlined.

2 EPI.Q-TG LOCOMOTION UNIT FUNCTIONING PRINCIPLE

The most peculiar aspect of Epi.q mobile robots is the three-wheeled locomotion unit with epicyclic transmission. Figure 1 shows the scheme of the epicyclic gearing; the main parts are: the planet carrier A (leg length l_L), the solar gear B (radius r_S), three first planet gears C (radius r_{PG1}), three second planet gears D (radius r_{PG2}) and three wheels E (radius r_W); the planet carrier is connected to the robot chassis F by means of a revolute joint with axis parallel to the axes of gears and wheels.

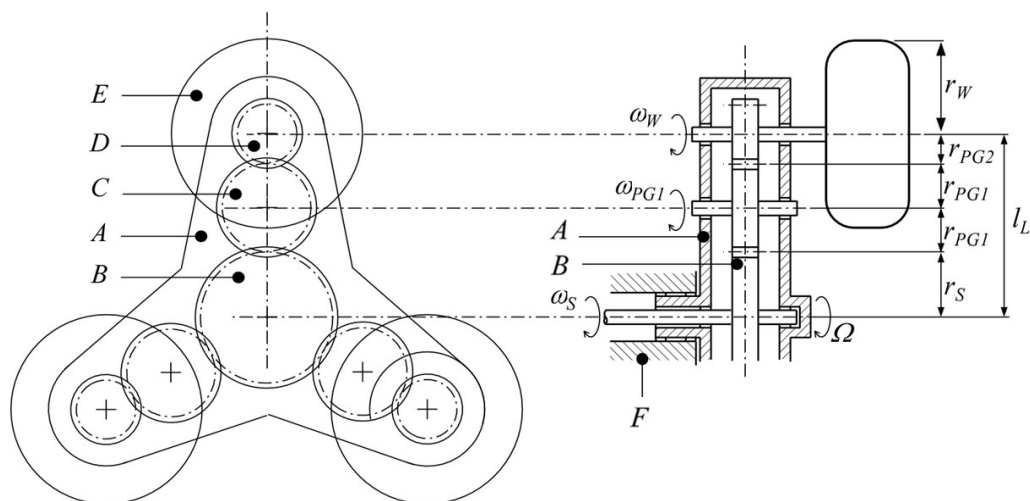


Figure 1: Epi.q locomotion unit functional scheme.

The tripod geometry of the Epi.q locomotion unit allows to switch between wheeled locomotion (*advancing mode*, see Figure 2, left) and legged locomotion (*automatic climbing mode*, see Figure 2, right). In normal conditions the robot moves in advancing mode, and this grants high speed and range. When a contact between front wheel and an obstacle occurs, the front wheel stops and the planet carrier starts to rotate around the front wheel, allowing the robot to overcome the step (even with height h_O bigger than the wheel diameter) in automatic climbing mode.

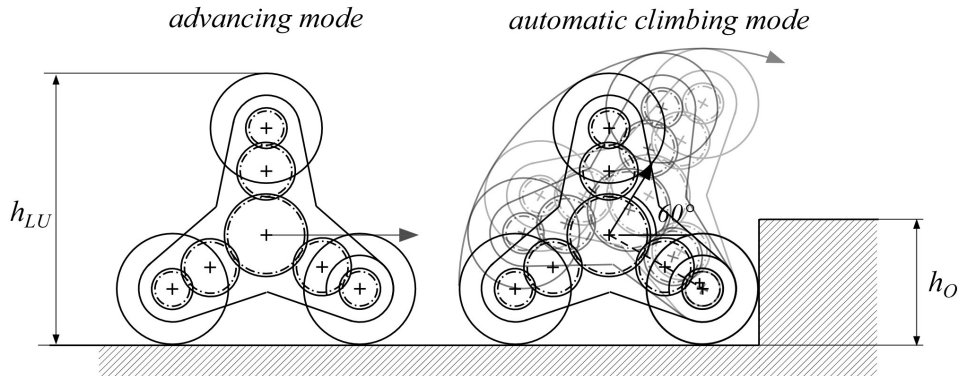


Figure 2: Advancing mode and automatic climbing mode.

