Additive Manufacturing-Oriented Redesign of Mantis 3.0 Hybrid Robot

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Abstract. The paper presents the third version of the hybrid leg-wheel ground mobile robot Mantis, a small-scale platform designed for inspection and surveillance tasks. The locomotion system is based on the cooperating action of a couple of actuated front legs and wheels, along with a passive rear carriage. The system performs wheeled locomotion on even grounds and hybrid locomotion in case of terrain irregularities or obstacles. This architecture combines high speed, energy efficiency, maneuverability and stable camera vision on flat terrains with good motion capabilities in unstructured environments. In the embodiment design presented hereafter, referred to as *Mantis 3.0*, the rear carriage has been equipped with four passive wheels, instead of two as in the previous versions, in order to improve the stability during steep stair climbing maneuvers; moreover, the legs, the main body and the rear carriage have been significantly redesigned in order to be realized by additive manufacturing techniques, with the final aim of obtaining a low-cost device suitable for Open Source distribution.

Keywords: Hybrid leg-wheel locomotion · Ground mobile robot Step climbing · Additive manufacturing · Low-cost robotics

1 Introduction

In the last years, the importance of service robotics has been continuously growing. In particular, the applications of terrestrial [1, 2], aerial [3, 4] and underwater [5, 6] mobile robots in unstructured environments are becoming more and more widespread.

Mobile robots can be used to replace the direct human intervention in dangerous situations, for example in presence of chemical or radioactive contamination, reducing risks and operational costs; moreover, small-scale robots can inspect narrow spaces, otherwise not reachable. In this scenario, the development of locomotion systems for inspection, surveillance, and homeland security is today a fundamental research area. As a matter of fact, ground mobile robots are primarily characterized by their locomotion mechanism, while the on-board equipment is selected on the basis of the specific task. Most robotic locomotion systems can be divided into seven classes: wheeled (W), legged (L) and tracked (T), along with the four possible hybrid

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combinations (LW, LT, WT, LWT). Other different locomotion systems are present in the scientific literature (adhesive robots, slithering robots, snake-like robots), but they are conceived for specific tasks, not for general-purpose operations.

The general features of these seven classes are discussed in [7–9]. Summarizing:

- the classes comprising wheels (W, LW, WT, LWT) can provide high speed on regular and compact surfaces and high energy efficiency;
- the classes comprising legs (L, LW, LT, LWT) have high obstacle crossing capability;
- the classes comprising tracks (T, WT, LT, LWT) are efficient on soft and yielding terrains.

Focusing on small-scale robots for surveillance/inspection, some specific requirements must be considered, such as maneuverability in narrow spaces and stable camera vision.

Moreover, if the robot is small and lightweight, the inertial forces acting during locomotion are less critical than for large and heavy robots; therefore, if legged locomotion is adopted, simplified hybrid locomotion mechanisms can be used, leveraging on the advantages of legs while avoiding the high mechanical and control complexity of large legged robots (such as bipeds and quadrupeds). Some examples of this approach are stepping-triple-wheel robots [10–12], rotating legged robots [13–15], robots with legs with outer circular profile, which can act as wheels [16–18].

Also the robots of the Mantis family belong to this category. The Mantis architecture [19] is based on a main body equipped with two actuated front wheels (Fig. 1, *fw*), two actuated front legs with praying mantis shape (*fl*) and a passive rear carriage (rc). In Mantis 1.0 and 2.0, the rear carriage is equipped with two idle wheels. The shape of the legs is specifically designed to climb obstacles, and in particular square steps and stairs [20]. In the second version of the robot, the legs have been equipped with auxiliary wheels (*aw*) to improve the efficacy of the step-climbing maneuver [21, 22]. Mantis robots are designed to carry a maximum payload of 1 kg (cameras and

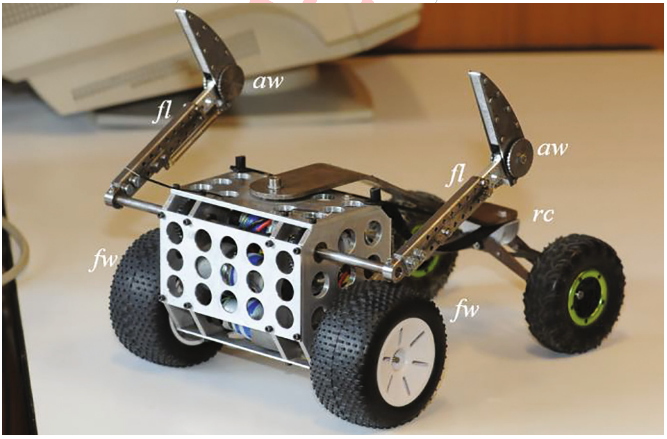

Fig. 1. The Mantis 2.0 prototype.

sensors for surveillance tasks), with overall dimensions of about 350 × 300 × 200 mm.

