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Functional Design of a Hybrid Leg-Wheel-Track Ground Mobile Robot

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Abstract: This paper presents the conceptual and functional design of a novel hybrid leg-wheel-track ground mobile robot for surveillance and inspection, named WheTLHLoc (Wheel-Track-Leg Hybrid Locomotion). The aim of the work is the development of a general-purpose platform capable of combining tracked locomotion on irregular and yielding terrains, wheeled locomotion with high energy efficiency on flat and compact grounds, and stair climbing/descent ability. The architecture of the hybrid locomotion system is firstly outlined, then the validation of its stair climbing maneuver capabilities by means of multibody simulation is presented. The embodiment design and the internal mechanical layout are then discussed.

Keywords: ground mobile robot; hybrid locomotion; step climbing

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1. Introduction

In the last decade, the world market of service robotics has increased remarkably, overcoming the market of industrial robotics [1]. In particular, ground mobile robots are the most widespread category of service robots, with important application fields such as precision agriculture [2], planetary exploration [3], homeland security [4], surveillance [5], reconnaissance, and intervention in case of terroristic attacks and in the presence of radioactive or chemical contamination [6].

Independently of the robot payload, which depends on the specific application, a great research effort has been spent to develop innovative locomotion systems for ground mobile robots [7–9]. While locomotion on flat and even terrain can be simply and effectively performed by wheels (W) with high speed and energy efficiency [10], in case of unstructured environments, the use of tracks (T) and legs (L) is also a valuable option.

Tracked robots can move on uneven and yielding terrains, since their contact surface with the ground is much larger than the one of wheeled robots [11–13]. On the other hand, they usually move slower and with lower energy efficiency. In addition, they are more subject to vibrations with respect to wheeled robots.

Legged locomotion, which is, differently from wheeled and tracked locomotion, biologically inspired, is the most effective solution in case of irregular terrains and obstacles, but it is generally slower and less energetically efficient on flat grounds; the main hindrance to the diffusion of legged robots is their cost and complexity, especially for the ones with dynamic gait [14,15]; the higher complexity of the dynamic gait is related not only to control, but also to the mechanical architecture, characterized by a high number of actuators. To overcome this issue, at least for small mobile robots, with limited structural stresses due to the inertial effects, the complexity of the leg architecture can be simplified: Examples are robots with rotating and compliant legs [16,17], or hybrid leg–wheel robots with stepping triple wheels [18,19].

Hybrid locomotion systems combine the benefits of different locomotion systems. One of the most advanced and impressive hybrid locomotion robots is the legged-wheeled

Handle by Boston Dynamics [20], which is a biped with two wheels at the end of the legs; a similar concept has been adopted in the design of the Centauro quadruped, by IIT [21]. At a smaller scale, there are many examples of hybrid robots which combine legs, wheels, and tracks in a simplified manner, with lower cost and consequently a wider range of potential applications: the four possible combinations of L, W and T (LW, LT, WT, LWT) are compared in [8] in terms of maximum speed, obstacle crossing capability, step/stair climbing capability, walking capability of soft terrains and on uneven terrains, energy efficiency, mechanical, and control complexity.

Considering locomotion solutions involving tracks (T, WT, LT, LWT), there are many possible layouts. Robots can have non-articulated or articulated tracks with passive relative mobility [22]; if the relative mobility of the articulated tracks is actuated to improve obstacle crossing capability, they can be considered as LT hybrid robots. Another option is to link tracked modules in series to compose snake-like climbing robots [23].

Focusing on LT hybrid robots, there are different ways to combine legs and tracks. Besides the most obvious approach of using them in parallel [24–26], peripheral tracks can be placed on the leg links [27]; this approach is also used for the Kylin robot, with LWT hybrid locomotion [28].

When wheels are present and it is required to use them to increase speed and range on even and compact grounds, they can be activated using many different systems. For example, the contact of the wheels with the terrain can be enabled or disabled by the position of the legs, as in the LWT Kylin robot.

Another possibility is to extract the wheels from the robot body to suspend the robot on wheels. This solution has the benefit of enhancing the vehicle maneuverability, which is a drawback of purely tracked robots; an example is the hybrid WT robot presented in [29].

