Collaborative Cross and Carry mobile roBots → The C^3Bots project

Agile reconfigurable mobile manipulators for payload transport

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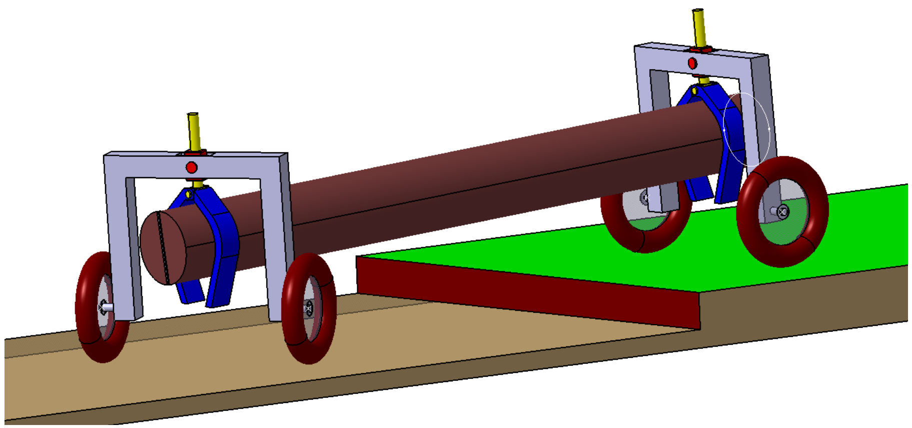
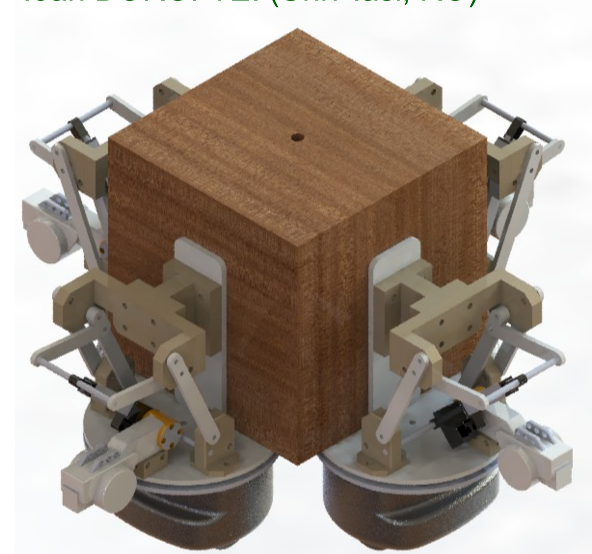
AUVERGNE
La Région juste et grande





GDR robotique

Introduction to the C^3Bots project

C^3Bots =
Collaborative
Cross &
Carry
Mobile RoBots

General goal

C^3Bots = **Collaborative Cross & Carry** Mobile Ro**Bots**

- ✔ **Modularity**: Several **mono-robots** that combine into a single **poly-robot**
- ✔ **Reconfigurability** according to payload / env.

- ✔ Unstructured environments
- ✔ **Obstacle** crossing
- ✔ **Stability**

- ✔ Manipulation and **transport**
- ✔ Payloads of **any mass & shape**
- ✔ Removal man task

Scientific topics

- Design of a mechatronic system achieving the tasks with **minimal DoF (**→ simplicity)
- Static and dynamic models to maximize the poly-robot **margin of stability**
- **Perception** and **control** to guaranty efficient **connections** mono-robot/mono-robot and mono-robot/payload
- Optimal **reconfiguration** of the mono-robots for the task (number, poses, cooperation strategies)

The C³Bots project – Examples of tasks

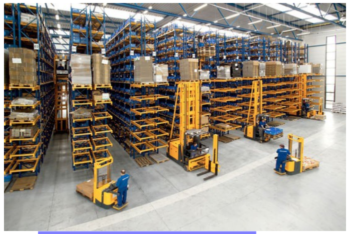
Object transport on smooth ground

Obstacle crossing with heavy payload

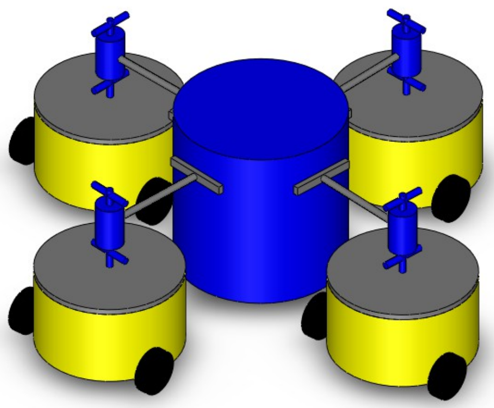
Co-manipulation and transport with two operators

