A New Principle for Climbing Wheeled Robots: Serpentine Climbing with the OpenWHEEL Platform

J.C. FAUROUX, F. CHAPELLE, B.C. BOUZGARROU

Mechanical Engineering Research Group (LaMI)
Blaise Pascal University (UBP)
and French Institute for Advanced Mechanics (IFMA)
Campus universitaire de Clermont-Ferrand / Les Cézeaux, BP 265
63175, AUBIERE Cedex, France

fauroux | chapelle | bouzgarr @ifma.fr

***Abstract* – This paper describes an innovative principle for climbing obstacles with a two-axle and four-wheel robot with articulated frame. It is based on axle reconfiguration while ensuring permanent static stability. A simple example is demonstrated based on the OpenWHEEL platform with a serial mechanism connecting front and rear axles of the robot. A generic tridimensional multibody simulation is provided with Adams software. It permits to validate the concept and to get an approach of control laws for every type of inter-axle mechanism. This climbing principle permits to climb obstacles as high as the wheel while keeping energetic efficiency of wheel propulsion and using only one supplemental actuator. Applications to electric wheelchairs, quads and All Terrain Vehicles (ATV) are envisioned.**

***Index Terms* – Wheeled Robot, Climbing Robot, Static Stability, OpenWHEEL, Articulated Frame.**

I. Introduction

The wheeled terrestrial propulsion is known to be a very energy-efficient way of moving, because energy is mainly used for propulsion and not lift [1]. Wheels are particularly fast on flat grounds but have difficulties to deal with obstacles and terrain discontinuities. In that case, legged locomotion regains interest. Several robots offer a hybrid architecture by mounting wheels on legs [2, 3, 4], sometimes with a modular configuration [5], combining more than two locomotion types [6], or presenting original articulated frames [7, 8] in order to position and orientate wheels for specific purposes. Those special mobile robots generally focus on improving mobility, stability or climbing capabilities. However, this improvement is often obtained at the price of higher complexity, great number of joints, low stiffness and great number of wheels.

This paper intends to propose an original and efficient obstacle climbing strategy that was implemented on a opened architecture of mobile wheeled-robot. The objective was to climb high obstacles (as high as the wheel) with static stability and to keep a good compromise between climbing performance, complexity, stiffness and technological pragmatism. This last point includes a reasonable number of wheels.

II. Existing Wheeled Robots with High Mobility

A. *Mono-mode robots or vehicles*

Robots of this type have only one mode of locomotion: rolling. For obstacle crossing, they classically rely on high wheels (wheel radius higher than the obstacle height), long travel suspensions for keeping all wheels in contact with the ground and all-road tires. Many commercial robots are based on this architecture. Some have four wheels and are very close to car architecture [9]. Others adopt only three wheels [10] for permanent stability or a high number of wheels for improving driveability. The six-wheel architecture is quite an efficient solution for planetary exploration robots such as Adam [11] or All Terrain Vehicles [12].

B. *Multi-Mode wheeled robots with articulated frame*

These robots have several modes of locomotion such as rolling / climbing / equilibrating / peristalsis capabilities.

Some are passive solutions for adaptation of rough terrains (no additional motorized degree of freedom), e.g. with 6 wheels: Sojourner [13], Nexus 6 [14] (both with rocker-bogie suspension type) and Shrimp [15]. Shrimp is able to cross obstacles with height twice of the wheel diameter. It has six wheels with non-conventional position: four lateral wheels mounted on independent parallelograms, a front wheel with great displacement and a rear wheel attached to the frame. Micro5 [16] shows characteristics of simple and lightweight five drive-wheel vehicle with four wheels in the corners and one central supporting wheel improving climbing capabilities.

Other solutions present active concepts such as center of mass active repositioning [17]. Others offer peristaltic locomotion modes such as the Lama robot, based on a Marsokhod chassis [8]. Some use binary actuation to change the configuration of the suspension [18].

A large number of mobile robots are specially designed for the task of step-climbing. [19] presents a holonomic omnidirectional vehicle with passive suspension and seven motorized wheels (and free rollers). A control method based on the variable kinematics model distributes the load among all wheels.

