58

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

Jean-Christophe.FAUROUX@ifma.fr
Clermont University – French Institute for Advanced Mechanics (IFMA)
LaMI – B.P. 10448 – 63000 CLERMONT-FERRAND, France

Philippe.VASLIN@isima.fr
Clermont University – Blaise Pascal University (UBP)
LIMOS – B.P. 10448 – 63000 CLERMONT-FERRAND, France

Wheeled / Legged / Hybrid Locomotion on unstructured terrain

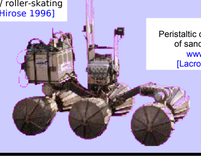
- **Crawling** / **Walking** is used by most terrestrial animals : efficient in **natural environment** with irregular and unstructured ground but **slow**, difficult to **control**, and requires a lot of **energy**.
- **Wheels** are used on most human vehicles : **energy-efficient** and **fast** but only on **smooth** and **hard terrain**.
- **Hybrid locomotion** combines wheels and active legs or frame

WorkPartner (230 kg, 1.4m long, 7km/h)
4 wheels on legs (3 DOF per leg)
automation.tkk.fi [Halme 2003]

Roller-Walker (24kg, 0.5m long)
Convertible wheels / actuators only on legs
Dual locomotion mode: walking / roller-skating
www-robot.mes.titech.ac.jp [Hirose 1996]

Nomad
Dual Ackermann steering strategy
www.frc.ri.cmu.edu/projects/lorax
[Rollins 1998, Apostopoulos 2001]

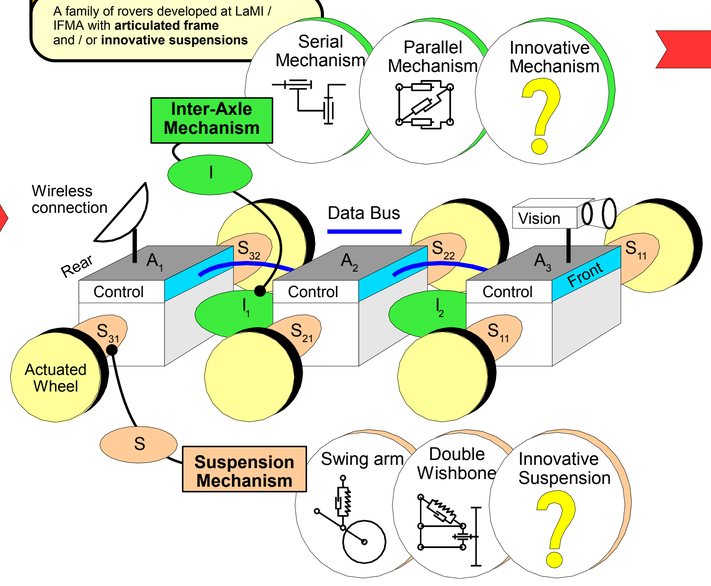
- The present work aims at keeping the interesting **obstacle crossing capacities** of hybrid locomotion but replaces the multiple legs by a single **deformable frame**, that allows to **decrease the number of actuators**



Lama
Peristaltic crossing of sandy areas
www.laas.fr
[Lacroix 2002]

OpenWHEEL

A family of rovers developed at LaMI / IFMA with **articulated frame** and / or **innovative suspensions**



OpenWHEEL i3R

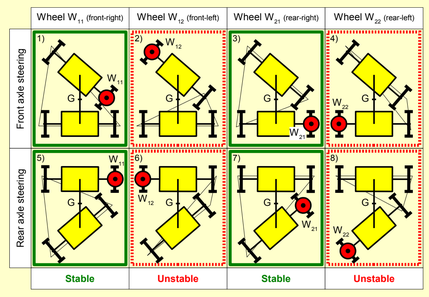
Origin of the **name i3R**:
- **i** for the inter-axle central mechanism
- **3R** for the number of revolute joints used in this mechanism
- two **passive steering rotations** for front and rear axles
- one **central active warping** joint