Bio-inspired co-manipulation

Object transport with several operators



Industrial logistics with several carts on flat ground



The **C³BOTS poly-robot**
Collaborative **C**ross and **C**arry mobile ro**BOTS**

Co-manipulation of a heavy payload on flat ground

Co-manipulation of a heavy payload with obstacle crossing

Co-transport of stretchers on irregular ground

Co-transport of a rigid long object on a flat ground

Co-manipulation of compliant bars on a flat but unstructured environment (building area)

Collaborative

Cross

Carry

Long objects

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C³Bots project: two general architectures

C³Bots =
Collaborative
Cross &
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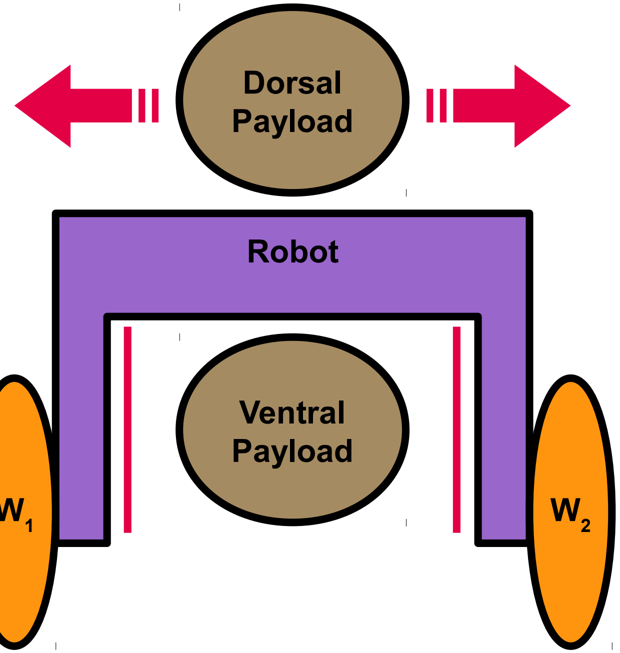
Mobile RoBots



C³Bots AT VLP
All-Terrain
Ventral Long Payload

- Ventral storage → limited laterally by propulsion devices
- Reconfiguring # of robots
  → payloads of **any length**

C³Bots DGP
Dorsal General Payload

- Dorsal storage → non limited in width & length
- Reconfiguring # of robots
  → payloads of **any shape**

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C³Bots project: two general architectures

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- C³Bots context
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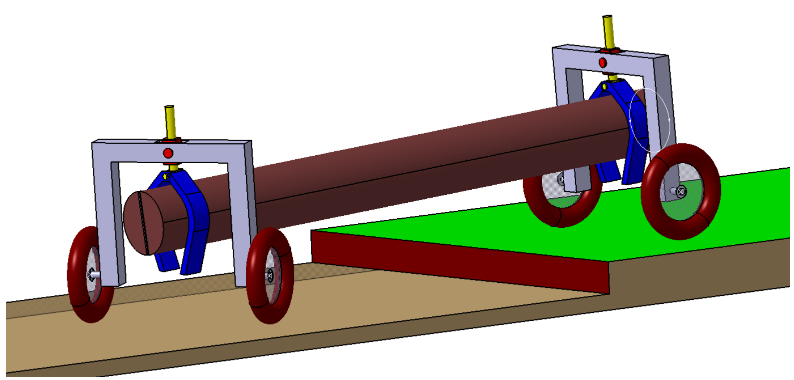
- Conclusion

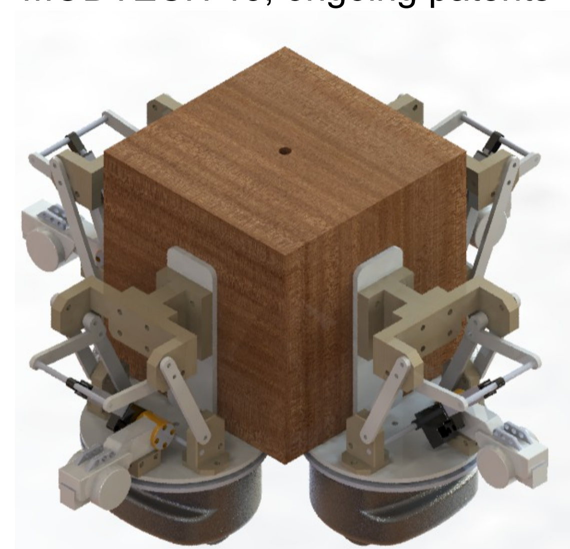
C³Bots AT VLP
All-Terrain
Ventral Long Payload

- Post-Doctoral period of Mohamed KRID
- Co-supervision: Bouzgarrou / Fauroux
- Heavy long payloads should be stored lower → **ventral storage**, between axle wheels
- **Which kinematic** chain to connect the payload to the mono-robots ?
- Pub: EUCOMES 14, 2 patents