The eight-wheeled robot OctalWheel [20] can challenge tasks such as climbing over obstacles and even stairs. OctalWheel is based on the same principle as Ibot 3000 [21], an armchair with four driving wheels for handicapped people which can go up and down staircases thanks to a rotative chassis and dynamic balancing capabilities. Helios V [22] is also a six wheeled off-road vehicle with four low-pressure tires and two high-pressure tires with variable position, designed for carrying tasks or powering a wheelchair.

III. Principles

A. General Architecture of OpenWHEEL

The concepts presented in this work are implemented on a mobile-robot generic platform called OpenWHEEL. It is "generic" in the way it should be understood as a modular assembly of various canonical components such as wheels (with electric motor inside the hub for compactness), suspension mechanisms, axles, inter-axles mechanisms and other parts such as electronic equipment (Fig. 1).

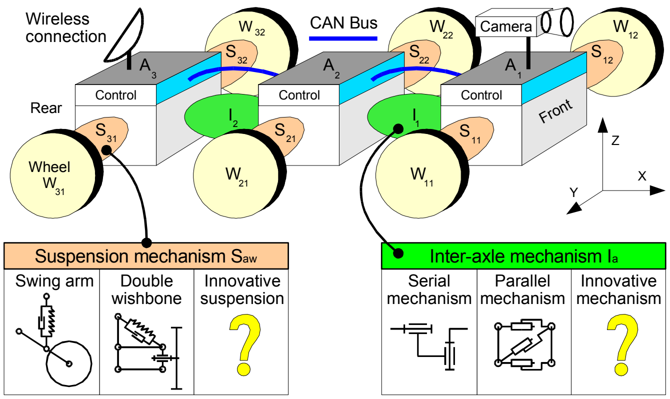


Fig. 1 The general architecture of the OpenWHEEL platform.

This version of OpenWHEEL can be decomposed into several axles (or pods). An axle A_a is an assembly of two wheels W_{a1} and W_{a2}, two suspension mechanisms S_{a1} and S_{a2} and a central box including independent power supply and control. Two consecutive axles A_a and A_{a+1} are connected by an inter-axle mechanism named I_a.

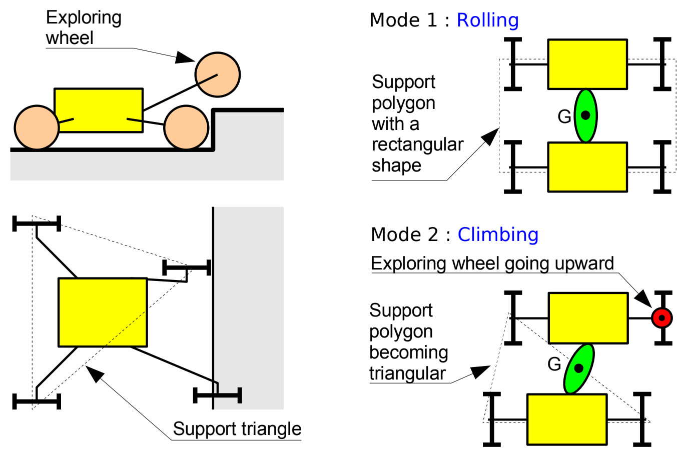
The purpose of the work was not to focus on the kinematic architecture of suspension mechanism S_{ai} and inter-axle mechanism I_a. We just consider that S_{ai} are optional and that I_a are here to maintain coherence between axles during motion.

The serial or parallel nature of I_a will not be deeply discussed here but it is worth noting using a parallel robot may be interesting. Such robots are generally considered to be capable of high stiffness [23] and this is a strong requirement for maintaining the relative positions of the axles during climbing. Parallel mechanisms are infrequent for this use on vehicles. The Souryu robot from Hirose [24] is one of the very few robots with an inter-pod parallel mechanism. However, it does not have the same climbing strategy as OpenWHEEL and uses tracks instead of wheels. The case of tracked vehicles will not be treated here, though some of them have very interesting articulated frames [6].