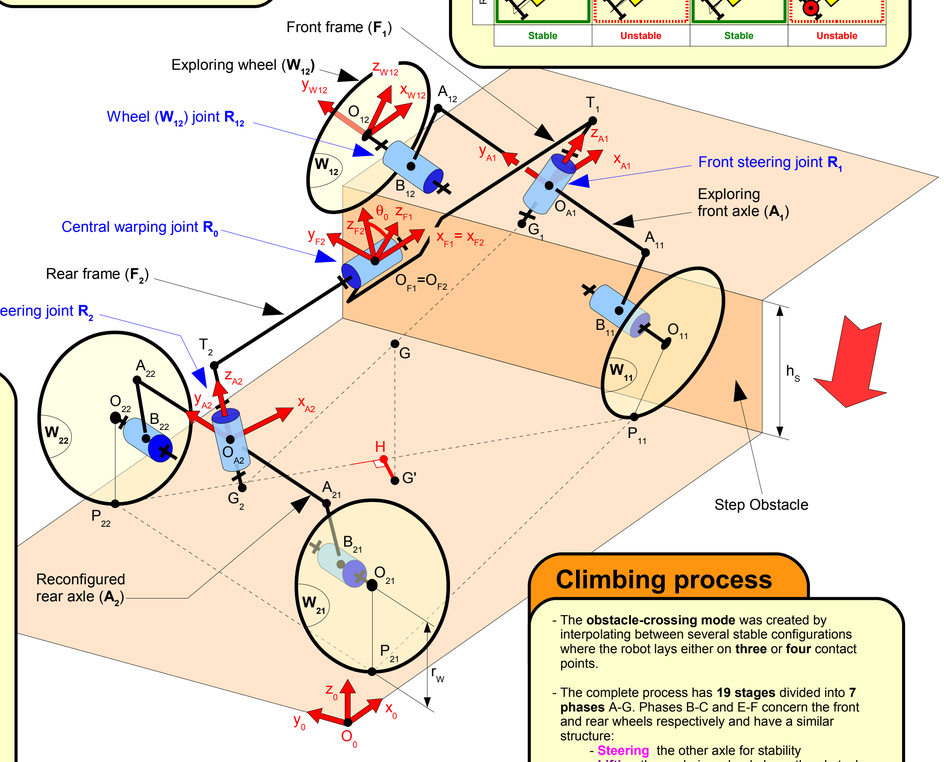
OpenWHEEL i3R is an **agile** mobile robot with **low actuation** (only one central active joint, passive steering induced by wheel actuation) and **multiple modes of locomotion** for rolling on smooth surfaces or crossing obstacles

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}) and 1 **exploring wheel** to crawl over the obstacle (wheel W_{12} on figure below)

