OpenWHEEL i3R - A new architecture for clearance performance

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Abstract

This article describes the development of a sequential geometric model in order to control our all-terrain robot OpenWHEEL i3R and refine the robustness of its climbing strategy. This robot is a 4-wheel mobile robot based on an articulated chassis that allows to overcome obstacles up to two thirds of the height of its centre of gravity by warping its central joint. The kinematics and a motion strategy in 19 steps have been jointly validated on two small-scale and one full-scale prototype. Permanent static stability is guaranteed during climbing, by actuating only the central joint of the robot, in addition to the wheels. This principle of minimal actuation, and some other particularities of the geometric model, are presented in this work.

Keywords: wheeled robot, minimally actuated frame, obstacle climbing, sequential geometric model.

1. Introduction

Our studies are devoted to the elaboration of an innovative principle for climbing obstacles within the framework of an open architecture for designing wheeled robots, keeping the efficiency of the wheels while improving mobility and static stability by a good compromise between climbing performance, complexity, stiffness and technological pragmatism. This last point clearly includes a reasonable number of wheels and actuators. The application field of the climbing method and paradigms described in this paper is then more precisely located at the interface between commercial wheeled vehicles and mobile robots with original kinematics.

Vehicles are considered as systems driven by their own propulsion device and intended to move people and payloads in an outside environment, most of the time controlled by a human operator. Usual applications are transport, military activities, agriculture, and leisure. Mobile robots have a higher degree of autonomy and are more specially designed to challenge with complex reproducible tasks. For this aim, they usually have reactive behaviour with the help of sensors for internal and external perception, actuators, control laws and strategies for interpretation of sensory data and decision (Devy 1995). They are usually intended to exploration or inspection tasks, often at low speed. The mechanical architecture can allow mono or multi-modes of locomotion. Most of the time, all the wheels are motorised. Mobile robots differ with chassis internal mobilities, than can be passive (without actuators) or include some actuated mobilities (active robots). Additional sensors allow to adapt to unknown factors and to changes of the ground (reactive robots).

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 (Bekker 1969). Wheels are particularly fast on flat grounds but have difficulties to deal with obstacles and terrain discontinuities. Climbing obstacles remains a challenge for these systems. Qualities such as low power consumption, reliability and adaptability to the ground insuring a good locomotion are no more guaranteed. In that case, legged type of locomotion regains interest (discrete discontinuous ground contacts). It needs complex control and require high energy for high speed. Several robots offer a hybrid architecture by mounting wheels on/with legs, e.g. (Grand 2004, Halme 2003, Hirose 1996, Nakajima 2004), combining more than two locomotion types (Michaud 2003), climbing by hopping (Kikuchi 2008), or presenting original articulated frames (Apostolopoulos 2001, Lacroix 2002, Rollins 1998) in order to locate 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.

All these previous considerations also allow to think that there is enough room for generic and modular mechanical architectures, possibly close to commercial vehicles, developed from new climbing strategies with very slightly actuated frame. Focus is particularly set on new displacements for climbing over obstacles and terrain discontinuities while ensuring static stability. Wheeled locomotion, a mode not really present in nature, should be developed even more towards all-terrain locomotion.

The paper introduces a modular architecture and the associated climbing mode making possible to obtain high climbing capacities, while remaining slightly actuated, without complex legs to keep good stiffness, and sufficiently generic to be easily adaptable and transposable on existing wheeled vehicles systems (e.g. All Terrain Vehicles (ATV) or quad bikes). The global motorization is chosen to be distributed on the wheels, with one electric motor attached to each wheel, for compactness and genericness. Only one internal supplemental motor will be located at the centre of the frame as described in the following section 2. Section 3 shows our small-scale and full-scale demonstrators, and the geometric model used to control and improve the obstacle climbing strategy is presented in section 4.

2. Kinematics and climbing strategy

OpenWHEEL paradigm

OpenWHEEL is the name we give to a family of rovers with articulated frame and/or innovative suspensions. The name “i3R” defines its kinematics: “i” for inter-axle, highlighting the central mechanism joining the axles; “3R” for the number of revolute joints present in the robot: one passive steering rotation per axle and one central active warping joint. This kinematics allows good performance, *i.e.* the speed of the wheeled propulsion combined with the agility offered by an articulated chassis. Kinematics of OpenWHEEL i3R was first defined in (Fauroux 2006) and features an articulated frame allowing the rover to climb on obstacles and a small number of wheels (4 wheels = 3 wheels for stability + 1 exploring wheel).

A sequential motion strategy was jointly developed to cross an obstacle with a step-profile. The kinematics and strategy are crafted to be "kept as simple as possible", while remaining within the limits of static stability. They were designed to be easy to transfer to a commercial vehicle such as a quad bike or ATV for transport tasks or semi-autonomous inspection, in a spirit of robustness and reliability, notably for the possibility of bearing payload on the field.