B. Reconfiguration for Climbing: the Exploring Wheel Paradigm

The number of wheels in the OpenWHEEL architecture should be understood as free *a priori*. Fig. 1 shows three pairs of wheels but this value is just to show generality of the concept. Among terrestrial vehicles, six-wheel architectures are not very common because they are expensive and bring steering problems. The vast majority of commercial vehicles have only four wheels. It should be noted that only three wheels are required to ensure permanent stability but the three-wheel architecture is not widespread for road vehicles. The side-cars and carrier tricycles do not have a lot of success, probably because of non-symmetry and dynamic instability.

However, we will keep the idea of stability on three wheels and use it for a four-wheel vehicle. The wheel not used for stability is called "the exploring wheel". This wheel is dedicated to explore above the obstacle and then should be put on it to offer a new support point. After that, another wheel becomes the exploring wheel and the process can go on. This is summarized in Fig. 2.



a) General four-wheel robot b) Robot with two-pod architecture

Fig. 2 The exploring wheel paradigm.

From now on and even if a parallel mechanism is envisioned in a close future, internal coherence between axles will be maintained with a very simple serial mechanism made of three revolute joints $(R_1 R_0 R_2)$ with axes parallel to $\boldsymbol{z}$, $\boldsymbol{x}$ and $\boldsymbol{z}$ respectively (Fig. 3). For stability calculations, we assume that the inter-axle mechanism has a negligible mass relatively to the axles. The center of mass of each axle A_a is called G_a and the overall center of mass is called G. It is the middle of G_1G_2.

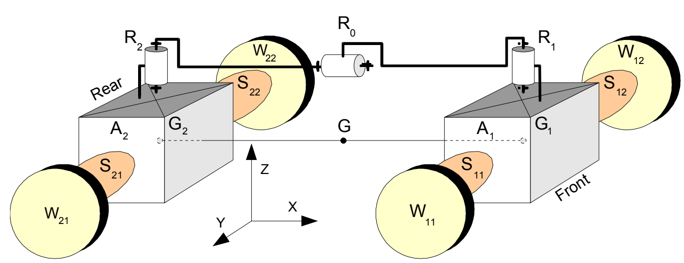


Fig. 3 The inter-axle serial mechanism used in this work.

This design was chosen because it allows the rotation of each axle A_a on itself along the axis $(G_a, \boldsymbol{z})$ without slip of the wheels, thus permitting to change the location of contact points on the ground without moving the vehicle. The central joint R_0, which is actuated, permits a global warping of the frame for elevating one wheel over the plane of the three remaining contact points.

Choosing such a simple *(RRR)* example is only for simplifying mechanism representation. Enumerating the whole family of the inter-axle mechanisms compatible with the requested mobilities is not the purpose of this paper and is another interesting and tough problem currently in process.

Synthesis of those mechanisms can be based for example on the specification of motion via the theory of displacement group [25] or on theory of linear transformations [26]. It should be kept in mind that all the principles that follow are valuable for the entire family of inter-axle serial and parallel mechanisms.

C. *Stability Property*

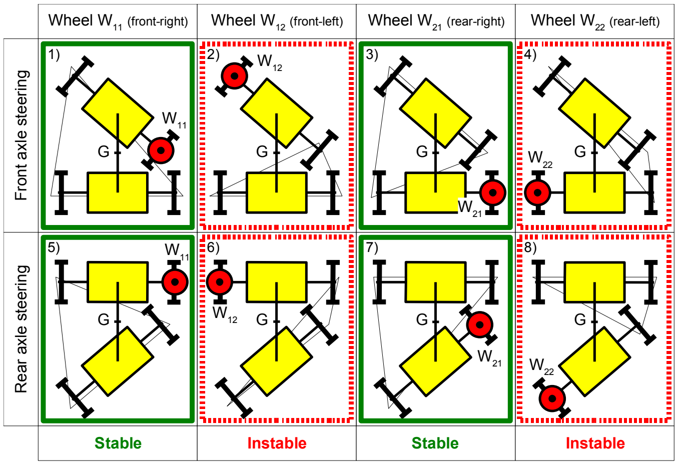


Fig. 4 Stable and unstable configurations when turning to the right.