In both locomotion modes, the locomotion unit is actuated by a single actuator connected to the solar gear B; the transition between the two modes is mechanical, without control intervention, depending on the dynamic conditions. The transition between advancing mode and automatic climbing mode occurs not only in presence of obstacles, but also when the robot is moving on a slope that exceeds a limit value or when the robot is accelerating over a limit value, as discussed in [10]. The limit slope/acceleration that triggers the locomotion mode transition can be tuned in the functional design phase by varying the geometrical ratios between $l_L, r_S, r_{PG1}, r_{PG2}, r_W$.

3 FRAME ARCHITECTURE OF THE EPI.Q-TG PROTOTYPE

The whole mobile robot is composed of three main parts: the *forecarriage F*, the *central body CB* and the *rear axle RA* (see Figure 3). The forecarriage is equipped with two locomotion units, independently actuated for differential steering. The forecarriage and the central body are connected by a vertical revolute joint with angular excursion of $\pm 40^\circ$ (*vertical joint VJ*, see Figure 3). A second revolute joint (*horizontal joint HJ*, see Figure 3) guarantees a correct contact between wheels and ground, also in case of not flat terrain. The rear axle is characterized by two idle locomotion units, with the same geometry of the front ones but without actuation. The upper part of the forecarriage frame contains the motor drives and the control devices, while cameras, sensors and batteries are placed on the upper and lower flat surfaces of the central body.

Figure 3 shows also the mechanical scheme of the forecarriage: two gearmotors (M_1 and M_2) are offset located to minimize the forecarriage width; therefore the front locomotion units are actuated with the interposition of two straight gears (G_1 and G_2). The gearmotors are characterized by a peak torque of 0.5 Nm and a maximum angular speed of 81 rpm, which corresponds to a maximum robot speed of 0.96 m/s. The main geometrical and mass characteristics of Epi.q-TG are: length 450 mm, width 280 mm, height 200 mm, mass 4 kg (including 2600 mAh Li-Po battery and a wireless camera).

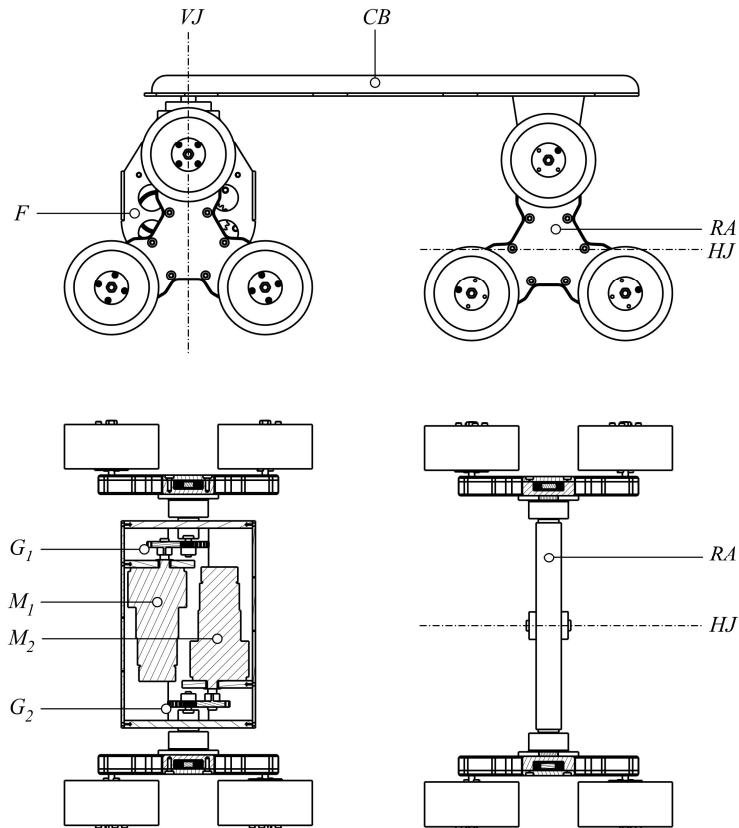


Figure 3: Epi.q-TG mechanical architecture.

4 MOTION PERFORMANCE OF THE EPI.Q-TG PROTOTYPE

The Epi.q-TG prototype has been tested in a great variety of uneven terrain conditions. The tests have shown that the tripod geometry of the locomotion unit provides good motion capability even in case of soft and yielding terrains. In this conditions, for example in case of grassy (see Figure 4) or rocky (see Figure 5) terrains, the random unevenness of the ground causes a continuous transition between legged and wheeled locomotion, which is not simultaneous for the four locomotion units; however this mixed chaotic locomotion allows to effectively overcome the unevenness.

