Design and Modeling of a Mobile Robot with an Optimal Obstacle-Climbing Mode

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***Abstract*—This work is focused on designing new wheeled-vehicles with enhanced capacities in natural environment. Design is not only for the mechanical architecture (articulated chassis and suspensions) but also for the associated obstacle-climbing mode. In the frame of our generic OpenWHEEL architecture, a new climbing mode is created for a *4sRR* robot. The use of GeoGebra, a hybrid geometric-algebraic sketcher permits to generate an obstacle-climbing sequence in sixteen stages. A global optimization problem is then outlined mixing variables of structural (geometry and mass) and kinematical (vehicle posture) nature.

Keywords—Vehicle and mobile robot design; static stability; obstacle-climbing mode; OpenWHEEL architecture; optimization

I. INTRODUCTION

Wheeled vehicles represent the vast majority of terrestrial vehicles, probably because of the high energetic efficiency of wheeled propulsion [1] and high-speed capacity. However, on rough terrain and natural environment where the ground surface is much more irregular, qualities such as low power consumption, reliability and adaptability to the ground insuring a good locomotion are no more guaranteed. In this context, the wheel is not so efficient. If the ground surface is submitted to slope discontinuities, a wheeled vehicle can eventually be blocked and alternative solutions such as legs or tracks regain interest. This paper attempts to present the design process of the mechanical architecture of a highly efficient wheeled-vehicle for natural environment. Focus is particularly set on new displacement modes for climbing over obstacles and terrain discontinuities while ensuring static stability.

Climbing abilities are strongly connected with the mechanical architecture of the vehicle, particularly with the kinematics of frame (possibly articulated) and suspension mechanisms. The designer should not be captive of what is considered to be the classical architecture of a vehicle in the twenty-first century, that is to say a four-wheel vehicle with a central engine and transmission mechanisms to two or four wheels. It is important to envision, from now on, what could become a vehicle with distributed power. For instance, electric engines could be dispatched on every wheel. Prospective works were made for urban vehicles, such as the Michelin Active Weel prototype [2] with electric motor and adaptative suspension inside the wheel. The only limit that prevents the use of distributed electrical motors for the majority of vehicles is a very tough technological frontier concerning energy storage. However, new technologies such as lithium-polymer batteries, carbon nanotube ultra-capacitors [3] or fuel cells give encouraging signs. For this reason, it is important to keep the same pace of innovation for mechanical vehicle architectures.

Concerning all-terrain vehicles, advanced propositions can be found for mobile robots, particularly spatial exploration robots. Part II introduces some of these existing original robots while Part III addresses the general problem of designing a new vehicle or mobile robot architecture. Our generic Open-WHEEL architecture is then introduced, with insights on the family of vehicles that can be derived from it. One architecture named *4sRR* is chosen for a deeper analysis.

After that, Part IV presents a general method for designing a climbing sequence of the vehicle on an obstacle. An interactive geometry sketching software (GeoGebra [4]) is intensively used to maximize stability via a design function. This leads to the principal result of this work: a climbing sequence decomposed into six phases and sixteen stages. Since one stage has a smaller stability margin than the others, an optimization problem is outlined in Part V for dimensional design. Finally, conclusions and future work are presented. This work may give applications to new types of all-terrain vehicles (ATVs) such as quad bikes, high performance wheel-chairs for disabled people and spatial exploration robots.

II. EXISTING MOBILE ROBOTS

Many types of locomotion modes exist, based on crawling, legged, wheeled or tracked locomotion. Crawling robots create locomotion by deformation of their structure and multiple contacts with the ground. These robots can progress on rough terrains and even cross obstacles. They need complex control and require high energy for a moderate speed.

Legged systems allow locomotion on rough terrains including obstacle crossing. Their strength and complexity is due to the discontinuity of ground contact. Control is not trivial and stability (especially on two legs) requires many sensors and actuators. They require a lot of energy to go fast.

Wheeled vehicles are able to move fast on smooth surface with moderate energy consumption [1]. Wheels are both used to sustain the vehicle and create locomotion. When adding suspension systems, wheeled vehicles can comfortably move on rough terrain with continuous slope. However, climbing obstacles remains a challenge for these systems, depending on structural architecture and components.

Permanent stability is often obtained by a greater number of wheels, implicating higher energy consumption and complexity for steering. Tracked vehicles are also an interesting and stable solution ensuring a lot of traction force but at the cost of high friction energy loss, particularly when skid steering [5].

This short panorama demonstrates that no locomotion mode is perfect and each of them should be useful depending on the application. Some laboratories even developed various solutions from each type [6]. However, we think that wheeled locomotion, a mode not really present in nature, should be developed even more towards all-terrain locomotion. Some existing wheeled robots have brought innovative architecture in their design and original solutions for climbing obstacles.

Micro5 [7] uses an original design with five wheels. One central wheel and a frame divided longitudinally in two halves allow permanent stability and provide climbing capacities.

Nomad [8] can change distance between its wheels so that its stability can be improved, depending of the type of terrain. The vehicle is divided in two halves (right and left). On each half, wheels are deployed and steered simultaneously by arms, allowing a reconfiguration of the chassis. Nomad can also turn using two different ways (dual Ackerman and skid steering).

The two following robots combine efficiently wheels and legs to offer several modes of locomotion:

Hybtor [6] is a “hybrid tractor” with four wheeled legs. Each leg has three motorized joints, including wheel actuator. It is capable of rolling and walking. Steering is obtained via a central articulation. However, structural and control complexities limit its characteristics (speed, climbing abilities) and increase electric consumption.

Hylos [9] was given four legs, each one with four actuated revolute joints, including wheel steering and actuating. It is reconfigurable and has great characteristics but its serial design requires high stiffness, many actuators and complex control to allow it to climb and move on rough terrains.