Using the two-axle architecture for the vehicle, it is now possible to study its stability. Obviously, when both axles are parallel (Fig. 2.b), if one wheel is lifted, the vehicle becomes unstable because the center of mass *G* is always on the side of the support triangle.

The interesting point is that this instability is not systematic during turning phases. Let us consider a steering to the right. Fig. 4 summarizes all possible configurations for turning to the right: it is possible to control the front and/or the rear axle; in both cases, each of the four wheels may be lifted for obstacle climbing. It can be noticed that only four out of the eight possible configurations are stable. The results can be wrapped up into the unique following property: "Static stability during turns is ensured when the lifted wheel is inside the turn". This property is also true when both axles are controlled at the same time.

This result may now be applied to stability improvement during climbing. When a wheel is on the point to be lifted before an obstacle, vehicle stability can be improved by a steering of the other axle in order to bring a wheel as close as possible as the one to be lifted. This ensures that the support polygon is not too much deteriorated by the absence of ground-contact of the lifted wheel. This reconfiguration is very easy to perform in our case (Fig. 3) because the rotation center of each axle is located in the middle of the axle. Thus, a self-rotation of an axle can be performed without wheel-slipping and with minimal energy consumption. During frontal climbing, the front axle cannot be steered because the wheels are close to the obstacle. Consequently, the only way to improve stability in this case is to steer the rear axle (Fig. 4.5).