On the contrary, when the robot climbs a square step (see Figure 2, right) with approach direction perpendicular to the step the locomotion transition is simultaneous for the two front locomotion units and for the rear ones; in this case the maximum height of the step that can be overcome is $h_0 = 0.84 h_{LU}$ (where h_{LU} is the locomotion unit height, see Figure 2) in favorable friction conditions (friction coefficient f_s between wheels and ground higher than 1.1) [9].

As regards locomotion on inclined surfaces, the maximum slope is limited by the friction coefficient f_s , because in case of low grip the traction wheels start sliding; the Epi.q-TG prototype has been tested on slopes up to 33%, with friction coefficient $f_s \geq 0.83$. The capability of overcoming slopes is limited by the fact that traction is provided only by the front locomotion units, but the forecarriage is poorly loaded going uphill.

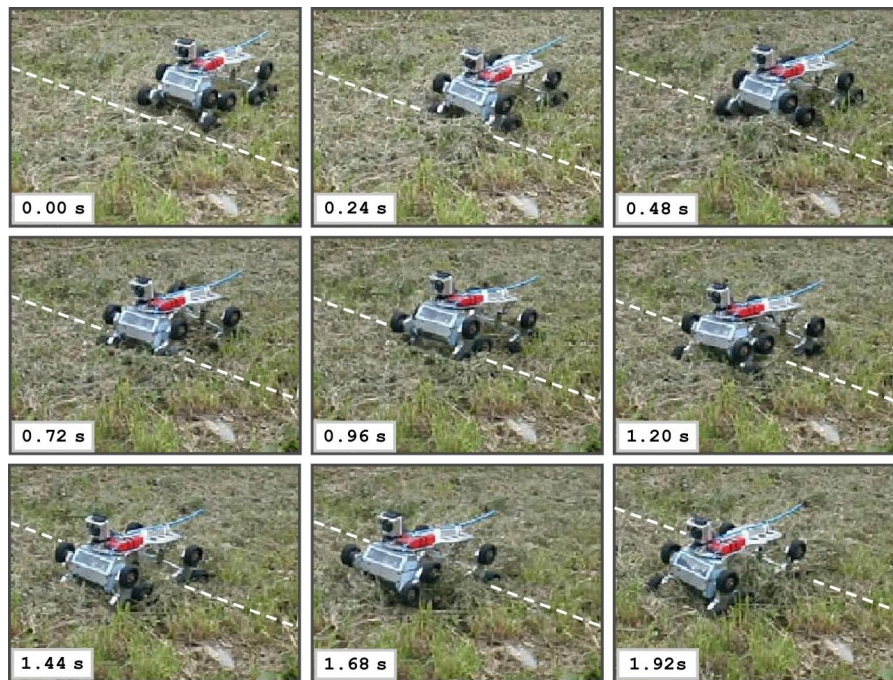


Figure 4: Locomotion on grassy terrain.

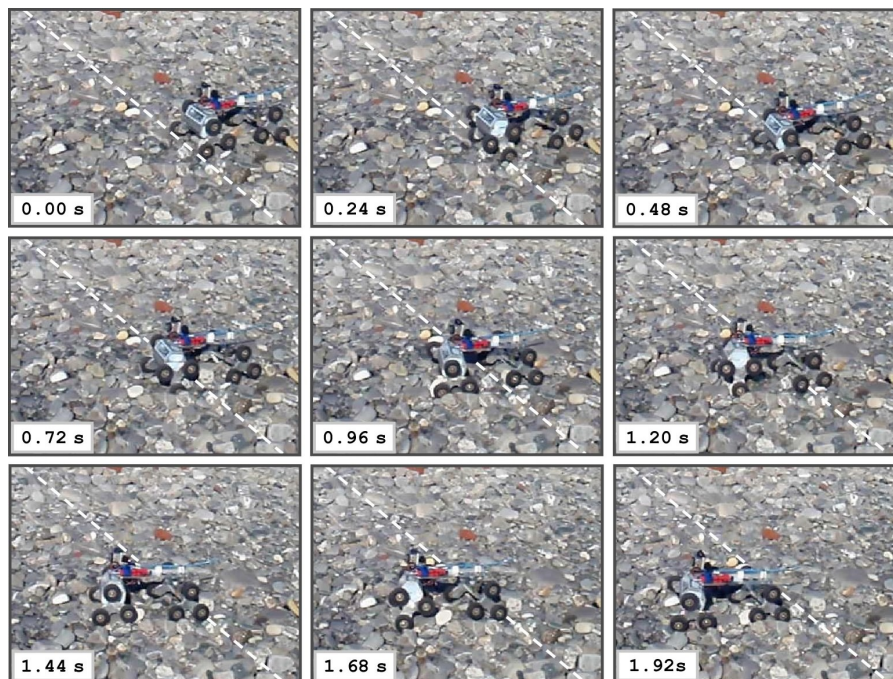


Figure 5: Locomotion on rocky terrain.