OpenWHEEL is likely to meet a variety of obstacles. The steepest possible obstacle to find in the external environment is a step-like obstacle. The motion strategy is built with the assumption that the horizontal length of this step is sufficient to permit the robot to stand on top of it on its four wheels. The robot is also capable to cross a hurdle (i.e. a thin and high obstacle) using modified movements. For the moment, there is no guarantee that it can behave properly with successive steps (*i.e.* a staircase), like (Gonzales 2009) for example.

OpenWHEEL kinematics

The kinematic structure of OpenWHEEL i3R is shown in Fig. 1. The robot is made of two axles named (A_a) with *a* the axle number (1 for front, 2 for rear). Wheels are numbered (W_{as}) with *s* the side number (1 for right, 2 for left). The axles are linked by a serial inter-axle mechanism made of two frames (F_1) and (F_2) connected by three revolute joints R_k and thus named i3R ('i' standing for “inter-axle”).

The central joint R_0 is actuated for the warping of the structure. The R_1 and R_2 joints are passive and are used for dual Ackermann steering. They also give a longitudinal mobility that allows to bring the exploring wheel on top of the obstacle (i.e. wheel W_{12} on Fig. 1). Analysis showed that the robot has a mobility of 3 while rolling and 4 while climbing (Bouzgarrou 2009). Stability is ensured when the projected centre of mass G' lays inside the lifting triangle ($P_{11}P_{21}P_{22}$ in Fig. 1). Distance HG' gives a geometric representation of the stability margin.

Each link (L) of the robot has a local reference frame R_L (O_L, x_L, y_L, z_L). The origins O_{F1} and O_{F2} of the links (F_1) and (F_2) are defined confounded and R_{F1} represent the reference frame of the whole robot. The angles α, β, γ represent respectively the yaw, pitch and roll of frame R_{F1} with respect to ground reference R_0. Angles θ_0, θ_1, θ_2 measure respectively the frame warping and axle steering of (A_1) and (A_2). They are defined by: $\theta_0=(\widehat{y_{F1}, y_{F2}})=(\widehat{z_{F1}, z_{F2}})$, $\theta_1=(\widehat{x_{F1}, x_{A1}})=(\widehat{y_{F1}, y_{A1}})$ and $\theta_2=(\widehat{x_{F2}, x_{A2}})=(\widehat{y_{F2}, y_{A2}})$. Only θ_0 is actuated. The steering angles θ_a are indirectly controlled via the self-rotation θ_{as} of the actuated wheels, with $\theta_{as}=(\widehat{x_{Was}, x_{Aa}})=(\widehat{z_{Was}, z_{Aa}})$. The centre of mass of axle (A_a) is denoted G_a and supposed located on line (O_{Aa}, z_{Aa}), at the middle of the axle (axles are laterally equilibrated).