Shrimp [10] represents a category of robots with fewer actuators. It is an articulated frame robot using six wheels with a specific setting. The rear wheel is directly connected to the chassis. In its middle, four wheels are attached to two independent parallelograms connected laterally to the chassis. The front wheel is mounted on a four bar linkage for a great displacement. During rolling, the contact points on the base of the wheels can adapt to convex as well as concave grounds. Permanent static stability, good adaptability and obstacle smoothing are obtained. Shrimp is able to climb a step as high as two diameters of its wheels with only actuators in the wheels, which is an interesting passive but adaptive solution with very simple control. To our knowledge, it knew few applications except for spatial exploration, probably because of high number of wheels (an eight wheel variant was developed) and geometric non-conformism.

This overview allows to draw some interesting conclusions and design rules for creating new mobile robots and vehicles. First, we will limit to wheeled vehicles because of energetic efficiency. Second, adding supplementary mechanisms in the frame (articulated frame, such as Micro5 or Nomad) or to guide the wheel (legged wheels such as Hybtor or Hylos) may greatly improve all-terrain capacities of wheeled vehicles. Third, too complex serial legs should be avoided because of lack of stiffness and control complexity. Fourth, it is interesting to minimize the number of actuators (Shrimp) and to allow some free degrees of freedom (DOF) in the frame for induced deformation and improving climbing capacities. Fifth, pragmatism should be kept in mind to avoid excessive mechanical and control complexity, high power consumption, great number of wheels and actuators. To this condition, implementation on common vehicles such as to agricultural vehicles, quad bikes or all-terrain wheelchairs may be envisioned.

III. DESIGNING A MOBILE ROBOT FOR CLIMBING

Designing a robot or vehicle is a complex process that is difficult to formalize. We propose a decomposition in three levels based on existing design techniques already used for transmission mechanisms [11] and vehicle design [12]. The first level is to choose a *design workspace*, in this case a vehicle architecture. Then comes *structural synthesis*, based on the analysis of the required mobilities. Finally, *dimensional design* is often performed by solving an optimization problem. Iterations should be made on each level: if no solution exists, the previous choice should be re-considered.

A. Choosing a Design Workspace: Vehicle Architecture

This work intends to explore a family of robots. Each one may be implemented using a mobile wheeled generic platform named OpenWHEEL[13]. It is 'generic' in the way it should be understood as a modular assembly of various canonical components such as wheels (with attached electric motor), suspension mechanisms, axles, inter-axles mechanisms and other components such as control microchips, sensors or communication devices (Fig. 1). For each wheel, the motor can be located inside the hub for compactness or outside with a speed reducer for higher torque. In both cases, there is no need for a transmission mechanism between the central box and the wheel.

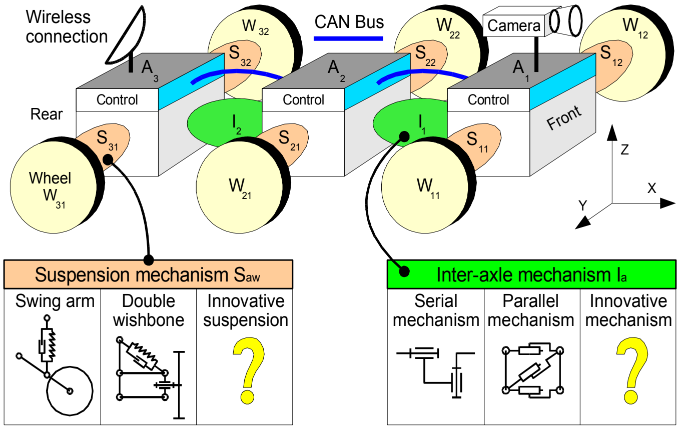


Figure 1. The OpenWHEEL architecture [13].

This version of OpenWHEEL is made of several axles (or pods) joined by intermediate mechanisms. It is a deliberate choice that was made to improve modularity. 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 the inter-axle mechanism named I_a.

Such an architecture is representative of many vehicles, such as Hybtor or Hylos. For defining a vehicle, one should define the number of axles, the inter-axle mechanisms I_a that are here to maintain coherence between axles during motion and the suspension mechanisms S_{aw}. For a rigid frame, the inter-axle mechanism may be considered as rigid (no DOF). This architecture covers a big sub-class of all the possible wheeled-vehicles, those with an axle-based structure.

In order to designate solutions extracted from this class of mechanisms, we propose the following naming convention. Inter-axle mechanisms are designated by the symbol *iJJJ* where *i* means "inter-axle mechanism" and *JJJ* is the conventional description of the corresponding kinematic chain, a series of several *J* letters. Each *J* letter represents a joint type, such as P (prismatic joint), R (revolute joint), S (spherical joint), etc. Several consecutive identical joints can be factorized (e.g. *RRRR* becomes *4R*). Similarly, suspension mechanisms are designated by *sJJJ*.

B. *Structural Design of a Climbing Robot*

Structural design should answer questions such as "how many wheels" and "what nature for the inter-axle and suspension mechanisms". The answers are tightly connected with the specifications of the design problem. The main concern of this work is to design a vehicle with climbing capacities. We will focus on the frontal climbing of a simple obstacle such as a single step, a ground slope discontinuity separating a low level surface from a high level surface with a sort of vertical wall. This problem is typically encountered by a vehicle such as a wheelchair in front of a pavement border. Similar but different future problems could be the climbing of a hump or a staircase but the solutions may be rather different.

Other requirements were partially enumerated at the end of Part II. The vehicle should use a minimal number of wheels mounted on articulated frame and legs, with a minimal number of actuators and possibly internal DOF. Leg and frame mechanisms should be as simple as possible.

