EXPERIMENTAL VALIDATION OF STABLE OBSTACLE CLIMBING WITH A FOUR-WHEEL MOBILE ROBOT OpenWHEEL i3R

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Abstract: *This paper describes the experimental validation for stable climbing of an obstacle such as a step with a mobile robot that has only four wheels. The robot structure OpenWHEEL i3R is described, with two axles linked by a 3R intermediate serial mechanism. The climbing process is the interpolation between a series of poses where static stability is guaranteed. Experiments are performed on a reduced scale model including five actuators. The comparison of the real behavior of the robot with the simplified bi-dimensional model initially used brings results to improve design and control of the robot, particularly stability margin and wheel adherence. Conclusions are drawn about this new climbing mode and future work is traced for an improved control.*

Keywords: *mobile robot, wheel, articulated frame stability, obstacle climbing, OpenWHEEL i3R*

1 Introduction

Agile mobile robots are expected to become widely used in a close future, not only for spatial exploration of alien planets. Applications on the earth already exist and prove to be challenging too, particularly in the current sustainable context. A fleet of agile and mobile robots could provide services where a single heavy vehicle cannot do the task. Multiple applications can be imagined: for agriculture, heavy tractors have the disadvantage to compact the soil and could be replaced by a fleet of lightweight mobile robots capable to spread a selective treatment; beaches and polluted areas could be checked and cleaned thanks to a swarm of small robots; in case of a natural disaster in urban area, the casualties could be located via autonomous mobile explorers capable to communicate and to scan the streets and houses.

All these future scenarios require fast and agile robots and this paper describes the agility improvement that may be conferred to a wheeled robot capable to climb obstacles such as a single step or a pavement edge. Stable climbing of these types of obstacles is generally difficult to guarantee for vehicles with only four wheels, which are the most common. This work is based on the OpenWHEEL platform, a generic and opened architecture of mobile robot, particularly on the OpenWHEEL i3R kinematics that was presented in [1].

After a brief overview of some existing agile mobile robots, the paper introduces the OpenWHEEL i3R platform and presents its main principles for locomotion, climbing and stability improvement. It also reminds the principle of the climbing process in nineteen stages, which is the core of this work. Then, the experimental setting is presented as well as the reduced scale robot that was built, including five electric actuators. Experimental results follow, as well as results concerning stability during climbing and robot design for improved stability. Finally, conclusion are presented about the efficiency of this original climbing process and future directions are traced for a better control.

2 Agile Mobile Robots

From a general point of view, locomotion systems can be seen as poly-articulated mechanical systems that interact with environment via a set of unilateral adherent or slipping contacts to the ground. These contacts may change in nature and number according to time and space [2]. Wheels are a very energy-efficient terrestrial locomotion system, because energy is mainly used for propulsion and not lift [3]. Wheels are particularly fast on flat grounds but have difficulties to deal with obstacles and terrain discontinuities.

Several robots offer a hybrid architecture by mounting wheels on legs [4, 5, 6], combining more than two locomotion types [7], or presenting original articulated frames [8, 9] in order to locate and orientate wheels for specific purposes. However, this improvement is often obtained at the price of higher complexity, great number of joints, low stiffness and great number of wheels.

The mobile robots from the OpenWHEEL family share a common architecture based on axles (or pods) joined by intermediate mechanisms. According to the nature of the these mechanisms, one can define an entire family of mobile robots. These robots use wheel propulsion, that is efficient on flat grounds, but enrich the rolling mode with additional modes of motion for higher mobility and enhanced capacities, taking inspiration from robots that can equilibrate themselves (Hylos [4], Workpartner [5], spatial exploration [10] and military robots such as RobuROC6 [11]) and climb high obstacles.

Another characteristics is that motorization is distributed on each wheel, thus allowing more flexibility for designing an original articulated frame suitable for agile mobile robots.

The last property that we want to confer to our robots is mechanical simplicity. The number of actuators should be kept minimal, in the same spirit of reactive and adaptative mobile robots such as Shrimp and Crab mobile robots [12].

3 Locomotion principles of OpenWHEEL i3R

This paper will focus on the OpenWHEEL i3R version that was first described in [1], although other structures were also analyzed in previous work [13].