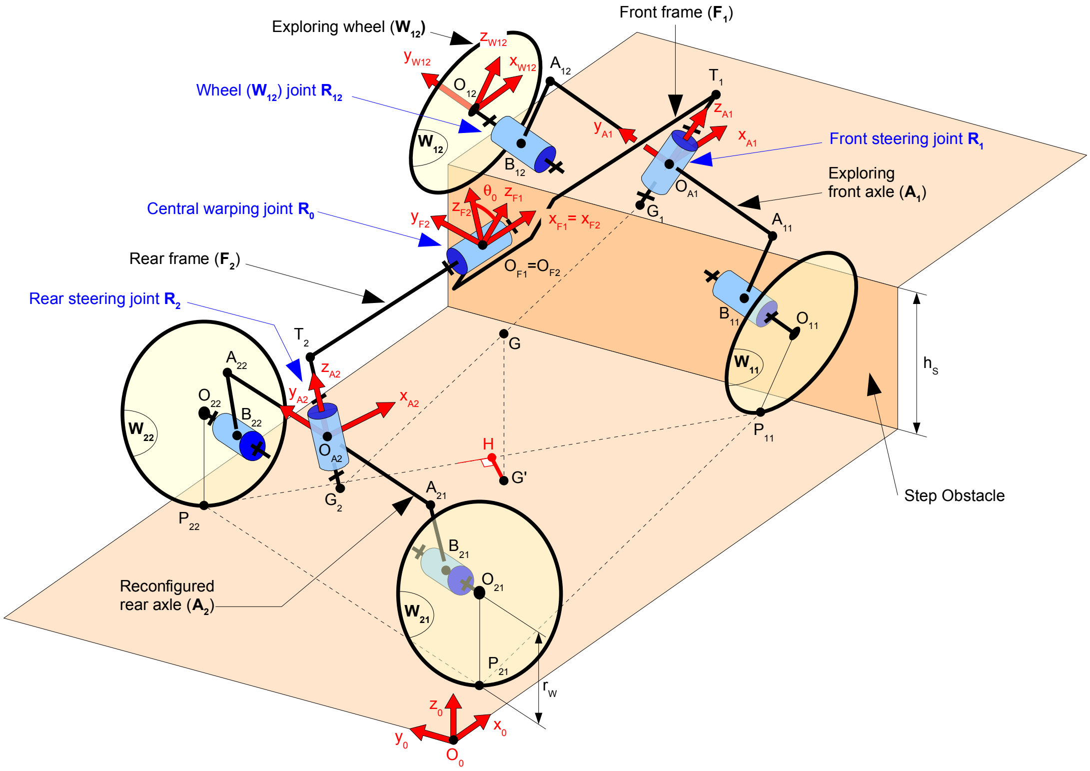

Fig 1 : Kinematic structure of OpenWHEEL i3R (Fauroux 2009).

OpenWHEEL climbing strategy

The climbing process is a sequence of stages that connect successive characteristic poses of the robot. All the poses & stages are stable, *i.e.* when a wheel is lifted, the projection of the centre of gravity is kept within the support triangle formed by the three other wheels.

In order to climb the obstacle, each wheel has to become successively the "exploring wheel", being lifted over the obstacle while the robot lays only on three contact points P_{as}. Before lifting the exploring wheel (W_{as}), the robot must be controlled in such a way that the wheel $(W_{a's})$ of the same side s but of the other axle a' is brought as close as possible to (W_{as}). This allows to maintain G strictly above the triangular lifting polygon and to guarantee stability. The robot motion during climbing is described qualitatively in Fig. 2 and the stability margin, represented in 3D on Fig. 1 by distance *HG'* is approximated here in 2D in the top view.

A sequence of nineteen stable key positions was presented in (Fauroux 2006) and motion interpolation between them allows to obtain a complete process with quasi-static stability. The process is divided into seven phases and nineteen stages. Phase A brings the vehicle against the obstacle. Phase B is for (W_{11}) climbing. It is decomposed into four stages: stage 2 where the robot reconfigures the rear axle (A_2) to bring (W_{21}) close to (W_{11}); stage 3 where (W_{11}) is lifted via θ_0 warping; stage 4 where (W_{11}) is brought forward because of rear axle (A_2) pushing forward; stage 5 where (W_{11}) lands on top of the obstacle via θ_0 unwarping. Phase C unrolls the same process for (W_{12}). Phase D brings the second axle in contact with the obstacle. Similarly, phase E and F are for (W_{21}) and (W_{22}) respectively. The final F phase serves only to unsteer θ_1 and θ_2. The whole procedure was validated first by an Adams 3D multi-body model (Fauroux 2006) and by a small-scale demonstrator.

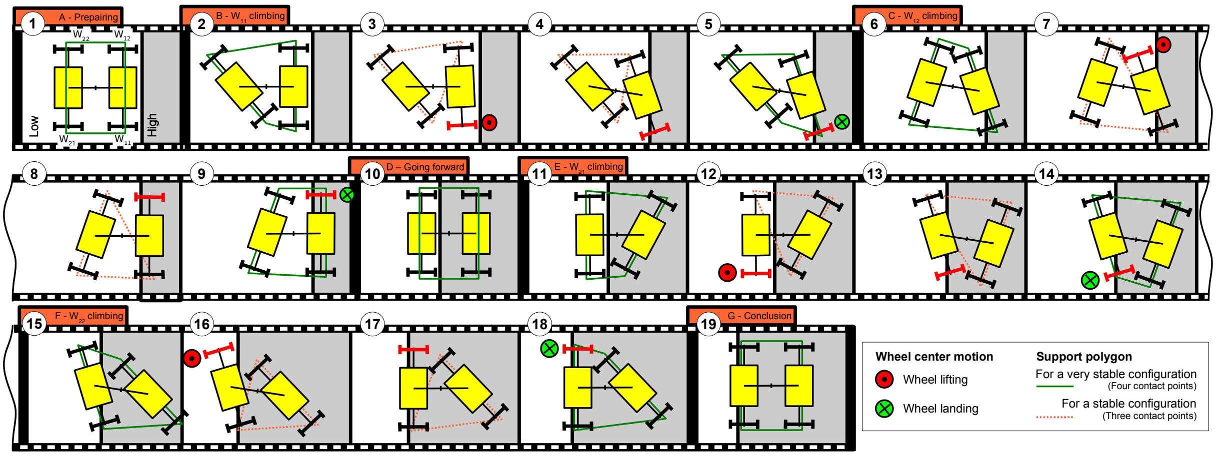

Fig 2 : Climbing process of OpenWHEEL i3R in 19 stages.