1) *The Exploring Wheel Paradigm*

The minimal number of required wheels can be defined using what we call "the exploring wheel" paradigm [13]. It is well known that the minimal number of supporting contacts to ensure stability for a solid body is three. This means that there should be at least three wheels on the vehicle to ensure stability without any active control. This has already been experimented on vehicles such as side-cars or small utility vehicles. They hardly had success, probably because of non-symmetry and delicate dynamic behavior.

For climbing vehicles, our idea is to use a variable number of wheels in contact with the ground. During climbing, a minimum of three wheels will ensure vehicle stability while the fourth will be the "exploring wheel", going on top of the obstacle for finding a new contact point.

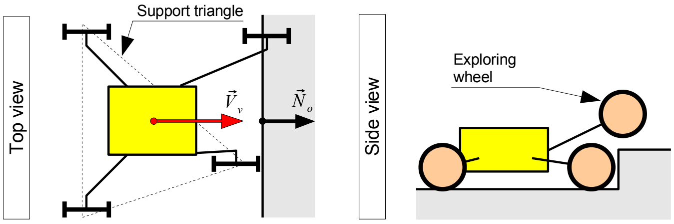


Figure 2. The Exploring Wheel Paradigm.

After that, another wheel becomes the exploring wheel and the process iterates. Before and after the climbing phase, the vehicle relies on all the wheels.

Fig. 2 represents a four-wheel vehicle using the exploring wheel paradigm. The number of four wheels is a good compromise between simplicity and stabilization capacities. Four wheels are ideal for transporting a central payload with good stability. Of course, a higher number of wheels could be used but this goes against the simplicity rule. Five and seven-wheel vehicles are extremely rare and the odd numbers of wheels lay the stress on the problem of the last wheel location. Putting it in the center of the frame (Micro5 [7]) is not ideal for payload volume. Six and eight-wheel vehicles are more common but they are generally complex because of combined steering mechanisms, reserving them to heavy and all-road utility and military uses.

2) *Finding Inter-Axle and Suspension Mechanisms*

The next problem is to determine the mechanisms to guide the four wheels of the climbing vehicle. Frontal climbing is assumed, with no attempt to steer during climbing. This means the inter-axle mechanism I_1 is supposed to be locked. Each wheel is considered as a thin cylindrical or toric body that can be symbolized by a disk. The plane of the disk should be kept parallel to the sagittal plane of the vehicle (*XZ* symmetry plane) and vehicle climbing should be initiated with an ascending movement of the exploring wheel W_{11} in its plane Π_{11}. This means any type of ascending trajectory may be suitable (Fig. 3), provided it is obtained with a simple mechanism. As the self-rotation of the exploring wheel has no importance for exploring, the two components of the wheel center position should be defined in plane Π_{11}. This means at least two translations in the *X* and *Z* directions should be allowed: the *X* translation for bringing the wheel towards the obstacle; the *Z* one for lifting the wheel over the obstacle. The *Y* translation is allowed during lifting but the track width of the vehicle should not change after landing on the upper part of the step.

These mobility requirements on the exploring wheel may be satisfied by a great number of solutions. It may be a central frame with warping capacities, which is interesting because of a unique central actuator that is capable of alternatively lifting

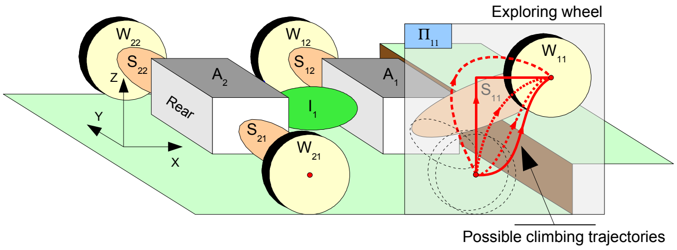


Figure 3. Several possible trajectories of the exploring wheel during climbing.

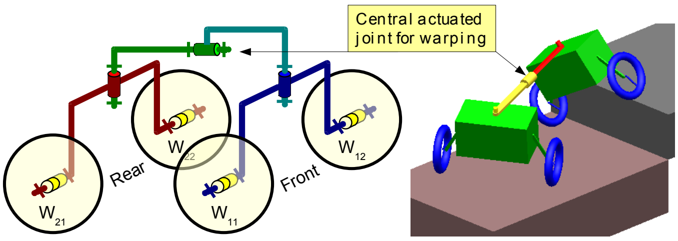


Figure 4. The OpenWHEEL *i3R* robot: kinematic graph & Adams model [13]

one of the wheels, depending on the equilibrium state. This solution was developed for our OpenWHEEL *i3R* prototype (Fig. 4, [13]) and is currently experimented at several scales.

It may also be four dispatched leg-mechanisms allowing the same mobility to each wheel (Fig. 5).

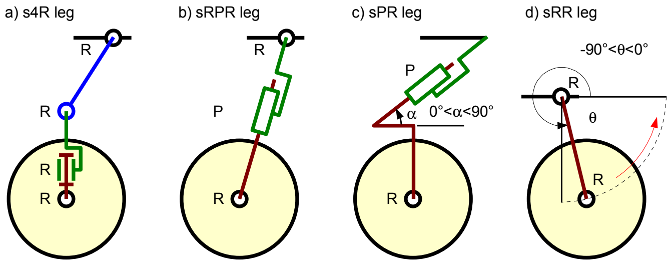


Figure 5. Kinematic graphs of various legs that may provide lifting ability.

The leg mechanism may have a high DOF, such as the *s4R* mechanism of the Hylos robot. Because of high DOF and serial structure, the mechanism must be reinforced for better stiffness (Fig. 5a). Another type of leg could be the *sRPR* structure. When the leg is quasi-vertical, the prismatic joint may also include a suspension system (Fig. 5b). Both solutions need two DOF for positioning the exploring wheel. This could even be reduced to only one DOF for extreme simplicity, provided the wheel goes frontward and upward simultaneously. In this case, the X and Z displacements are coupled. The *sPR* leg fulfills the requirements if the direction of the prismatic joint is orientated with a correct α angle (Fig. 5c). A sliding joint with non linear trajectory, such as one of the B-spline trajectories shown on Fig. 3 may also be considered. Another interesting solution is the *sRR* leg structure. The frontward-upward movement is obtained in the "south-east" part of the circular trajectory of the wheel center (Fig. 5d).

