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

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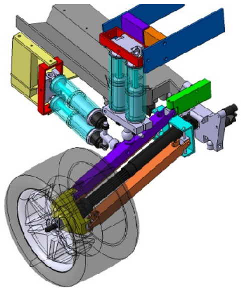
The Joint International Conference of the XI International Conference on Mechanisms and Mechanical Transmissions (MTM) and the International Conference on Robotics (Robotics'12)



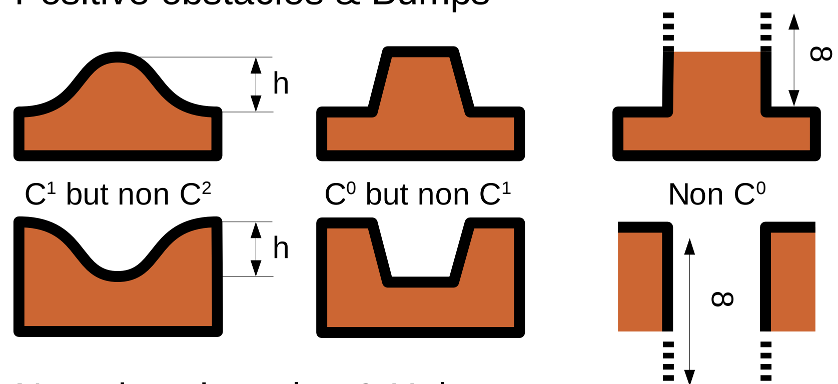
Longitudinal suspension

Parallel Vertical & 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

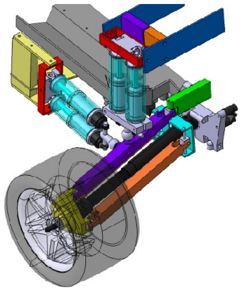


Negative obstacles & Holes

BMX race bike: C^1 obstacles

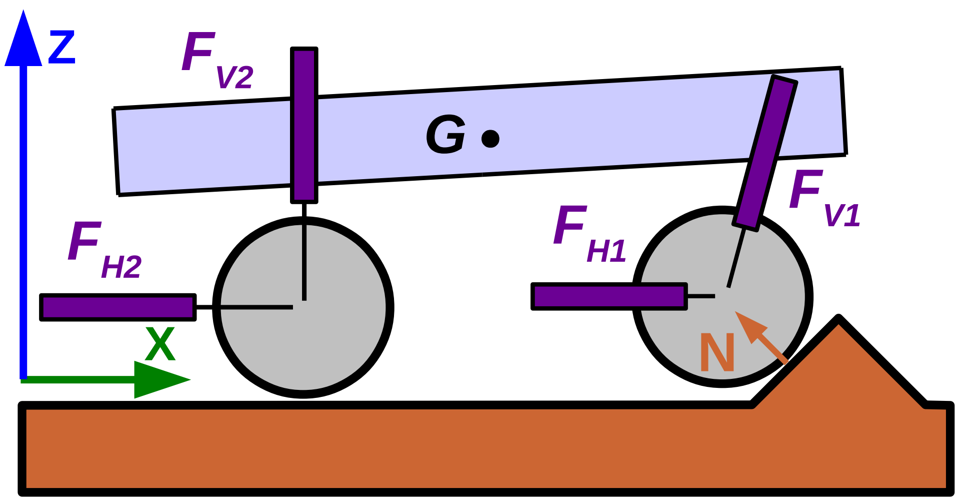
Slope bike competition: C^1 and C^0

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.

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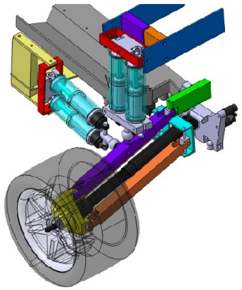
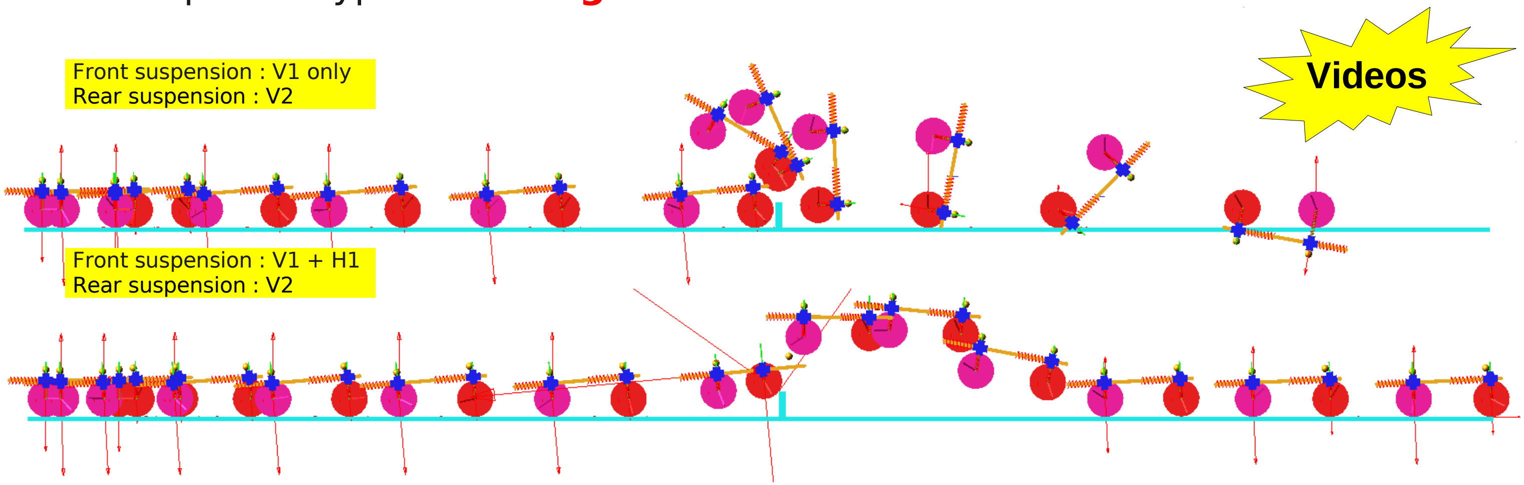


2D dynamic modelling

- A suspension with 2 DOF
  - Work published in [HUDEM 2010]
    J.C. Fauroux, J. Dakhlallah, B.C. Bouzgarrou, " A New Concept of FAST Mobile Rover with Improved Stability on Rough Terrain ", in Proc. of HUDEM'2010, 8th International Advanced Robotics Programme (IARP) Workshop on Robotics and Mechanical assistance in Humanitarian De-mining and Similar risky interventions, 10-12 May, 2010, National Engineering School of Sousse, Tunisia. Paper #26, 16 p.
  - 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 supension 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

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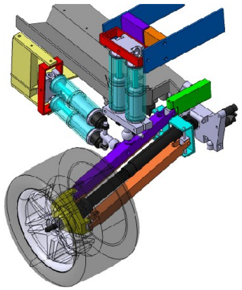


Parallel Vertical & Longitudinal Suspension

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

Experimental obstacle-crossing

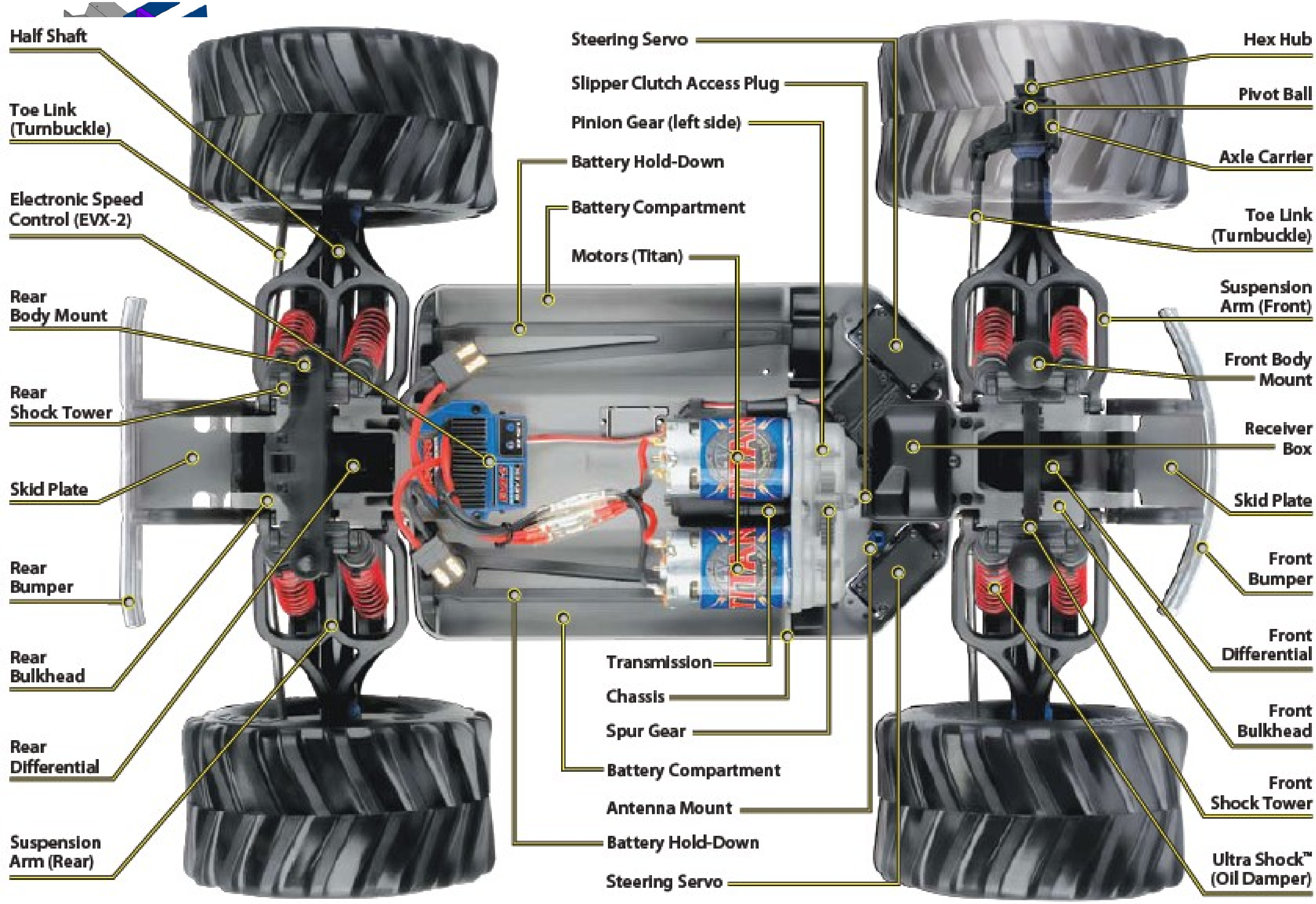
- First, an experimental approach of obstacle-crossing
  - ✔ Complex phenomena : non-linear fast crash of deformable mechanisms with friction and sliding
  - ✔ Published in [CLAWAR 2011]

J.C. Fauroux and B.C. Bouzgarrou. " Dynamic Obstacle-Crossing of a Wheeled Rover with Double-Wishbone Suspension ", in "Field Robotics", Edited by Philippe BIDAUD, Mohammad O. TOKHI, Christophe GRAND and Gurvinder S. VIRK, World Scientific Publishing, ISBN-13 978-981-4374-27-9, Proc. 14th International Conference on Climbing and Walking Robots, CLAWAR'11, Septembre 06-08, 2011, Paris, France, pp. 642-649.