Controlling the robot requires to write a geometric model for each stage, which is named in this paper a *sequential geometric model*, because the model of stage *n+1* strongly depends on the sequence of motion during stages *1* to *n.*

3. Demonstrators at two scales

Before building a full-scale OpenWHEEL i3R robot, which is a long, complex and expensive work, two low scale models were built using Lego Mindstorms robotics kits. These models have several benefits:

- they allow to validate the climbing process, which does not depend on the scale,
- small size and weight allow working safely in a confined space,
- modular elements permit to adjust some settings easily with minimal re-design,
- the high level control hardware (sensors, programmable logic controller) and software architecture can be kept unchanged at all the scales.

Small-scale demonstrators

Built from Lego Mindstorms RCX elements, the first model, denoted V1 (Fig. 3), operates in open loop because this generation of actuators do not include a coder. It allowed to highlight a number of critical points on certain stages of the crossing (Fauroux 2008).

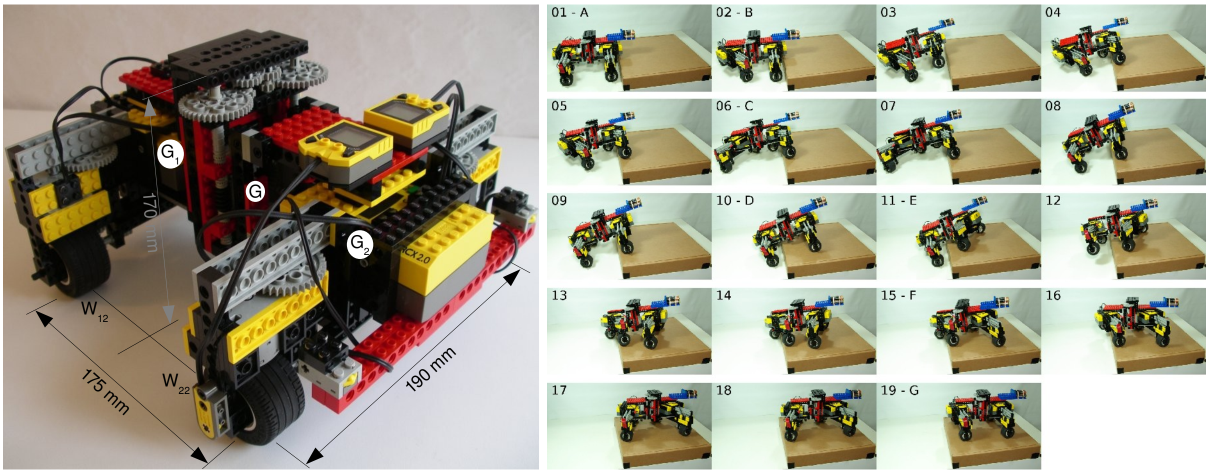

Fig 3 : Small scale version of OpenWHEEL i3R V1 with RCX kit (a). Climbing process (b).

The most critical point is that the tilting of the model may compromise obstacle crossing (Fig. 4). Tilting a vehicle of angle β with a high centre of gravity *G* shifts backward the position of the projected centre of gravity *G'* and induces instability in stages 12 and 16 during climbing of the rear axle. Distance P_2G' is given by equation (1).

$$P_2G'=b\cos(\beta)/2-h_l\sin(\beta) \qquad (1)$$

with b being the wheelbase length and h_l the leg length. The robot seems temporarily heavier from the rear. This phenomenon was analysed in (Fauroux 2009) and required the installation of a frontal counterweight CW (Fig. 4). A qualitative analysis showed that a counterweight of 144g with a robot mass of 1530g, located 90mm forward of G_1 allowed to bring *G* forward of 16mm (9% of the wheelbase length *b* = 175mm) and cured the instability.

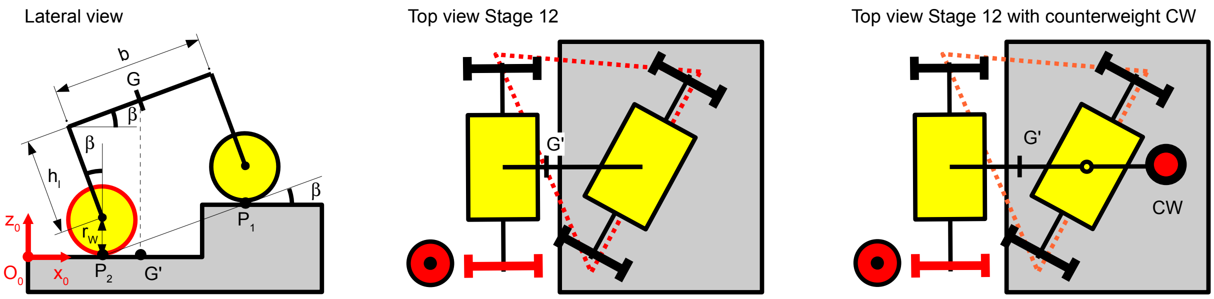

Fig 4 : Obstacle crossing is compromised by tilting angle β and restored by a new mass repartition.