Of course, there is a great number of feasible kinematic graphs for frame and leg-mechanisms. Current work is in progress to enumerate extensively all the possible mechanisms. In this paper, we only try to show the design process that led us to choose the *sRR* leg mechanism for its minimal DOF and mostly for its interesting climbing abilities. They will be presented and detailed in section IV.

3) The 4sRR Vehicle Architecture

With four identical *sRR* legs, we obtain a vehicle structure that we call *4sRR*. This structure has already been used on several robots (Fig. 6).

In the nineties, Jet Propulsion Laboratory developed several spatial exploration robots such as Gofor (Fig. 6a, [14]) or NanoRover (Fig. 6b). The *sRR* leg structure was chosen and has several interests. It allows good adaptation to irregular grounds. The circular movement of the wheel center allows vertical and longitudinal combined movements. This was used mainly for suspension and stabilization on these robots. However, to our knowledge, there was no attempt to use the combined frontward-upward movement for developing a climbing strategy. In 2004, the authors developed a *4sRR* version of the OpenWHEEL platform (Fig. 6c) with hub-wheels and suspension arms. The climbing actuators are not yet included on the photograph.

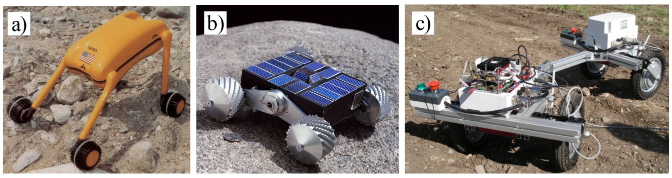


Figure 6. Three existing versions of sRR robots:
a) Gofor, JPL, 1992 [14] b) NanoRover, JPL, 1994 [14] c) OpenWHEEL 4sRR

A remaining design problem is to ensure steering capacities to the vehicle (preferably without skid). One solution is to include a revolute joint close to the wheel center with an axis perpendicular to the wheel axis. This can be seen on the *s4R* Hylos architecture. The difficulty is to keep this steering axis more or less perpendicular to the ground surface while steering, which generates control complexity. On other JPL robots such as SRR (Sample Return Rover), this steering joint is guided by a pantograph, thus allowing a simpler control. Locating the steering revolute joint at the root of the leg is another solution but it does not keep the rolling direction and a complementary mechanism must be added. The simple solution that was finally chosen is an inter axle *iR* mechanism with a vertical-axis steering-joint located between the axles (Fig. 7). As mentioned before, this joint is locked during climbing phases, when only three wheels touch the ground.

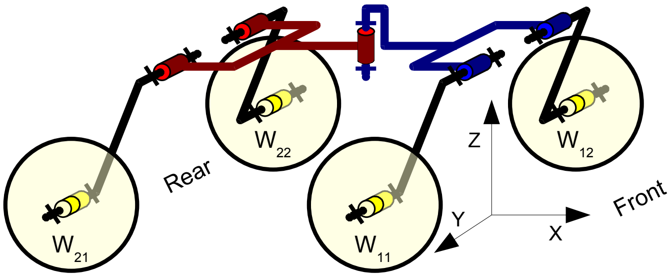


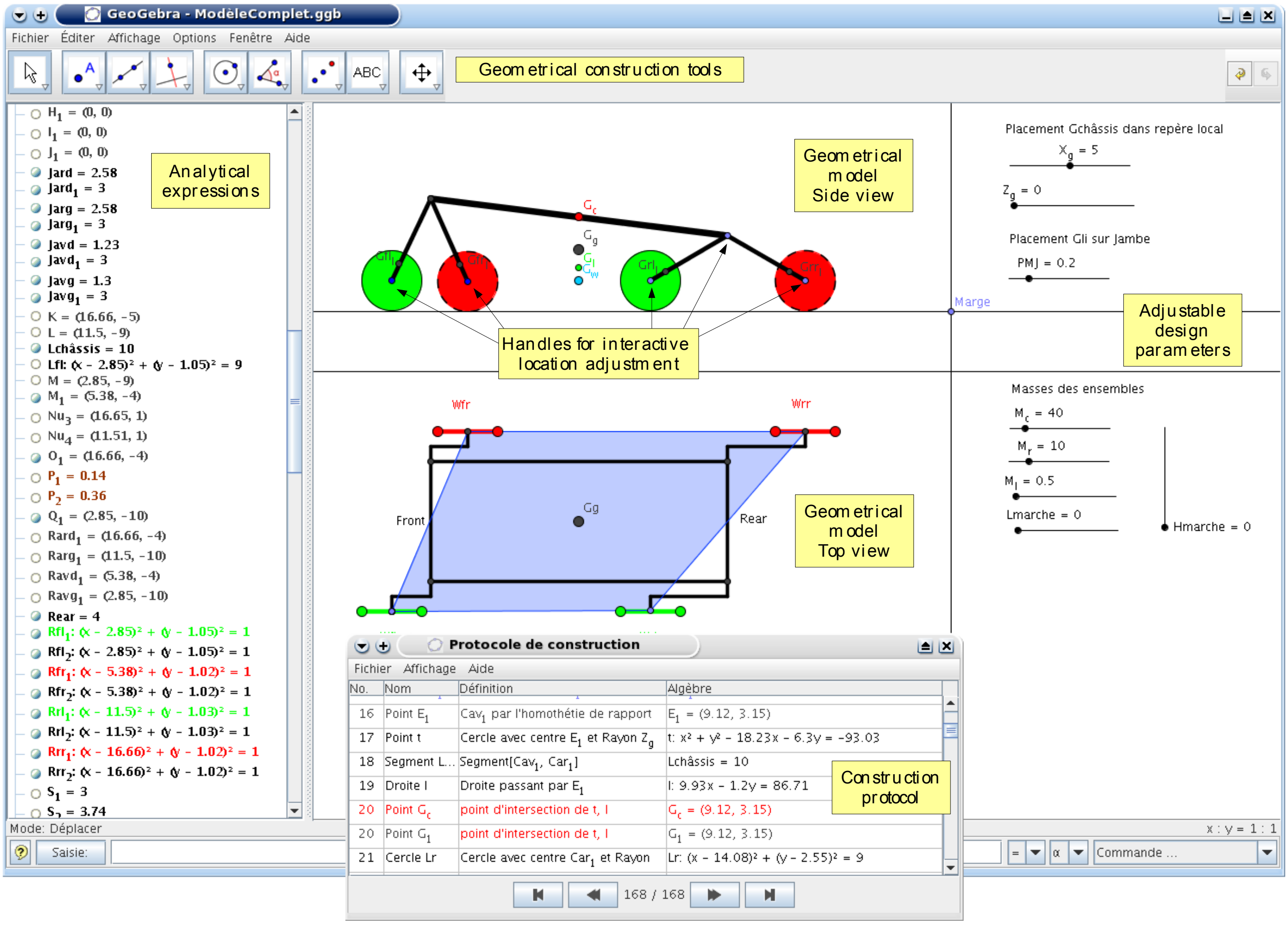
Figure 7. Kinematic graph of the chosen OpenWHEEL *iR-4sRR*.

