# Crawling, walking or rolling for obstacle-crossing ? Bio-inspiration for the OpenWHEEL i3R agile mobile robot.

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## 1. Locomotion on unstructured grounds

Terrestrial animals mostly use locomotion techniques such as crawling or walking. Crawling is based on a deformation of the complete animal body (*e.g.* worms, snakes...) (Behn 2009) whereas walking relies on a deformation of dedicated organs such as legs (*e.g.* quadrupeds, bipeds...) (Gonzalez 2006). Both techniques are suitable for displacement in natural environment with irregular and unstructured ground. On the contrary, the terrestrial displacements of human vehicles generally rely on the wheel concept, which is energy-efficient on smooth and hard terrains (Bekker 1969) but gets blocked on irregular grounds featuring obstacles that are steep or high with respect to wheel radius.

Then appeared the concept of hybrid locomotion, using wheels mounted on legs. It improves agility on obstacles, at the price of structural loss of stiffness and complex control. Representative examples of robots using hybrid locomotion are Hylos (Grand 2004) that uses wheels on legs with 3 Degrees Of Freedom (DOF) or WorkPartner, with a comparable architecture (Halme 2003).

The present work aims at keeping the interesting obstacle crossing capacities of hybrid locomotion but replaces the multiple legs by a single deformable frame, that allows to decrease the number of actuators. Although the Nomad robot is supposed to have a transformable chassis (Rollins 1998, Apostolopoulos 2001), it still uses separate actuators for each wheel. On the contrary, the concept presented in this paper factorizes the disseminated actuators into a central mechanism included into the chassis. It may have some similarities with the Lama robot (Lacroix 2002) that uses internal mechanisms between axles to achieve peristaltic locomotion on low-cohesion grounds, or the Roller-Walk (Hirose 1996) that is a skating robot but here, the objective is obstacle crossing.

## 2. Model of the OpenWHEEL i3R robot

We anticipate that future mobile robots will not rely on a central engine and passive suspensions like most of the cars. OpenWHEEL is the name given to a family of rovers with articulated frame and/or innovative suspensions. The name "i3R" qualifies a particular robot of this family from its kinematics: "i" for the inter-axle central mechanism; "3R" for the number of revolute joints used in this mechanism: two passive steering rotations for front and rear axles and one central active warping joint.

This kinematics (Fig. 1a) was first defined in (Fauroux 2006) and combines the speed of the wheeled propulsion with the agility offered by an articulated chassis. OpenWHEEL i3R is an *agile* mobile robot with *low actuation* (only one central active joint, passive steering induced by wheel actuation) and *multiple modes of locomotion* for rolling on smooth surfaces or crossing obstacles. The rover can climb on obstacles with only 4 wheels: 3 wheels for stable support of the robot (points $P_{11}$, $P_{21}$, $P_{22}$ on Fig. 1a) and 1 exploring wheel to crawl over the obstacle (wheel $W_{12}$ on Fig. 1a).

## 3. Experimenting the obstacle-crossing hybrid locomotion mode

The obstacle-crossing mode was created by interpolating between several stable configurations where the robot lays either on three or four contact points. The complete process has 19 stages divided into 7 phases A-G. Stability was evaluated by a simplified 2D model in top view (Fig. 1b).

Fig. 2a shows a multibody model of the crossing of the front-right wheel, created with Adams software. Experimental validation of this process was given in (Fauroux 2008) on a reduced model made with Mindstorms robotic kit (Fig. 2b). Two other versions are currently under construction, with the bigger one being 1.5m long and weighing 200kg (Fig. 2c).

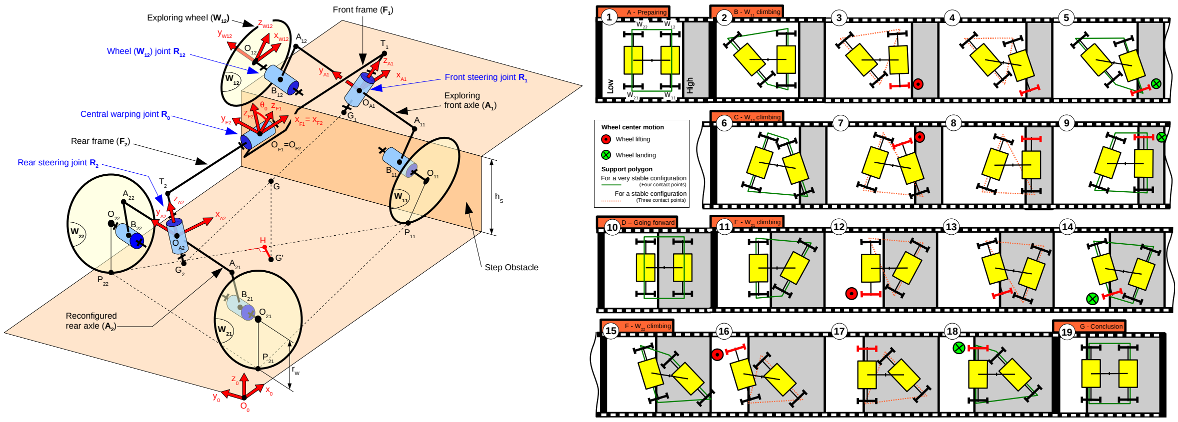


*Fig 1 : (a) Kinematic structure of OpenWHEEL i3R. (b) Obstacle-crossing process in 19 stages.*

At present, the crossing mode allows to cross obstacles as high as two thirds of the height of the robot Centre of Gravity (CoG) denoted *G*. Experimentations also showed that, for a symmetric robot with the same weight on the front and rear, the front axle crossed the obstacle easily whereas the rear one could not (Fauroux 2009). This comes from the fact that the CoG of a ground vehicle is always above the contact points of the wheels on the ground. During obstacle-crossing, the tilting angle grows, and the projected CoG *G'* goes to the rear. This decreases the static margin of stability during the end of crossing. Overall, the current crossing strategy on OpenWHEEL-i3R is quite delicate as the internal DOFs of the deformable frame are used to generate a sort of serpentine crawling gait but affect at the same time the contact forces and traction capacities of the wheels.