The second noticeable phenomenon is named steering-warping coupling. It was solved by a corrective modification of control and requires a formalized model that will be presented in Section 4. The last phenomenon is the loss of contact adherence when the normal force decreases or where the obstacle blocks the advance of a wheel, and can be avoided by control adjustments or supplemental sensors for collision detection.

Model V1 climbs obstacles of 55mm (Fig. 3b), which seems to be close to the maximum performance for this particular implementation of the robot. The maximum obstacle height does not depend on the wheel diameter and represents 66% of the height of its centre of gravity, which is the metrics we recommend to quantify crossing performance.

A second small scale model, named V2, was based on the Mindstorms NXT next generation kit (Fig. 5). With actuators that include a coder, V2 allowed to test some control laws with closed loops using the NXC programming language, a C like language including a complete NXT API (Hansen 2010). The V2 model has stronger actuators and smaller reduction ratios than V1, which ensures higher dynamics, but still lacks of rigidity.

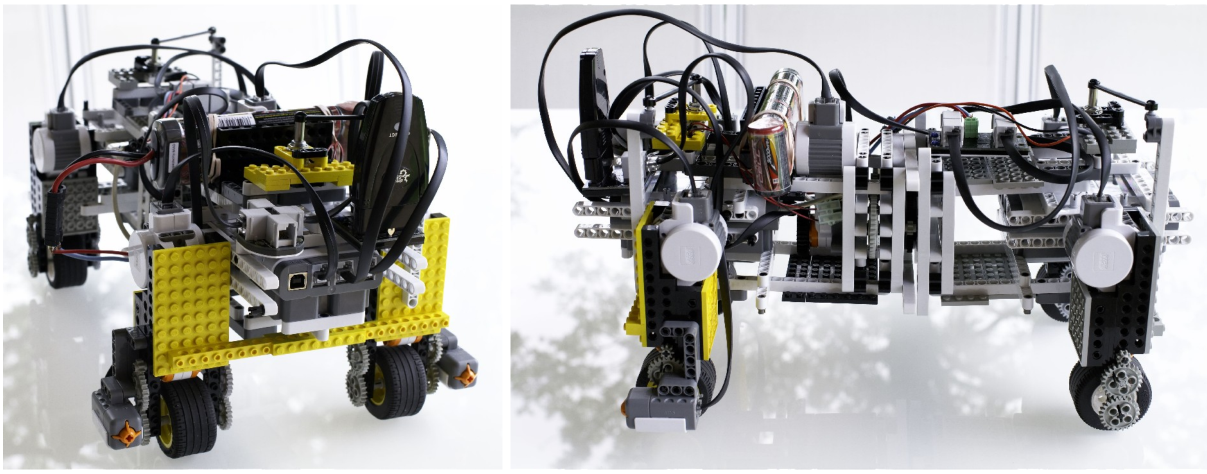

Fig 5 : Small scale version of OpenWHEEL i3R V2 with NXT kit and advanced control.

Several sensors where added in V2, such as steering rotation sensors to measure θ_1 and θ_2 , distance ultrasound sensors to measure horizontal distance and height of the obstacle, contact sensors on the front to start the climbing process and a 3D accelerometer used as an inclinometer to measure the tilt angle. The NXT control program was designed for V2 and to be be directly implanted on the full-scale demonstrator with only scale constant adjustments.