IV. Designing a Climbing Sequence with a 2.5D Model

This section describes an original method for obstacle climbing with the *iR-4sRR* robot that was designed in section III.

A. Qualitative Design with an Interactive Geometry Sketcher

To describe the *4sRR* OpenWHEEL robot, a simple model has been built using an interactive geometry sketcher named GeoGebra [4]. This is a free software that is regularly updated and is particularly interesting for geometric demonstrations and preliminary design problems. It has some common points with the sketcher module of a CAD software but is dedicated to bi-dimensional euclidian geometric constructions. Graphic entities such as points, lines, vectors and circles are available.



```
H1 = (0, 0)
I1 = (0, 0)
J1 = (0, 0)
Jard = 2.58
Jard1 = 3
Jarg = 2.58
Jarg1 = 3
Javd = 1.23
Javd1 = 3
Javg = 1.3
Javg1 = 3
K = (16.66, -5)
L = (11.5, -9)
Lchâssis = 10
Lfl: (x - 2.85)² + (y - 1.05)² = 9
M = (2.85, -9)
M1 = (5.38, -4)
Nu3 = (16.65, 1)
Nu4 = (11.51, 1)
O1 = (16.66, -4)
P1 = 0.14
P2 = 0.36
Q1 = (2.85, -10)
Rard1 = (16.66, -4)
Rarg1 = (11.5, -10)
Ravd1 = (5.38, -4)
Ravg1 = (2.85, -10)
Rear = 4
Rfl1: (x - 2.85)² + (y - 1.05)² = 1
Rfl2: (x - 2.85)² + (y - 1.05)² = 1
Rfr1: (x - 5.38)² + (y - 1.02)² = 1
Rfr2: (x - 5.38)² + (y - 1.02)² = 1
Rrl1: (x - 11.5)² + (y - 1.03)² = 1
Rrl2: (x - 11.5)² + (y - 1.03)² = 1
Rrr1: (x - 16.66)² + (y - 1.02)² = 1
Rrr2: (x - 16.66)² + (y - 1.02)² = 1
S1 = 3
S2 = 3.74
```

Placement Gchâssis dans repère local

$X_g = 5$

$Z_g = 0$

Placement Gli sur Jambe

PMJ = 0.2

Masses des ensembles

$M_c = 40$

$M_r = 10$

$M_l = 0.5$

Lmarche = 0

Hmarche = 0

No.	Nom	Définition	Algèbre
16	Point E_1	Cav_1 par l'homothétie de rapport	$E_1 = (9.12, 3.15)$
17	Point t	Cercle avec centre E_1 et Rayon Z_g	t: $x^2 + y^2 - 18.23x - 6.3y = -93.03$
18	Segment L...	Segment[Cav_1, Car_1]	Lchâssis = 10
19	Droite l	Droite passant par E_1	l: $9.93x - 1.2y = 86.71$
20	Point G_c	point d'intersection de t, l	$G_c = (9.12, 3.15)$
20	Point G_1	point d'intersection de t, l	$G_1 = (9.12, 3.15)$
21	Cercle Lr	Cercle avec centre Car_1 et Rayon	Lr: $(x - 14.08)^2 + (y - 2.55)^2 = 9$

Figure 8. The geometric OpenWHEEL *4sRR* robot model with GeoGebra software.

Geometric operations can be performed such as building a middle, intersecting curves, creating a tangent, etc. Each entity has also an algebraic representation: points are associated with a pair of coordinates, circles and lines with their analytic equation. This is very useful for the designer because it permits to parametrize a model with variables and to adjust it interactively when parameters are changed.

Fig. 8 presents the GeoGebra model of the robot. Because of 2D limitation, two views of the same 3D model are constructed: a side view and a top view. Interactive changes on one automatically have repercussions on the other. This is what we call a 2.5D model.