Mantis locomotion is purely wheeled on even terrains, with 0.7 m/s maximum speed, high energy efficiency and maneuverability (it can pivot around a vertical axis). The legs, independently actuated, can be used whenever necessary, to obtain a hybrid leg-wheel locomotion in case of obstacles or ground irregularities, or to lift up the robot after a capsize. Mantis, by now, is remote-controlled by a human operator.

This paper presents Mantis 3.0, characterized by a four-wheeled rear carriage and specifically redesigned for additive manufacturing. The paper is organized as follows: Sect. 2 discusses the functional issues which have led to the 3.0 redesign, in particular of the rear carriage and of the legs; Sect. 3 describes the constructive solutions for main body, legs and rear-carriage; Sect. 4 is the conclusion section.

2 Functional Redesign of the Mantis 3.0

The stability analysis of Mantis during stair climbing and descent, which is one of its key features, is reported in details in [22]; here, the main phases of step climbing are recalled in Fig. 2, with reference to a 320 × 170 mm step. This size has been selected because it is typical for private and public buildings. Even if the IBC – International Building Code for stair treads and risers – imposes a minimum going of 279 mm and a maximum rise of 178 mm, these limit values are quite unusual, therefore a robot design based on a 320 × 170 mm stair represents a compromise between robot overall size and capability of climbing almost all stairs.

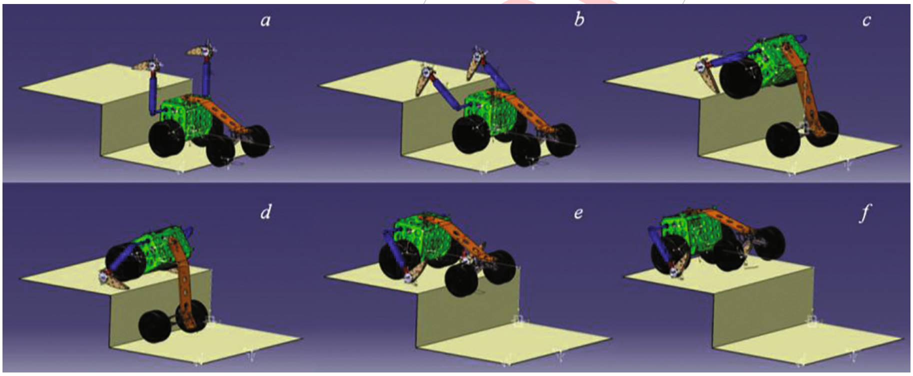

Fig. 2. Maximum pitch angle with 4-wheeled rear carriage.

The robot approaches the step (Fig. 2*a*), then the legs start to rotate lifting up the robot body (Fig. 2*b*–*c*–*d*); when the center of gravity of the robot is over the leg to ground contact line, the legs stop, and the robot rotates until the front wheels touch the step surface (Fig. 2*e*); then the legs rotate backward to lift up the rear carriage, and when it is sufficiently high, the front wheels can move forward the robot (Fig. 2*f*). In this last phase, the contact between legs and ground occurs through the auxiliary wheels placed on the leg extremities; these wheels are connected to the legs by one-way bearings, to reduce friction in the last phase of step-climbing without reducing traction during hybrid leg-wheel locomotion on irregular grounds.

Then, the step descent is performed going forward; to reduce the shock due to the initial collision of the leg tips with the lower step surface, the tips of the legs (Fig. 3, *lt*) can rotate with elastic return force with respect to the legs (*fl*), realizing a shock absorber.

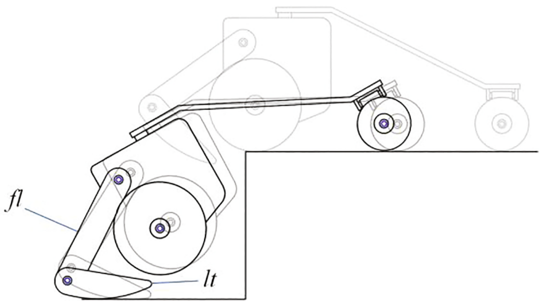

Fig. 3. During the step descent the rotating leg tips realize shock absorption.