In a previous study [30], a WT robot with two variable-shape tracks and four wheels is proposed; the contact between wheels and terrain can be enabled or disabled by varying the shape of the tracks.

The hybrid LWT Azimuth robot [31] is equipped with articulated legs with peripheral tracks and wheels; depending on the leg position, wheels, legs, or tracks can be active. The hybrid WT robot HELIOS-VI [32] has two tracks and two passive wheels placed at the end of a rotating arm, which regulates the contact of the wheels with the terrain to reduce the contact areas of the tracks, to improve maneuverability or to perform stair climbing and descent.

In other cases, the tracks can be transformed into wheels changing their outer shape by means of tensioning systems, exploiting the tracks elasticity [33,34]; the transformation of tracks into wheels can also be achieved by adopting complex articulated supports for the tracks [35].

This research is focused on the development of a hybrid LWT ground mobile robot for surveillance and inspection, named WheTLHLoc (Wheel-Track-Leg Hybrid Locomotion). Its locomotion system shows similarities with previously discussed robots, although the proposed solution is new and has unique features with respect to other solutions presented in scientific literature; similarities and differences will be highlighted in Section 2. The considered size is small (around 450 $\times$ 350 $\times$ 130 mm), since only cameras and environmental sensors are to be carried and good maneuverability in restricted spaces is considered a key feature of an inspection robot. Despite its limited dimensions, the combination of all the three locomotion systems allows to perform wheeled locomotion with high speed, energy efficiency, and range on flat and compact grounds, tracked locomotion on yielding and soft terrains, and mixed use of rotating legs, wheels, and tracks to overcome steps, stairs, and other obstacles.

The remaining of the paper is organized as follows: Section 2 discusses the conceptual design and the main functional features of the WheTLHLoc robot; Section 3 illustrates the maneuvers for stair climbing and descent, and the feasibility of the most critical one (climbing) is verified by multibody simulation in Section 4; Section 5 presents the embodiment design and the internal layout of the robot, and finally Section 6 outlines conclusions and future work.

2. Conceptual Design of the Hybrid Robot WheTLHLoc

The starting point of the conceptual design of the proposed hybrid locomotion robot is the goal of combining tracks for soft and yielding terrains and wheeled locomotion on flat and compact terrains. This combination can be obtained in different ways, as discussed in the previous section. The proposed locomotion system (Figure 1) is in some ways similar to the one of HELIOS-VI [32], but enhances its capabilities thanks to the following design choices:

- Instead of a single short rotating arm placed on the front of the vehicle, it makes use of two independently actuated rotating legs (Figure 1, *L)*;
- The wheels at the leg ends (Figure 1, *W*) are not passive, but independently actuated by gearmotors (Figure 1, *WM*);
- The common revolute axis of the two legs (Figure 1, *A*), is centered with respect to the robot body, and the legs can perform complete and continuous rotations around it;
- Two omni wheels (Figure 1, *OW*) are placed on the rear of the robot, so that the contact of the tracks (Figure 1, *T*) with the terrain is avoided when the robot is supported on the two wheels and on one of the omni wheels;
- The main robot body (Figure 1, *MB*) is externally symmetric with respect to the *xy* plane.