3.1 The OpenWHEEL-i3R mobile robot

For the current work, a structure with two axles A_1 - A_2 and a serial inter-axle mechanism will be used (Fig. 1). It includes two bodies (F_1, F_2) and three revolute joints (R_0, R_1, R_2) with axes parallel to x, z and z respectively in the

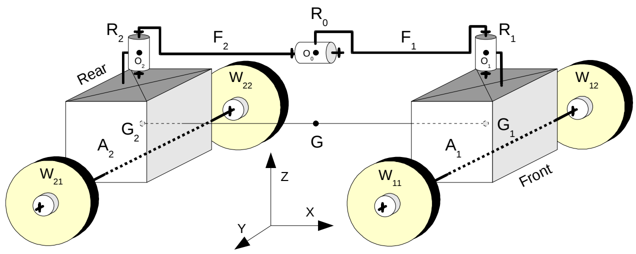

Fig. 1 OpenWHEEL i3R mobile robot structure with two axles A_a.

reference pose of the figure. From now on, this mechanism will be named i3R ('i' for “inter-axle” and 3R for the three revolute joints). For preliminary 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 if both axles A_1 and A_2 are identical.

Joint R_0 is actuated by a high torque actuator so the vehicle can warp its frame and lift one wheel while the three other wheels support the vehicle (Fig. 2). The lifted wheel can be used to go on top of an obstacle and is named the “exploring wheel”. Stability of the robot is ensured if the projection G' of the center of mass G on the ground lays inside the lifting polygon ($P_{12}P_{22}P_{21}$ in Fig. 2).

Joint R_1 - R_2 are located in the middle of axles A_1 - A_2 respectively and allow to steer axles without moving the robot. They are passive joints so steering A_a is induced exclusively by differential actuation of the wheels W_{aw}. This means the OpenWHEEL-i3R robot has only five actuators, one for each wheel and one for frame warping around R_0.

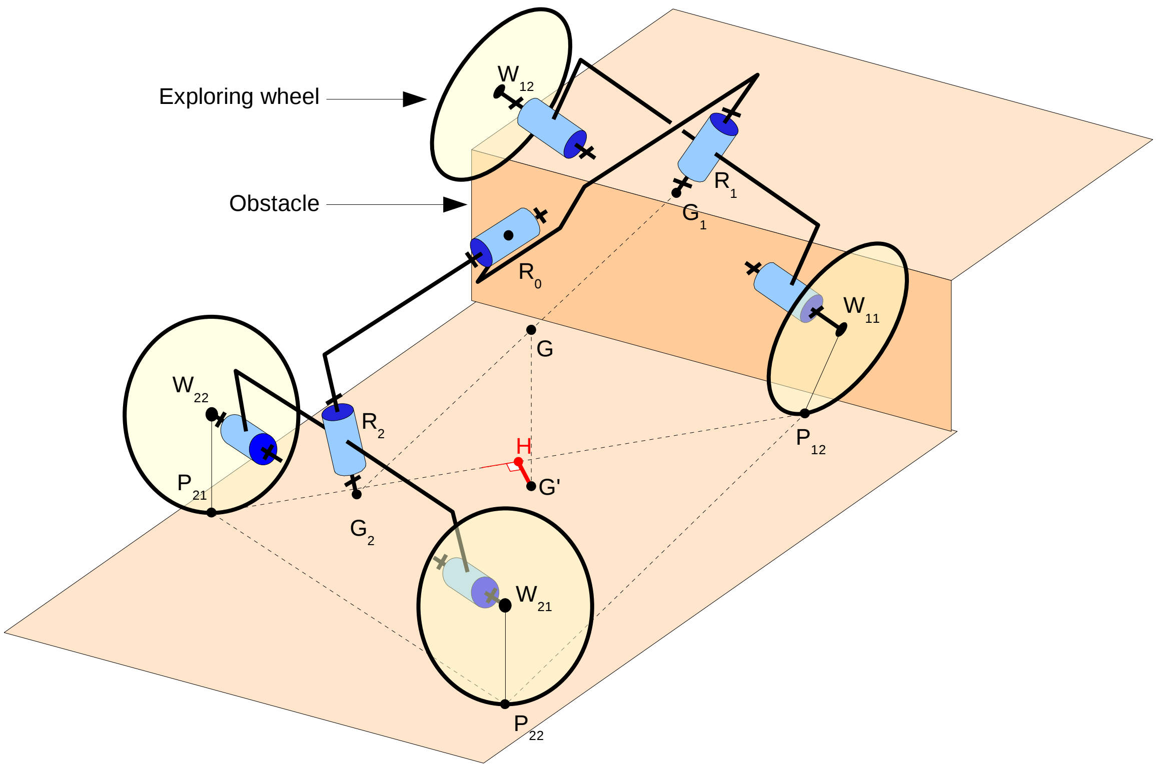

Fig. 2. The concept of exploring wheel (here W_{12}).