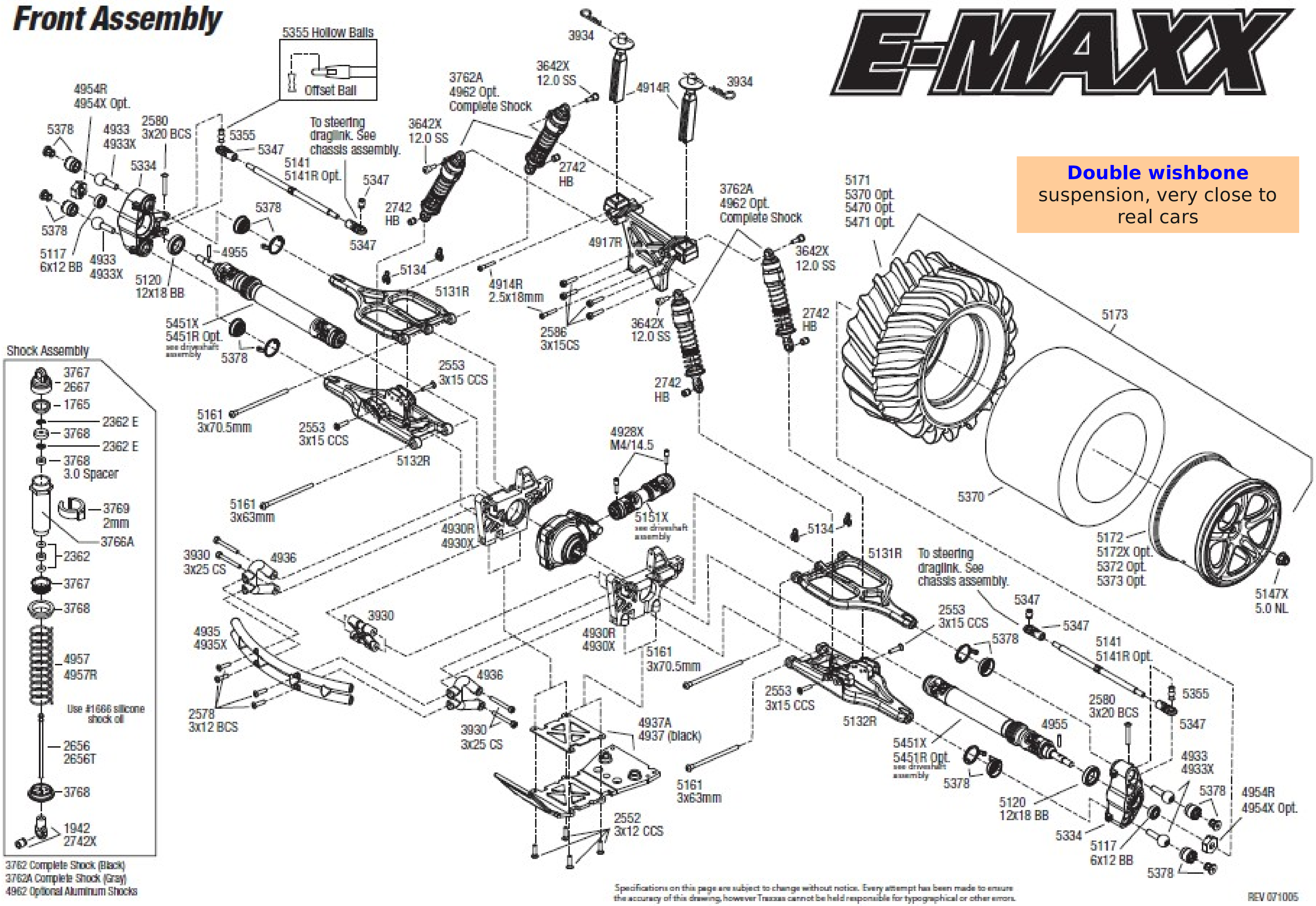
- Choosing a mobile platform
  - ✔ A fast & robust vehicle
  - ✔ Small scale decreases the repair cost
  - ✔ Easy to tip-over

E-Maxx electric model #3903 (Traxxas)
www.traxxas.com

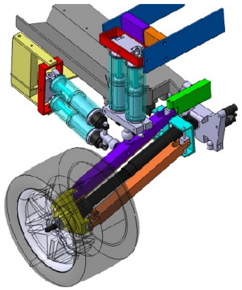
Vehicle	E-Maxx
Mass	5.16 kg
L x l x h	518 x 419 x 242 mm
Wheelbase	335 mm
Track width	330 mm
Centre of mass	Centred
Wheel diameter	150 mm
Transmission	4x4
Max speed	14 m/s


Half Shaft
Toe Link (Turnbuckle)
Electronic Speed Control (EVX-2)
Rear Body Mount
Rear Shock Tower
Skid Plate
Rear Bumper
Rear Bulkhead
Rear Differential
Suspension Arm (Rear)
Steering Servo
Slipper Clutch Access Plug
Pinion Gear (left side)
Battery Hold-Down
Battery Compartment
Motors (Titan)
Transmission
Chassis
Spur Gear
Battery Compartment
Antenna Mount
Battery Hold-Down
Steering Servo
Hex Hub
Pivot Ball
Axle Carrier
Toe Link (Turnbuckle)
Suspension Arm (Front)
Front Body Mount
Receiver Box
Skid Plate
Front Bumper
Front Differential
Front Bulkhead
Front Shock Tower
Ultra Shock™ (Oil Damper)

E-MAXX

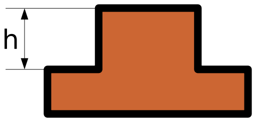


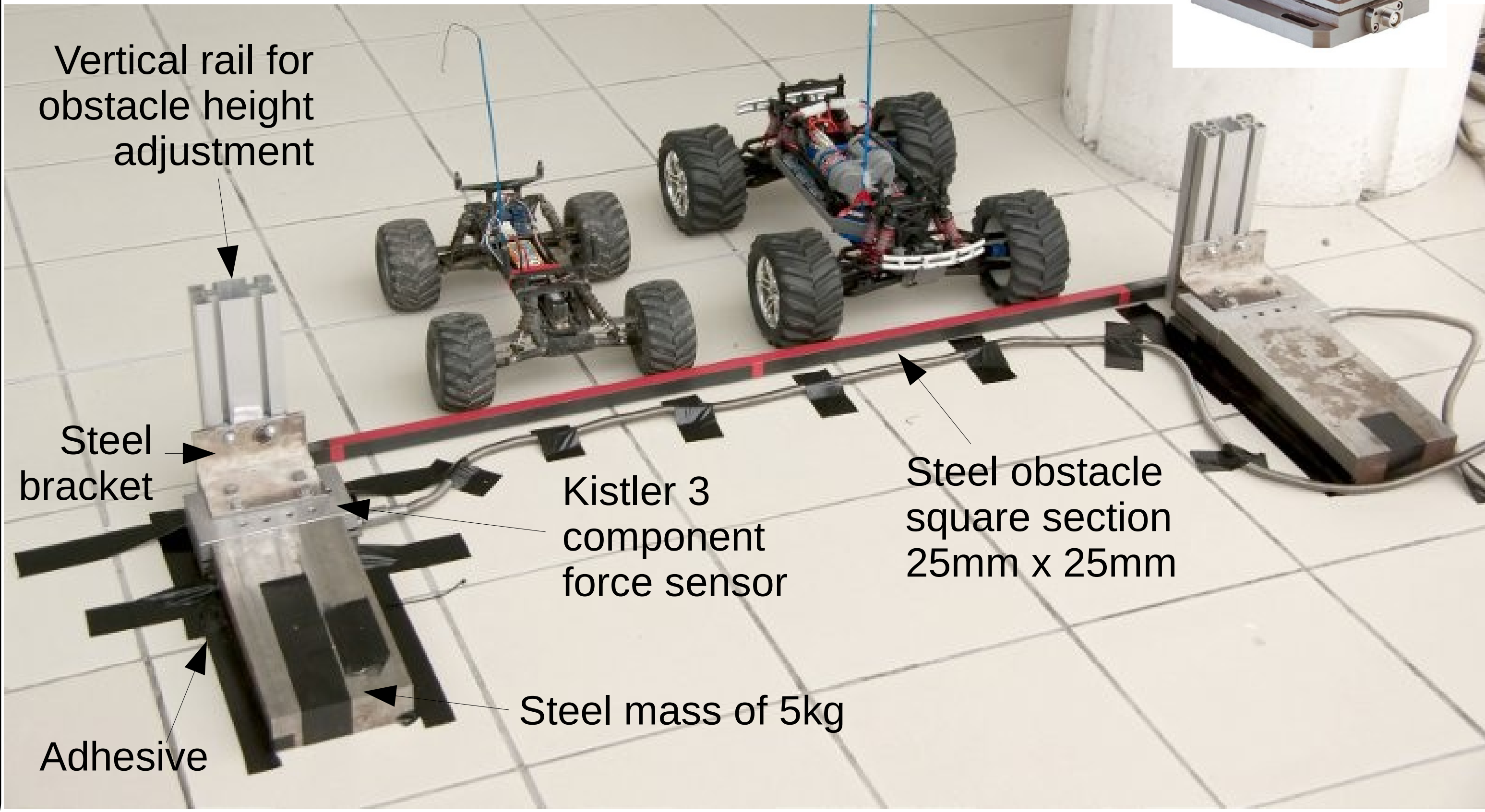
Double wishbone suspension, very close to real cars

