Synthesis of spatial parallel mechanisms for a vertical and longitudinal all-terrain suspension

Jean-Christophe.Fauroux@ifma.fr

Clermont University
French Institute for Advanced Mechanics (IFMA)
EA3867, FR TIMS / CNRS 2856
Mechanical Engineering Research Group (LaMI)
BP 10448, F-63000, FRANCE

International Conference MTM-Robotics 2012, 6-8 June 2012, Clermont-Ferrand
Longitudinal suspension

- Wheeled locomotion on surfaces
  - Wheels are mostly suitable for motion on $C^1$ continuous surfaces (tangency continuity)
  - Obstacles in unstructured environment may provide only $C^0$ continuity (contour continuity)

Considered obstacles have a $C^1$ continuity and possibly only $C^0$

Positive obstacles & Bumps
- $C^1$ but non $C^2$
- $C^0$ but non $C^1$

Negative obstacles & Holes
- Non $C^0$

BMX race bike: $C^1$ obstacles

Slope bike competition: $C^1$ and $C^0$

Trial bike: $C^0$ obstacles
Wheels for obstacle crossing

Vehicle reference frame
- X in the direction of **longitudinal** motion
- Z in the **ascending** direction
- Y oriented **laterally** so that (X,Y,Z) is direct

Obstacles
- **Obstacles** ≃ shapes with a roughly **vertical front surface** along Z
- Strong component of their normal vector along -X
- At **high speed**, the X reaction component becomes important

Concept of a suspension allowing also the **longitudinal X damping motion** for better obstacle-crossing.
2D dynamic modelling

- A suspension with 2 DOF
  - Work published in [HUDEM 2010]
  - Multibody model (Adams) with 2DOF suspensions (vertical Z and longitudinal X) and a serial structure
  - Simplified hypotheses: rigid bodies and wheels with contact and friction

- Encouraging results
  - With a longitudinal X suspension on front wheel, a high obstacle can be dynamically crossed. Without the X suspension → tip-over
  - A longitudinal DOF in the suspensions could benefit to longitudinal stability
Experimental obstacle-crossing

- First, an experimental approach of obstacle-crossing
  - Complex phenomena: non-linear fast crash of deformable mechanisms with friction and sliding
  - Published in [CLAWAR 2011]
    

- Choosing a mobile platform
  - A fast & robust vehicle
  - Small scale decreases the repair cost
  - Easy to tip-over

### Vehicle E-Maxx

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>E-Maxx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>5.16 kg</td>
</tr>
<tr>
<td>L x l x h</td>
<td>518 x 419 x 242 mm</td>
</tr>
<tr>
<td>Wheelbase</td>
<td>335 mm</td>
</tr>
<tr>
<td>Track width</td>
<td>330 mm</td>
</tr>
<tr>
<td>Centre of mass</td>
<td>Centred</td>
</tr>
<tr>
<td>Wheel diameter</td>
<td>150 mm</td>
</tr>
<tr>
<td>Transmission</td>
<td>4x4</td>
</tr>
<tr>
<td>Max speed</td>
<td>14 m/s</td>
</tr>
</tbody>
</table>

E-Maxx electric model

#3903 (Traxxas) www.traxxas.com
Double wishbone suspension, very close to real cars
Experimental obstacle

- **Adjustable C⁰ obstacle**
  - Steel bar adjustable in height h
  - Includes force measurement devices (Kistler 9257B)

- **Purpose**
- **Prev. works**
  - HUDEM 10
  - CLAWAR 11
- **Synthesis**
- **Dimensioning**
- **Conclusion**
Speed measurement

- Speed measured by vision
  - 30 Hz camera located on top of the impact zone
  - Tiled floor with periodic pattern of 300mm
  - Instantaneous speed comes from the 2 last images before impact

- Distance ran in 1/30th of second (30Hz camera)

- Parallel Vertical & Longitudinal Suspension
  - Purpose
  - Prev. works
    - HUDEM 10
    - CLAWAR 11
  - Vehicles
  - Patents
  - Synthesis
  - Dimensioning
  - Conclusion
Force measurement

- 3 DOF force-plate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm)</td>
<td>170</td>
<td>140</td>
<td>60</td>
</tr>
<tr>
<td>Force range (kN)</td>
<td>-5</td>
<td>+5</td>
<td>-5</td>
</tr>
<tr>
<td>Stiffness (kN/µm)</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Natural frequency (Hz)</td>
<td>2300</td>
<td>2300</td>
<td>3500</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>7,3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Acquisition 1kHz

Results

- Impact force increases with obstacle height
- Peaks of 400N
- $F_x \approx F_z$ for $v=8\text{m/s}$ and $h=65\text{mm}$
- Need for a horizontal component of suspension
Design of experiment (DoE)