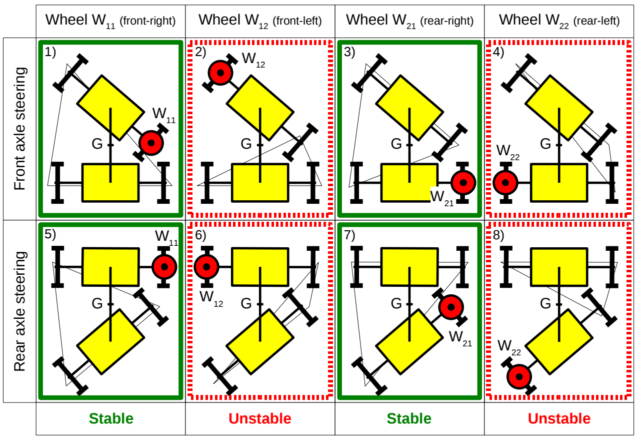

Fig. 3. Stability on 3 wheels occurs if the lifted wheel is inside the turn.

Steering an axle is useful to change the direction of motion but also to maintain static stability of the vehicle on three wheels. Fig. 3 summarizes all possible configurations for turning to the right. It is possible to control the front axle (first row) and / or the rear axle (second row). In both cases, each of the four wheels is lifted for obstacle climbing and static stability of the robot is evaluated. It can be noticed that only four out of the eight possible configurations are stable and keep their center of mass *G* inside the support triangle. 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".

3.2 Description of the climbing sequence in 2D

The stability property of Fig. 3 was used in [1] to construct a climbing process made by a discrete sequence of stable stages. Each stage represents a pose of the robot where static stability is guaranteed. Graphically, this means that the smallest distance of the projected center of mass *G'* to the sides of the lifting polygon is sufficiently big relatively to a characteristic length of the robot. In Fig. 2, this is represented by distance *G'H* which is long enough with respect to e.g. the wheelbase of the vehicle.

When designing the climbing process, a new stage was created in two conditions:

– change in the number of contact points on the ground
– activation of actuators from a different group, among the three groups (axle A_1, axle A_2, central actuator R_0)

Using this logic, the sequence represented in Fig. 4 was built. It is slightly reorganized with respect to the sequence initially presented in [1]. The sequence includes nineteen stages regrouped into seven phases:

– Phase A: bringing front axle A_1 against the obstacle
– Phase B: climbing with wheel W_{11}
– Phase C: climbing with wheel W_{12}
– Phase D: bringing rear axle A_2 against the obstacle
– Phase E: climbing with wheel W_{21}
– Phase F: climbing with wheel W_{22}
– Phase G: un-steering all the axles

The climbing phases B-C-E-F all follow the same construction in four stages:

– Steering the non climbing axle to improve stability
– Lifting the exploring wheel
– Bringing it forward above the obstacle
– Bringing it down to the top of the obstacle

This sequence is expected to function properly but it is not unique. Many equivalent variants can be imagined. For example, wheel W_{12} can be lifted at phase B instead of phase C. Another example concerns stage 4, where no trajectory of the rear axle is explicitly given: the only purpose of this stage is to bring the exploring wheel W_{11} above the obstacle.

This first 2D approach permits to construct and describe a process for frontal climbing on obstacles. However, it is still qualitative and five simplifying hypotheses are assumed:

– negligible mass of the inter-axle mechanism
– non-deformable bodies (i.e. infinite part stiffness)
– small warping rotation-angles to avoid representation of complex 3D poses
– punctual ground-wheel contact with toric wheels
– perfect rolling without slipping assuming that normal forces are sufficient to ensure enough traction.