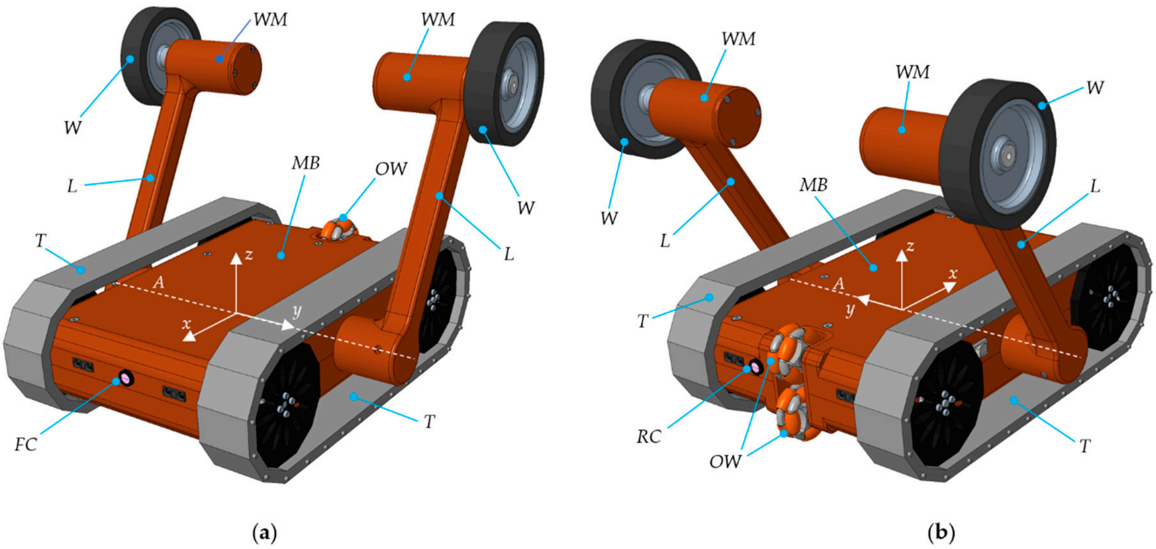


Figure 1. Conceptual design of the hybrid leg-wheel-track robot Wheel-Track-Leg Hybrid Locomotion (WheTLHLoc): (**a**) Front view; (**b**) rear view (*W*: Wheel; *L*: Leg; *T*: Track; *MB*: Main body; *WM*: Wheel gearmotor; *OW*: Omni wheel; *FC*: Front camera; *RC*: Rear camera; *A*: Leg axis).

The main camera is placed on the front of the robot (Figure 1, *FC*), but a secondary camera is placed on the rear (Figure 1, *RC*) since during step climbing (Section 3) and in other scenarios it is necessary to move backwards; additional environmental sensors can be placed inside the robot body, on the basis of the required tasks.

The main features of this design are the following:

i. It is possible to alternate wheeled locomotion on flat and compact terrains (Figure 2a) and tracked locomotion on soft and yielding terrains (Figure 2b), both with differential steering; the switch between the locomotion modes is commanded by the rotation of the legs;
ii. The legs, longer than the arm of HELIOS-VI, can be used to overcome obstacles, even performing differential steering, if required in case of asymmetrical obstacles;

iii. When the robot is in the wheeled locomotion (*WL*) position, the field of view of the front camera is optimally exploited (Figure 2a);
iv. Since the robot main body is symmetric with respect to the *xy* plane, it is fully operative even after an overturn; it is very unlikely that after a fall the robot remains on one flank, and even in this case a rotation of the leg in contact with the terrain can put again the robot on the tracks;
v. The rotation of the legs and the action of the wheels can be used in case of irregular terrains and obstacles, i.e., when the use of only tracks is not sufficient to advance; in this case, the two legs can be moved independently in presence of asymmetric ground irregularities (Figure 2c);
vi. In particular, the combined motion of legs, wheels, and tracks can be used to overcome steps and stairs, according to the sequences discussed in Section 3.

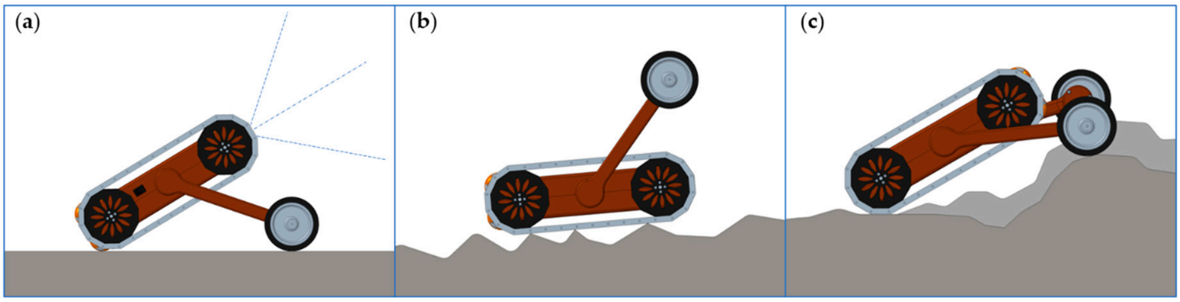


Figure 2. (**a**) Wheeled locomotion on flat and compact surfaces; (**b**) tracked locomotion on yielding terrains; (**c**) hybrid leg-wheel-track locomotion to overcome obstacles.