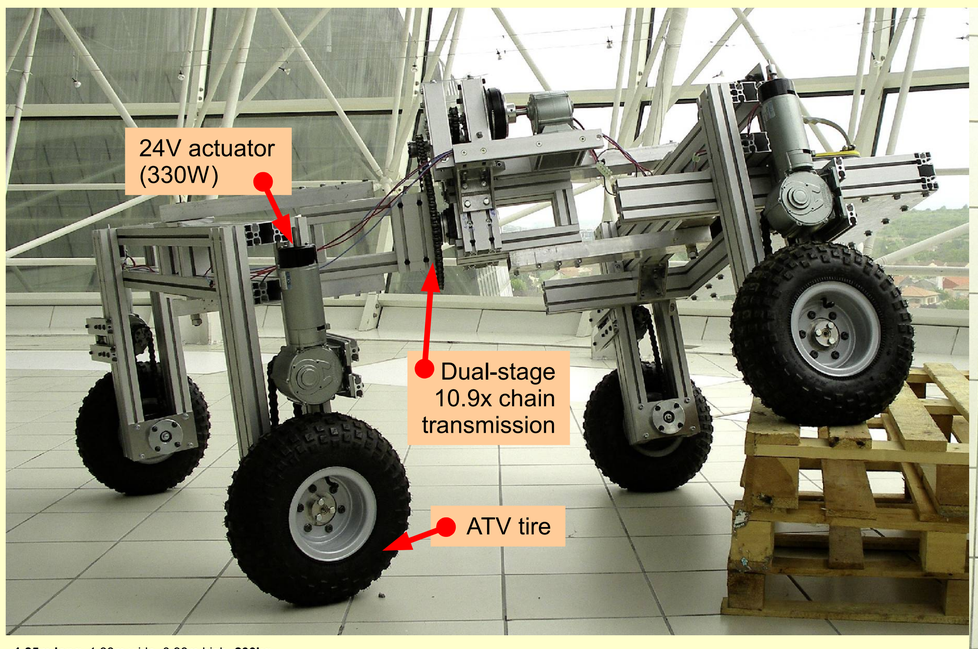
Paradigm for stable climbing

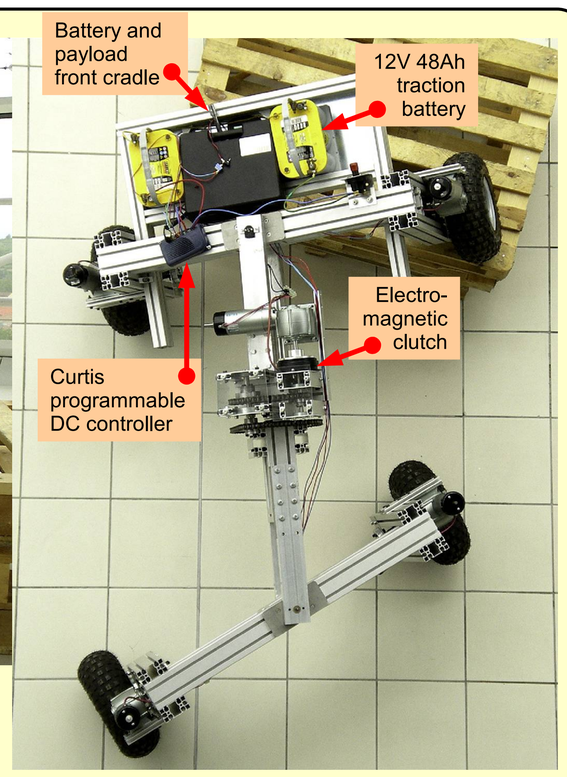
Static stability on 3 wheels
- Configurations 2) 4) 6) 8) are **unstable**
- The **stable** configurations 1) 3) 5) 7) occur when the exploring wheel is located on the **inside of the turn**