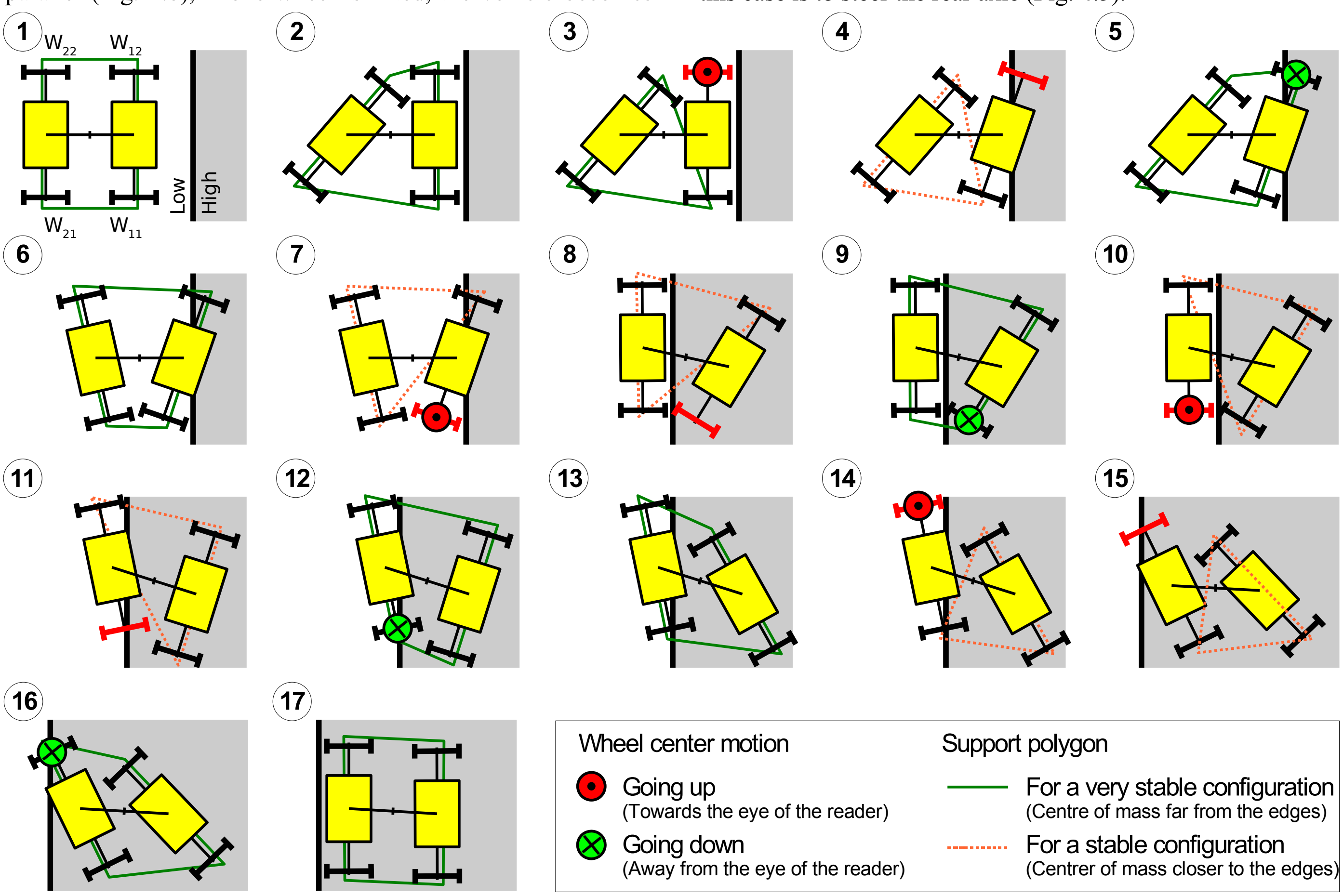


Fig. 5 Serpentine frontal climbing of a single step obstacle.

IV. A New Principle for Climbing

The stability property explained in previous section was used to design a continuous series of poses of the OpenWHEEL platform that meet two criteria at the same time:

– being compatible with the the Exploring Wheel paradigm
– ensuring permanent stability

Fig. 5 presents the principle for frontal climbing of a single step obstacle, with a serpentine overall movement comparable to what is commonly seen for crawling robots [27]. It is split into seventeen discrete states but motion continuity is assumed between states. For going from one state to the next one, a single “functional motion” is necessary. A functional motion is a motion that can be described in term of function, for instance “lifting the center of wheel 2” or “moving horizontally towards the top of the step”. This description is good for qualitative design but depends on the constraints of the system (joints and rolling without slip of the wheels). Moreover, a single functional motion can correspond to a complex spatial motion.

Fig. 5.1 shows the vehicle approach of the obstacle, up to contact of frontal wheels. Fig. 5.2. is for stability reconfiguration: the rear axle is rotated around z in order to bring wheel W_{22} close to W_{12}. This ensures stability while W_{12} is lifted via active warping of central joint R_0 (Fig. 5.3). Then, W_{12} is brought over the obstacle (Fig. 5.4) and stability is kept though it deteriorates a little because the center of mass gets closer to the side of the support polygon. Finally, W_{12} lands on the obstacle and becomes a new supporting point for the robot. This is the whole cycle for one wheel. Then, it goes again with the three other wheels. There is a rear reconfiguration (Fig. 5.6) to anticipate W_{11} lifting (Fig. 5.7). Then the whole vehicle rolls without slipping (Fig. 5.8) and wheel W_{11} can land again (Fig. 5.9). As the stable configuration is already obtained, W_{21} can be lifted (Fig. 5.10), approached over the obstacle (Fig. 5.11) and put again on the ground (Fig. 5.12). After a final reconfiguration of the front axle (Fig. 5.13), the last wheel W_{22} is lifted (Fig. 5.14), the vehicle goes on while steering (Fig. 5.15) and W_{22} lands again (Fig. 5.16). Finally, both axles are steered back to the straight direction (Fig. 5.17) and vehicle can go on.