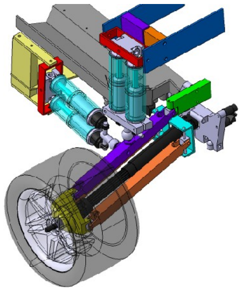


Experimental obstacle

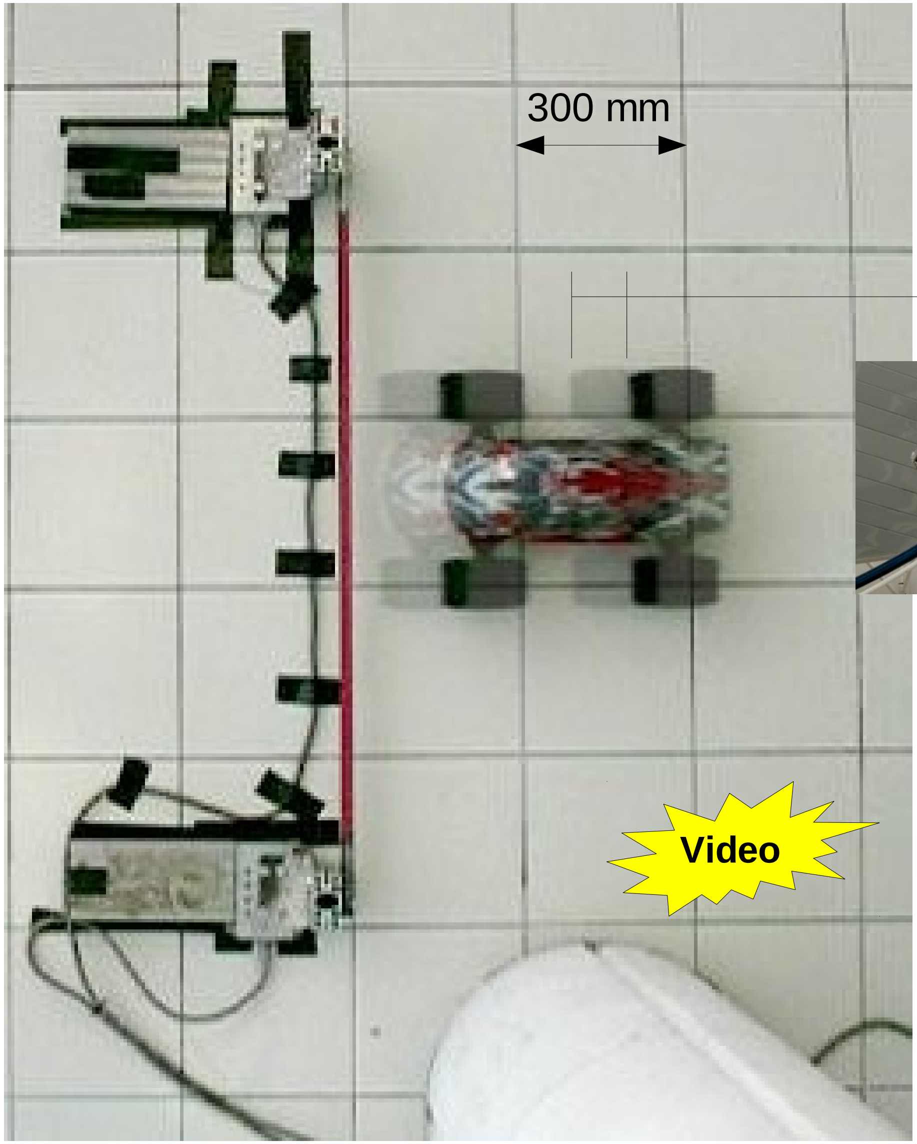
- Adjustable C^0 obstacle
  - ✔ Steel bar adjustable in height h
  - ✔ Includes force measurement devices (Kistler 9257B)







Speed measurement



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

- 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

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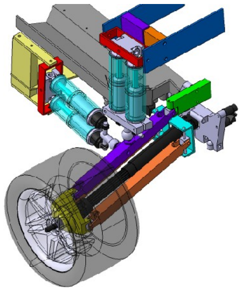
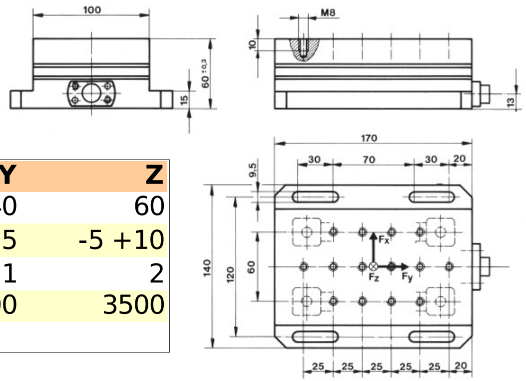
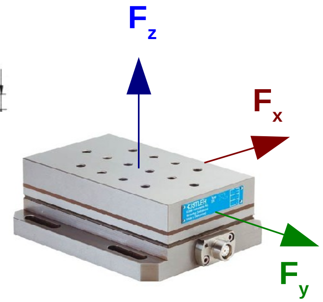


Force measurement

- 3 DOF force-plate

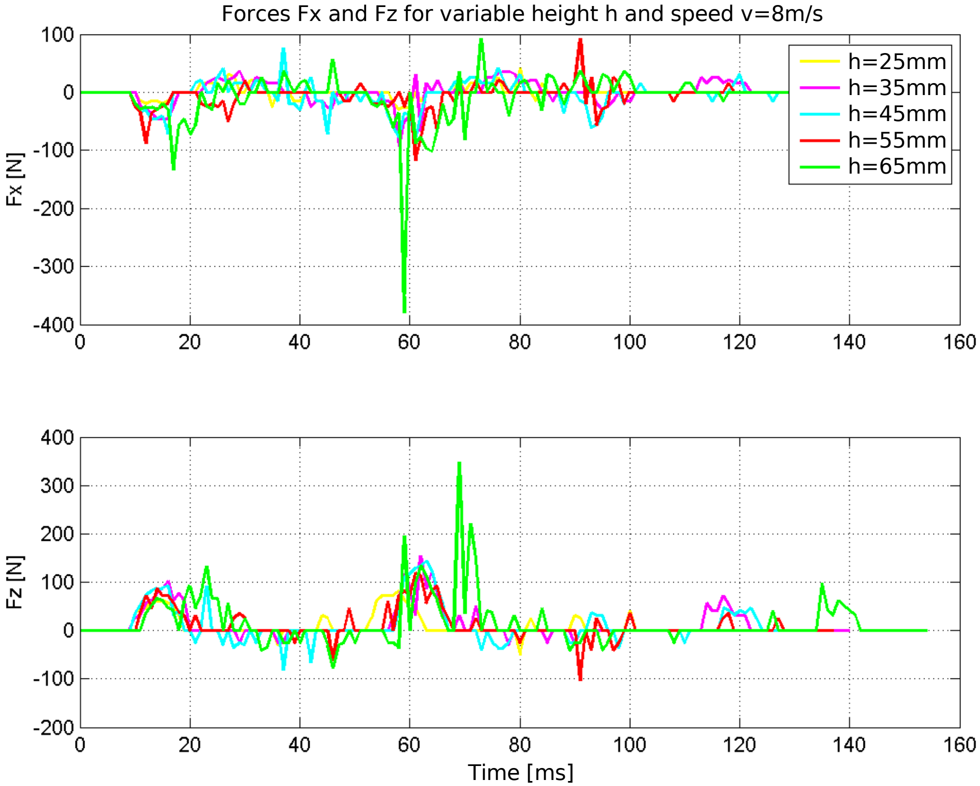




Parameter	X	Y	Z
Dimensions (mm)	170	140	60
Force range (kN)	-5 +5	-5 +5	-5 +10
Stiffness (kN/µm)	1	1	2
Natural frequency (Hz)	2300	2300	3500
Mass (kg)	7,3		

  - ✔ Acquisition 1kHz

- Results
  - ✔ Impact force increases with obstacle height
  - ✔ Peaks of 400N
  - ✔ **$F_x \approx F_z$** for v=8m/s and h=65mm
  - ✔ Need for a **horizontal component of suspension**



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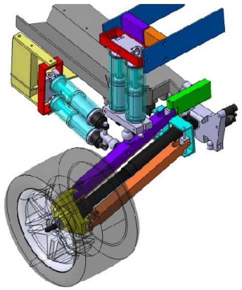
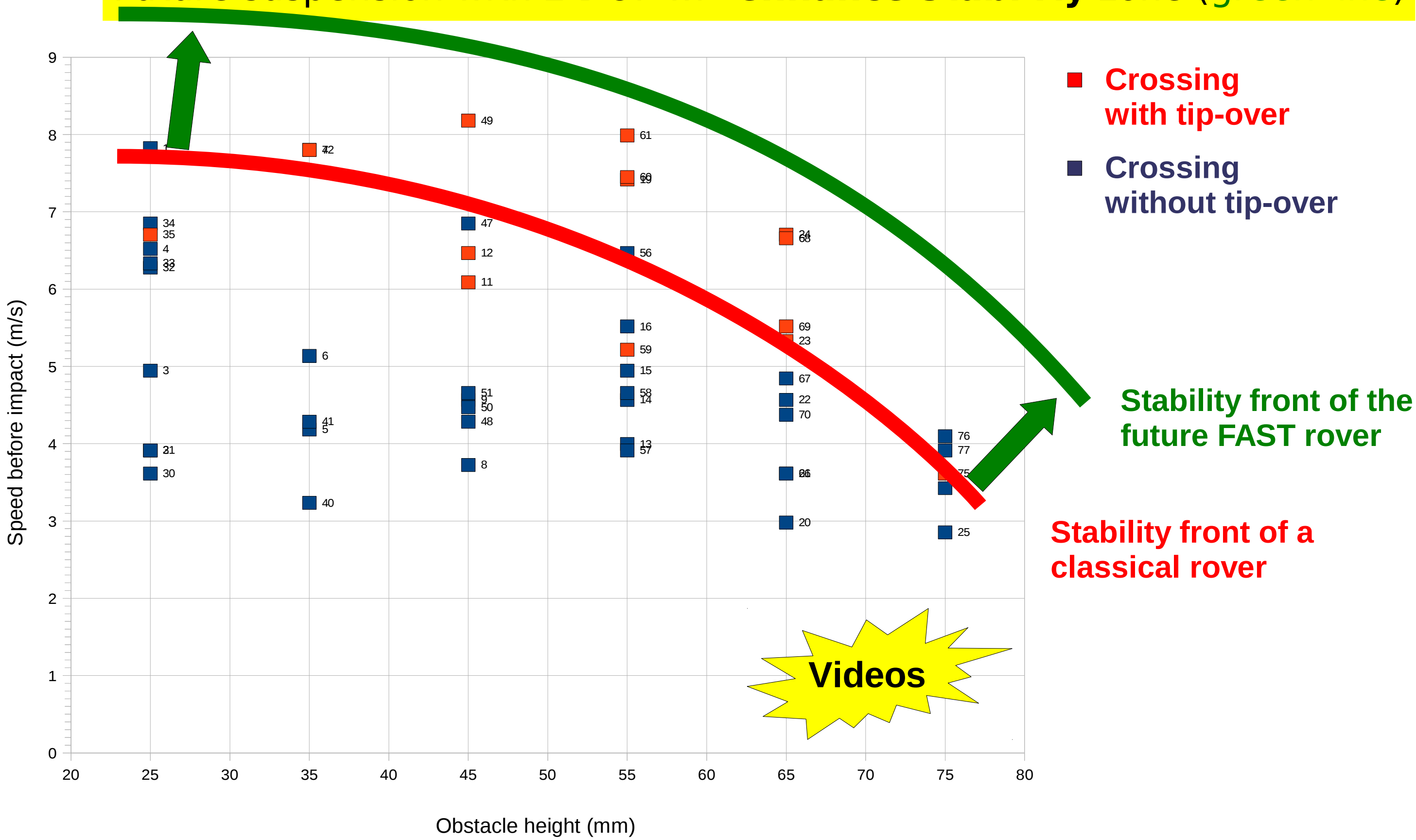
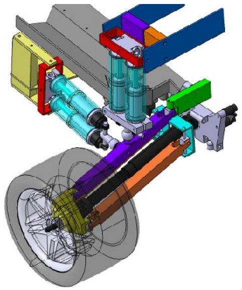