As previously mentioned, the proposed locomotion system presents similarities with the one of HELIOS-VI, though it shows the following differences: (i) Independently actuated and longer legs, which can perform complete and continuous rotations in case of obstacle overcoming and stair climbing; (ii) actuated wheels to perform purely wheeled locomotion with differential steering; (iii) capability of operating after an overturn, due to the main body symmetry.

Regarding the wheeled locomotion, there are some similarities with the Kylin robot [28]: Two actuated wheels are placed at the end of rotating arms, and passive omni wheels are adopted. The advantages of the WheTLHLoc with respect to the Kylin are: (i) The possibility of using the longer legs, also in combination with the tracks, to overcome obstacles; (ii) the capability of operating after an overturn due to the symmetry; (iii) the most compact and robust design.

The capability of operating after and overturn is in common with the hybrid WT robot discussed in [29], but in comparison to this one, the following benefits of WheTLHLoc can be outlined: (i) The capability of using legs, wheels and tracks in combination to overcome obstacles and climb stairs (Figure 2c); (ii) the polygon of the contact points for the wheeled locomotion is much larger, allowing higher stability during turns, acceleration and breaking, and consequently higher motion performance.

3. Step and Stair Climbing and Descent

As already stated, the overall size of the robot is quite compact, since the considered payload is represented by cameras and environmental sensors for surveillance and inspection. Moreover, a small robot can travel in narrow spaces that cannot be explored by humans and is much more portable. On the other hand, a drawback of small robots is their capability of facing stairs.

The climbing of steps and stairs can be performed according to the sequence represented in Figure 3 (frames a to m). In case of single steps, the sequence a–m is performed once, while it is repeated n times in case of n steps.

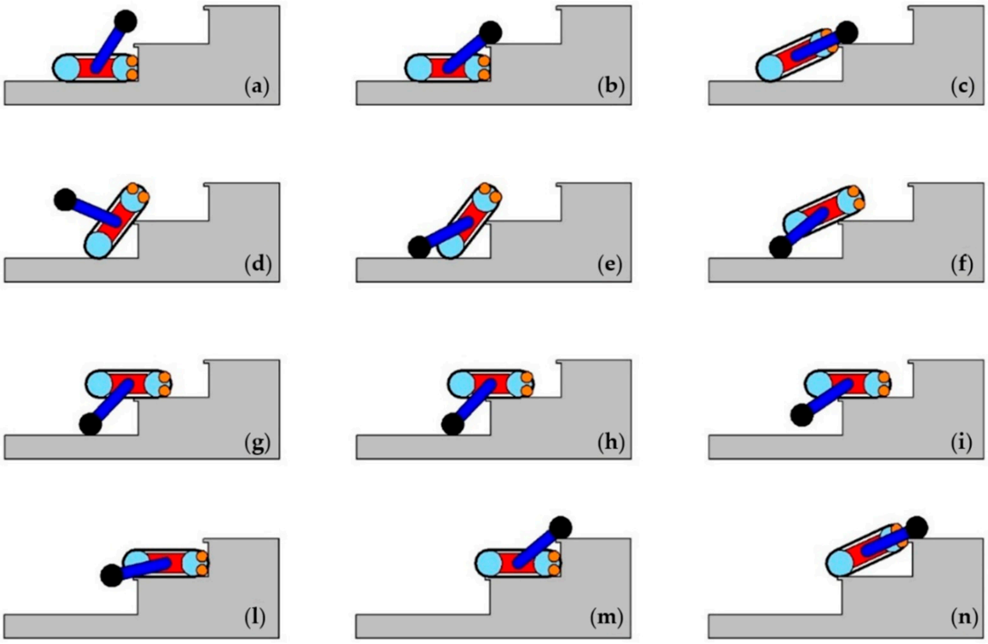


Figure 3. Stair-climbing sequence: the legs lift up the robot body (**a**–**c**), then rotate backward to complete the step climbing (**d**–**h**); then the robot goes forward by tracks (**i**–**l**) to face the next step (**m**,**n**).