C³Bots DGP
Dorsal General Payload

- Ph.D. of Bassem HICHRI (Oct 2015)
- Co-supervision: Adouane / Doroftei / Fauroux / Mezouar
- Structured terrain (for the moment)
- Payload of **any shape**
- **Dorsal** storage
- Pub: DARS 14, EUCOMES 14, MODTECH 13, ongoing patents



Existing devices: mobile robots

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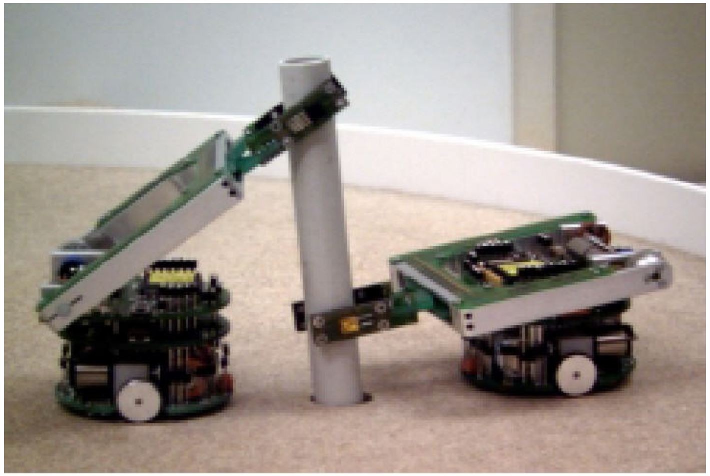
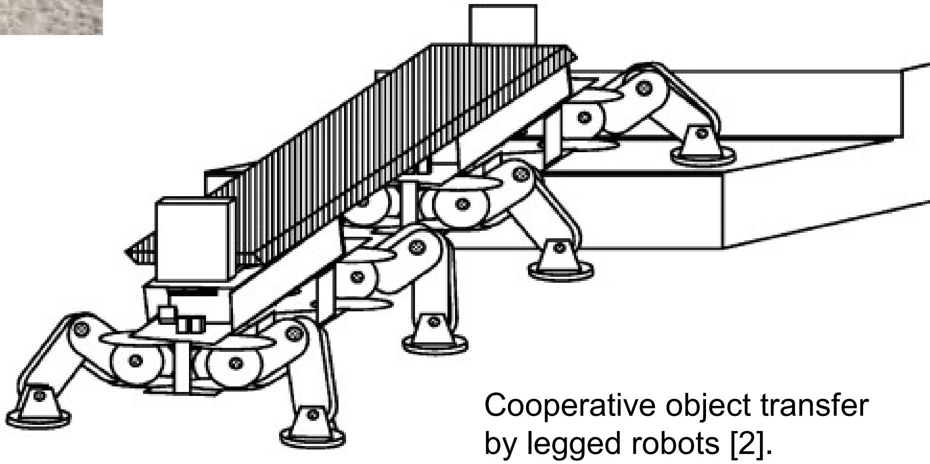
Robots that carry objects

Mars rover pair cooperatively transporting a long payload [1]



Collaborative stick-pulling [3]



Cooperative object transfer by legged robots [2].

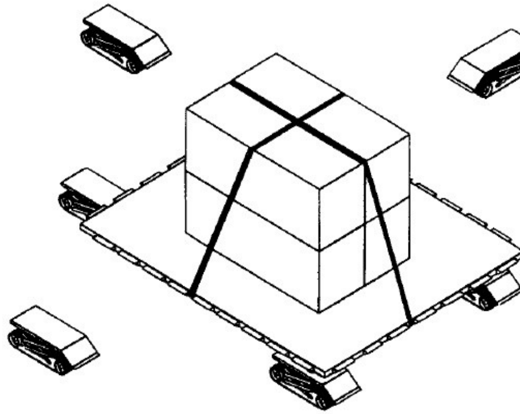
[1] Trebi-Ollennu and all. *Mars rover pair cooperatively transporting a long payload*. In Robotics and Automation, 2002. Proceedings. ICRA '02. Vol. 3, pp. 3136-3141, 2002.

[2] Aiyama, Hara, Yabuki, Ota, and Arai. *Cooperative transportation by two four-legged robots with implicit communication*. Robotics and Autonomous Systems, 29(1), 13-19, 1999.

[3] Ijspeert, Martinoli, Billard and Gambardella. *Collaboration through the exploitation of local interactions in autonomous collective robotics: the stick pulling experiment*, Autonomous Robots, 11(2), 149-171, 2001.