Parallel Vertical & Longitudinal Suspension

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)





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

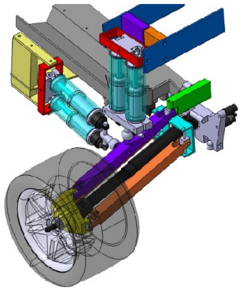
(b) Military truck Nexter Aravis

(c) ATV Polaris Sportsman XP850

(d) Buggy BooXT

(e) RC car HPI Maverick Scout Crawler

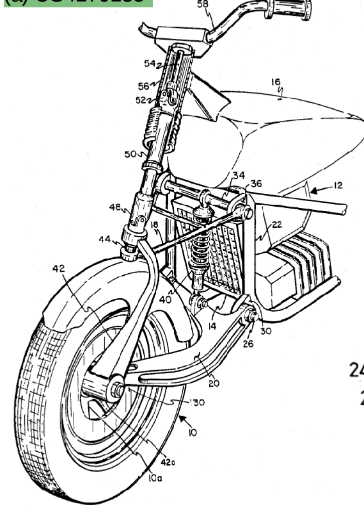
(f) Robot Robosoft RobuROC 6



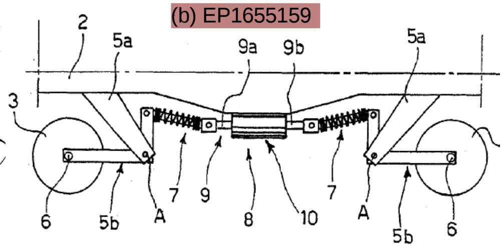
Suspension patent analysis

- 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

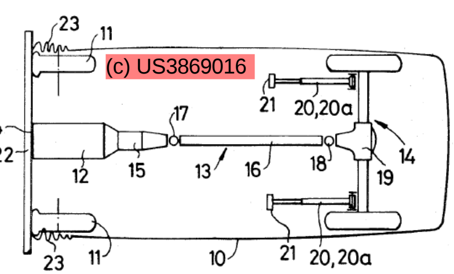
(a) US4179135



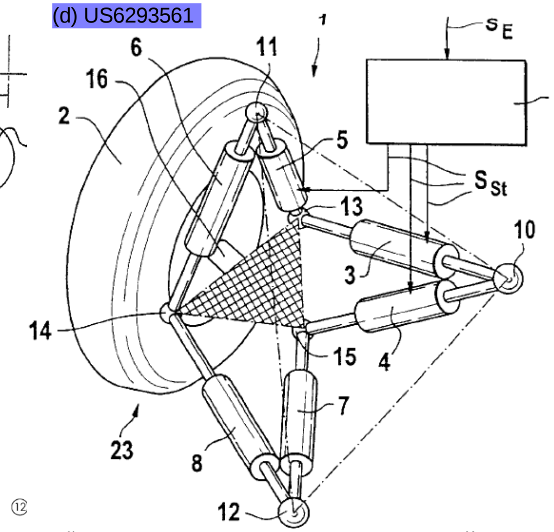
(b) EP1655159

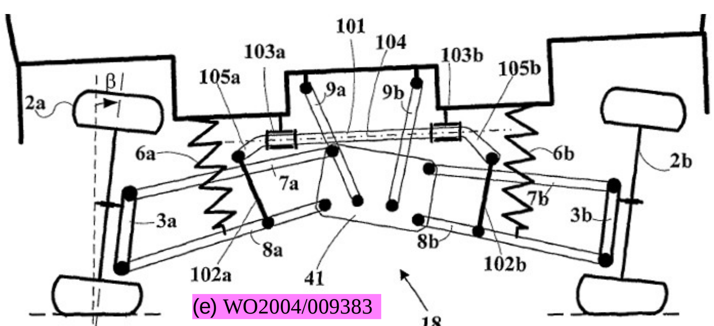


(c) US3869016

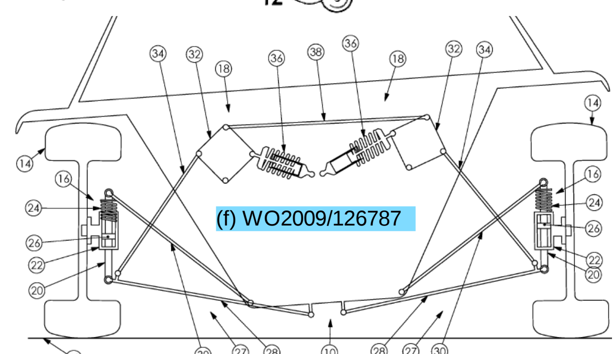


(d) US6293561





(e) WO2004/009383



(f) WO2009/126787

Parallel Vertical & Longitudinal Suspension

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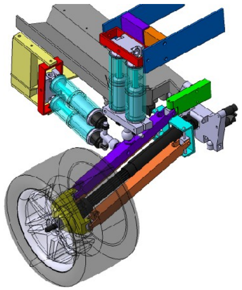
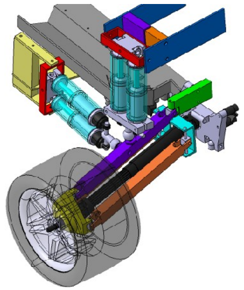


Synthesis of new suspensions

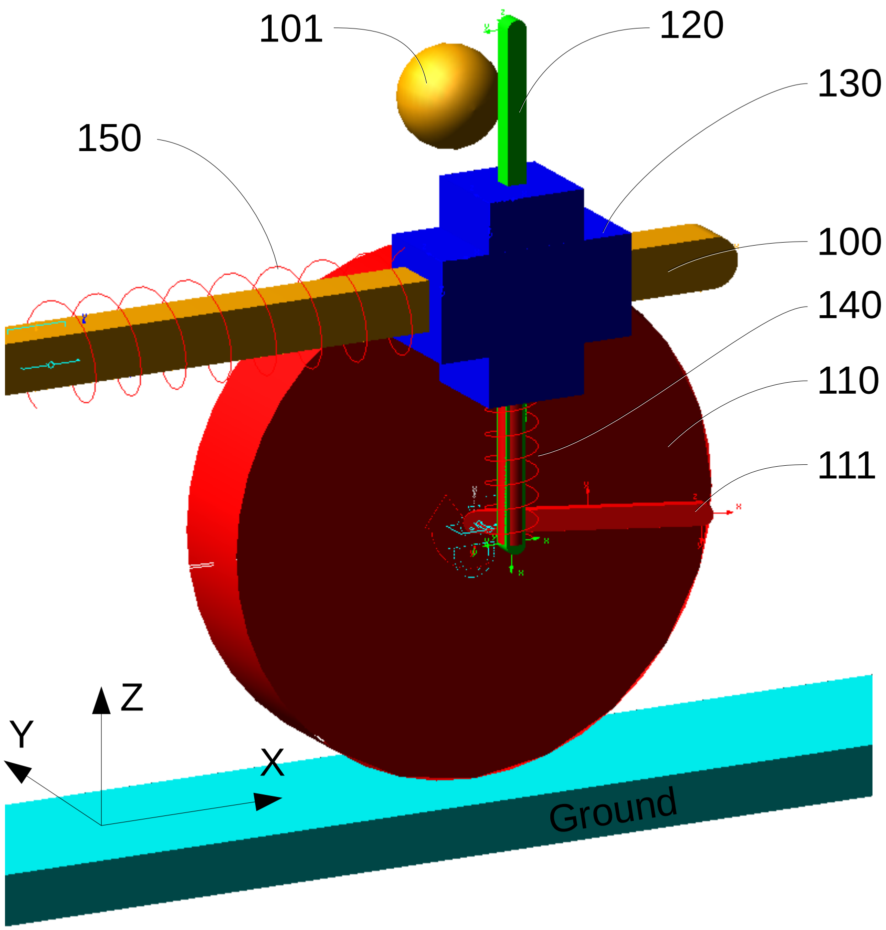
Parallel Vertical & Longitudinal Suspension

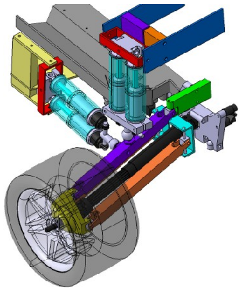
- New suspensions must be designed
  - To absorb both **vertical (Z) and longitudinal (X)** reaction forces against obstacles (cf. models [HUDEM 10])
  - The **X** and **Z** motions should be of the **same order of magnitude** (cf. experiments [CLAWAR 11])
  - Usable on front and rear axles → **the wheel 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