OpenWHEEL i3R V3

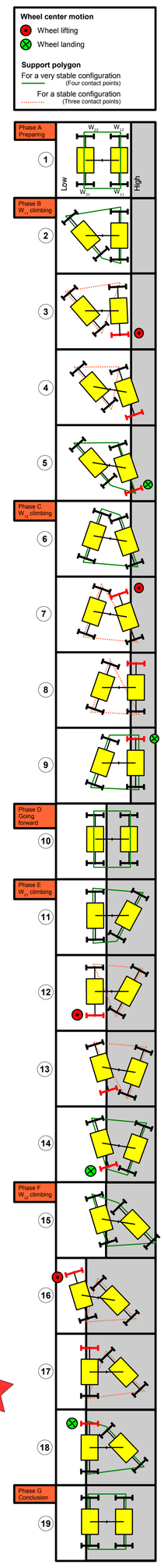


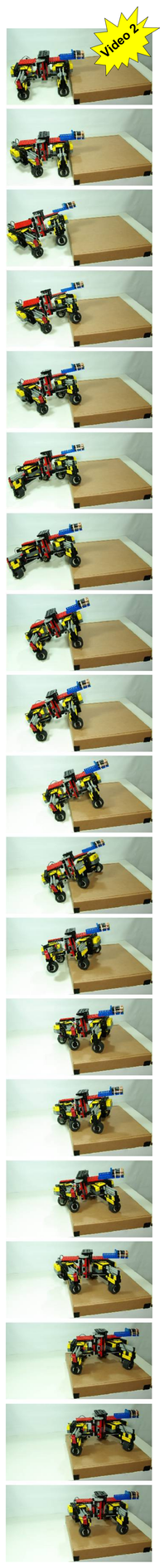


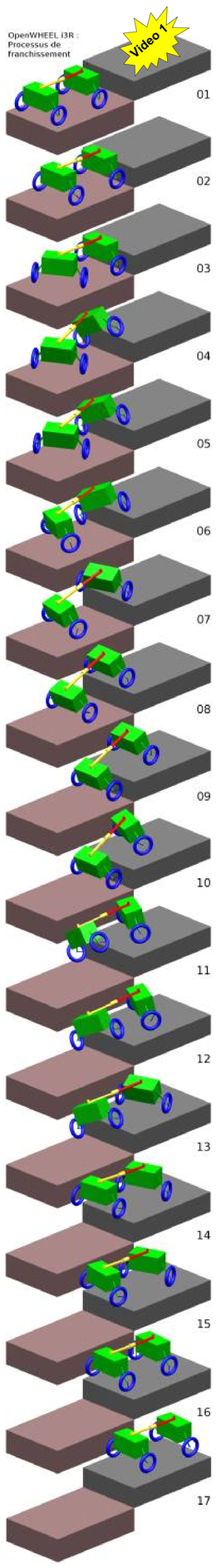
- **1.85m long**, 1.38m wide, 0.98m high, **200kg**
- 24V DC actuators **330W** with peak torque of **100Nm** + external encoder + Two or four 12V 48Ah traction batteries
- Central **clutch** → no overconstraint when rolling → no suspension required
- **Fast** 45° central **warping** : only one second (15x faster than V1)
- The same high level NXT controller as V2 generates 8kHz **PWM** Pulse Width Modulated motor signals
- Used as an average tension to control low level Curtis DC controllers (24V, 70A)

Climbing process

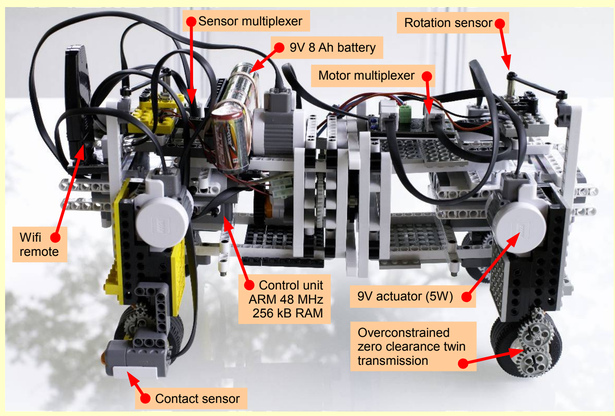
- The **obstacle-crossing mode** was created by interpolating between several stable configurations where the robot lays either on **three** or **four** contact points.
- The complete process has **19 stages** divided into **7 phases** A-G. Phases B-C and E-F concern the front and rear wheels respectively and have a similar structure:
  - **Steering** the other axle for stability
  - **Lifting** the exploring wheel above the obstacle
  - **Bringing** the exploring wheel **forward**
  - **Landing** the exploring on the obstacle
- **Stability** is evaluated by a simplified **2D** model in top view (figure below, left column).
- A **3D** multibody model (Adams) confirms feasibility (figure below, rightcolumn) [Fauroux 2006]



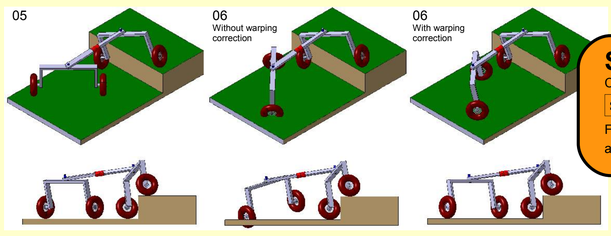




OpenWHEEL i3R V2



- Small scale (50cm) with **closed loop control** with access to PID parameters
- Powerful 9V **actuators** (5W) and many **sensors** : contact, steering angle, distance (US), 3D accelerometer to measure tilting
- When not horizontal, steering reconfiguration generates **induced axle warping**
- Solution: **unwarp** the central joint / **declutch** the central joint