After approaching the step, the rotation of the legs lifts up the robot body (frames a–c); let us note that the robot, which is not fully symmetric with respect to the *yz* plane, must face the step with the rear side, otherwise in the following phase (frame d) it would not be possible to use the traction of the tracks due to the presence of the omni wheels. Therefore, if the robot approaches the stair moving forward, a 180° pivoting must be performed by differential steering before climbing the first step, imposing an equal speed to the two tracks with opposite directions. This maneuver can be used whenever it is necessary to switch direction.

Once the central zone of the tracks is in contact with the step edge (frame d), the legs rotate backwards until they touch the ground behind the robot (frame e) and completely lift the robot over the step (frames f to h); in this phase, both tracks and wheels rotate, pushing the robot forward. Once the robot center of mass is sufficiently beyond the step edge, the robot moves forward on the tracks while the legs rotate forward (frame i–m) to face the next step, if present, or to complete the task.

The successful execution of this sequence is not assured in any dynamic and friction condition, since the friction of tracks and wheels with the ground is necessary to complete the maneuver in the phase corresponding to the frames d to g; therefore, the motion strategy must be planned and verified by analytical approach or numerically. In Section 4, the multibody simulation of the stair climbing maneuver is discussed.

The stair descent can be executed inverting the stair climbing sequence, as shown in Figure 4. In the descent, the successful execution of the maneuver is less critical, since it is not necessary to overcome the gravity force by means of the traction of wheels and tracks.

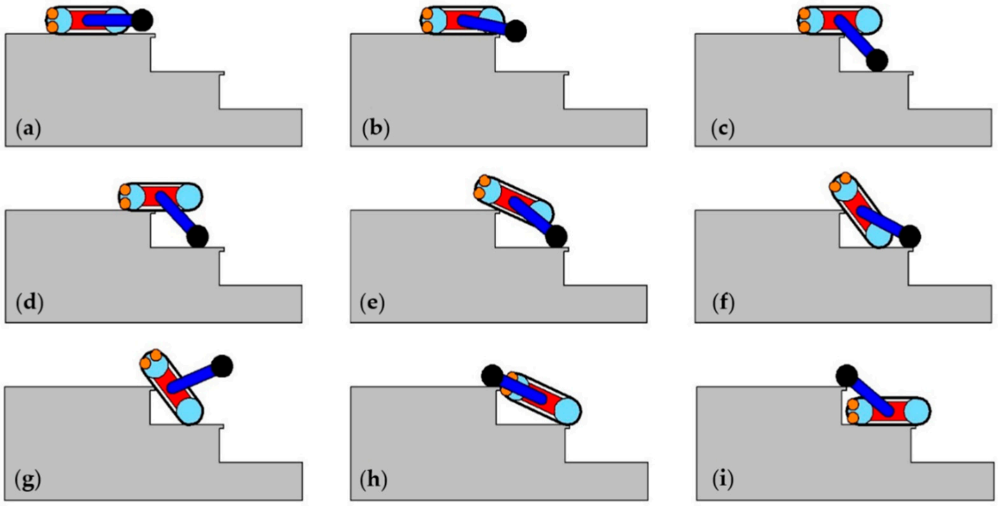


Figure 4. Stair-descent sequence: the robot approaches the descent by tracks (**a**,**b**) and uses the legs to come down gradually without shocks until the tracks touch the next step (**c**–**f**); then the legs rotate backwards (**g**) to complete the step descent (**h**,**i**).

4. Multibody Simulation of Stair Climbing

The feasibility of the stair climbing maneuver discussed in Section 3 has been checked with a dynamic model implemented in Recurdyn, a multibody software commonly used to simulate complex mechanical systems involving a large number of components and to perform efficient contact analysis by means of penalty algorithms [36]. In particular, these features can be exploited to simulate the complex dynamic behavior of a tracked system, composed of a high number of bodies (sprockets, track links, and rollers) in contact with each other and with the ground in configurations, which are highly variable during the vehicle motion [37].