Existing devices: mobile robots

Collaborative robots



Army-Ant: object lifting on robot bodies [3]

Swarmanoïd [5]

[4] Bay, *Design of the Army-Ant cooperative lifting robot,* IEEE Robotics Automation Magazine 2(1), 36-43, 1995.
[5] Dorigo, *Swarmanoid: a novel concept for the study of heterogeneous robotic swarms*, IEEE Robotics & Automation Mag., 2012.
[6] Siegwart, Lamon, Estier, Lauria, and Piguet, *Innovative design for wheeled locomotion in rough terrain*, Robotics and Autonomous Systems, 40(2–3), 151–162, 2002.
[7] Michaud *et al*, *Co-design of AZIMUT, a multi-modal robotic platform,* Proc. ASME 2003 Design Eng. Tech. Conf. and Computers and Info. In Eng. Conference, pp. 46-50. 2003

Obstacle crossing and leg-wheel hybrid locomotion

Shrimp [6]
6 wheels on 2 // bogies and 1 front linkage
Deformable adaptative frame. Low actuation

Azimut [7]
Four orientable tracks can be used as legs

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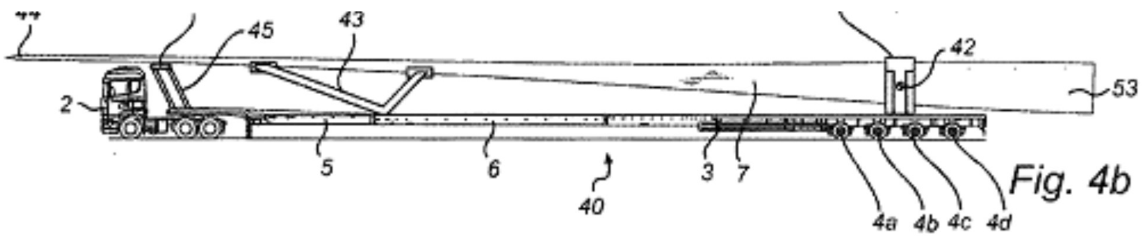
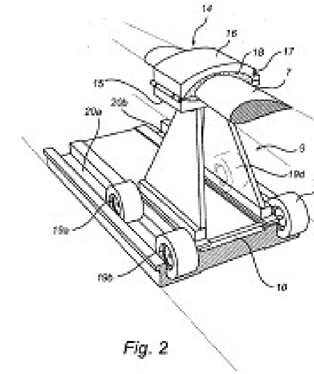
Existing devices: specialized transport

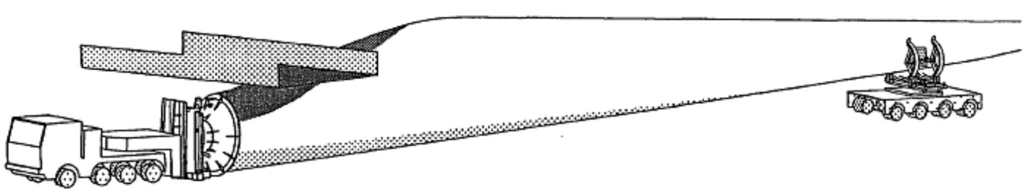
Transporting long payloads

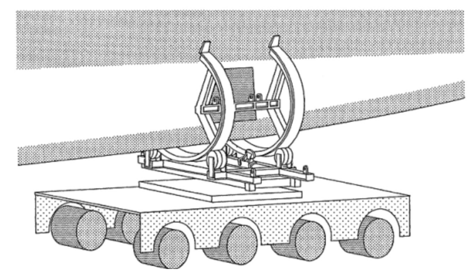
Several patents for **long payload** transport (giant windmill blades)





Telescopic vehicle and process for transporting a long payload [EP2328795B1]
- Truck + rear trailer connected by an extensible beam
- **Reconfigurable** according to payload length





Vehicle for transporting over-dimensioned payloads [EP1465789B1]
- **Payload used as a part** of the transporting system
- Low attachment to the trailer + blade orientation

→ **reconfiguration for obstacle overcoming** (tunnels)

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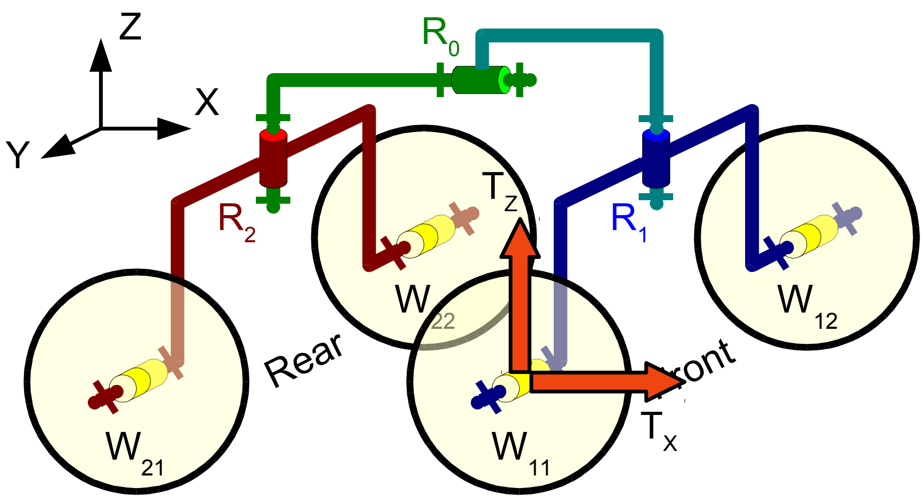
OpenWHEEL i3R