The previously discussed step ascent/descent strategies work properly, but there are some weak points:

- during the step climbing, in the maximum pitch phase (Fig. 2*d*), the margin of static stability is low, and the maneuver becomes unstable if the payload increases the vertical position of the robot center of mass [22]; stability in this phase can be increased by adopting a longer wheelbase, but wheelbase length is limited by the length of the step on which the robot must stand horizontally; moreover, a longer wheelbase reduces the robot maneuverability;
- the front step descent works well on a single step, but stability is critical during stair descent, where capsize may occur in case of piloting errors.

For these reasons, a four-wheeled rear carriage has been conceived, with the main geometrical parameters shown in Fig. 4, shortening the robot wheelbase but adding two idle wheels placed backwards. The advantages of this configuration are shown in the climbing sequence a_1–a_3 of Fig. 5: in the maximum pitch position (a_2) the rear carriage-ground contact is with the two additional wheels, and the robot behaves like having a longer wheelbase. On the other hand, when the robot is horizontal on the step (a_1) the wheelbase is shorter, and this allows to climb steeper stairs, with shorter steps.

The four-wheeled rear carriage can be used also to exploit a different strategy for step descent, going backwards (Fig. 5, sequence d_1–d_3). The shock absorption of the first impact (d_2) is demanded to the compliance of the auxiliary rear wheels; however, this impact is not critical since the main body, hosting motors, mechanics and payload, does not move significantly; the position of the auxiliary wheels, higher than the other wheels (Fig. 4), improves stability in this phase. In the following of the descent the main body falls down and the impact is with the leg tips (d_3); therefore, a different design of the tips is necessary, as discussed in Sect. 3. Mantis 3.0 is designed for ascent and descent of stairs with maximum rise of 170 mm and minimum going of 320 mm.

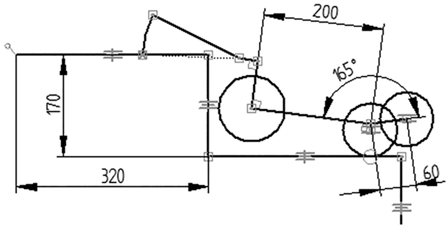

Fig. 4. Main geometrical parameters of the six-wheeled rear carriage.

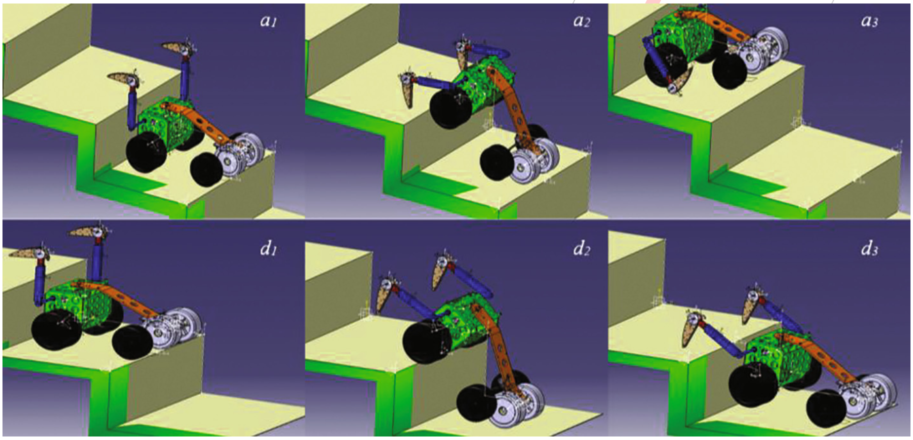

Fig. 5. Sequences of step ascent (a_1–a_3) and descent (d_1–d_3).

3 Embodiment Design of Mantis 3.0

Figure 6 shows an overall view of the Mantis 3.0 3D model. All the frame parts have been redesigned in order to be realized in ABS by additive manufacturing.

Figures 7 and 8 compare the exploded views of the Mantis 2.0 main body, composed of aluminum alloy plates, and of the Mantis 3.0 main body, realized with 5 horizontal layers (*a–e*) which host gearmotors and mechanics, two front and rear carters (*f, g*) locked by eight vertical bolts (*h*). On the back of the main body, a carter (*i*) hosts the battery for fast recharge or replacement.

Figure 9 compares the 2.0 and the 3.0 versions of the legs. It is possible to note that the 2.0 leg is composed by two main parts (*a, b*) connected by a revolute joint with axis *rj*, while the 3.0 leg is composed of two main parts (*c, d*) connected by a prismatic joint with axis *pj*, in order to perform properly the shock absorption in the impact of Fig. 5, d_3; the compliant element (*e*) which acts as spring/damper in the relative motion of the two parts is realized by molded silicone, with a mold obtained by 3D print. The number of components and the cost of the new leg are much lower.