The side view is used to set up the geometric configuration of the robot. Each wheel center can be moved and the pitch angle of chassis can be adjusted. The model is independent of the scale and length unit so the notation *lu* will be used to represent length units. The considered design parameters are the following:

- Components dimensions: frame length (10 lu by default on the figures), leg length (3 lu), wheel radius (1 lu).
- Obstacle height (3 lu by default, as high as the leg).
- Mass m_c and center of mass G_c of the chassis: X_{Gc} is the longitudinal position and Z_{Gc} the altitude of G_c in local coordinates. By default, G_c is centered on the frame and has a zero altitude (no extra payload). m_c equals 40 mass units by default.
- Mass m_l and center of mass G_l of the four legs: the altitude of the center of mass of each leg can be adjusted but will be set by default at 0 (bottom of the leg). This means the mass will be concentrated at the end of the leg.
- Mass m_w of each wheel. By default, it is fixed at 10 units, so the total mass of the wheels is the same as the mass of the chassis. This is reasonable if the actuators, typically heavy components, are supposed located inside the wheels (hub-wheels).
- Global center of mass G_g is automatically computed by GeoGebra according to (1).

$$G_g = \frac{m_c . G_c + 4m_l . G_l + 4m_w . G_w}{m_c + 4m_l + 4m_w} \qquad (1)$$

It can be noticed that several implicit hypotheses were assumed: masses are supposed concentrated in centers of masses; non deformable bodies are assumed; contact of the wheels on the ground are punctual; no roll angle is considered. This last assumption keeps sense: even if the vehicle may roll in real life, frontal climbing may be performed without roll.

B. *Static Equilibrium as a Design Constraint*

A major design constraint is to guarantee static stability of the vehicle during the whole climbing process. As we use the exploring wheel paradigm, the vehicle will be supported by three or four wheels during climbing. Stability is obtained when the projection of the center of mass on the support polygon is included inside the polygon. This criterion can be graphically checked on the GeoGebra model because the computing of G_g is automatic, as well as the construction of the support polygon, either quadrilateral or triangular.

Moreover, it is interesting to express a criterion giving a numerical value for the stability margin. To compute this margin, the quadrilateral or triangular support polygon is built at each phase of the climbing process. Then segments perpendicular to each side of the polygon and going to the projection of G_g are drawn. The stability margin S may be computed as the minimum length of S_i, the length of these segments, as expressed by (2). Fig. 9 shows construction of stability parameter for each type of support polygon.

$$S = min\ (S_1, S_2, S_3, S_4) \text{ or } S = min\ (S_1, S_2, S_3) \qquad (2)$$

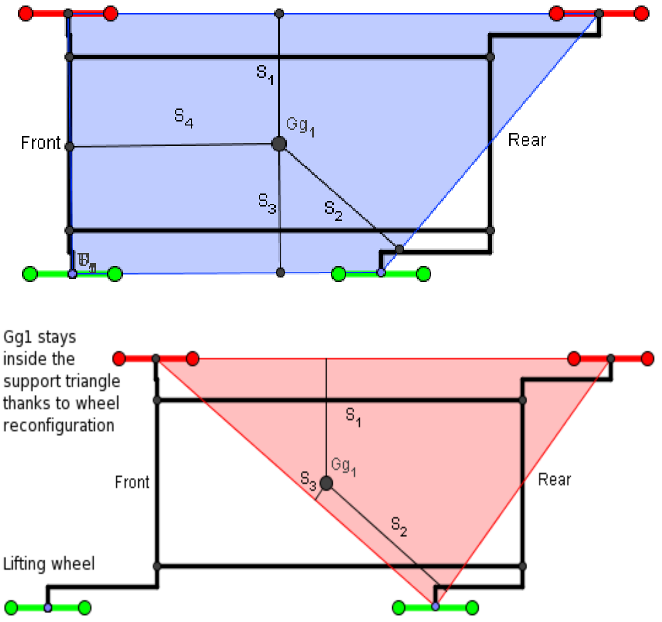


Figure 9. Stability margin for a quadrilateral and triangular support polygon.

C. *The proposed Climbing Sequence*

The exploring wheel paradigm and the GeoGebra model were used jointly to design a continuous series of poses of the OpenWHEEL *4sRR* platform that ensure permanent stability. Fig. 10 and 11 present a climbing sequence for frontal climbing of a single step obstacle. The process is split into sixteen stages. Each stage represents a discrete state of the robot but motion continuity is assumed between stages. To go from one stage to the next one, a single “functional motion” is necessary. It is a motion that can be described in term of function (e.g. “ lifting wheel W_{12} ”). The notion of stage is also justified from the control point of view. The process is split in two stages at a specific time to emphasize a discontinuity on one of the control laws (i.e., one or several actuators changing state or reversing). The sixteen stages are grouped into six phases from A to F that are described below:

- Phase A (Stage 1) is the rolling approach of the obstacle.
- Phase B (Stages 2-5) is the climbing of W_{12}. It is decomposed into several stages: reconfiguration to improve stability (Stage 2); lifting W_{12} (Stage 3); stable rolling on three wheels towards obstacle (Stage 4); landing W_{12} on top of the obstacle (Stage 5).
- Phase C (Stages 6-9) is the climbing of W_{11}. The reconfiguration stage 6 brings W_{21} as close to W_{11} as possible before its lifting (Stage 7). Lifting is obtained by reverse rotation of the leg backwards, which is compatible with rolling closer to the obstacle (Stage 8). Finally, W_{11} lands on top of the obstacle (Stage 9).
- Phase D (Stages 10-12) is the climbing of W_{21}. It is shorter because the robot is already stable for lifting wheel W_{21} and there is no need for any reconfiguration phase.
- Phase E (Stages 13-15) is the climbing of W_{22}.
- Phase F (Stage 16): conclusive rolling on the obstacle.