Requirements

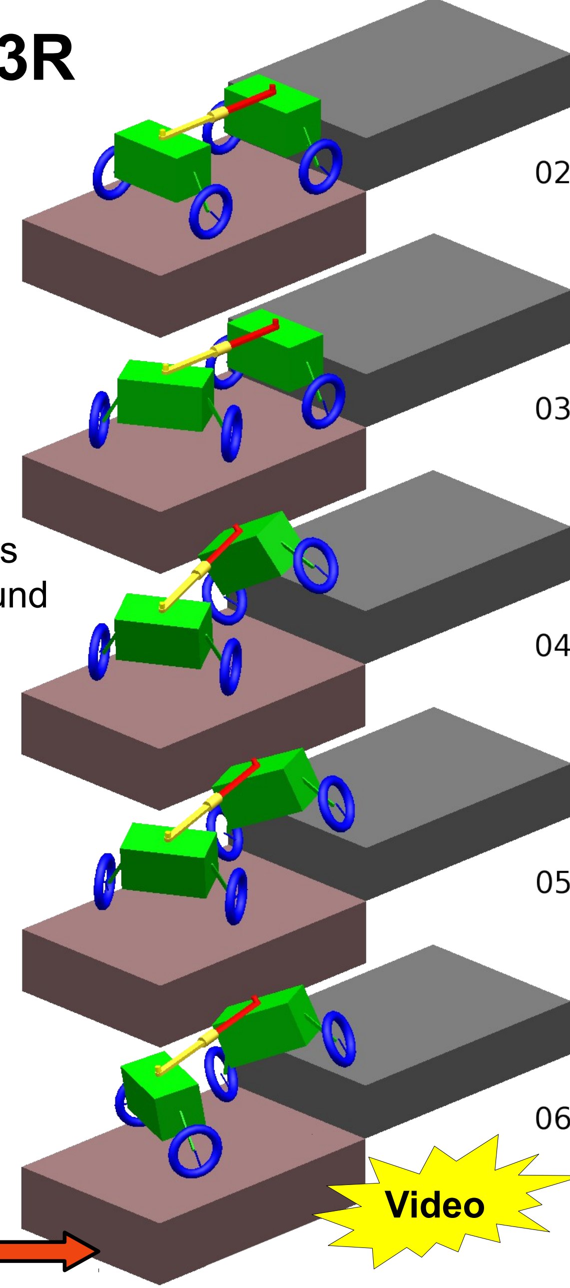
- Only 4 wheels for stable obstacle crossing
- Minimal actuation

Kinematics

- Each wheel can cross the obstacle : $T_X + T_Z$
- Kinematical **conciseness**: each joint has multiple uses
  - R_0 : T_Z lift of the 4 wheels + fitting irregular ground
  - R_1 & R_2: steering + $\approx T_X$ + stabilization



- A complete **stable climbing process** in 19 stages



[8] Fauroux, Chapelle and Bouzgarrou. *A New Principle for Climbing Wheeled Robots: Serpentine Climbing with the OpenWHEEL Platform*, Proc. of IROS'2006, Beijing, China, October 9-15, pp.3405-3410, 2006