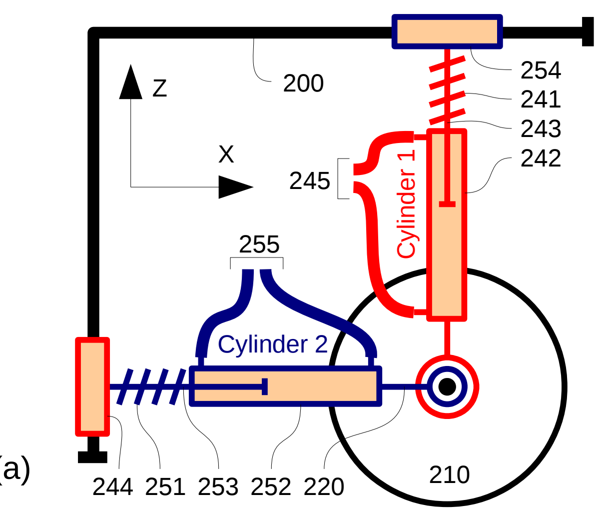


V2 - 2D Max. regular parallel

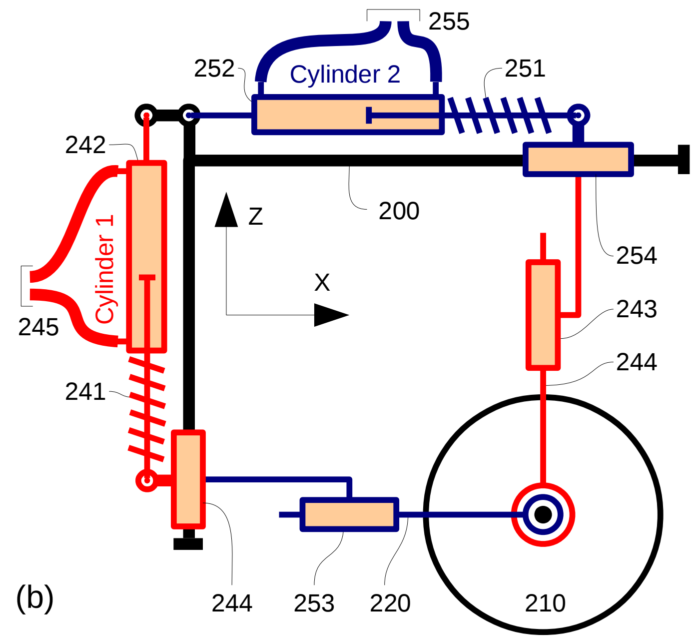
- 2DOF with a parallel decoupled mechanism
  - ✔ 2 **PCR limbs** copying the serial structure of V1
  - ✔ Cylinders can be **active** / **adjustable** / **passive**
  - ✔ Same mobility, **stiffness is improved** in case of shocks
  - ✔ In (a), X shocks absorbed by Cylinder 2, **no flexion** of rod 243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

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

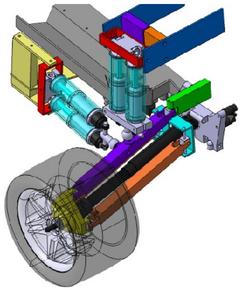
  - ✗ Horizontal limb **too low**
  - ✗ No **steering**
  - ✗ **Prismatic joints**: expensive & may lock (butting)



(a)



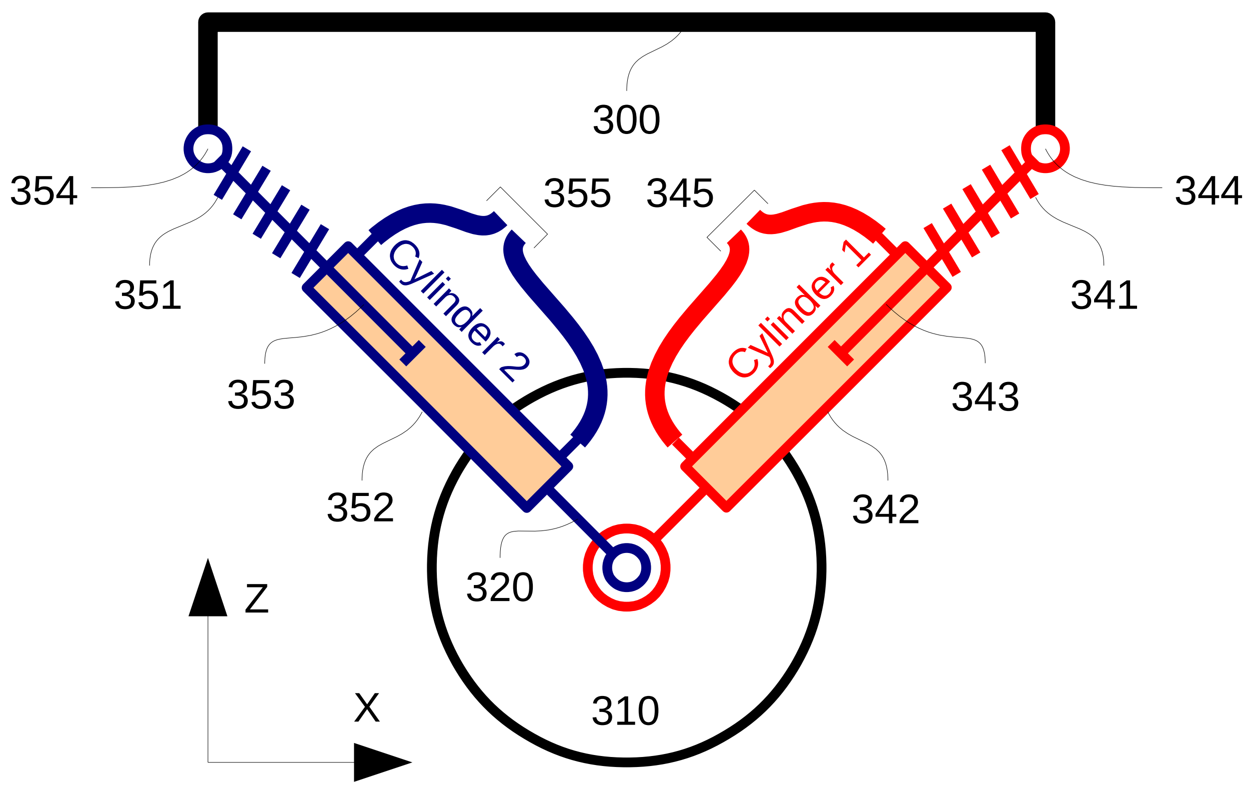
(b)



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



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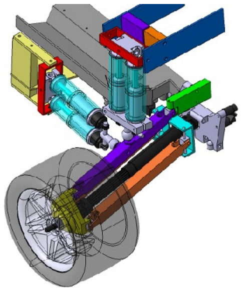

V4 - 3D Hybrid mechanism

- 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

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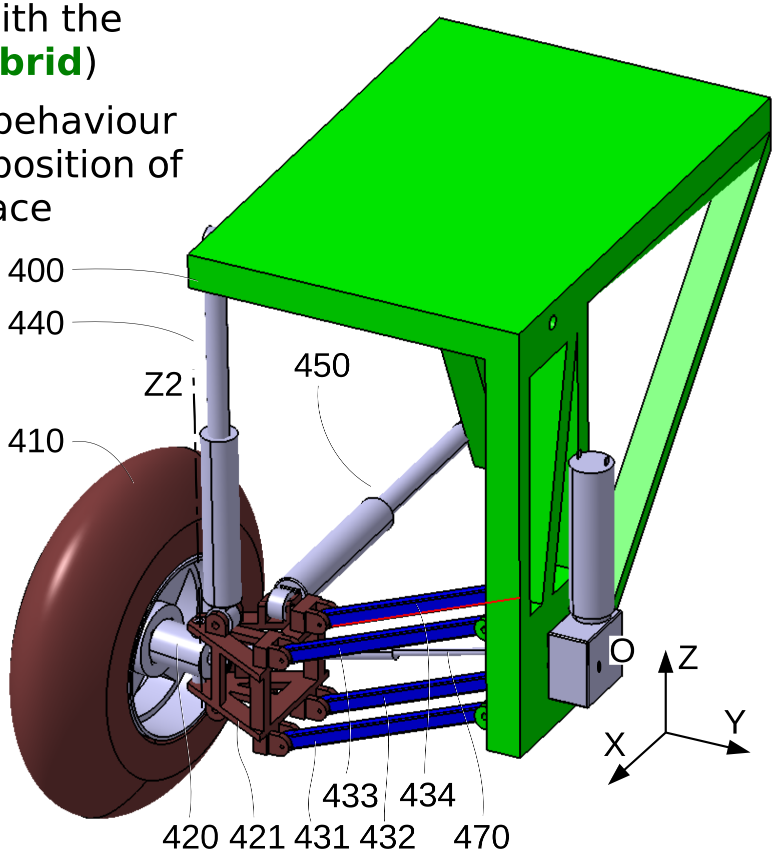
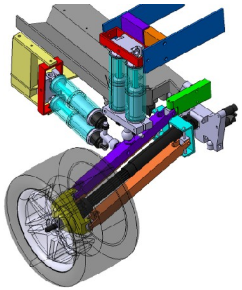
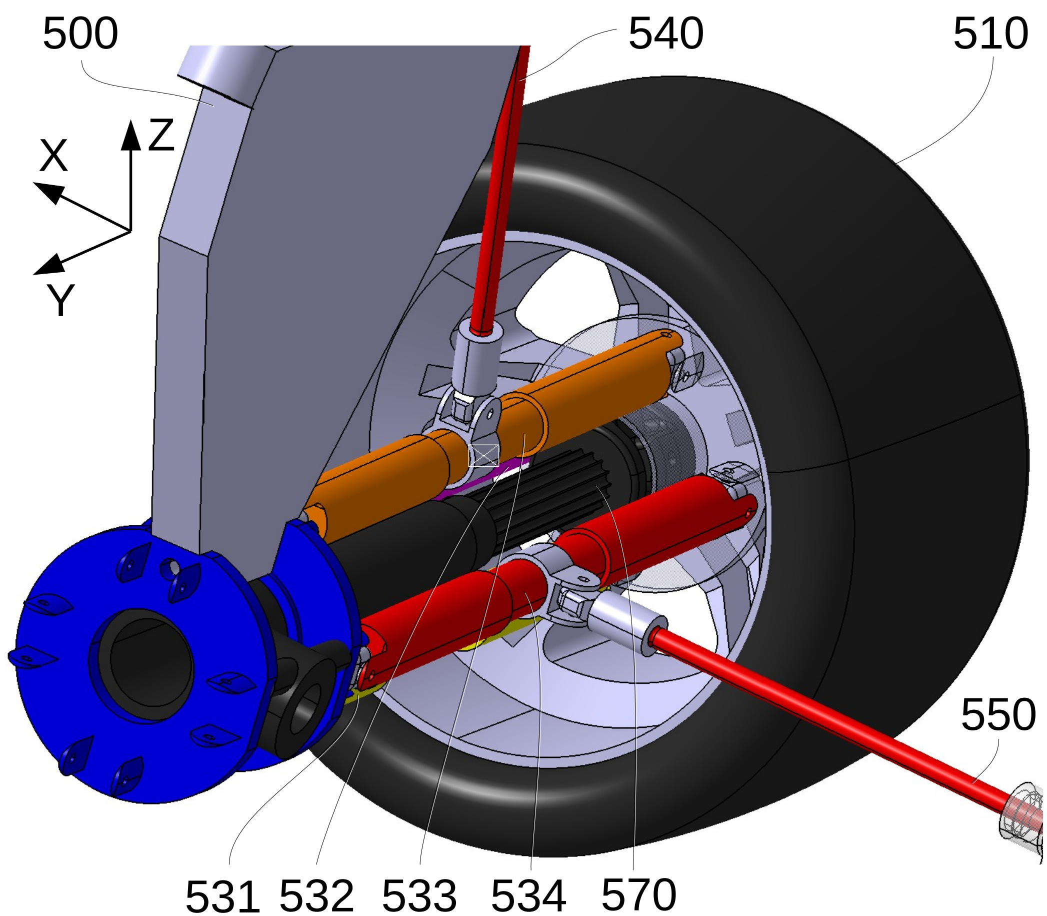