From this statement arises the idea to improve the current crossing-performance by giving the robot a capacity that is quite common in the animal world : dynamic management of the location of the centre of gravity over the contact points with the ground. This can be described as “balancing”.

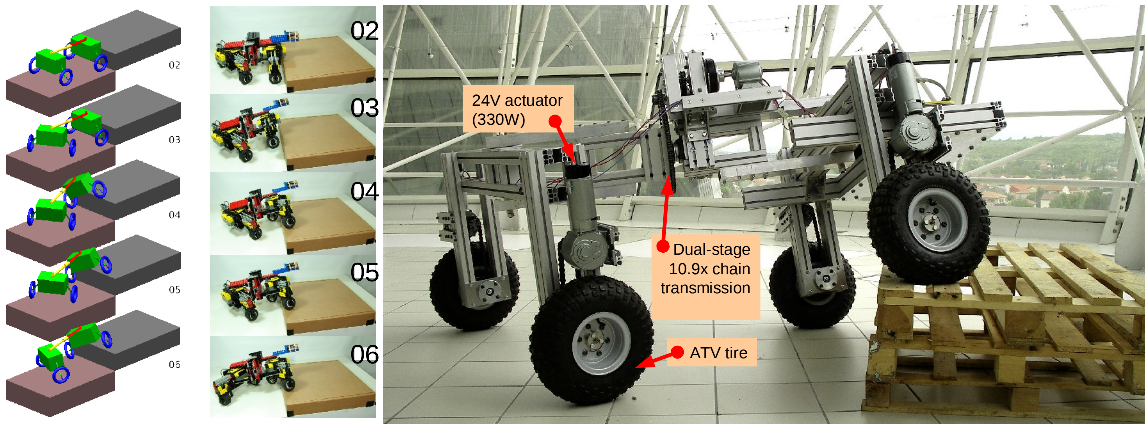


*Fig 2 : Obstacle-crossing: (a) Multibody model (b) Mindstorms small scale (c) Full scale (1.5m, 200kg).*

## 4. Bio-inspiration from balancing of walking natural creatures

Balancing can occur both for standing equilibrium and for walking. Human upright standing equilibrium has been (and is still) extensively studied (Mouzat 2001a & b, 2003) using theoretical and technical tools of posturology (Gagey 1995): displacements of the subject's centre of pressure (CoP) are computed from the measurements of a six-component force-plate and analysed with regard to different dynamic models (e.g. single or double inverted pendulum). Motion analysis of animal and human gaits is also a very old topic (Muybridge 1883), although it mostly covers locomotion on flat and even terrain.

Some rare research concerns walking on inclined surfaces and longitudinal balancing. (Leroux 2002) shows that walking uphill induces an increasingly flexed posture of hip, knee and ankle at initial foot contact as well as a progressive forward tilt of pelvis and trunk. During quiet standing, however, the trunk and pelvis remain aligned with respect to earth’s vertical at any surface inclination. A few analyses from Muybridge concern human staircase climbing and horse obstacle jumping. They also show that longitudinal balancing relies strongly on hip-tilting (for bipeds) or combined hip and shoulder-tilting (for quadrupeds). Biped also use their upper limps for static or dynamic equilibration.

Lateral balancing is another important task during walking. For bipeds, the trunk is supported most of the time by one leg and the CoM is moved laterally by combined rolling of hip and ankle (Hof 2007). An inverted pendulum model was also used in this case.

# 5. Improving balancing and architecture of OpenWHEEL-i3R

OpenWHEEL i3R has a quasi-static low-speed motion. Only its static stability was evaluated. Criteria such as Center of Pressure or Zero Moment Point would suit faster motion (Ridderström 2003).

At present, longitudinal balancing of OpenWHEEL i3R is obtained with a fixed counterweight in front of the vehicle. It is optimized to improve climbing of the second axle (Fig. 1b, stages 11-16) but cannot be adjusted during obstacle-crossing. This may generate instability while going down from the obstacle. A simple solution for dynamic adjustment of longitudinal balancing could be to mount batteries and/or payload on a longitudinal slider on each axle.

OpenWHEEL already performs lateral balancing by adjusting the steering angle of the axle that does not contain the exploring wheel (stages 3, 7, 12 and 17). Lateral balancing could also benefit from a lateral sliding of the payload. However, bio-mimetic solutions based on adding a DOF for hip-rolling to each wheel would seriously increase the number of actuators, decrease stiffness and contradict the principle of factorization presented in §1. A more promising solution would be to replace the current inter-axle mechanism, which is comparable to the skeleton of vertebrates, by an exoskeleton, such as for arthropods, thus liberating more central space for payload.

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