This is the main reason for the development of an all-wheel drive version. Moreover, the introduction of traction on the two rear locomotion units can also increase the motion capability on uneven and low-friction terrains and the climbing capability in case of square steps, because the robot is not only lifted by the front units but also pushed from the back ones.

5 FOUR-UNIT DRIVE EPI.Q ARCHITECTURE

The Epi.q mobile robots with four locomotion units have twelve wheels; however, since each locomotion unit is actuated by a single shaft, the possible alternatives to realize total traction can be derived from four-wheel-drive automobile schemes. There are many schemes of automotive total traction, from the classical one, permanent with three differential gears, to more sophisticated ones, for example to improve performance on low-friction terrains or to select the 2WD or 4WD modes.

Nevertheless, all of these schemes are too complex from the mechanical point of view with respect to the constructive requirements of small mobile robots and to the simplicity-inspired design approach of the Epi.q family. In order to maintain the forecarriage architecture of the Epi.q-TG prototype, with differential steering, the simplest solution is the scheme of Figure 6: the connections between the three main parts of the robot body are realized by the same vertical and horizontal joints (*VJ* and *HJ*), but the idle rear axle is replaced with an independently actuated one.

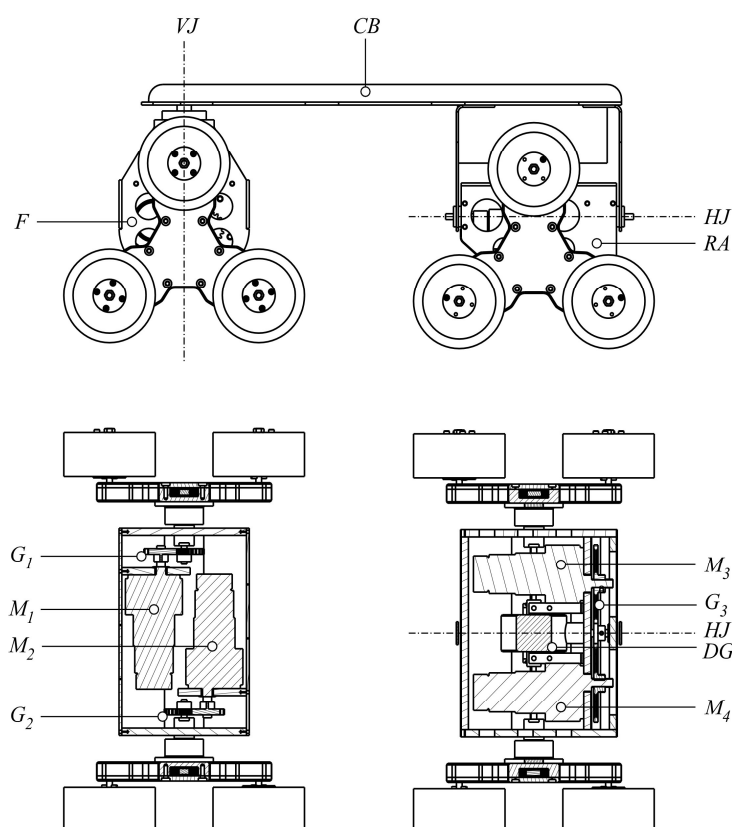


Figure 6: Epi.q-AWD mechanical architecture.

The two rear locomotion units are actuated by two gearmotors M_3 and M_4 , which are equal to M_1 and M_2 , but are connected in parallel by three toothed wheels (double straight gear G_3) to the input shaft of the differential gear DG (see Figures 6 and 7). The differential gear DG distributes an equal amount of torque to the two rear locomotion units, and allows a correct kinematic steering while curving.