Figures 5–7 represent simulation results related to a stair with 300 mm of run and 160 mm of rise (standard size for buildings). Figure 5 shows the angular position vs. time graph for wheels (red), tracks (black) and legs (green). These motion laws have been designed to realize the climbing sequence of Figure 3 and are imposed to the actuators in the simulation. The laws are characterized by constant speed phases and stop phases. Since instantaneous speed variations are not feasible (they would require infinite acceleration), constant speed phases and stop phases have been linked by cubic splines to obtain twice continuously differentiable motion laws without acceleration peaks.

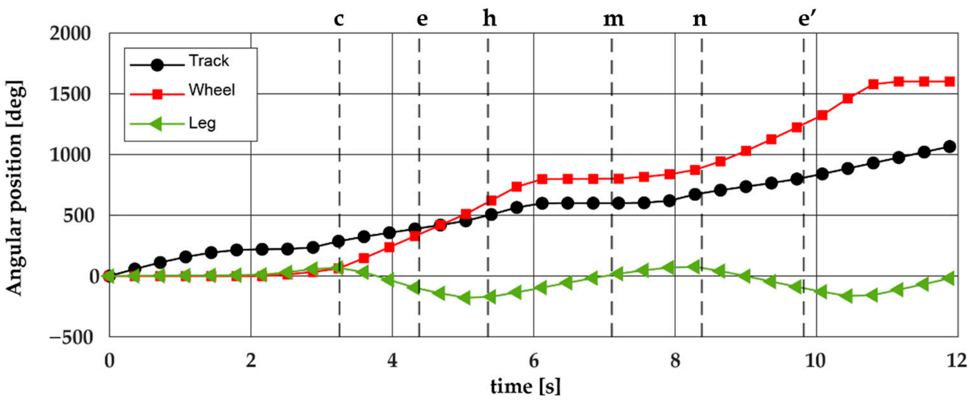


Figure 5. Motion laws of tracks, wheels, and legs (angular positions vs. time) imposed in the multibody simulation to realize the stair climbing sequence of Figure 3; stop phases and constant speed phases are linked by cubic splines to avoid acceleration peaks.

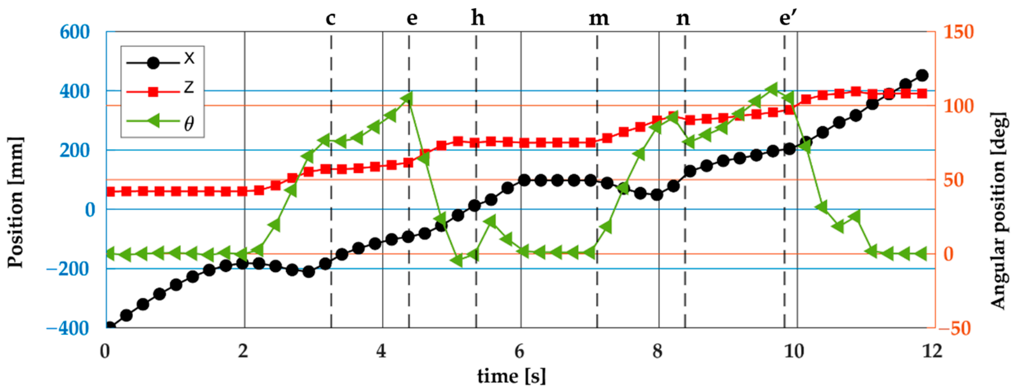


Figure 6. Multibody simulation results of the stair climbing sequence of Figure 3: Horizontal (x) and vertical (z) displacements of the reference frame origin of the robot main body (Figure 1) and pitch angle θ of the robot main body.