As a conclusion, this first bi-dimensional approach permits to construct and to describe a process for climbing obstacles. However, it is still qualitative and four simplifying hypotheses were assumed: null mass of the inter-axle mechanism; small warping rotation-angles to avoid complex tridimensional poses; punctual ground-wheel contact; perfect rolling without slipping. This new principle will be validated by a tridimensional model in the next section. It should also be noticed that Fig. 5 presents only one of the several coherent strategies for climbing. Another problem will be to choose which actuators to use and there are sometimes several possible choices. For instance, between Fig. 5.3 and Fig. 5.4, bringing W_{22} over the obstacle can be obtained via rear wheel actuation and/or activation of joint R_1. The best design will be the one that minimizes the number of actuators in the robot, but this paper will not develop this optimization approach.

To our knowledge, this climbing process is original. It might seem complex to generate steering for going straight ahead. However, this is an elegant solution to ensure stability of a four-wheel vehicle without adding any supplemental roller and with only one central actuator.

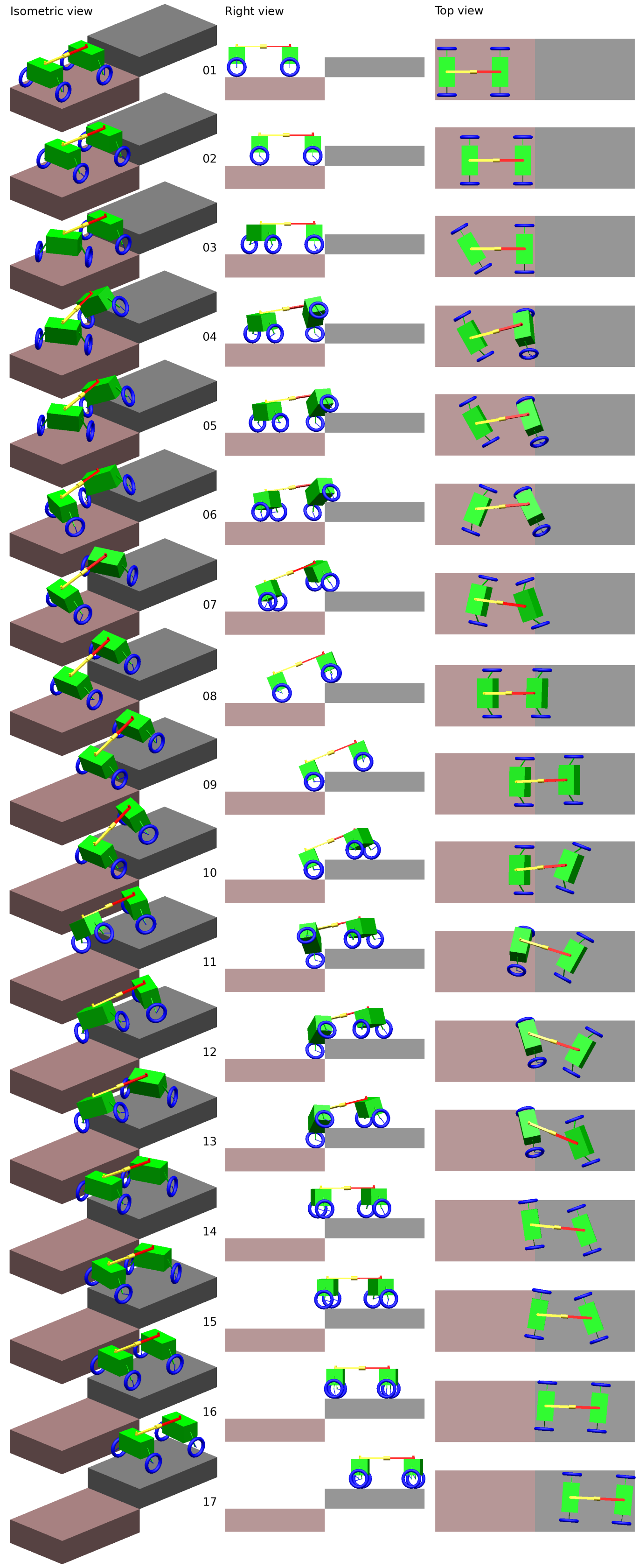


Fig. 6 Tridimensional multibody kinematical model of serpentine climbing.