V. OPTIMIZING THE CLIMBING SEQUENCE

Using a 2.5D GeoGebra model, we have proved that this climbing sequence is feasible and allows to climb obstacles as high as the leg. Photographs of a reduced Lego model (Fig. 10-11, third column) also demonstrate that this process is correct even on a real model bypassing the simplifying hypotheses of section IV-A. This preliminary design work opens many tracks for future researches.

First, it seems that other climbing sequences are possible. The one that is presented is not unique. Exploring the available solutions may be done by using continuity between stages, integrating design rules and making design choices that creates branching in the design tree.

Another interesting perspective is to optimize a given climbing sequence. Looking at Stage 3 in Fig.10, it can be seen that the stability margin may be improved by rotating rear legs even more, thus enlarging the longitudinal gap between W_{21} and W_{22}. Bringing W_{21} to the rear improves the stability margin S by moving the global mass center G_g to the rear. Bringing W_{22} to the front simultaneously improves S by enlarging the support polygon and deteriorates S by moving G_g to the front. The change on S is globally positive but non linear with respect to the θ angle of the legs. However, the pitch angle of the vehicle is much higher. This is associated to an uncomfortable and dangerous movement. Expressing the analytical equations of the model is currently in progress and will be used to obtain an optimization problem where two antagonist objective functions are optimized: the stability margin S should be maximized and the pitch angle should be kept as horizontal as possible.

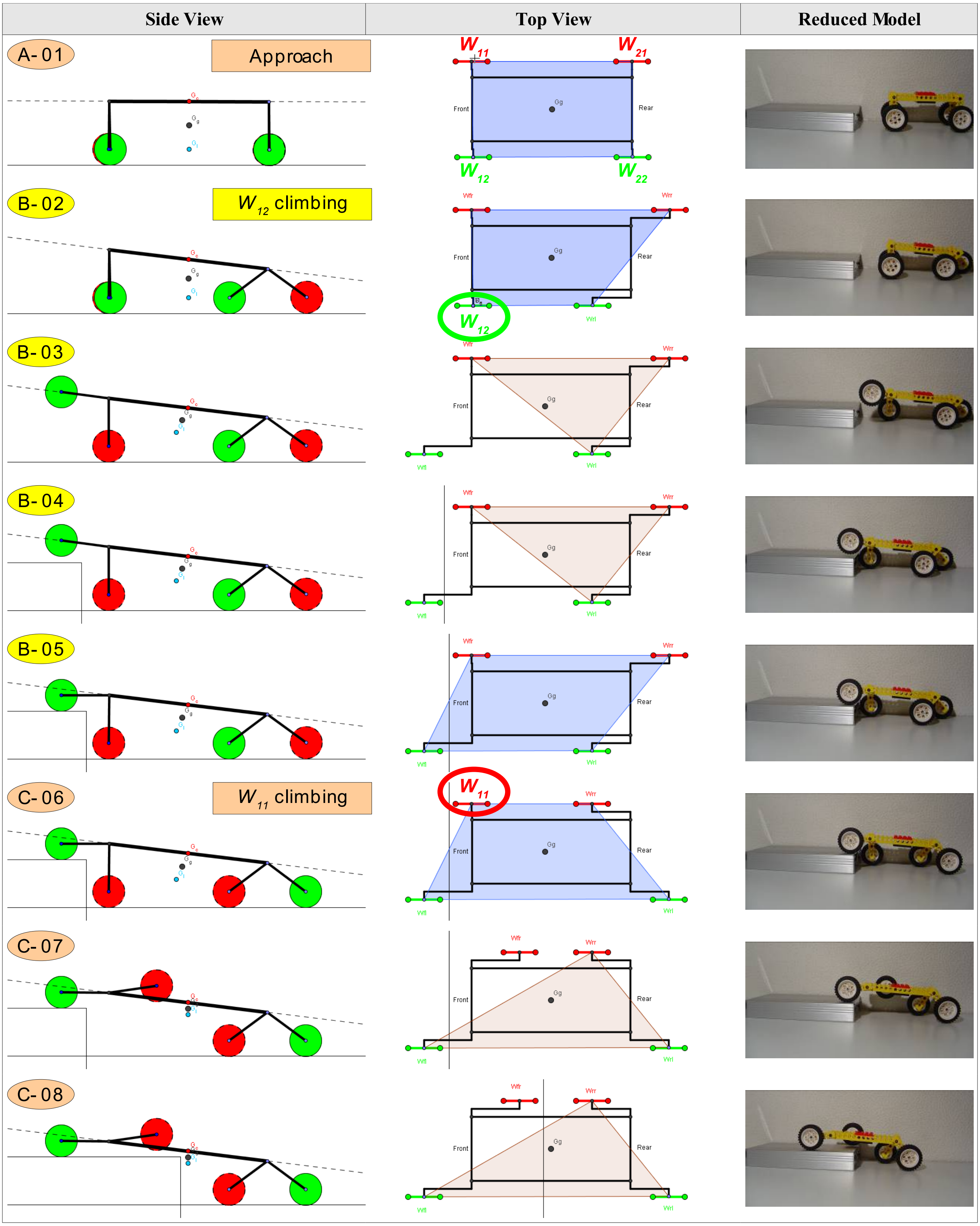


Figure 10. The proposed climbing sequence of OpenWHEEL *4sRR* in six phases and sixteen stages (Stages 01-08).