CAD by Anthony Riesemann (IFMA project 2009)



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



CAD by Richard Cousturier (IFMA project 2010)

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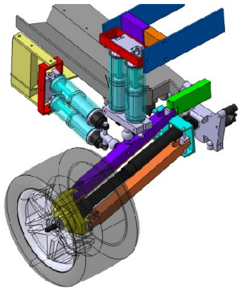
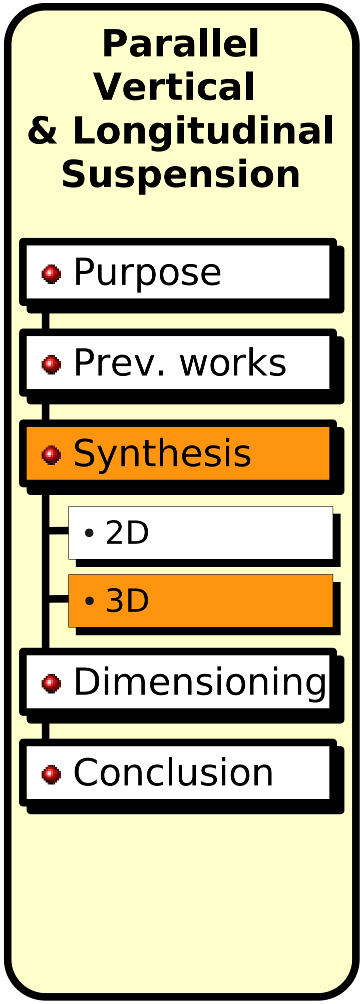
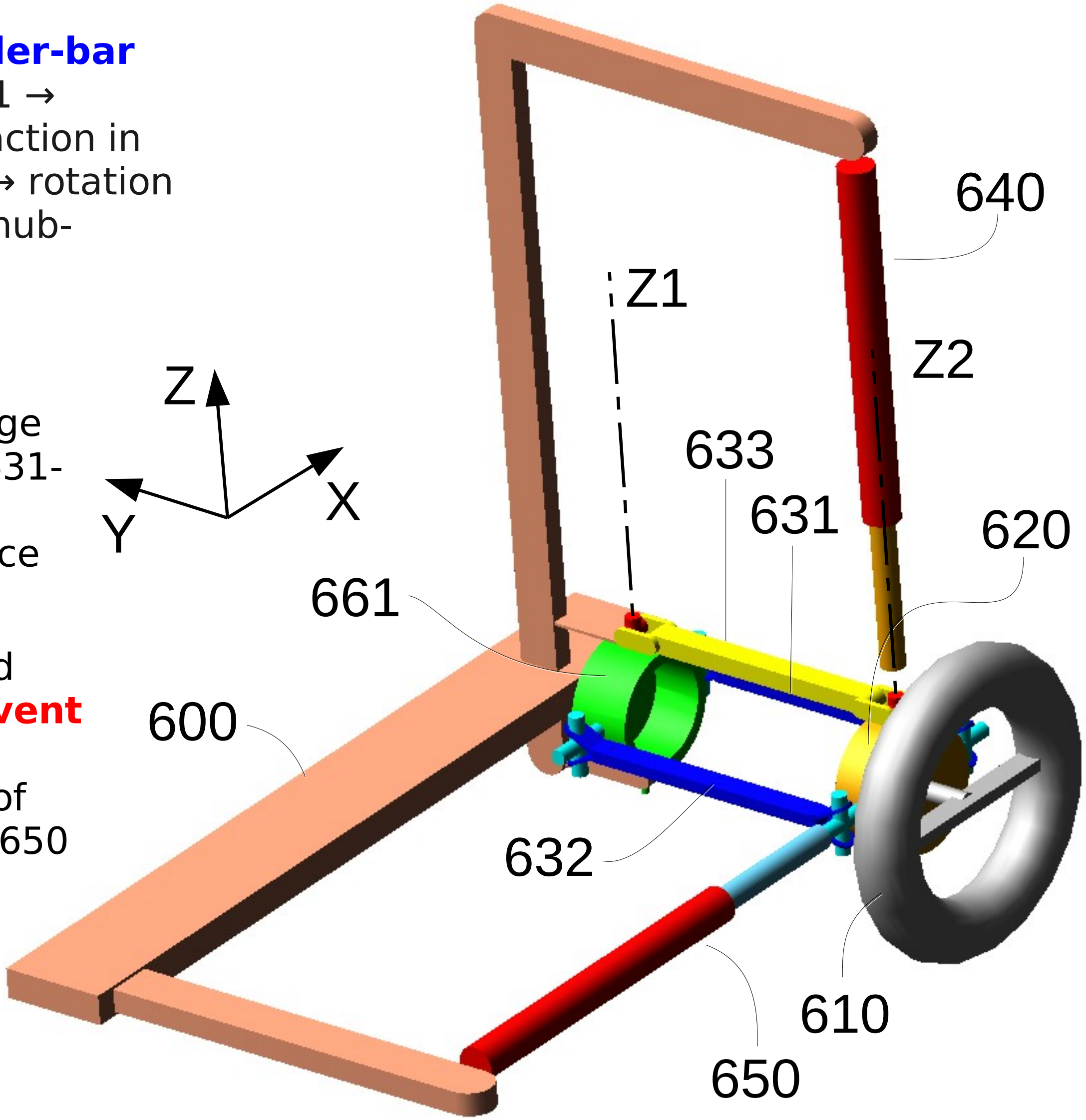


V6 - 3D parallel mechanism



- 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



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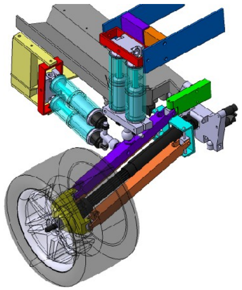
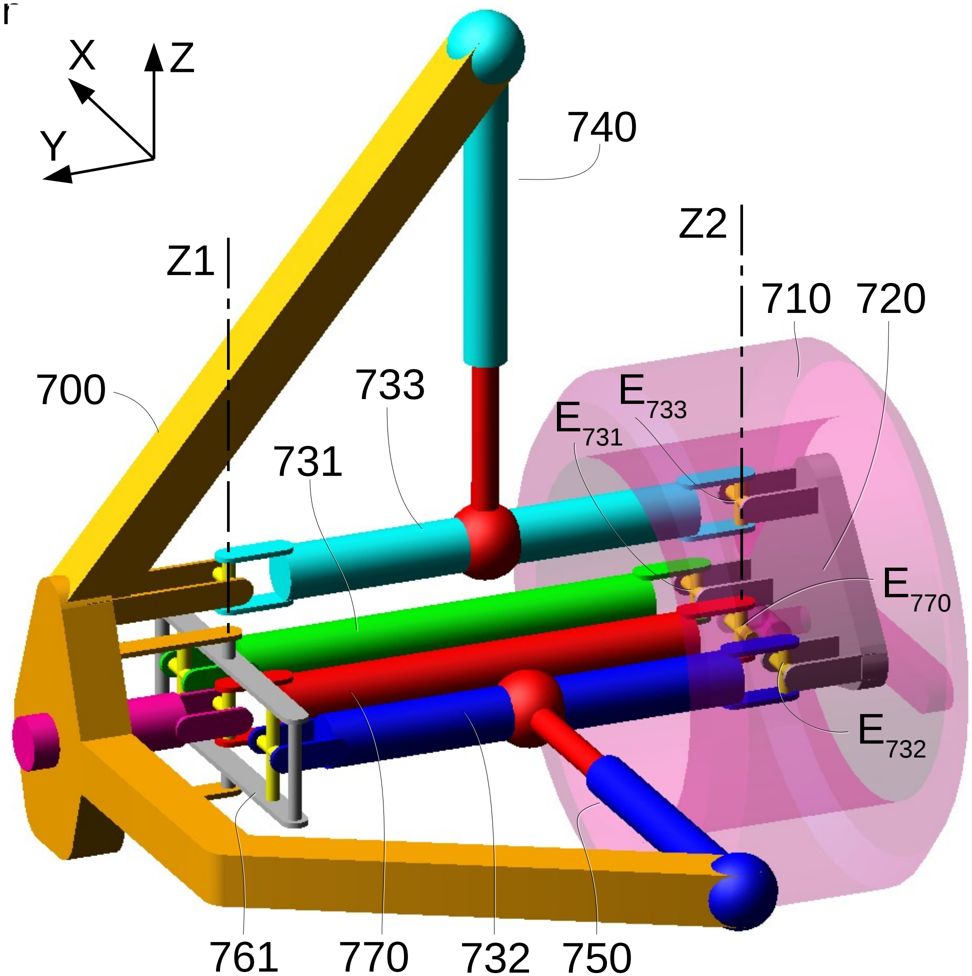


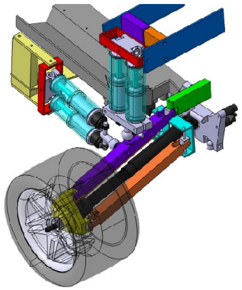
Parallel Vertical & Longitudinal Suspension