Full-scale demonstrator

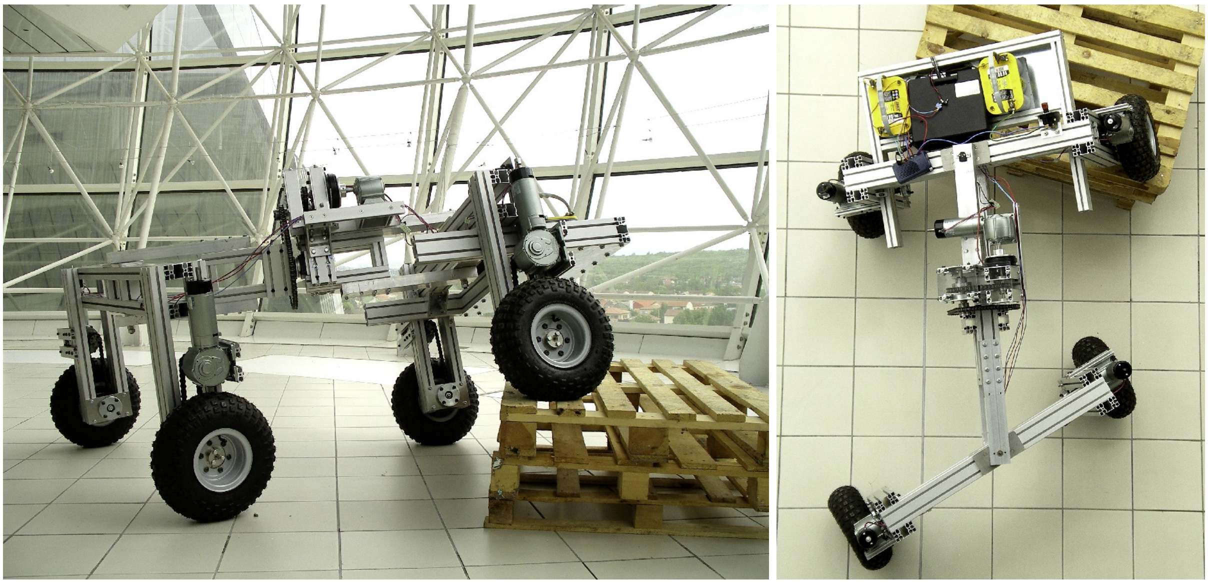

Fig 6 : Full-scale OpenWHEEL i3R V3.

The full scale OpenWHEEL i3R V3 robot is around 1.85m long,1.38m wide, 0.98m high with a total weight approaching 200kg. The robot frame is rigid and made of modular aluminium profile. The five identical 24V DC actuators have a power of 330W each, a nominal torque of 30Nm that can exceed 100Nm for short periods and an incremental coder for control. With a reduction ratio of 10.9, the central mechanism is capable to warp the robot of 45° in only one second, which is fifteen times faster than the small-scale version V1 and may even generate unexpected dynamic loss of equilibrium. This problem can be avoided by adjusting acceleration ramps in the Curtis 1228 DC controllers, that modulate intensities up to 70A. Two or four 12V 48Ah on-board batteries store the energy. V3 is also equipped with a central electric clutch that allows to decouple the warping mechanism when rolling and to guarantee contact for the four wheels whatever the geometry of the ground (no overconstraint).

4. Control and Sequential geometric model

OpenWHEEL i3R can be tele-operated on smooth terrain. However, the step-climbing process is complex and is supposed to be left completely automatic. The pilot has only to choose when to trigger climbing. An approximate control in open loop of the robot was made for OpenWHEEL V1 based on the sequence presented in Fig. 2. Open WHEEL V2 and 3 are controlled in closed loop and use a more detailed sequential geometric model. This requires to write a 3D geometric model for each of the 19 stages. This allows to adjust the model according to the scale of the considered robot and to tune the control strategy to the dimensions of the obstacle. Doing so, smaller obstacles will be crossed with smaller motions, which means a faster, more energy efficient and more stable climbing process.

Design parameters

The considered design parameters are summarised in Table 1. They characterize the geometry and scale of the different versions of the robot.

Name	Definition	OW V1	OW V2	OW V3
b	Wheelbase length T_1T_2	175 mm	260 mm	1210 mm
t	Track width $O_{a1}O_{a2}$	190 mm	151 mm	1250 mm
r_w	Wheel radius	25 mm	25 mm	190 mm
h_l	Leg height	72 mm	105 mm	500 mm
m	Mass	1530 g	2330 g	< 200kg
k_0	Reduction ratio for central joint	560	35	10,9
k_w	Reduction ratio for the wheels	15	3	1,3

Table 1 : List of geometric parameters for the different versions of robots.

Steering reconfiguration for stability

Before lifting the exploring wheel, the stability margin must be increased by steering the other axle. This is done at stages 2, 6, 11 and 15, that is to say the first stage of the climbing phase of each wheel. For instance for stage 2 (Fig. 7), the required steering angle of axle 2 is denoted θ_2^{S2} and must be smaller than $\theta_{a\,max}$, which is defined at $\pi/4$ for design reasons and to avoid the singular configuration where all contact points P_{as} are aligned.

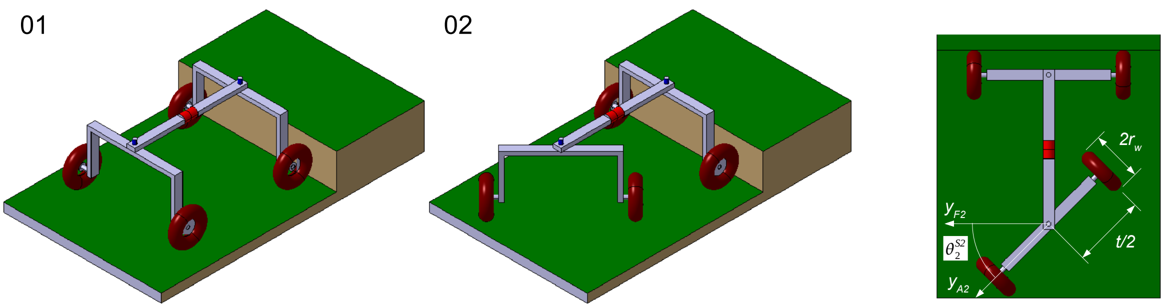

Fig 7 : Model for steering reconfiguration at stage 2.