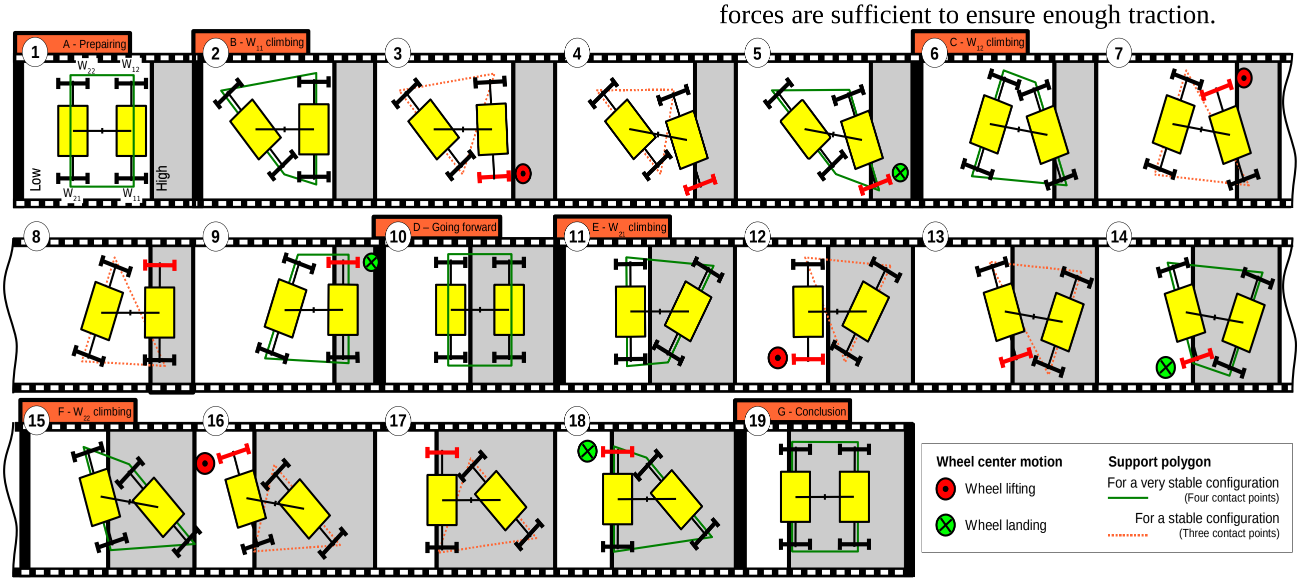

Fig. 4. 2D modeling of a climbing process in nineteen phases.

Although a 3D validation with Adams software gave encouraging results [1], this climbing process has to be validated by experimentation on a real robot.

4 Experimental setting

4.1 Mechanical architecture

This part describes the preliminary implementation of the OpenWHEEL i3R robot at a reduced scale with Lego Mindstorms robotics kit. This kit is interesting for fast prototyping at low cost and preliminary validation of a future version at full scale. The reduced robot is built in a modular way with four sub-assemblies including wheels and actuators (Fig. 5).

The wheel (part 1) has a rubber air tire and excellent friction properties (diameter 49.6 mm, width 28 mm). Each wheel is combined with its own electric motor *E* and a speed reducer to create a motor-wheel sub-assembly with low speed and high torque. The actuator, which is massive (42g) relatively to the other components, is located exactly on top of the wheel to improve normal contact force and at the smallest possible altitude to lower the center of mass. A two-stage speed reducer was used with a transmission ratio of 1/15. An over-constrained frame with redundant bearings and rigid assembly was built around the actuator and fixed to the central-box of the axle via coupling systems (arrows C). The mass of the sub-assembly is 149 g. Each axle includes two sub-assemblies connected to a central box including batteries, control system and infrared communication to the other axle. The total mass of an axle is 633 g.

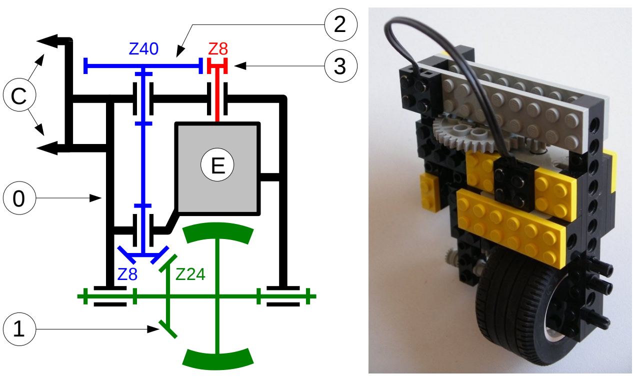

Fig. 5. A wheel sub-assembly with actuator and speed reducer.

The inter-axle mechanism includes a high torque actuated joint R_0 represented in Fig. 6. The actuator is the same as the one used for the wheels (1.1 W of absorbed electrical power, 0.58 W of provided mechanical power with a typical loaded speed at 9V of 200 rpm with a corresponding torque of 3.2 N.cm [14]). The speed reducer is designed to be non-reversible thanks to worm gears and a high ratio of 1/560. Backlash is minimized in joint R_0 thanks to a redundant overconstrained transmission with two worm-gears that also decrease internal stress into the gear teeth.

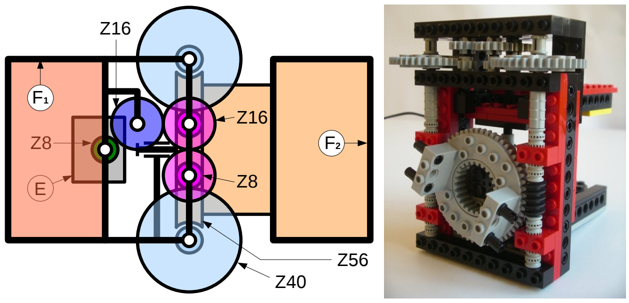

Fig. 6. Structure of the inter-axle speed reducer of joint R_0.