- **Summary of 77 experiments** (h:25→75mm,v:3→8m/s)
  - High obstacles → crash by **tip-over** (red dots)
  - A **stability front** (red line) separates experiment with / without tip-over
  - The front has a **decreasing non-linear** shape
  - Future suspension with 2 DOF will **enhance stability** zone (green line)

![Diagram showing stability front and experiments](image_url)

- **Purpose**
- **Prev. works**
  - HUDEM 10
  - CLAWAR 11
  - Vehicles
  - Patents
- **Synthesis**
- **Dimensioning**
- **Conclusion**

**Videos**

Jean-Christophe FAUROUX
IFMA, Clermont-Ferrand

11th International Conference MTM-Robotics 2012, 6-8 June 2012, Clermont-Ferrand
Existing all-terrain vehicles

- Designed to be efficient for obstacle-crossing
  - **Wheels of great diameter** with respect to the obstacles to cross
  - Robust **rigid axle** (a) or **double wishbone** suspensions (b-d)
  - Deformable frame with **parallel linkage** for trial low speed crossing (e)
  - Some mobile robots have **joints between axles** but no suspension (f)
  - **No commercial vehicle** has a long-travel **X-suspension** of its wheels

(a) Car GMC 2500 HD
(b) Military truck Nexter Aravis
(c) ATV Polaris Sportsman XP850
(d) Buggy BooXT
(e) RC car HPI Maverick Scout Crawler
(f) Robot Robosoft RobuROC 6
Suspension patent analysis

- Longitudinal X motion is uncommon in suspension patents
  - ✔ Trailing and **leading** (a) arms allow coupled X-longi motion of the wheel
  - ✔ **Front-rear coupled** trailing arms (b) or crash-deformable (c)
  - ✔ 6 DOF coupled motions with a *Gough-Stewart parallel* suspension (d)
  - ✔ OCP (e) or *SACLI* suspensions couple vertical and lateral motions

---

**Parallel Vertical & Longitudinal Suspension**

- **Purpose**
- **Prev. works**
  - • HUDEM 10
  - • CLAWAR 11
  - • Vehicles
  - • Patents
- **Synthesis**
- **Dimensioning**
- **Conclusion**

---

Jean-Christophe FAUROUX
IFMA, Clermont-Ferrand

**11th International Conference MTM-Robotics 2012**, 6-8 June 2012, Clermont-Ferrand
Synthesis of new suspensions

- New suspensions must be designed
  - To absorb both **vertical (Z)** and **longitudinal (X)** reaction forces against obstacles (cf. models [HUDEM 10])
  - The **X** and **Z** motions should be of the **same order of magnitude** (cf. experiments [CLAWAR 11])
  - Usable on front and rear axles → **the wheel needs 4 DOF**
    - Z and X suspension translations
    - Z rotation for steering
    - Y rotation for transmission
  - X and Z translations should be **as decoupled as possible** (for active suspension control). Also decoupled from steering & power transmission

- This work describes nine 2D and 3D kinematics
V1 - 2D Serial suspension

- 2DOF with a serial mechanism
  - [HUDEM 10]
  - **Vertical** joint: Wheel leg 120 ↔ Glider 130
  - **Horizontal** joint: Glider 130 ↔ Frame 100
  - Vertical joint is closer to the wheel → avoids collision of lower parts / ground
  - ✔️ Longitudinal crash generates **bending** of leg 120
  - ✗ No steering
V2 - 2D Max. regular parallel

- 2DOF with a parallel decoupled mechanism
  - 2 PCR limbs copying the serial structure of V1
  - Cylinders can be active / adjustable / passive
  - Same mobility, stiffness is improved in case of shocks
  - In (a), X shocks absorbed by Cylinder 2, no flexion of rod 243
  - In (b), Cylinders 1-2 are attached to the frame to decrease the non-suspended mass

- The suspension is maximally regular: Jacobian ≡ Unit matrix

\[
\begin{bmatrix}
\dot{X} \\
\dot{Z}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\dot{q}_1 \\
\dot{q}_2
\end{bmatrix}
\]

- Horizontal limb too low
- No steering
- Prismatic joints: expensive & may lock (butting)
V3 - 2D Coupled Parallel

- 2DOF with a parallel coupled mechanism
  - 2 RCR limbs
  - **No flexion**, only compression → part downsizing
  - **R joints** instead of P: cheaper, no butting
  - ✗ **Coupled** control
  - ✗ Still no **steering**
  - ✗ Lack of **lateral Y stiffness**

---

**Parallel Vertical & Longitudinal Suspension**

- **Purpose**
- **Prev. works**
- **Synthesis**
  - 2D
  - 3D
- **Dimensioning**
- **Conclusion**

---

**11th International Conference MTM-Robotics 2012**, 6-8 June 2012, Clermont-Ferrand
V4 - 3D Hybrid mechanism

- 4 DOF with a parallel-serial partially coupled mechanism
  
  ✔ Good **lateral stiffness** thanks to U-U bars 431-434
  
  ✔ **Spherical translation** of the wheel (N // bars, N>2)
  