The kinematics equation (2) based on rolling without slipping of wheels (W_{a2}) gives the opposite rotations θ_{21}^{S2} and θ_{22}^{S2} of the wheels required to generate the steering angle θ_2^{S2}.

$$\theta_{21}^{S2} = -\theta_{22}^{S2} = t\,\theta_2^{S2}/2r_w \tag{2}$$

Written in actuator configuration space, equation (2) becomes (3).

$$\theta_{act\ 21}^{S2} = -\theta_{act\ 22}^{S2} = k_w t\,\theta_2^{S2}/2r_w \tag{3}$$

However, it is not safe to rely on the non-slipping hypothesis. Using the additional steering rotation sensor, a much more robust solution is to increase θ_{21}^{S2} and decrease θ_{22}^{S2} at the same rate until the steering angle θ_2^{S2} reaches the expected value $\theta_{a\,max}$.

Steering-warping coupling

Steering-warping coupling is a phenomenon that concerns stages 6, 11 and 15. In order to anticipate the lifting of the exploring wheel (W_{as}) , the other axle $(A_{a'})$ has to be steered. When the robot is not horizontal any more (*i.e.* the steering axis $z_{Aa'}$ is no more normal to the ground plane), the wheels of axle $(A_{a'})$ cannot stay in the plane of the ground after steering, and one contact is lost. This can be solved by a corrective warping of R_0 .

For example at phase 6 (Fig. 8), if the front frame *(F₁)* is supposed fixed to the ground and submitted to a roll angle α and a pitch angle β with respect to the fixed frame (T_1, x_0, y_0, z_0) , the wheel-centre point O_{21} is calculated by the product

$$O_{21} = R_y(\beta).R_x(\alpha).T_x(-b/2).R_x(\theta_0).T_x(-b/2).R_z(\theta_2).T_z(-h_l).T_y(-t/2).T_1 \quad (4)$$

with R and T being homogeneous matrices for rotation / translation and T_1 being the point defined in Fig. 1. The vertical coordinate of O_{21} in the ground frame (T_1, x_0, y_0, z_0) is

$$z_{O21} = \cos(\beta)[\cos(\alpha)(\frac{-t}{2}\sin(\theta_0)\cos(\theta_2) - h_l\cos(\theta_0)) + \sin(\alpha)(\frac{-t}{2}\cos(\theta_0)\cos(\theta_2) - h_l\sin(\theta_0))] - \sin(\beta)[\frac{t}{2}\sin(\theta_2) - b] \quad (5).$$

z_{O22} can be deduced from (5) by replacing parameter t by $-t$. The difference of altitude between O_{21} and O_{22} does not depend on b and h_l and can be simplified into

$$z_{O22} - z_{O21} = t[\cos(\beta)\cos(\theta_2)\sin(\alpha+\theta_0) + \sin(\beta)\sin(\theta_2)] \quad (6).$$

As the track width *t* is positive, the condition to keep O_{21} and O_{22} at the same altitude is

$$\sin(\alpha+\theta_0) = -\tan(\beta)\tan(\theta_2) \quad (7).$$

As angles α and β can be measured with a 3D accelerometer fixed to the front frame *(F₁)* and used as an inclinometer, equation (7) allows to extract the corrective warping θ_0 for a given steering θ_2 .