OpenWHEEL i3R

Locomotion mode in 19 stages

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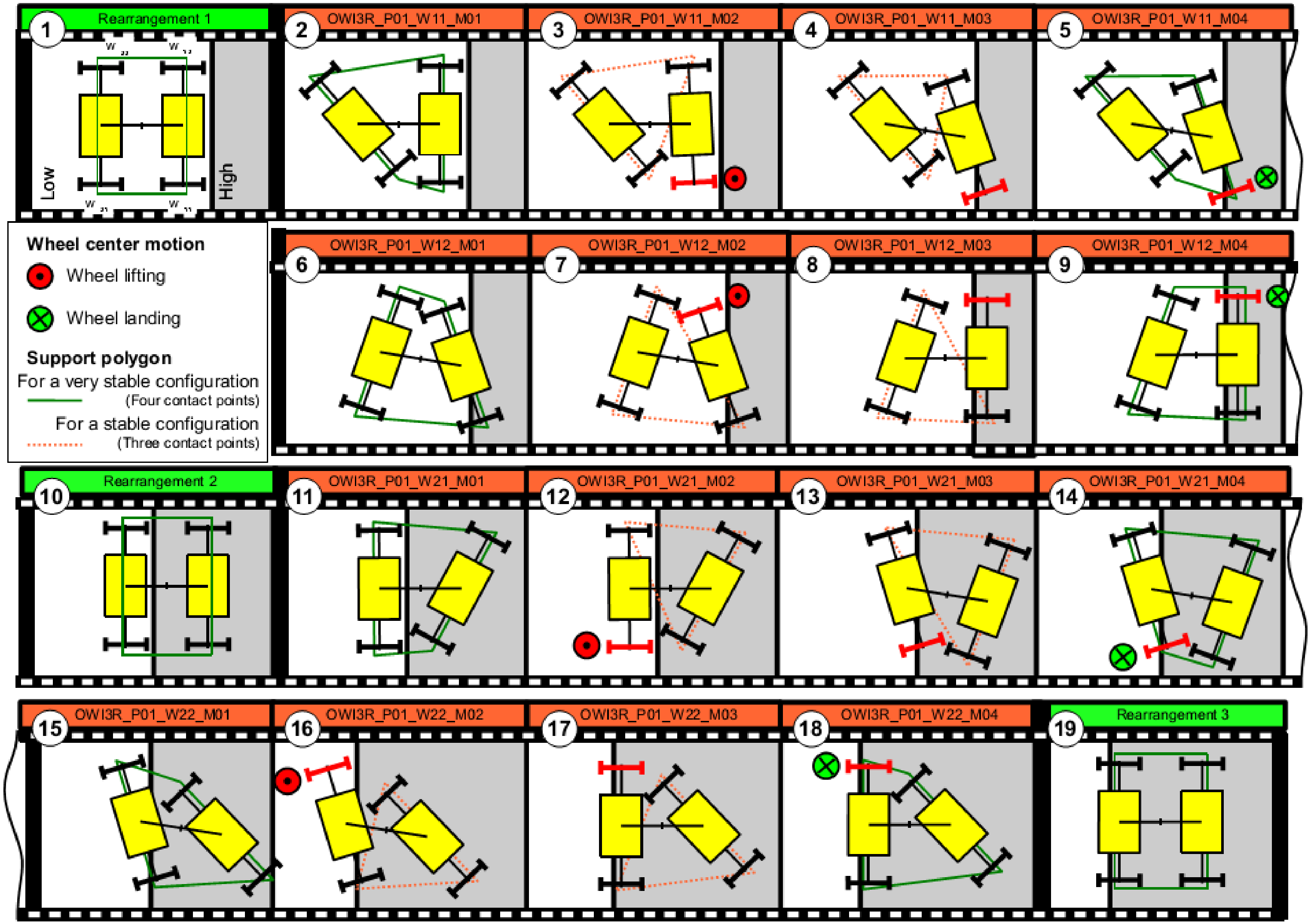

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OpenWHEEL i3R

Related publications

[1] Jean-Christophe FAUROUX, Frédéric CHAPELLE and Belhassen-Chedli BOUZGARROU " A New Principle for Climbing Wheeled Robots: Serpentine Climbing with the OpenWHEEL Platform ", Proc. of IEEE/RSJ Int. Conf. on Intelligent Robot and Systems, IROS'2006, Beijing, China, October 9-15, 2006, pp.3405-3410, file IROS06-553.pdf.

[2] Jean-Christophe FAUROUX, Morgann FORLOROU, Belhassen-Chedli BOUZGARROU, Frédéric CHAPELLE " Design and Modeling of a Mobile Robot with an Optimal Obstacle-Climbing Mode ", in Proc. 2nd World Congress in Design and Modelling of Mechanical Systems, CMSM'2007, March 19-21, 2007, Monastir, Tunisia, 9p., Paper p98.pdf.

[3] Jean-Christophe FAUROUX, Belhasse-Chedli BOUZGARROU, Frédéric CHAPELLE, " Experimental validation of stable obstacle climbing with a four-wheel mobile robot OpenWHEEL i3R ", in Proc. 10th International Conference on Mechanisms and Mechanical Transmissions, MTM'2008, October 8-10, 2008, Timisoara, Romania, 8p.

[4] Belhassen-Chedli BOUZGARROU, Frédéric CHAPELLE, Jean-Christophe FAUROUX, " Preliminary Design and Analysis of the Mobile Robot OpenWHEEL i3R ", in Proc. 3rd Third International Congress on Design and Modelling of Mechanical Systems, CMSM'09, March 16-18, 2009, Hammamet, Tunisia, ID207, 9p.