Since forecarriage and rear axle are independently actuated, there is no mechanical connection between the front and the rear locomotion units, so it is necessary to coordinate them by means of the control system. To this aim, the gear ratios are selected in order that the overall transmission ratio of G_3 and DG is equal to the one of the gears G_1 and G_2 ; the two front motors M_1 and M_2 have two independent input voltages for differential steering, while the two rear motors M_3 and M_4 have the same input voltage, equal to the mean value of the front ones. Therefore, if the input voltage of the four motors is equal, the robot follows a straight trajectory, while steering is enabled by different input voltages of the front motors. The assessment of the effectiveness of this all-wheel drive solution is the main objective of the experimental campaign on the Epi.q-AWD prototype, currently under construction.

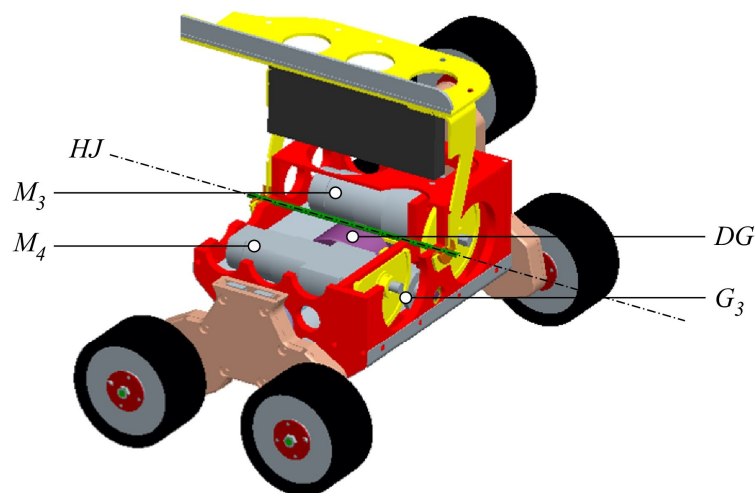


Figure 7: Epi.q-AWD actuated rear axle.

6 CONCLUSIONS

The Epi.q family is a series of mobile robots characterized by the peculiar mechanical scheme of the three-wheeled locomotion units, which are based on a epicyclical transmission. This epicyclical mechanism is underactuated: there is only one motor per locomotion unit, but the locomotion unit itself has two degrees of freedom: the rotation of the planet carrier and the simultaneous rotation of the three wheels. In case of rotation of the three wheels the locomotion is wheeled (*advancing mode*), with high speed and energetic efficiency; in case of rotation of the planet carrier, the locomotion is legged (*automatic climbing mode*), and this allows to overcome obstacles and terrain unevenness. The switch between the two locomotion modes is mechanical, without active control intervention; using this approach, it is possible to realize an hybrid wheeled-legged robot, which merges the benefits of both the categories, with a relatively low cost.

Moreover, there are remarkable advantages in terms of reliability and simplicity of the trajectory control scheme.

Up to now, two Epi.q prototypes have been realized, with different constructive features, but characterized by the same overall frame architecture: a forecarriage with two actuated locomotion units, a central body that carries payload and batteries, and a rear axle with two idle locomotion units; these three parts are connected by two revolute joints to allow differential steering and adaptation to terrain unevenness.

The experimental tests on these prototypes have shown the effectiveness of the proposed three-wheeled locomotion unit in terms of step climbing ability and motion on uneven and smooth terrains; nevertheless, the main drawback of Epi.q robots with respect, for example, to tracked robots, is the limited climbing ability in case of high slopes and/or low friction terrains. To overcome these limitations, a four-unit drive version of the robot (Epi.q-AWD) has been designed and is currently under construction. The total traction has been realized without increasing too much the overall complexity of the mechanical design: the two locomotion units of the rear axle are actuated with the interposition of a differential gear, but there is no mechanical connection between the front locomotion units and the rear ones.

The application of the total traction is indeed the natural final evolution of the Epi.q family, while the previous versions can be considered intermediate steps, primarily focused on the refinement of the locomotion unit mechanical design. If the experimental tests confirm the expected motion performance of the Epi.q-AWD, this prototype will be an interesting pre-industrial demonstrator of a general-purpose small mobile robot for structured and unstructured environments, with a widespread range of potential application fields, not only in the security area.

After the experimental phase on the Epi.q-AWD, most of future research efforts will be devoted to the integration of an intelligent navigation system for autonomous operation (till now, Epi.q robots are radio-controlled by a human operator).

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