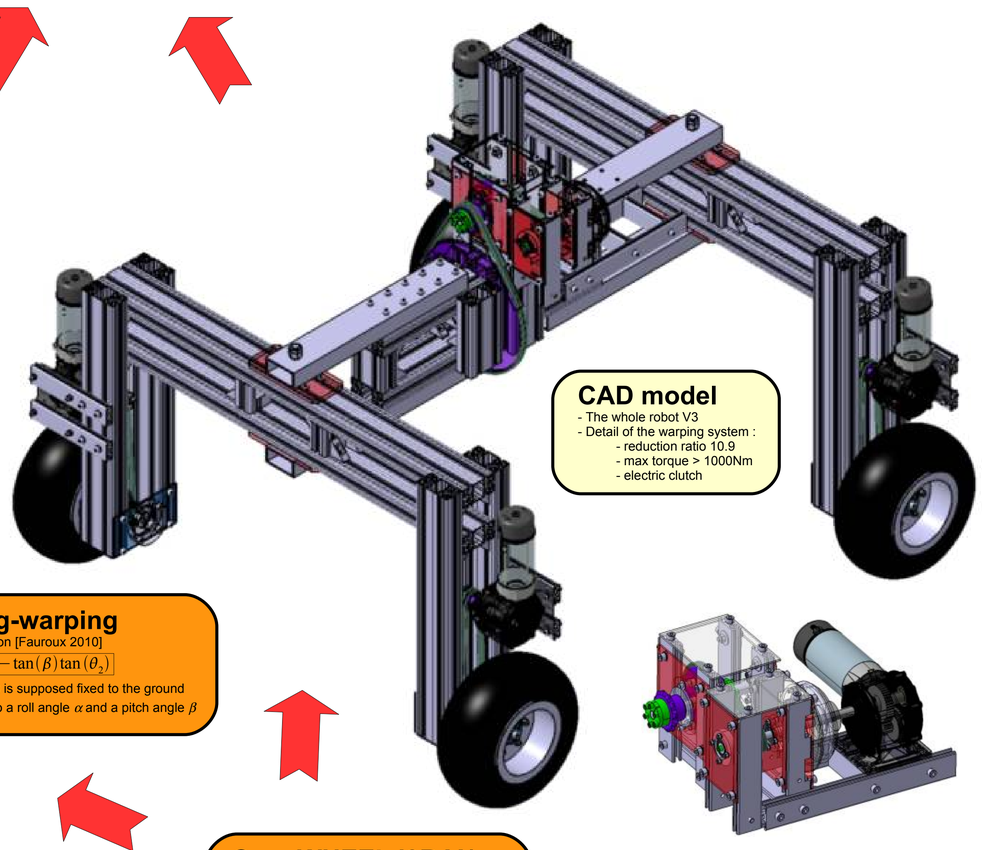


Steering-warping

Coupling equation [Fauroux 2010]

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

Front frame *(F1)* is supposed fixed to the ground and submitted to a roll angle α and a pitch angle β



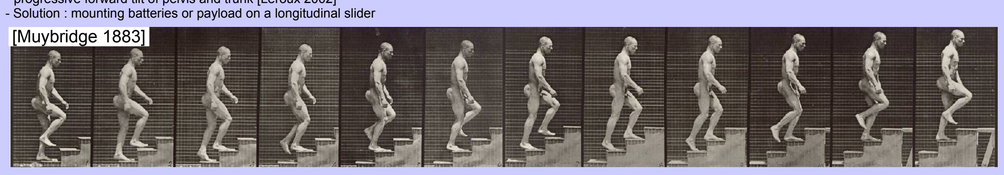
CAD model

- The whole robot V3
- Detail of the warping system :
  - reduction ratio 10.9
  - max torque > 1000Nm
  - electric clutch