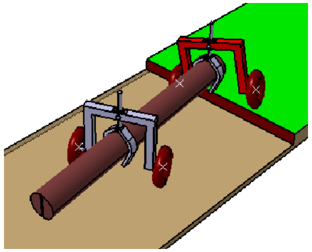
[5] Jean-Christophe FAUROUX, Belhassen-Chedli BOUZGARROU, Frédéric CHAPELLE, " Improving Obstacle Climbing with the Hybrid Mobile Robot OpenWHEEL i3R ", in "Mobile Robotics - Solutions and Challenges", Edited by O.Tosun, H.L. Akin, M.O. Tokhi, G.S. Virk, World Scientific Publishing, ISBN-13 978-981-4291-26-2, Proc. 12th International Conference on Climbing and Walking Robots, CLAWAR'09, Septembre 09-11, 2009, Istambul, Turkey, pp. 765-772.

[6] Jean-Christophe FAUROUX, Frédéric CHAPELLE and Belhassen-Chedli BOUZGARROU. " OpenWHEEL i3R - A new architecture for clearance performance ", in Proc. of ROBOTICS 2010, International Symposium, 3-4 September 2010, Clermont-Ferrand, France. Paper 1.c, 10 p.

[7] Jean-Christophe FAUROUX and Philippe VASLIN. " Crawling, walking or rolling for obstacle-crossing ? Bio-inspiration for the OpenWHEEL i3R agile mobile robot. ", in Proc. of International Workshop on Bio-Inspired Robots, International Symposium, April 6-8, 2011, Nantes, France. Poster #58, Summary 3 p.

[8] Jean-Christophe FAUROUX, Belhassen-Chedli BOUZGARROU, Nicolas BOUTON, Philippe VASLIN, Roland LENAIN and Frédéric CHAPELLE. " Agile wheeled mobile robots for service in natural environment ", Book chapter, pp.295-337. Service Robots and Robotics: Design and Application, A book edited by prof. Marco Ceccarelli, University of Cassino, Italy. ISBN 978-1-4666-0291-5. IGI GLOBAL, 419 p., 2012. www.igi-global.com.

From OpenWHEEL i3R to C³Bots AT/VLP



C³Bots =
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  - Kin. synthesis
  - Control synth.
- C³Bot DGP
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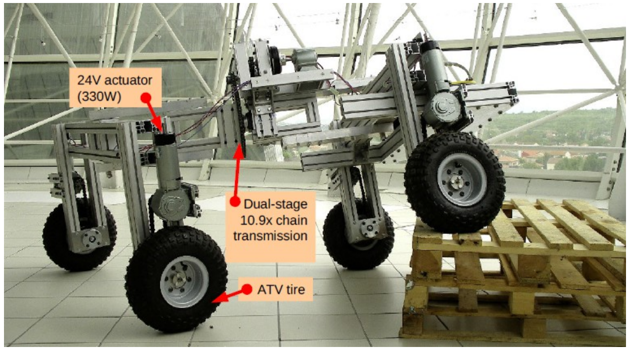
Requirement R1 = Adding modularity to OpenWHEEL i3R



Poly-robot

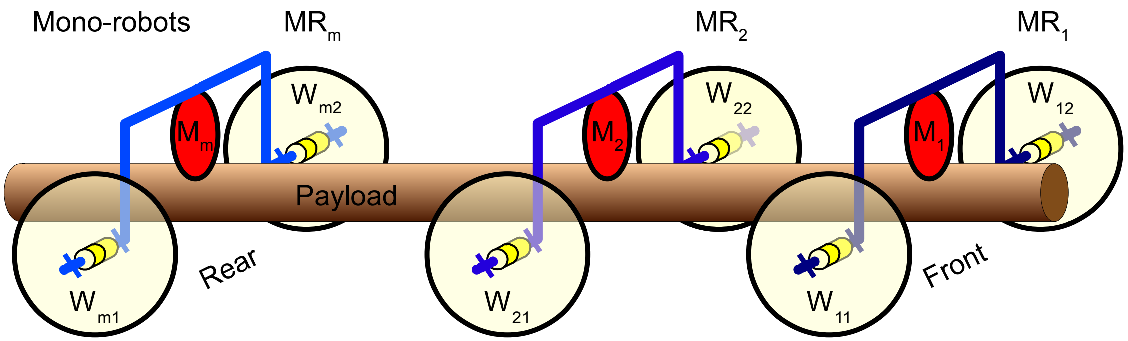
=

Mono-robot 2

U

Mono-robot 1

Requirement R2 = Including the payload into the poly-robot



Unknown kinematic chains

- Find the unknown mechanisms M_a from the mono-robot MR_a with a = 1...m
- Kinematical **conciseness**