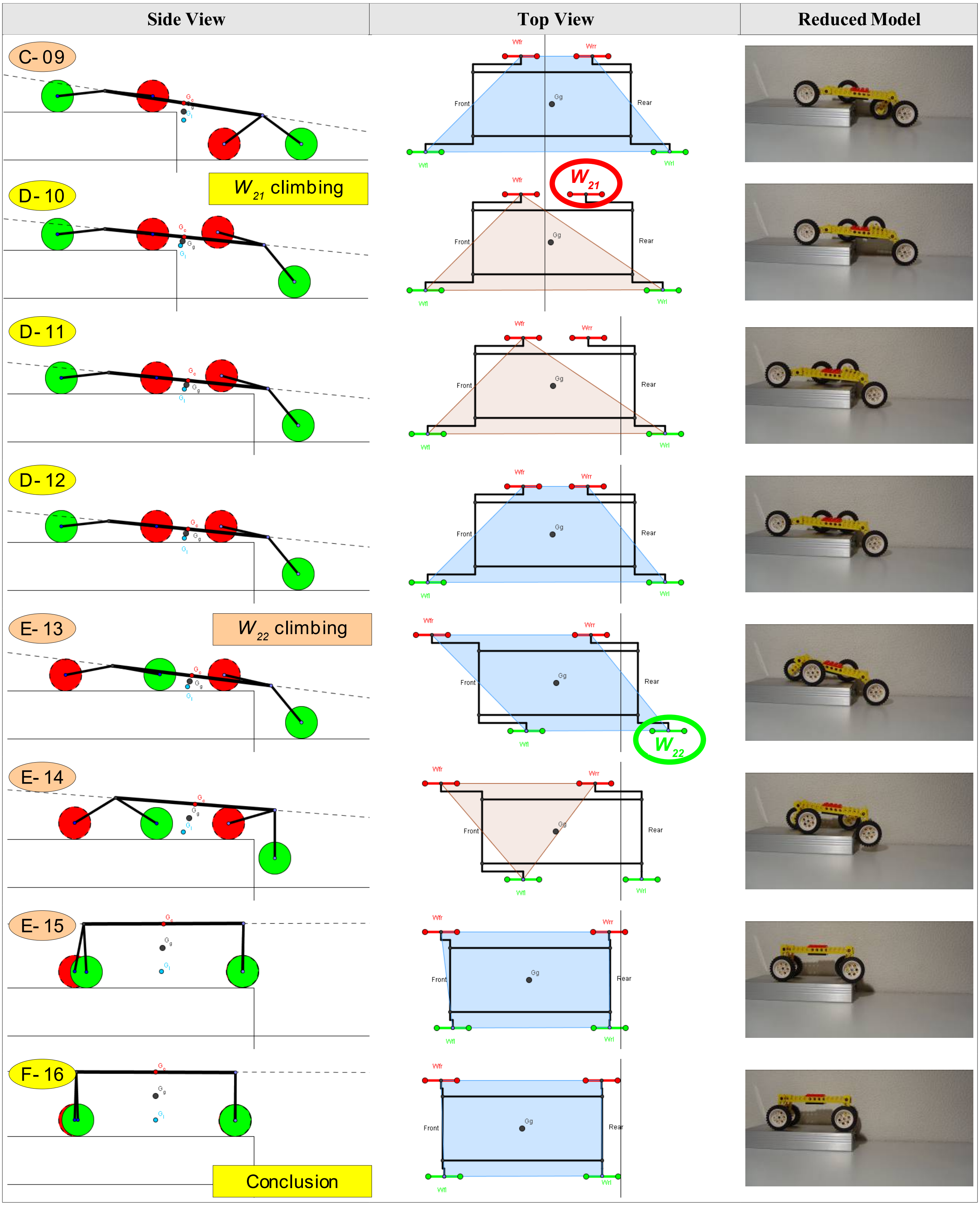


Figure 11. The proposed climbing sequence of OpenWHEEL *4sRR* in six phases and sixteen stages (Stages 09-16).

As we can see on Stage 14 in Fig. 11, the fourth wheel W_{22} is delicate to lift because G_g is very close to the edge of the support triangle. To raise W_{22}, combined control on the three other legs and wheels is needed to ensure stability. Optimizing the stability margin S can be performed for stage 14 only. It consists in optimizing simultaneously two types of parameters: mass and geometric parameters on one side, that affect the entire climbing process; kinematical parameters of the controlled joints on the other side (eight wheel and leg angles), that only have a local effect on the selected phase. However, as the phases are ordered, changing the kinematical parameters on one phase may have consequences on the subsequent phases. It appears clearly here that optimizing the climbing sequence must be done by taking into account simultaneously structural and kinematical parameters on the entire climbing sequence. This is a tough problem currently investigated by the authors.

VI. Conclusion on the Results and Remaining Work

This work presented a general method for designing and modeling a vehicle or mobile robot with an optimal obstacle-climbing mode. The case of all-terrain vehicles climbing a single step was presented. The design method was decomposed into three levels: defining a design workspace; exploring solutions via structural synthesis; building an optimization problem to perform dimensional design.

This paper presented a non-exhaustive approach for the two first levels. The design workspace was built considering the existing mobile robots and deciding to envision the class of vehicles with an axle-structure and wheels mounted on legs (OpenWHEEL architecture). A simplified structural synthesis approach permitted to focus on leg mechanisms allowing two coupled translations in the sagittal plane with only one DOF. A very simple *sRR* leg structure was chosen among several.

The case of the *4sRR* OpenWHEEL robot was treated with a mixed 2.5D geometrical/algebraical model and GeoGebra software. An obstacle-climbing sequence was designed to ensure permanent static stability of the vehicle. This stability constraint was qualitatively and interactively checked thanks to a stability margin formula that was automatically computed by GeoGebra. The 2.5D model and a real reduced model confirm the feasibility of the approach.

Future work was traced for optimal dimensional design. It should be based on a combined optimization of structural and kinematical parameters with a multi-objective function. The stability margin and the pitch angle should be optimized simultaneously in all the stages of the climbing process. Another difficult topic will be to minimize the number of actuators and to define their state (actuated, blocked or free). An interesting solution may be to use only one actuator on the wheel and a mechanical "switch" to dispatch energy on the leg revolute joint when necessary.

This work on mobile robot design may also serve as a more general reflection on design methodology that transforms a set of constraints into a mechanical solution.

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