Bio-inspiration from balancing of walking natural creatures

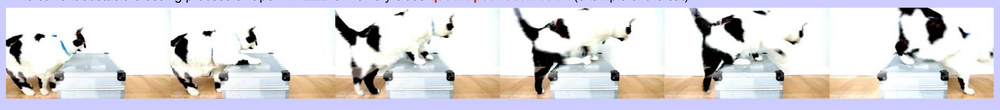
- OpenWHEEL i3R: a **hybrid** mobile robot with **deformable frame**
- Can climb obstacles as high as **2/3** of the altitude of its centre of mass with only **4 wheels**
- Only **1 supplemental actuator** → minimal actuation, good stiffness
- **3** small and full scale **implementations** / **1 control architecture**
- **Problems & solutions** : front-rear non-symmetry, steering-warping coupling

- **Longitudinal balancing** to increase stability: walking uphill induces for bipeds an increasingly flexed posture of hip, knee and ankle at initial foot contact as well as a progressive forward tilt of pelvis and trunk [Leroux 2002]
- Solution : mounting batteries or payload on a longitudinal slider

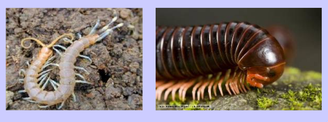


- **Lateral balancing** during obstacle crossing: centre of mass of bipeds is moved laterally by combined rolling of hip and ankle [Hof 2007]
- For OpenWHEEL, lateral balancing comes from **steering reconfiguration** (stages 3, 7, 12 and 17)
- Complementary solution : **lateral sliding** of payload

- The current obstacle-crossing process of OpenWHEEL i3R is very close **quadruped locomotion** (example of the cat)



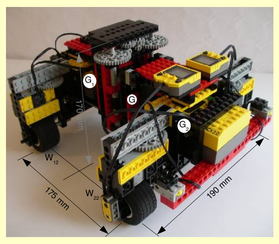
- Improving volume for payload → Replacing the inter-axle mechanism by an **exoskeleton**, such as for **arthropods**



- Towards new robots & vehicles for **agile all-terrain mobility** & **clearance performance**

OpenWHEEL i3R V1

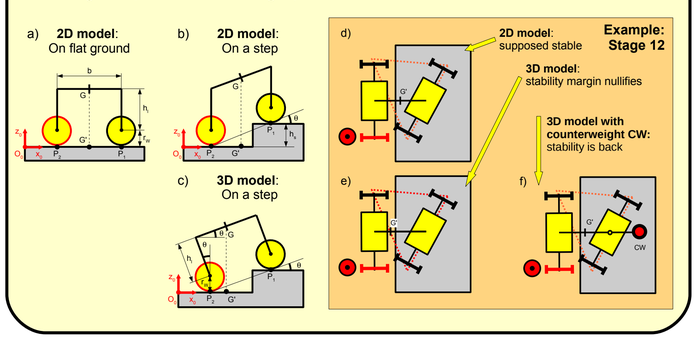
OpenWHEEL i3R V1, a reduced model built with the Mindstorms RCX robotics kit
- 1.5kg autonomous robot
- The first to **validate** the **autonomous climbing** process
- **Open loop** (no coders in the motors)
- 9V DC actuators (1.1W)
- Two controllers synchronized by IR message exchange
- Best **obstacle height** : **55 mm**, **67%** of the height of the centre of mass



Front-rear non symmetry [Fauroux 2008]

- Axle A_1 **climbs easily** whereas axle A_2 **has difficulties**
- Solved by **adding a counter-weight CW** of 150 g
- Non-symmetry was not predicted because of 2D approximation
- On flat ground, the 2D model is **exact**
- With some pitch:
  - In **2D**, stability margin $P_2G'=b\cos(\theta)/2$
  - In **3D** $P_2G'=b\cos(\theta)/2-h_1h_s/b$

- Stability is favoured at **stages 3** and **7** and penalized at **stages 12** and **16**
- Adding CW **equilibrates the climbing capacities** of front and rear axles



The authors wish to thank the following students from IFMA and UBP for their contribution to this work : Guillaume MALVAL, Emilie PORTALES, Morgann FORLOROU, Sylvain MARCO, Yohann KOBERLE, Damien ROUX, Laurent GENEVAY, Michel TOU, Fabien BIANCHINI, Romain CARTAILLER, Farhat HZAG, Sylvain METAIS, Christophe NOELLAT.