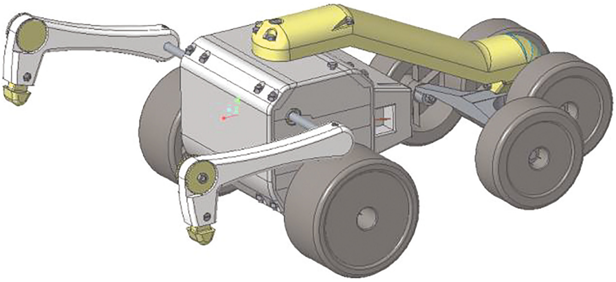

Fig. 6. Mantis 3.0 3D model – overall view.

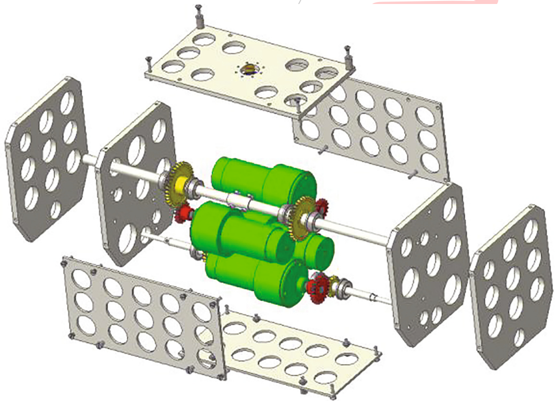

Fig. 7. Mantis 2.0 main body.

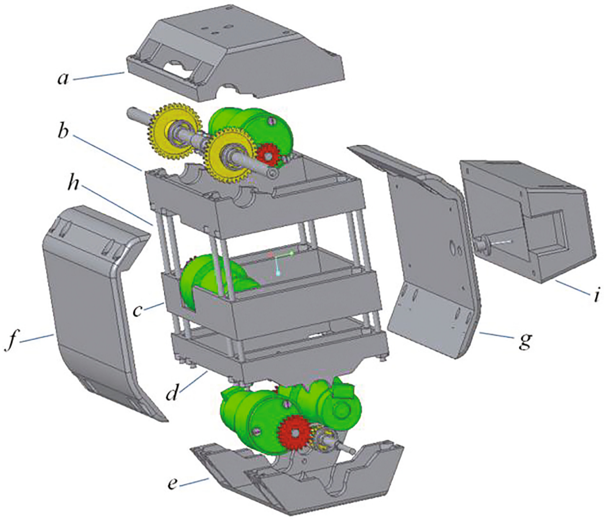

Fig. 8. Mantis 3.0 main body.

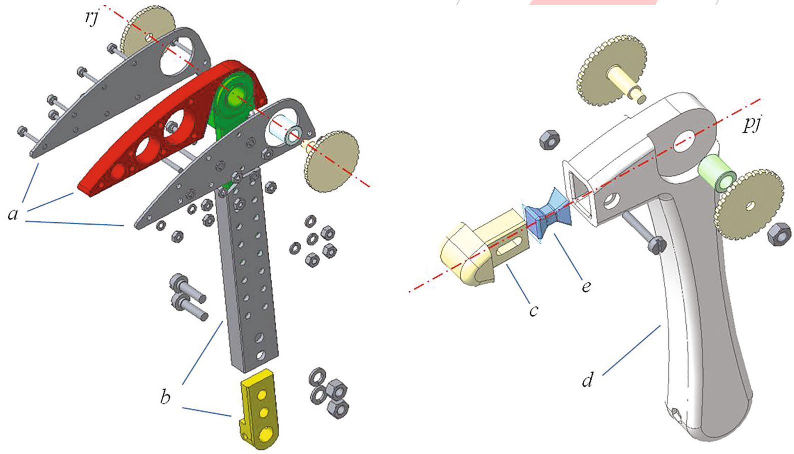

Fig. 9. Mantis legs: 2.0 (left) vs 3.0 (right).

4 Conclusions

The paper discusses the functional and embodiment redesign of the third version of the Mantis ground mobile robot (now six-wheeled), oriented to improve the performance in stair climbing and descent, on the basis of the results and indications of the experimental campaign on Mantis 1.0 and 2.0. In particular, the rear carriage and the legs have been functionally modified to perform different stair descent.

Moreover, all the robot parts have been redesigned in order to be produced by plastic additive manufacturing, remarkably reducing the cost. The final goal is to realize an Open Source robotic project, in which researchers can give their contribution to the development of knowledge regarding hybrid locomotion robotic systems.

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