V. Tridimensional Kinematic Validation

A. Adams Multibody Model

In order to validate precisely the feasibility of this new climbing principle, a tridimensional kinematic model was constructed with the Adams multibody simulation software (Fig. 6). The vehicle model is made of two axles, four wheels, two intermediate bars and seven revolute joints. The wheel diameter (300 mm) is the same as the obstacle height. The inter-axle mechanism is a bit longer (800 mm) than the one shown in Fig. 5 to avoid collisions between front and rear wheels when steering.

The main difficulty is that the vehicle is connected to the ground only by four contacts, which sometimes can lead to numerical convergence problems. In this model, normal force follows an impact model and tangential friction force a Coulomb model [28].

In this model, the main idea is to build a generic tool for designing new inter-axle mechanisms [29, 30]. The method can be used unchanged with another structure of inter-axle mechanism. In a first stage, the axles are moved by controlling each wheel and also ordering the *z* altitude of each wheel center while keeping ground contact as long as possible. After that, the motion laws of actuators R_0, R_1 and R_2 can be found. In a second stage, these laws are injected into the actuators and the altitudes of the wheels become free. This is a simple way to build the complex motion laws of the actuators.

B. Preliminary Thinking about Control during Climbing

Fig. 6 shows a strategy which differs partially from the one shown in Fig. 5. If we focus on Fig. 5.7 and 5.8, the vehicle has one front wheel on the obstacle, the second front wheel upward and rolls without slipping on the three wheels in contact with the ground in order to bring the exploring wheel on top of the obstacle. On Fig. 6.7 and 6.8, the rear wheels push the front axle which is only supported by the front right wheel. As joint R_1 is a free joint, the front axle naturally steers to the right and brings the front left wheel on top of the obstacle. This demonstrates that different motion sequences can be imagined to follow our climbing strategy.

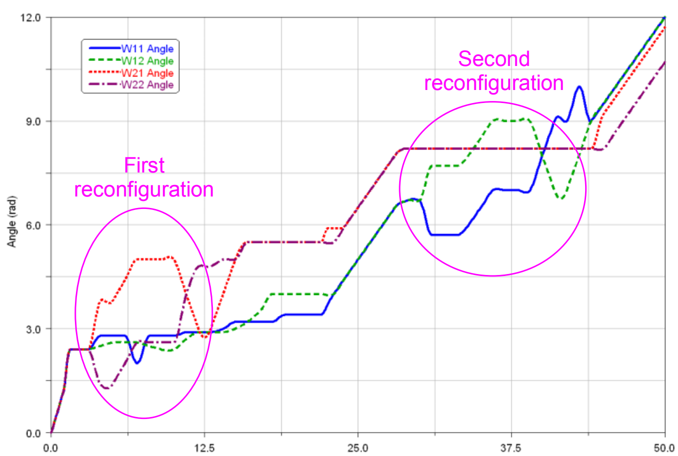


Fig. 7 Wheel rolling angles.

From Fig. 5 and Fig. 6, it can be noticed that the central joint R_0 is only actuated during the climbing phases, when the supporting polygon becomes a triangle. This actuator should have a slow speed and a high torque to be capable to warp the frame and lift one wheel. During normal rolling, actuator should be declutched and joint R_0 kept free to ensure passive adaptation to ground curvature. The other joints R_1 and R_2 could be kept free during all the climbing process, provided the three remaining wheel-ground contacts are without slip. If slip appears, an electric locking system could be added to R_1 and R_2 to maintain frame configuration (Fig. 5.7 and 5.8 for example) at minimal energy cost.

Fig. 7 shows the wheel rolling angles during time. The curves are rather intricate but globally ascending when vehicle goes forward. The reversing phases correspond to self-rotation of axle A_i obtained by reversing sense of W_{i2} relatively to W_{i1}.