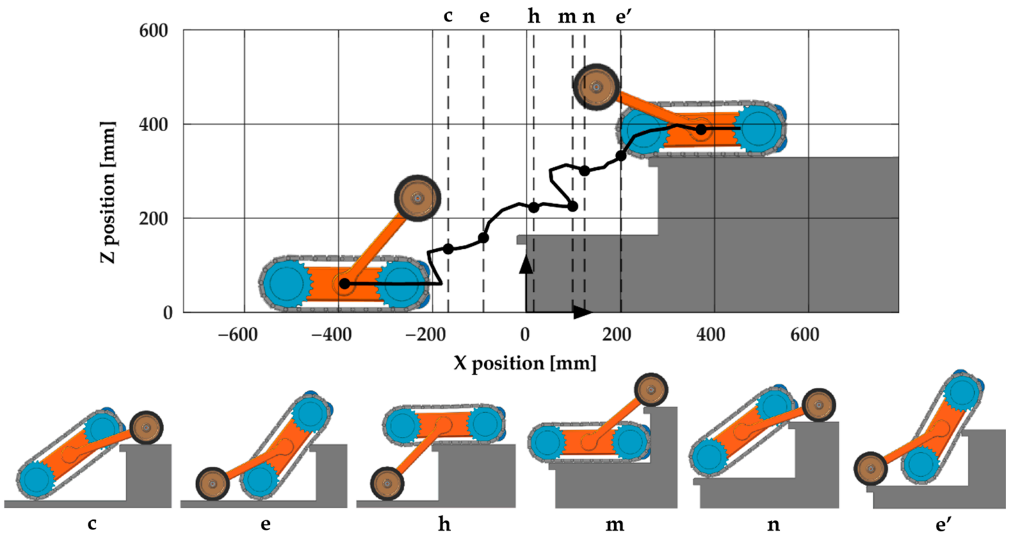


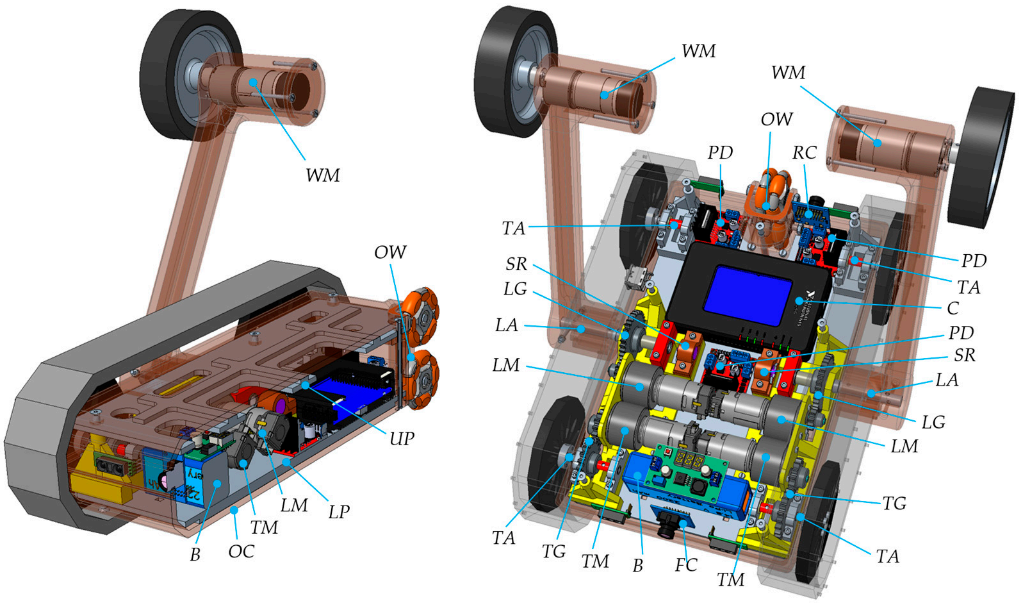
Figure 7. Multibody simulation results of the stair climbing sequence of Figure 3: Trajectory of reference frame origin of the robot main body (Figure 1).

Figure 6 represents the horizontal and vertical displacements of the robot reference frame origin (Figure 1) with respect to a fixed reference frame located at the lower edge of the first step (Figure 7), together with the robot pitch angle θ.

Figure 7 shows the trajectory of the robot body frame origin with respect to the fixed reference frame and six significant positions of the climbing process: c, e, h, m, n, e′. The symbols of such six positions correspond to the frame symbols of the stair climbing sequence of Figure 3. The position e′ is similar to **e** after climbing one step, so the cycle e–h–m–n–e′ can be repeated to climb all the stair. The time values corresponding to these six positions are marked in the graphs of Figures 5 and 6. The simulations have validated the feasibility of the maneuver and can be used to tune the climbing strategy as a function of the step geometry.

5. Internal Layout and Embodiment Design

In this section, the embodiment design of the robot is discussed. Figure 8 shows the internal layout of the robot body; the labels of the main components are listed in Table 1.



