Improving Obstacle Climbing with the Hybrid Mobile Robot OpenWHEEL i3R

Jean-Christophe.Fauroux@ifma.fr
Belhassen-Chedli.Bouzgarrou@ifma.fr
Frédéric.Chapelle@ifma.fr

IFMA
Campus de Clermont-Ferrand / Les Cézeaux, B.P. 265
63175 Aubière Cedex
FRANCE
Hybrid Locomotion

Locomotion systems can be defined 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 [Ben Amar, Bidaud 2007]

- **Terrestrial vehicles & robots**
  - Wheeled robots prevail (excellent energetic efficiency)
  - Lack of agility / blocked on obstacles
  - Legs / Tracks interesting for all terrain / climbing

- **Hybrid locomotion**
  - Combining the advantages of wheel and leg
  - Other solution: deformable frame

- **Our objective: Improving locomotion**
  - Wheeled robots
  - That climb step obstacles
  - With only four wheels
  - And a stable behaviour
Existing Hybrid Mobile Robots

- **Categories of Hybrid robots**
  - Wheels on legs vs. deformable frame
  - Active / passive
  - Difficulties: stiffness, power, control

**RobuROC 6** (150 kg, 1.5m long)
Active deformable frame
3 tiltable axles with passive warping
Able to turn on itself, climb obstacles
www.robosoft.fr

**WorkPartner** (230 kg, 1.4m long, 7km/h)
4 wheels on legs (3 DOF per leg)
Steering via central joint
Many locomotion modes
automation.tkk.fi

**Shrimp**
Passive deformable frame
6 wheels on 2 // bogies and 1 front linkage
Excellent climbing abilities but requires 6 wheels
www.asl.ethz.ch
Objectives of the Work

- **Within the OpenWHEEL project**
  - End of the *car central-engine paradigm*
  - New *articulated frames*
  - *OpenWHEEL project*, an open architecture for hybrid wheeled robots

- **Objectives of this work**
  - Study the OpenWHEEL *i3R* specific robot
  - Analyse its *behaviour* during obstacle *climbing*
  - *Dimensional analysis* for better climbing
OpenWHEEL i3R Architecture

- **Advantages**
  - Only four wheels like most vehicles
  - Active frame with only one actuator
  - Stable when climbing obstacle
  - Precise steering via double Ackermann

- **Introduction**
- **OpenWHEEL i3R Architecture**
- **Climbing proc.**
- **Non-symmetry**
- **Dim. analysis**
- **Conclusion**

**Wheel (W_{12})**
- Joint R_{12}
- Warping angle $\theta_0$
- Central warping joint $R_0$
- Rear frame ($F_2$)
- Rear steering joint $R_2$

**Exploring wheel (W_{12})**
- Joint $R_{12}$
- Warping angle $\theta_0$
- Central warping joint $R_0$
- Rear frame ($F_2$)
- Rear steering joint $R_2$

**Front frame ($F_1$)**
- Joint $R_{11}$
- Front steering joint $R_1$
- Exploring front axle ($A_1$)

**Step Obstacle**
- Lifting polygon
- Stability on three wheels

**Reconfigured rear axle ($A_2$)**

**Reconfigured rear axle ($A_2$)**

**Central warping joint $R_0$**

**Wheel ($W_{12}$)**
- Joint $R_{12}$
- Warping angle $\theta_0$
- Central warping joint $R_0$
- Rear frame ($F_2$)
- Rear steering joint $R_2$

**Front frame ($F_1$)**
- Joint $R_{11}$
- Front steering joint $R_1$
- Exploring front axle ($A_1$)

**Step Obstacle**
- Lifting polygon
- Stability on three wheels

**Reconfigured rear axle ($A_2$)**

**Central warping joint $R_0$**

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)

**Rear frame ($F_2$)**
- Joint $R_{22}$
- Rear steering joint $R_2$
- Reconfigured rear axle ($A_2$)
OpenWHEEL i3R Climbing Process

- **Properties for stability**
  - Can be stable on three wheels
  - **Axle steering**
    - does not change the position of the centre of mass
    - changes the position of the contact points

- **Checking stability on three wheels**
  - 2D model
  - Stable if the lifted wheel is inside the turn
  - Climbing process in 19 stages and 6 phases

---

**Wheel W_{11} (front-right)**

1) Front axle steering

2) Rear axle steering

**Wheel W_{12} (front-left)**

3) Front axle steering

4) Rear axle steering

**Wheel W_{21} (rear-right)**

5) Front axle steering

6) Rear axle steering

**Wheel W_{22} (rear-left)**

7) Front axle steering

8) Rear axle steering

Stable | Unstable | Stable | Unstable
OpenWHEEL i3R Climbing Process

Wheel center motion
- Wheel lifting
- Wheel landing

Support polygon
For a very stable configuration (Four contact points)
For a stable configuration (Three contact points)

Wheel lifting
Wheel landing
Wheel center motion

Architecture
Introduction
OpenWHEEL i3R
Climbing proc.
Non-symmetry
Dim. analysis
Conclusion

For a very stable configuration
(Four contact points)

For a stable configuration
(Three contact points)
OpenWHEEL i3R Climbing Process

- **Modeling and testing**
  - 2D model very helpful to build the complete climbing process
  - Not acceptable for high pitch angles or strong warping
  - Validation in 3D required
  - 3D Multibody model with Adams
  - Reduced size demonstrator built in Lego Mindstorms

**Architecture**

**Introduction**

**OpenWHEEL i3R**

**Climbing proc.**

**Non-symmetry**

**Dim. analysis**

**Conclusion**
Front-Rear Non-Symmetry

- Real testing revealed a non-symmetric behaviour
  - Axle $A_1$ climbs easily whereas axle $A_2$ has difficulties

- Solved by adding a counter-weight CW of 150 g
- Best obstacle height: 55 mm, 67% of the height of the centre of mass
Front-Rear Non-Symmetry

Explanation

- Non-symmetry was not predicted because of 2D approximation
- On flat ground, the 2D model is exact
- With some pitch - In 2D, stability margin \( P_2 G' = b \cos(\theta) / 2 \)
- In 3D \( P_2 G' = b \cos(\theta) / (2 - h_l h_s / b) \)
- 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

Introduction

OpenWHEEL i3R

Non-symmetry

Dim. analysis

Conclusion
Dimensional Analysis

- Which are the key parameters to maximize climbing performance?