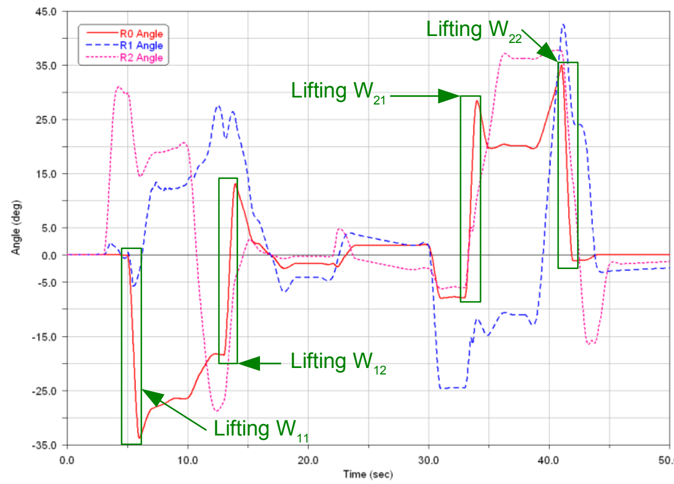


Fig. 8 Inter-axle joint angles.

Fig. 8 shows the rotation angles of inter-axle joints. The most interesting curve is rotation angle of R_0. Four large angle variations can be seen that correspond respectively to phases 4, 7, 11 and 14 of the climbing process described in Fig. 6. The angle variation on R_0 depends on the obstacle height and axle length. It should always be sufficient to lift the exploration wheel above the obstacle. A reasonable angle of 30 to 45° should not be excessed for keeping contact on the tire tread. A parametrized control in function of the obstacle height could be imagined but this implies that a sensor on the robot should be able to measure the obstacle height before contact. On the contrary, a cost-effective strategy could be to detect the obstacle by contact or ultrasonic sensors and to always lift the exploration wheel at its maximum.

Climbing strategies and control are currently implemented on physical prototypes of several scales. Fig. 9 shows the already existing pod structure of OpenWHEEL.

VI. Conclusion

This paper showed a new principle for climbing obstacles with a four-wheel robot. Such an architecture is interesting because it keeps energetic efficiency of wheel propulsion while ensuring climbing ability of high obstacles (at least as high as the wheel). A bidimensional model was first used for enumerating the series of poses that the robot should take for climbing a single step while continuously ensuring stability. A tridimensional Adams multibody model was then created to validate the climbing principle. The main difficulty for controlling such a climbing process is to generate motions of the inter-axle mechanism just-in-time before obstacle.

The Adams model was created in a generic way for finding automatically the joint motions of the inter-axle mechanism, independently of the kinematic architecture of this mechanism. In a further work, several types of serial or parallel mechanisms with the requested degree of freedom will be tested. This may be considered as a tool for early creative design of new articulated vehicle-frames.

In its four-wheel version, the OpenWHEEL mobile platform is much closer to the architecture of commercial vehicles than most of climbing robots. It brings climbing abilities without the overweight, size and energy consumption of the most climbing-efficient six-wheel robots. Only one supplemental central actuator is needed. Applications can be found for new electric wheelchairs with improved sidewalk-climbing capabilities. More generally, new efficient frames for quads and All Terrain Vehicles (ATV) can be envisioned.

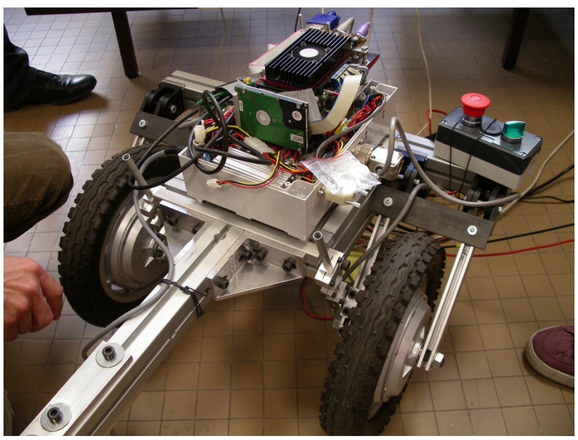


Fig. 9 Pod structure of OpenWHEEL V1.0 with onboard PC104 computer.

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