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

V7 - 3D parallel mechanism

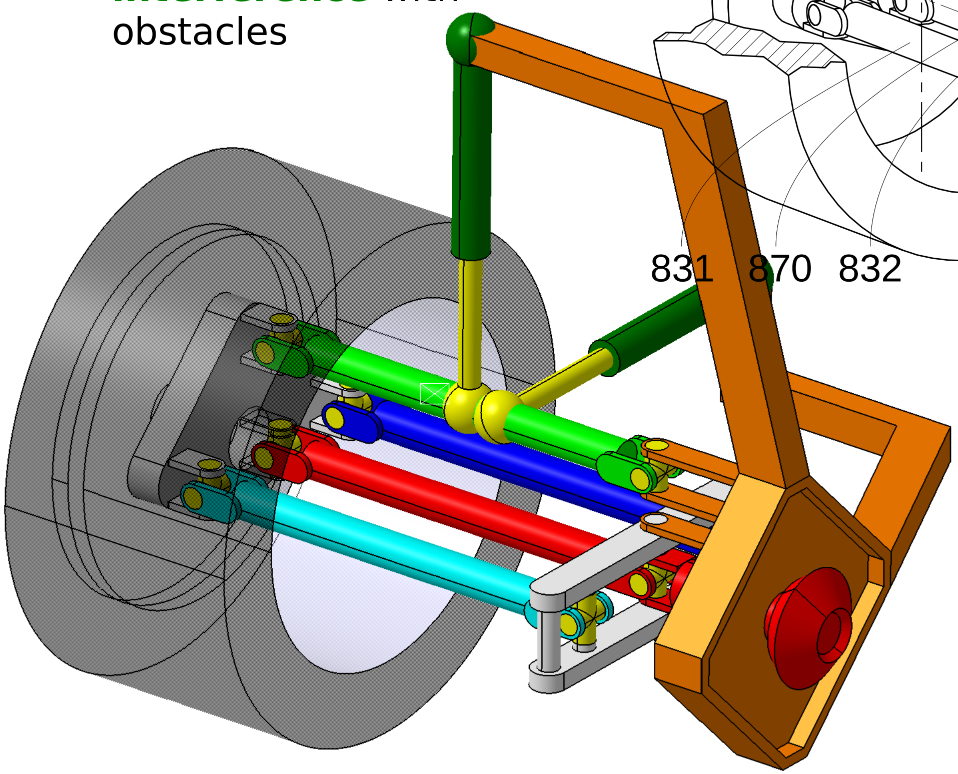
- 4DOF with only 3 bars
  - ✔ Dampers 740 and 750 attached around the **middle of bars** 733 and 732 → no collision with wheel 710
  - ✔ Steering axis Z2 passes through the centre of the wheel contact patch → **Minimal steering friction**
  - ✔ **Transmission line** 770 with shafts connected by U joints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

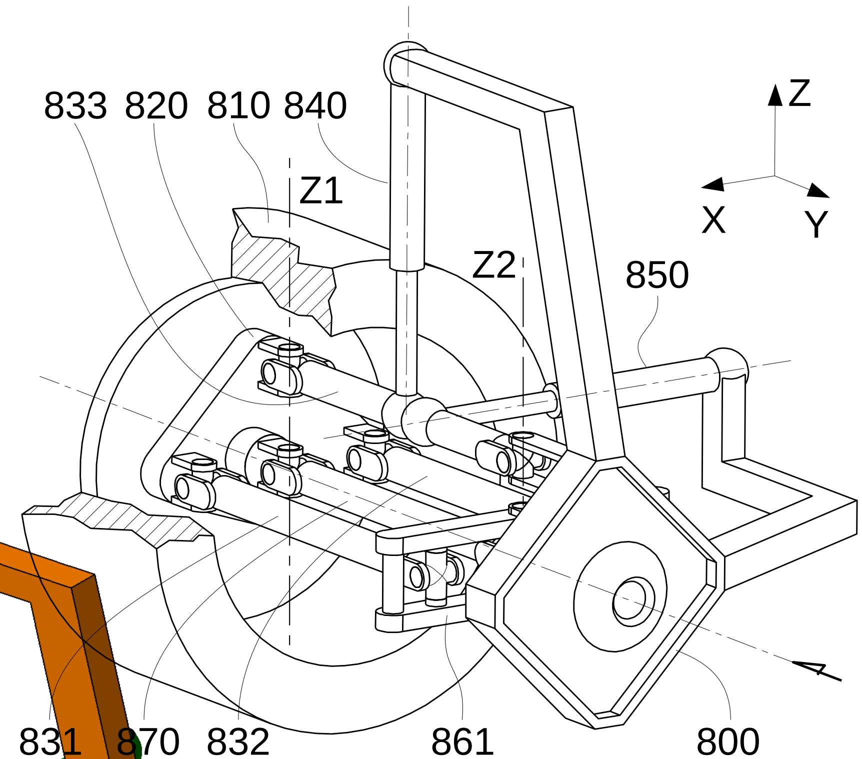




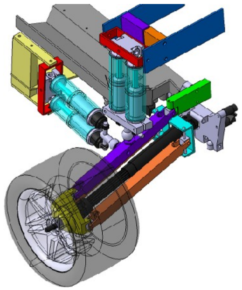
V8 - 3D parallel mechanism

- 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



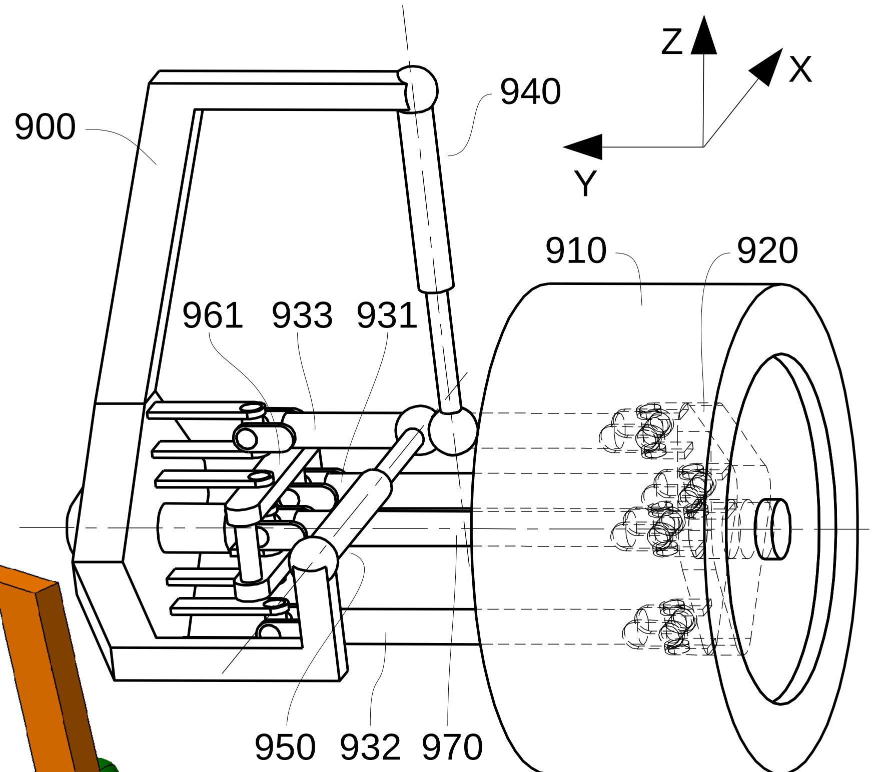


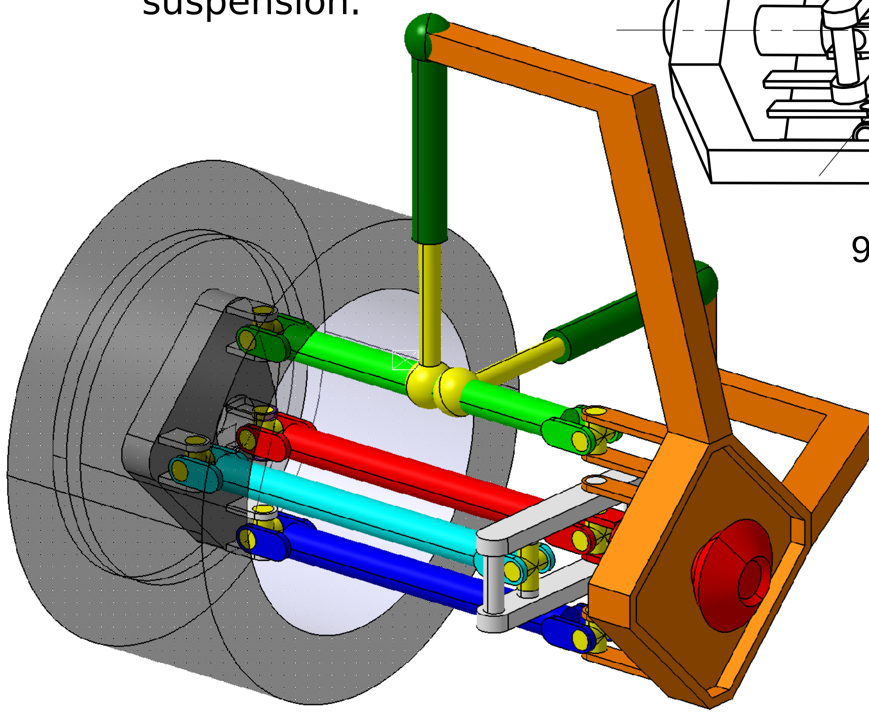
Parallel Vertical & Longitudinal Suspension