  ✔ **Steering** the hub-carrier via a R joint put in series with the parallel structure (**hybrid**)
  
  ✔ **Maximally regular** behaviour **ONLY** in the neutral position of the spherical workspace
  
  ✔ No more variations of the **pitch angle** of the hub-carrier 420 (as 320 had)
  
  ✔ **Transmission** is easy to integrate
  
  ✗ Deep recessed tyre-rims **prevent direct attachment** of dampers 440-450 to 421
  
  ✗ **Collision** 410-450 when steering

CAD by Anthony Riesemann (IFMA project 2009)
V5 - 3D Hybrid mechanism

- 4DOF with a variant of V4
  - Bars 531-534 located in a rhomboid layout
  - Tob-bar 533 provides easy connection to Z damper 540
  - Rear bar 534 provides easy connection to X damper 550
  - Damping attachment at mid-bars (no more inside the rim)

- Collision 510-550 when steering

Parallel Vertical & Longitudinal Suspension

- Purpose
- Prev. works
- Synthesis
  - 2D
  - 3D
- Dimensioning
- Conclusion

CAD by Richard Cousturier (IFMA project 2010)
V6 - 3D parallel mechanism

- 4DOF with only 3 bars
  - Rotating **rudder-bar**
    - 661 around Z1 → differential traction in 631 and 632 → rotation around Z2 of hub-carrier 720
  - **Improved integration:**
    - Steering linkage re-uses bars 631-632 from the lateral guidance linkage
  - Deep recessed tyre-rims **prevent direct attachment** of dampers 640-650 to 620
V7 - 3D parallel mechanism

- 4DOF with only 3 bars
  - Dampers 740 and 750 attached around the middle of bars 733 and 732 → no collision with wheel 710
  - Steering axis Z2 passes through the centre of the wheel contact patch → Minimal steering friction
  - Transmission line 770 with shafts connected by U joints
- Coupling between steering and horizontal damping
V8 - 3D parallel mechanism

- 4DOF with only 3 bars
  - Dampers 840 and 850 attached around the middle of top-bar
    833 → **No more coupling steering/X motion**
  - No bottom bar → **no interference** with obstacles
V9 - 3D parallel mechanism

- A variant of V8
  - Bars 932-933 (bottom-top) → lateral guidance
  - Front bar 931 for steering
  - Compatible with existing vehicles with double-wishbone suspension.

- Bottom bar → risk of interference with obstacles
Dimensional synthesis of V8

- CAD model and technological implementation
  - U-U limbs with **double damper**
  - Limbs 840 and 850 connect to 832 on **disjoint S joints**
  - Shifted **U joint** on transmission line

Parallel Vertical & Longitudinal Suspension

- Purpose
- Prev. works
- Synthesis
- Dimensioning
- Conclusion
Dimensional synthesis of V8

- CAD model and technological implementation
  - **Inter-bar distance** $B$ should be as large as possible:
    - Better steering stiffness
    - Limited by the non-interference between the bars and the tyre-rim
    - Avoid collision with transmission line, whatever the position
  - **Bar length** $L$ as long as possible $\rightarrow$ larger spherical translation radius
    - XZ planar motion approximation

Purpose

Prev. works

Synthesis

Dimensioning

Conclusion

Jean-Christophe FAUROUX
IFMA, Clermont-Ferrand
Real implementation of V8

- $w_1 > w_2$
- New steering linkage and stronger servomotor

Parallel Vertical & Longitudinal Suspension
- Purpose
- Prev. works
- Synthesis
- Dimensioning
- Conclusion
Conclusion

- **Innovating with a longitudinal suspension**
  - A suspension designed for FAST obstacle-crossing should have 4 DOF
    - Z vertical damping translation
    - Z steering rotation
    - **X longitudinal damping** translation
    - Y transmission rotation
  - Confirmed by **multibody 2D model**
  - Confirmed by **77 experiments**
  - Pushing-up the **tip-over stability limit** \( f(h,v) = \text{cte} \)

- **Structural synthesis of nine suspensions**
  - **3-2D** and **6-3D** kinematics
  - **8 parallel** and **6 spatial** kinematics
  - Most of them are **patented** [Fauroux-Cousturier 2012]
  - Campaign of obstacle-crossing **experiments** → comparing 4DOF vs. 3DOF
  - Associated **control** strategies.

- **Acknowledgements**
  - French National Research Agency (**ANR**) for funding this work through the **FAST project** (FAST Autonomous Rover)
  - **IFMA students** for their contribution to the FAST project: Frédéric KREIT, Anthony RIESEMANN, Aurélien AUTHIER, Solange OVAZZA, Richard COUSTURIER, Thibaud DEJEANTE and Romain VENDRÔME