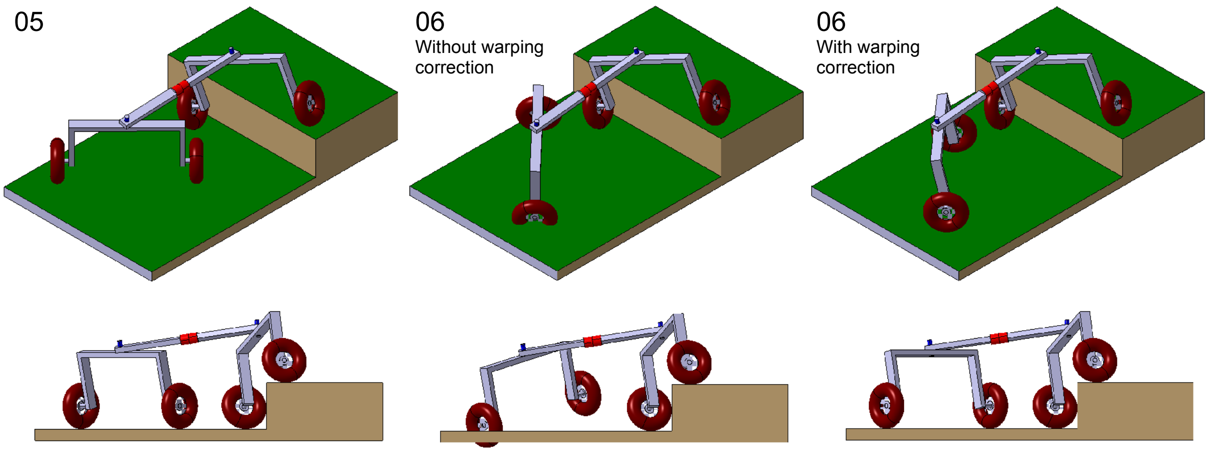

Fig 8 : Model for steering-warping coupling.

Lifting the exploring wheel

An exploring wheel is lifted at stages 3, 7, 12 and 16, which represent the second stage of each climbing phase. Lifting is controlled by θ_0 and calculated in equation (8) for stage 3.

$$\theta_0^{S3} \approx asin(h_s/t) \tag{8}$$

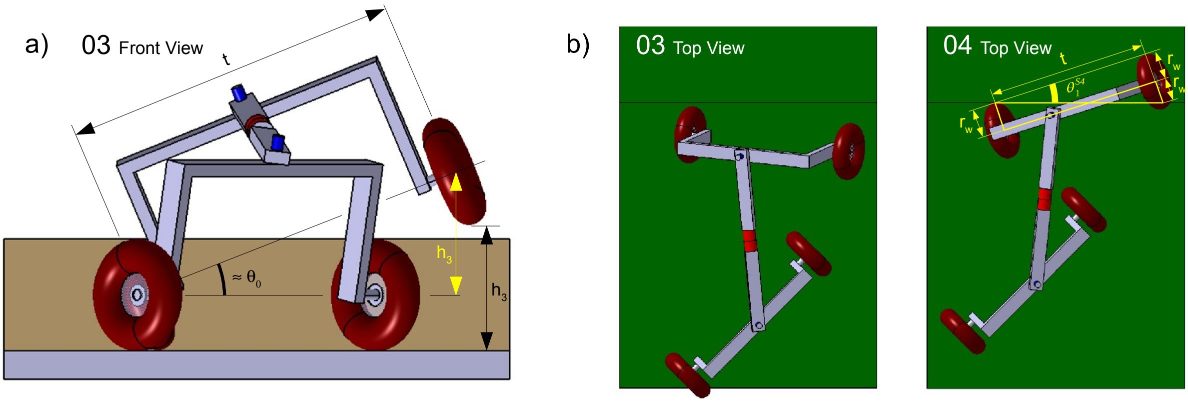

Fig 9 : Model for (a) lifting the exploring wheel (b) pushing the wheel over the obstacle.

Pushing the exploring wheel over the obstacle

An exploring wheel is pushed over the obstacle at stages 4, 8, 13 and 17, which are the third stage of each climbing phase. For stage 4 (Fig. 9a), the exploring wheel (W_{11}) is pushed forward by axle (A_2) until it lays completely over the step in top view, which leads to a limit on the front steering angle θ_1 given by equation (9).

$$\theta_1^{S4} \approx atan(2r_w/t) \tag{9}$$

Landing the exploring wheel on the obstacle

An exploring wheel lands on top of the obstacle at stages 5, 9, 14 and 18, that are the fourth and last stage of the climbing phase of each wheel. Landing is controlled by θ_0 in a similar way as lifting with equation (8).

5. Conclusion

This article presented the OpenWHEEL i3R mobile robot, a rover capable to roll on regular ground and to climb step-obstacles as high as two-thirds of its centre of gravity. OpenWHEEL i3R is interesting as it combines the rolling efficiency of the wheeled propulsion to the agility of the legged locomotion, with a simple control based on minimal actuation of the four wheels and only one central warping actuator. Three demonstrators were built to demonstrate the concept: two at small scale and one at full scale, comparable to a commercial vehicle such as an ATV. The robot control is interesting as it requires to take into account the whole sequence of stages in the climbing process. A sequential geometric model was built, based on a 3D geometric model for each stage. Control is based on the position of the joints and the main required equations are given here for lifting, pushing and landing the exploring wheel over the obstacle. Parasite phenomena and their associated equations are also identified, such as the negative effect of pitch angle, cured by a proper mass repartition, and steering-warping coupling, cured by an adjustment in warping control. The tests on the demonstrators are very encouraging and open perspectives on designing new highly efficient wheeled robots and vehicles for agile mobility on all-terrain and clearance performance.

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