The assembled robot is represented in Fig.7 and weighs 1430 g. Weight dispatching was measured with four scales located under the wheels. The front axle (m_1 = 716 g) appears to be heavier of ten grams than the rear one (m_2 = 707 g), a minor difference. This leads to relation (1).

$$\overrightarrow{G_1G} = m_2/(m_1+m_2)\overrightarrow{G_1G_2} = 0.497\overrightarrow{G_1G_2} \quad (1)$$

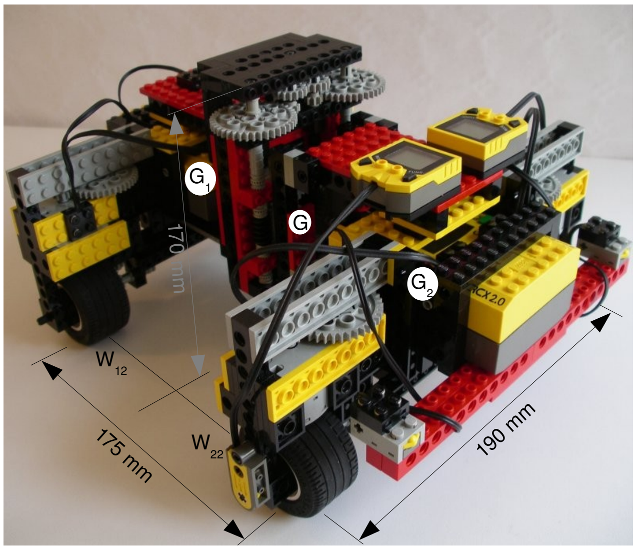

Fig. 7. The assembled reduced model with dimensions.

Due to the degree of overconstraint of a four-wheel vehicle on a flat ground, a singular behavior may occur: for a given wheel, the normal force can vary from zero to its maximum with very small angular variation of the warping angle of joint R_0. This may lead to control problems with non-deformable body hypothesis. Fortunately, a warping experiment on the scales shows that the real behavior is not so extreme. Because of the low tire stiffness, the normal force variation takes around 3 s from the neutral warping position to a complete disequilibrium.

It takes the robot 21 s to pass from the neutral position with four wheels on the ground to a 45° warped position around R_0, an extreme angle for acceptable tire contact on the ground. Lubrication is useful on the high torque R_0 joint and increases warping speed by a factor two. The translation top speed was also measured at 55 mm/s.

The reference obstacle is a flat 55 mm-high obstacle made of cardboard, higher than a single wheel diameter.

4.2 Control programming

Control programs of the robot are implemented in NQC language with BricxCC programming environment [15]. Two separate programs run in parallel: a master one for axle A_1 and a slave one that manages axle A_2 as well as inter-axle warping joint R_0. Modules exchange data through the infrared ports and use a protocol based on message sending and detection loops (Fig. 8). The stage decomposition is reproduced inside the program.

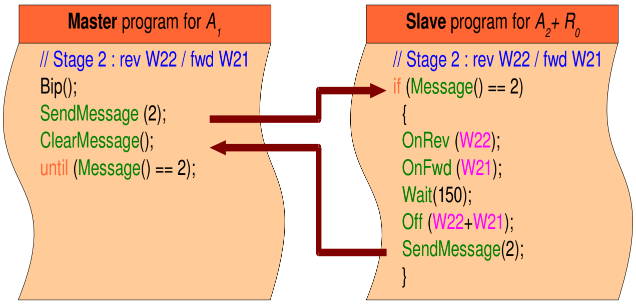

Fig. 8. A sample from the master-slave programs that control the axles.

5 Experimentation

5.1 Climbing process

The purpose of this experiment is to demonstrate the validity of the exploring wheel paradigm for climbing a step with OpenWHEEL i3R. For the moment, actuators are controlled at full speed with open loop control. The analysis of these preliminary results will help us to determine the most suitable sensors that will be added in the final model.

The initial tests were performed with stabilized power supplies for actuators. This minimizes tension variations due to battery power decrease. Final tests used batteries.

It is compulsory to start from the same pose before each climbing attempt. At the beginning, the robot is located in front of the obstacle, axles perpendicular to the central body and parallel to the obstacle wall. The warping central joint is centered (visual marks on the gears of the speed reducer). The climbing process was difficult to debug, particularly for the final stages, because it is not possible to memorize precisely the pose of the robot before a stage. The robot has to be put in the initial pose and all the preliminary stages have to be unrolled for obtaining the requested pose.

Photographs of the climbing process are given in Fig. 9. A video is also available with this paper [16]. Some stages are interesting to comment.

At stage 8, axle A_1 is supposed to steer passively around wheel W_{11} under the influence of the pressure of axle A_2. Unfortunately, the supporting wheel W_{11} started to slip because of insufficient normal force. The proposed solution was to unsteer slightly axle A_2, which induces a coupled lifting of the exploring wheel W_{12}. The contact force on W_{11} became sufficient after this alteration of the initial strategy.

Stage 10 is supposed to be a simple task where the robot goes forward with the same control for all the wheels. Unfortunately, real experiment show that no wheel have the same advance as its neighbor because of subtle differences between normal forces. This induces small steering.