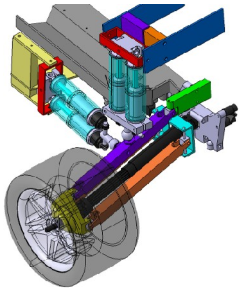
V9 - 3D parallel mechanism

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



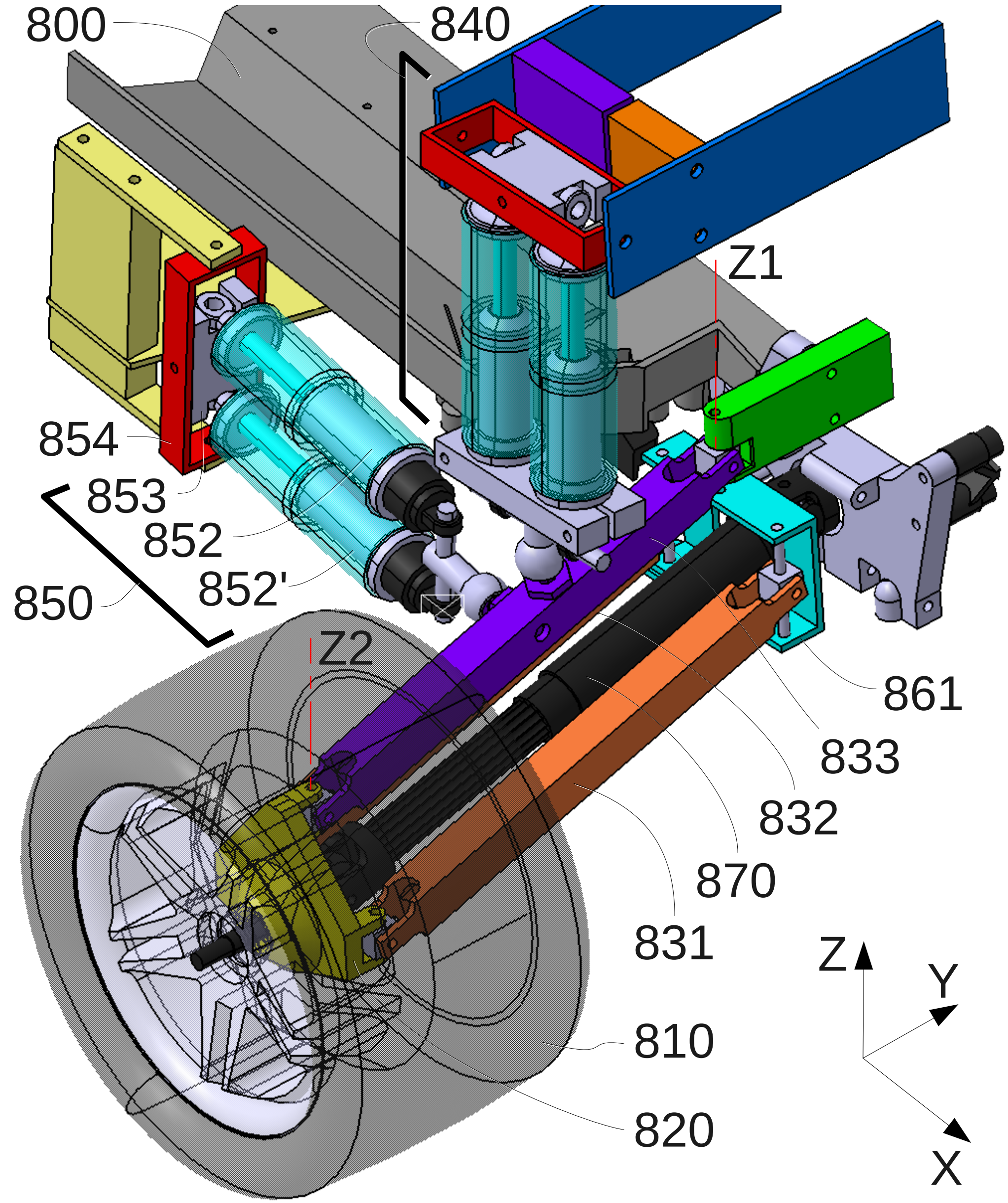


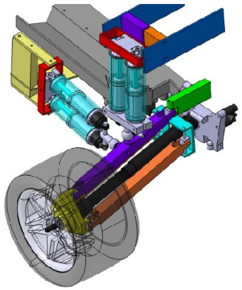
✗ Bottom bar → risk of **interference** with obstacles



Dimensional synthesis of V8

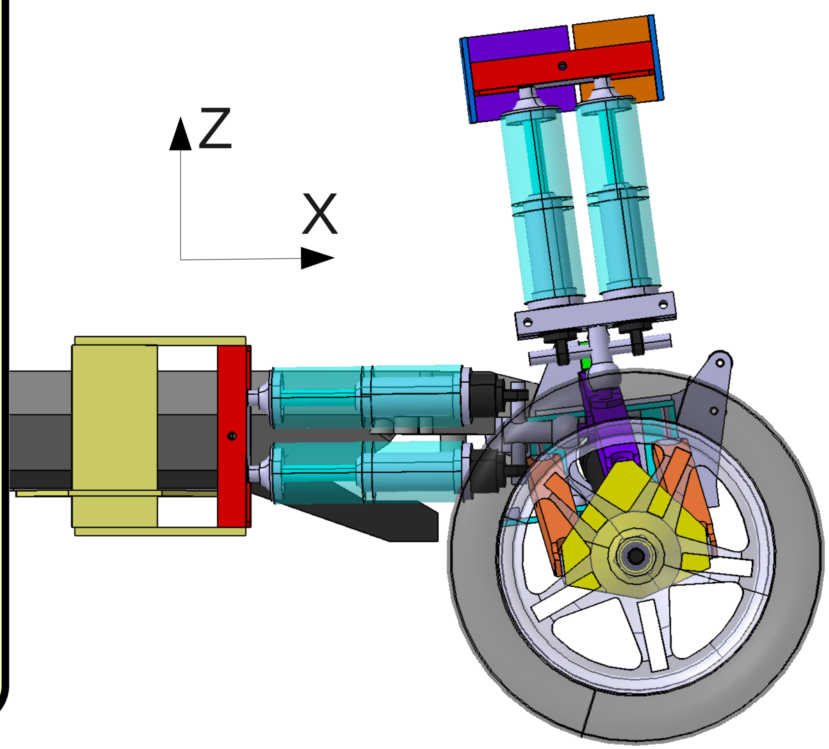
- CAD model and technological implementation
  - U-U limbs with **double damper**
  - Limbs 840 and 850 connect to 832 on **disjoint S joints**
  - **Shifted U joint** on transmission line

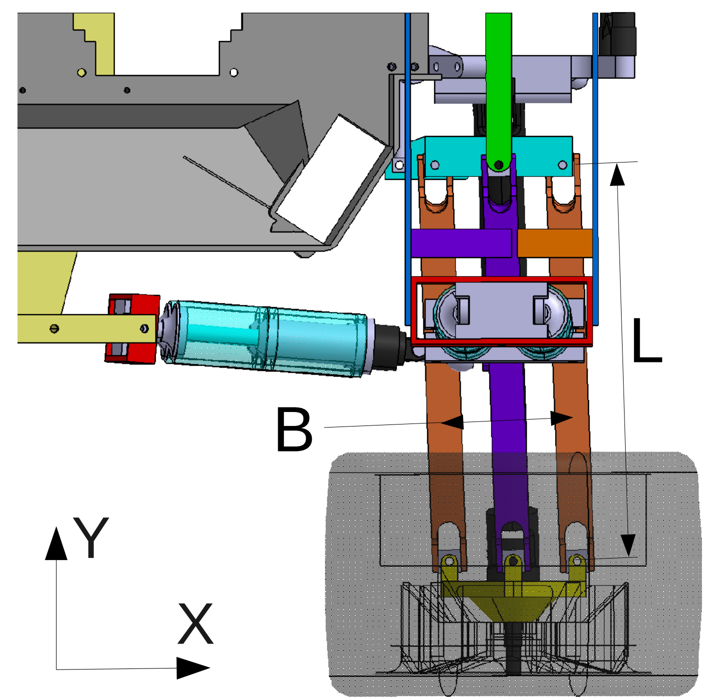


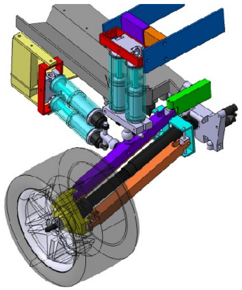


Dimensional synthesis of V8

- 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 → larger spherical translation radius
    - XZ planar motion approximation

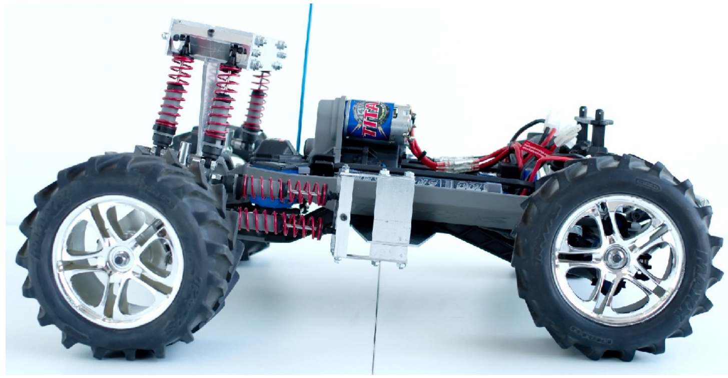


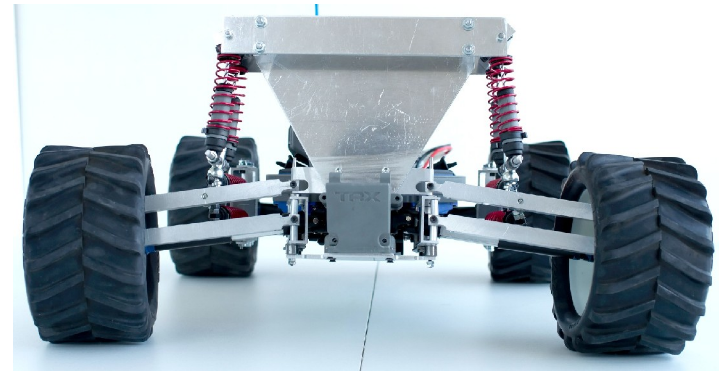


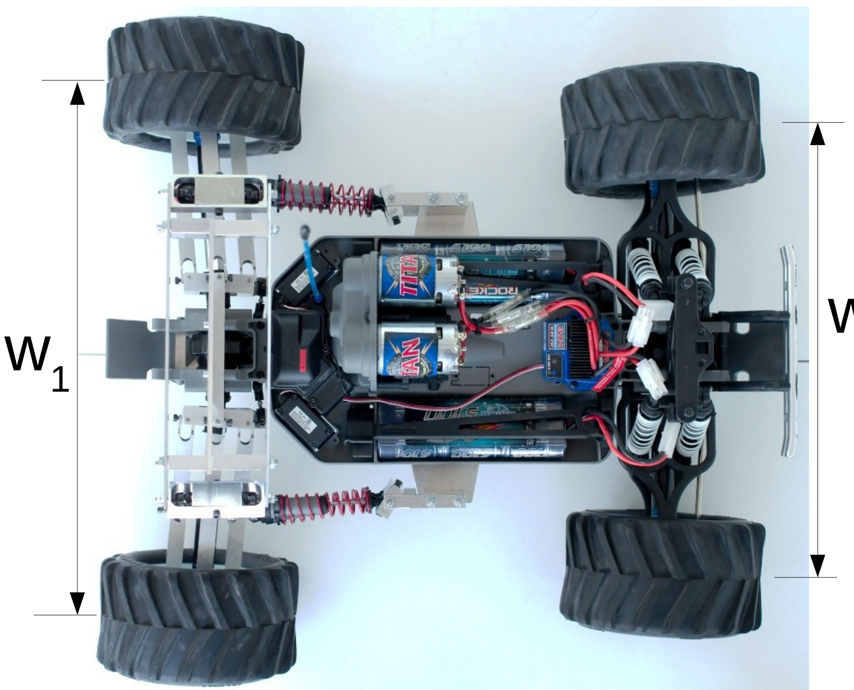


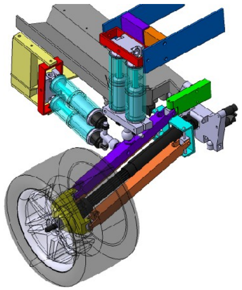
Real implementation of V8

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



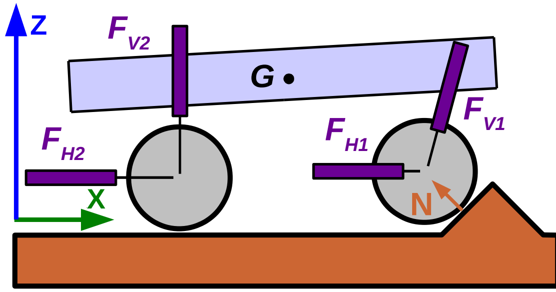






Parallel Vertical & Longitudinal Suspension

Conclusion



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