- Dimensional analysis of several parameters
  - Track width \( t \)
  - Wheelbase \( b \)
  - Wheel radius \( r_w \)
  - Leg height \( h_l \)
  - Mass
  - Mass repartition
Dimensional Analysis: Track Width $t$

**Influence of $t$ on the climbing capacity**

- The bigger the track width, the higher the obstacle
- $\theta_{0\text{Max}}$ is around 45° to avoid tire roll-off
- Bound for the minimal value of $t$

\[
h_{\text{Max}} = t \sin(\theta_{0\text{Max}})
\]

\[
t_{\text{Min}} = h_s / \sin(\theta_{0\text{Max}})
\]
Dimensional Analysis: Wheelbase $b$

**Influence of $b$ during steering**

- Minimum wheelbase $b_{\text{Min}}$ to avoid axle-collision when double steering
- Closure condition when wheels are in contact: $\frac{b}{2} = \frac{t}{2} \cos(\theta_{1\text{Max}}) + r_w \sin(\theta_{1\text{Max}})$
- Gives $b_{\text{Min}}$
- ... or $t_{\text{Max}}$

- Increasing $b$ attenuates the front-rear non-symmetry
- $b$ cannot be too long! $b_{\text{Max}} = 2.\ t$
Influence of wheel radius $r_w$ on the obstacle

- Vehicles **without** articulated frame only cross **small** obstacles: $r_{w \text{ Min}} = 4. h_o$
- With the articulated frame, wheel radius is independent of obstacle height.
- Suggested **index of performance**: % of the height of centre of mass.
Maximum wheel radius $r_w$

- If $r_w$ grows too much $\rightarrow$ wheel-wheel collision
- Exploring wheel has longer way along $x_0$ to go above the obstacle:

$$r_{w \text{ Max}} = t/2$$
Which leg height $h_l$?

- A minimum value of $h_l$ to avoid collision with obstacle edge
  \[ r_w + h_l \geq h_s \]
  \[ r_w + h_l \leq 2h_s \]
- Legs too high increase the front-rear non-symmetry

Lower bound on $h_l$
\[ h_{l,\text{Min}} = h_s - r_w \]

Upper bound on $h_l$
\[ h_{l,\text{Max}} = 2h_s - r_w \]
Dimensional Analysis: Mass

**Which mass?**
- Need for a minimal tangential force to climb
- When mass $\uparrow$, tangential force $\uparrow$ so mass is **not** a significant parameter
- On granular terrains, a heavy robot may dig ruts on the track

**Which mass repartition?**
- **Lateral** symmetry must be respected
- **Longitudinal** symmetry must be broken for $A_2$ to climb as well as $A_1$

**Which maximal obstacle height $h_{s \text{Max}}$?**
- Critical stages = the third stages of each phase = stages 4, 8, 13 and 17
- **Direct geometric model** + **Static analysis** must be solved for each stage

- Approximation of $h_{s \text{Max}}$
  \[ h_{s \text{Max}} = t \sin(\theta_{0 \text{Max}}) \]
Towards a Full Scale Experiment

- **List of main parameters**

- Each parameter can be bounded (the bound values of $\theta_0$, $\theta_1$, $\theta_2$ are set to $45^\circ$)

- Parameters sorted by order of selection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Lower bound</th>
<th>Upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track width</td>
<td>$t$</td>
<td>$t_{\text{Min}} = h_s \sqrt{2}$</td>
<td>$t_{\text{Max}} = b \sqrt{2} - 2r_W$</td>
</tr>
<tr>
<td>Wheel radius</td>
<td>$r_W$</td>
<td>$r_{W\text{Min}} = 4h_O$</td>
<td>$r_{W\text{Max}} = t/2$</td>
</tr>
<tr>
<td>Wheelbase</td>
<td>$b$</td>
<td>$b_{\text{Min}} = \sqrt{2}(t/2 + r_W)$</td>
<td>$b_{\text{Max}} = 2. t$</td>
</tr>
<tr>
<td>Leg height</td>
<td>$h_l$</td>
<td>$h_{l\text{Min}} = h_s - r_W$</td>
<td>$h_{l\text{Max}} = 2h_s - r_W$</td>
</tr>
</tbody>
</table>

- From these rules are deduced the dimensions of OpenWHEEL i3R in its fullscale implementation

- **Main dimensions**:
  - $t = 1.2m$
  - $r_W = 0.2m$
  - Mass 150 kg
  - Five DC actuators of 330W 30Nm
  - Central warping joint with clutch
Conclusion

**Main results**

- OpenWHEEL i3R: a *hybrid* mobile robot with *deformable frame*
- Front-Rear *non-symmetry*
- **Dimensional analysis** of its main parameters
- **Design rules** to build a robot according to the obstacles to be climbed
- **Fullscale implementation** of the robot is in progress