During ascending phases of an exploring wheel (stages 3, 7, 12, 16), it is possible to actuate it for getting a bonus tangential force against the wall. It is however facultative.

The landing stage of the exploring wheel (stages 5, 9, 14, 18) may become optional if the exploring wheel was lifted previously just at the good level to climb the obstacle. This is however a bit delicate because the obstacle height must be measured and flexibility of the frame must be predicted.

Experiments showed that subtle drifts may occur on some parameters, leading to important changes several stages later. The climbing process is quite sensitive to initial conditions and may drift easily without proper control. Additional sensors will be required for precise monitoring of the climbing process. Angular coders will be added for each of the actuators in the next version of the robot (four wheels, central warping joint R_0). Two other coders on passive joints R_1 and R_2 are needed for detecting end of angular travel.

Rolling without slipping is not guaranteed either. Each wheel has a variable capacity to transmit a torque that depends on the normal force that maintains it against the ground. The current strategy was defined by keeping in mind a mental representation of normal contact forces on the wheels during the process. This graphical representation is based of the position of the projected center of mass onto the lifting polygon (distance *HG'* in Fig. 2). Sensors that give the normal force on each wheel may be extremely useful in the full scale version of the robot for traction control.

5.2 Improving design and control for climbing stability

The control laws suitable for climbing the considered obstacle are given in Fig. 10. The total duration of the climbing is 89 s. Phases B-C-E-F are similar in length. Phases A-D-G are ten times shorter than the others. The stages used to warp the R_0 joint (stages 3-5-7-9-11-12-14-1618) take the majority of the climbing time (71 s i.e. 80%).

The warping angle never exceeded 26° on the considered obstacle (stage 3) and speed reduction must be very high to provide sufficient torque. This leads to architecture considerations relative to the power of the central actuator. For this prototype, the central actuator has the same power as the four others on the wheels. Warping is slow but energy saving. The next version of the robot needs a more powerful central actuator for faster warping. However, more power means heavier actuator so a compromise should be found.

These experiment also allow to compare the real 3D behavior with the simplified 2D model represented in Fig. 4. It can be noticed that rear axle A_2 has much more difficulty to climb than front axle A_1. This asymmetric behavior did not appear in the 2D model. It is probably due to the fact that a pitch angle α brings the center of