(**a**) (**b**)

Figure 8. Internal layout of the robot: (**a**) Section of the main body along the *xz* plane; (**b**) upper view (see the list of the main components in Table 1).

Table 1. Main robot components.

Component	Symbol in Figure 8	Characteristics
Outer Case	OC	3D printed kevlar-reinforced nylon
Upper structural plate	UP	3D printed micro-carbon-fiber-filled nylon
Lower structural plate	LP	3D printed micro-carbon-fiber-filled nylon
Leg gearmotor	LM	Micromotors RH-158-2s-12V, 26 rpm
Track gearmotor	TM	Micromotors RH-158-2s-12V, 33 rpm
Wheel gearmotor	WM	EMG 30, 12v, 170 rpm
Motor driver (PWM)	PD	L298N Dual H-Bridge motor controller
Leg axis	LA	Stainless steel tube (∅10 mm, 1 mm wall)
Track axis	TA	High carbon steel tube (C45, ∅6 mm)
Leg gear	LG	20:14, M2
Track gear	TG	18:12, M1.5
Omni wheels group	OW	Rotacaster 95A-50 mm
Controller	C	National Instruments MyRio 1900
Battery	B	HRB 50C-4S-RC-LiPo, 14.8V, 2200 mAh
Front camera	FC	Yosoo OV7670-300KP-VGA
Rear camera	RC	Yosoo OV7670-300KP-VGA
Slip ring	SR	12 mm-12wires miniature slip ring

The upper and lower internal plates (*UP* and *LP*) constitute the structural frame of the robot, on which the supports of the transmission components (gearmotors, axes, bearings, and gears of tracks and wheels) are fixed. The plates support also the other devices hosted in the robot body: Controller, battery, PWM drives, and video cameras. Free space is available in the front and rear sides to place additional components (e.g., environmental sensors, extra batteries) based on the required robot task. The structural components (plates and supports) are 3D printed in micro carbon fiber filled nylon, while the upper and lower external cases are 3D printed in Kevlar-reinforced nylon for higher impact resistance.

The wheel gearmotors (Figure 8, *WM*) are directly connected to the wheels, and the necessary power supply and encoder signals are transmitted by slip rings (Figure 8, *SR*), allowing continuous rotation, if necessary. The MyRio-1900 board by National Instruments (USA) has been selected as the control system, since it can properly manage the motion control of the six axes with encoders (two legs, two tracks, and two wheels), the video camera signals, and the WiFi connection with a host computer; moreover, it is equipped with a three-axis accelerometer to acquire data regarding the robot motion, and can manage an Inertial Measurement Unit.

6. Conclusions and Future Work

In this paper, the conceptual design of a novel small-scale leg-wheel-track hybrid locomotion robot, named WheTLHLoc, is presented. A comparison with respect to other hybrid mobile robots is outlined in Section 2, highlighting similarities and differences. The mechanical architecture of WheTLHLoc has been designed to combine the advantages of tracked locomotion on soft and yielding terrains and the ones of wheeled locomotion on flat and compact grounds. The switch between these two modes is realized by means of rotating legs carrying driving wheels. The robot is capable of performing step and stair climbing and descent by moving in proper combination legs, wheels, and tracks.

The effectiveness of the climbing maneuver is not obvious due to the limited dimension of the robot with respect to step height. Therefore, the feasibility has been verified by numerical simulation using the multibody software Recurdyn. Variations of this maneuver can be used to overcome obstacles with different shape, not squared, using the same principle of lifting the side of the robot close to the obstacle by the legs, then advance using the tracks, and finally completing the robot lifting by rotating backwards the legs.

The detailed embodiment design has been completed, as discussed in Section 5. In the following of the research, the first prototype of the robot will be realized for an experimental validation of the proposed hybrid locomotion system and its test in real surveillance and inspection tasks.

Author Contributions: L.B. conceived the locomotion system and the robot architecture; L.B., S.E.N., P.B., and M.B. developed the detailed embodiment design; P.F. supervised the scientific methodology for the functional design and the multibody simulations; M.B. performed the multibody simulations; all authors have prepared the manuscript. All authors have read and agreed to the published version of the manuscript.

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