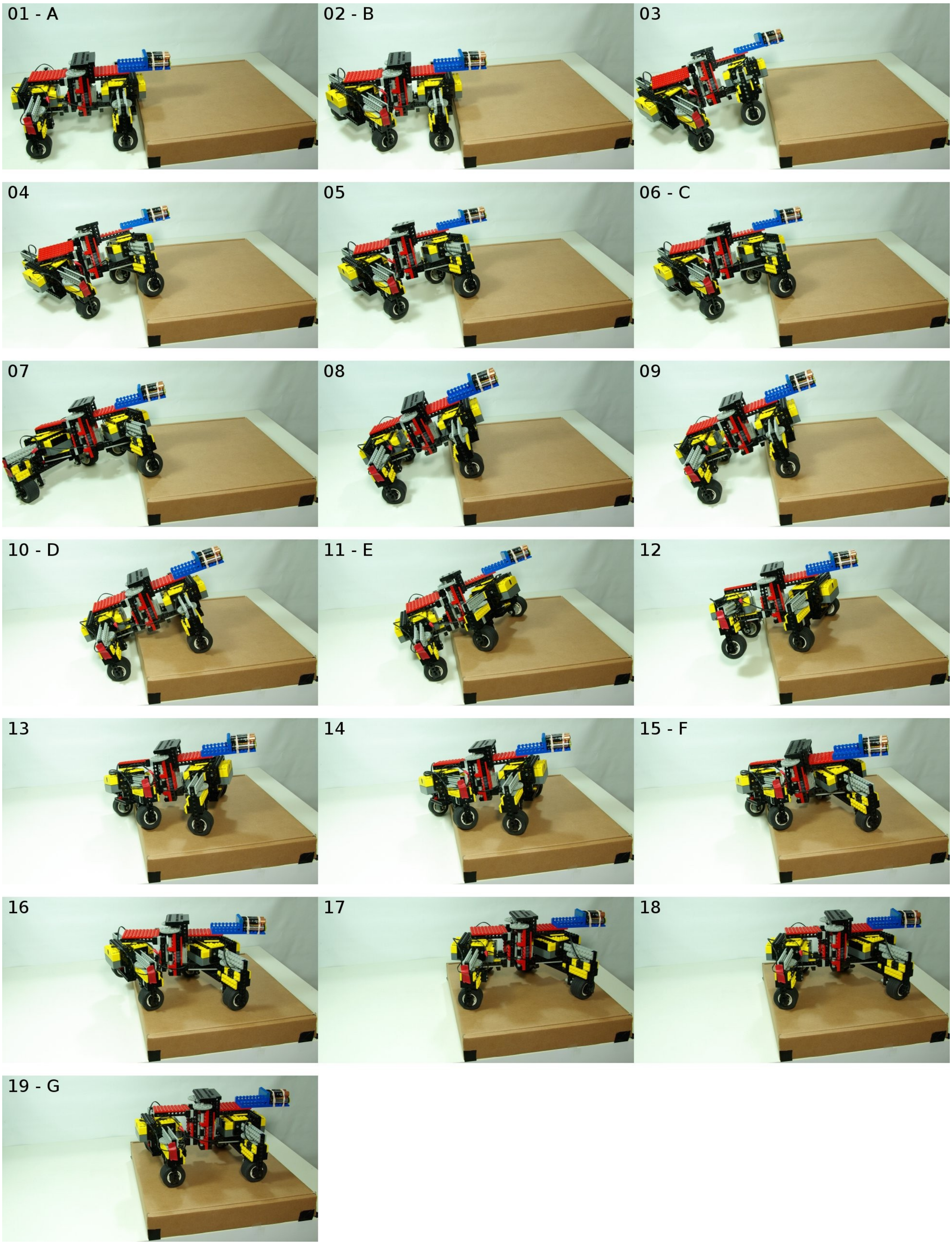

Fig. 9. Experimenting the climbing process in nineteen phases on an actuated and autonomous reduced model of the OpenWHEEL i3R.

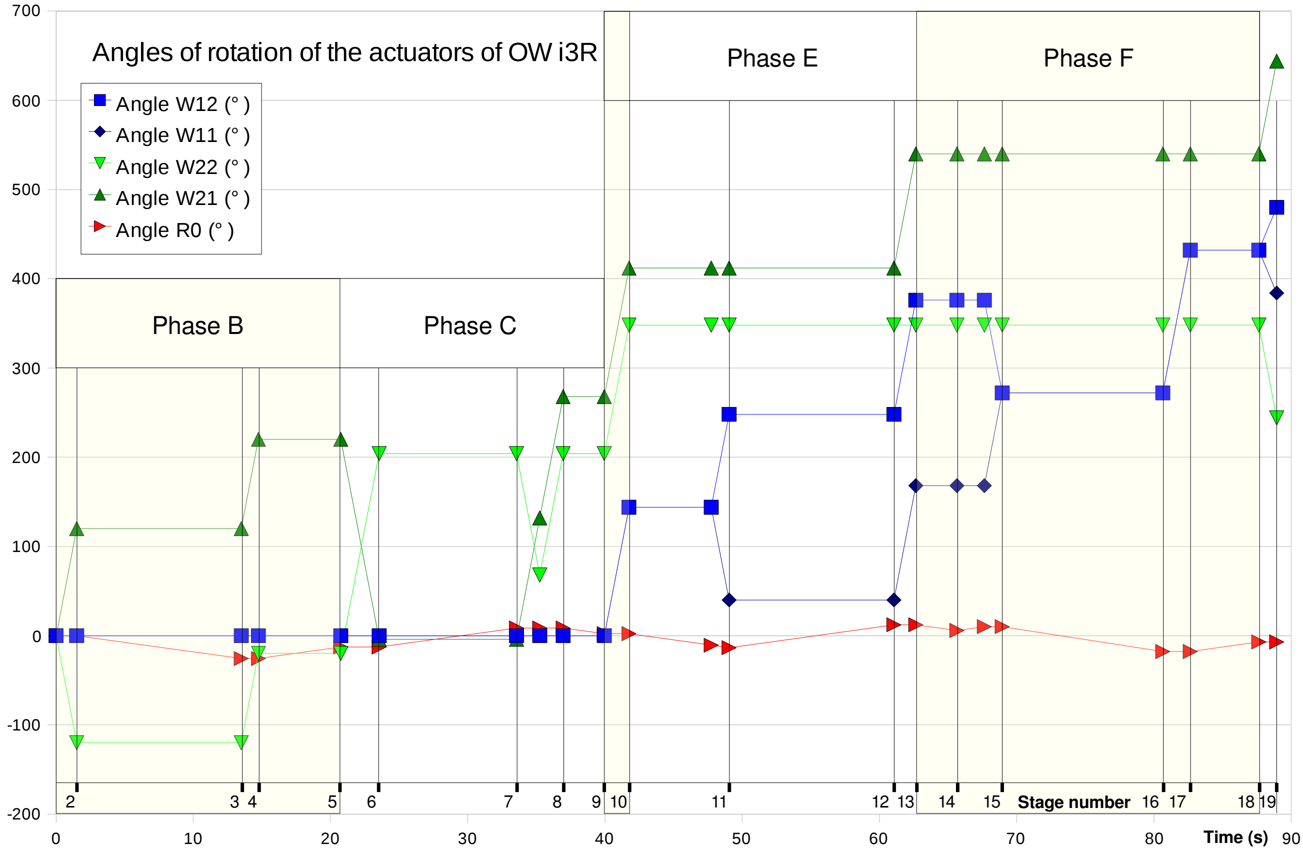

Fig. 10. Control laws of the five actuators of OpenWHEEL i3R.

mass G backwards of a value $Z_G \sin(\alpha)$ with Z_G being the altitude of G. This deteriorates the margin of stability at stages 12 and 16. In this case,

$$Z_G = 82\,mm \quad (2)$$

For improving climbing of the rear axle, we propose to put an additional mass at the front of the robot. It can be seen in Fig. 9: a blue frame loads five batteries used as a counterweight. The minimal number of five was determined experimentally. The additional mass is 144 g (9% of the total). It is located in front overhang and leads to a new mass repartition: m_1 = 938 g on the front axle and m_2 = 639 g on the rear. So the global center of mass G moves forward:

$$\overrightarrow{G_1G} = m_2/(m_1+m_2)\overrightarrow{G_1G_2} = 0.408\,\overrightarrow{G_1G_2} \quad (3)$$

With G_1G_2 being the wheelbase (175 mm on Fig.7), point G is brought forward of 16 mm, which represents 9% of the wheelbase. This is sufficient to re-equilibrate the climbing ability of both axles with a pitch angle of 11°. This counterweight may be seen as a payload. In future design, the center of mass will be brought forward for better climbing ability.

Another phenomenon that occurs in 3D and was neglected in 2D is that, as soon as there is a non null pitch angle α, steering an axle A_a of an angle θ_a cannot be done without a coupled rotation θ_0 on the warping joint R_0. This means that stages 6-9-11-15, where there is a reconfiguration via steering, will require and adjustment of θ_0 .

The good metrics for measuring climbing ability is not the wheel diameter because a robot with wheels of different diameter could also use the same climbing strategy. A suitable parameter can be the altitude Z_G of the center of mass G. The obstacle height is 55 mm, which is 67% of the altitude of G. This preliminary result is interesting. It means that if we built a version of this robot of the size of an all-terrain car, the altitude of G would be around one meter high and the robot could climb obstacles as high as 67cm, which is impossible for a car. This demonstrates the interest of the OpenWHEEL i3R concept for fast rolling displacement as all wheeled vehicles do but also an improved obstacle climbing capability.

6 Conclusion and future work

This experimental work allowed to prove the feasibility of climbing a single step obstacle with OpenWHEEL i3R, a mobile robot with only four actuated wheels and a central warping actuator. The robot climbed an obstacle as high as 67% of the height of the center of mass of the robot, which is an adimensional way to represent the performance. A climbing process in nineteen stages and seven phases was successfully tested to guarantee permanent stability when climbing, one exploring wheel being lifted over the obstacle while the three other wheels ensure stable support thanks to preliminary steering. This result seems to be close to the maximum performance for this particular implementation of the robot and a counterweight of 9% of the robot mass had to be added on the front to easy climbing of the rear axle.

Control during climbing is a delicate task. Open loop simplified control used in this case allowed to better understand subtleties of the robot behavior during climbing and showed that both the pose of the robot and the contact forces must be taken care of to keep stability at a sufficient level. Wheel traction may become insufficient to bring the exploring wheel forward (stage 13). Some additional sensors should be added in future version: angle encoders for the rotative actuators; angle sensors to measure passive steering of the axles; force sensors to monitor that the normal contact forces of the wheels on the ground are sufficient and to maintain a stability margin. With these sensors, future work will build a control strategy capable to adapt to the obstacle and to avoid wheel slipping according to the robot pose.

This work showed that new types of articulated frames may greatly improve mobile robot capacities. Future robots with actuators located in the wheels may differ completely from the automobile vehicles with a central engine that are built for the moment. The OpenWHEEL i3R concept allows to imagine an all-terrain vehicle of the size of existing four-wheel all-terrain cars that could climb one-meter-high obstacles. Other applications can be imagined, such as agile wheelchairs for disabled, quad ATVs or service field robots. Work is in progress to build a bigger version of OpenWHEEL i3R (one meter long, one hundred kilograms) that would take advantage of a more powerful central actuator for faster vehicle warping.

7 Acknowledgements

The authors wish to thank the TIMS Federation (Technologies for Innovation, Mobility and Safety) of Clermont-Ferrand University, France, for supporting and funding the OpenWHEEL project. They also thank T. Feutry and V. Bouzik [17] for their active contribution.

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