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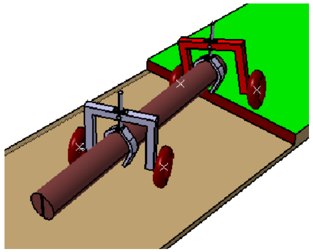

Required mobilities

Requirement R3
Stability condition

C[3]**Bots =**
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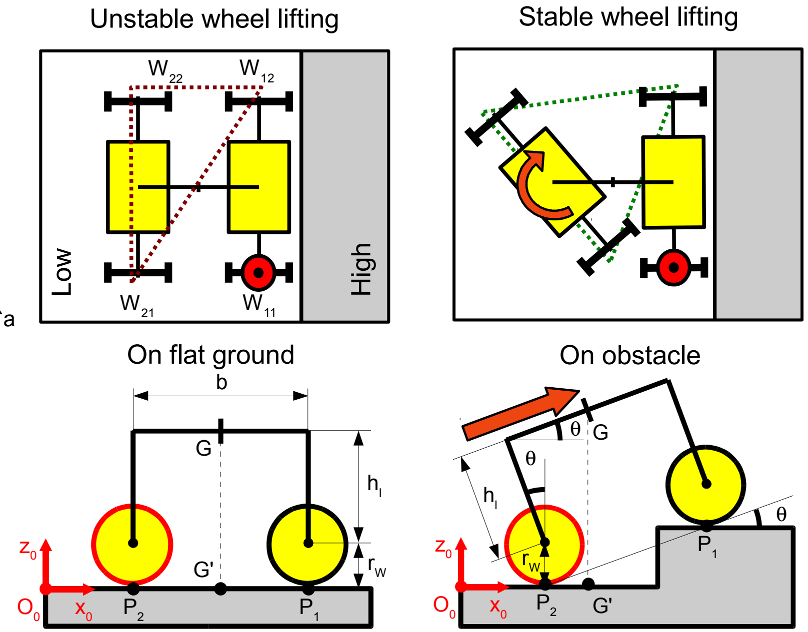
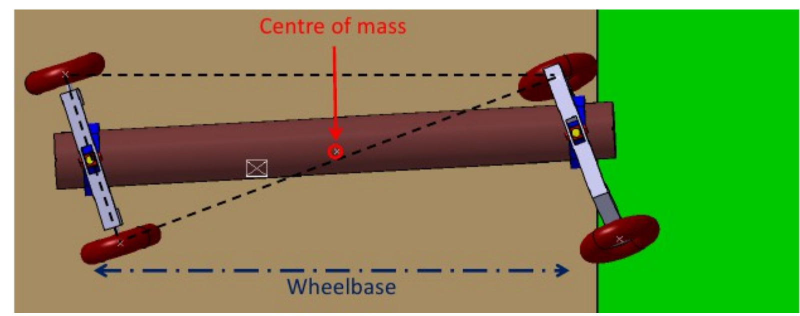
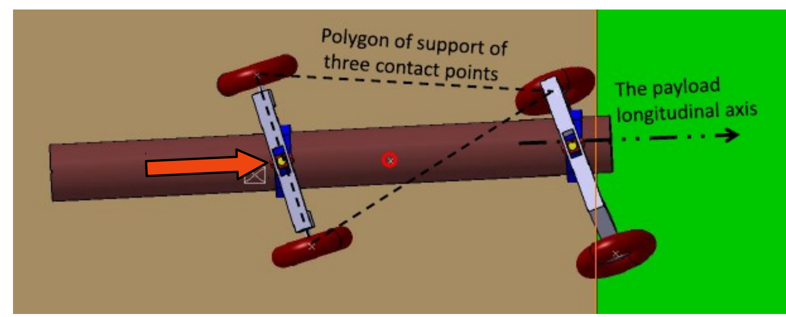
- Steering axle a+1 stabilizes the robot when axle a crosses the obstacle
  → **steering mobility R_z** required for MR_a

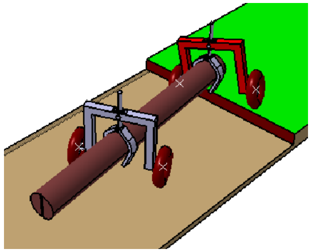
- Obstacle crossing → Frame tilting → Projected centre of mass G' goes to the rear $P_2G' = b\cos(\theta)/2 - h_l h_s / b$
  → the rear axle has difficulties to cross
  → required **mobility T_X of G**

- A poly-robot with a **long aspect-ratio** cannot stabilize itself during wheel-crossing only with steering
  → the mobility T_X of G can be achieved with a **mobility T_X on every MR_a**









Required mobilities

Requirement R4: Payload elevation

- The poly-robot should catch the payload on the ground and elevate it under its wheels
→ T_z **elevation translation** of gripper with respect to mono-robot

Summary of required mobilities

Mobilities of the gripper with respect to the frame of each mono-robot

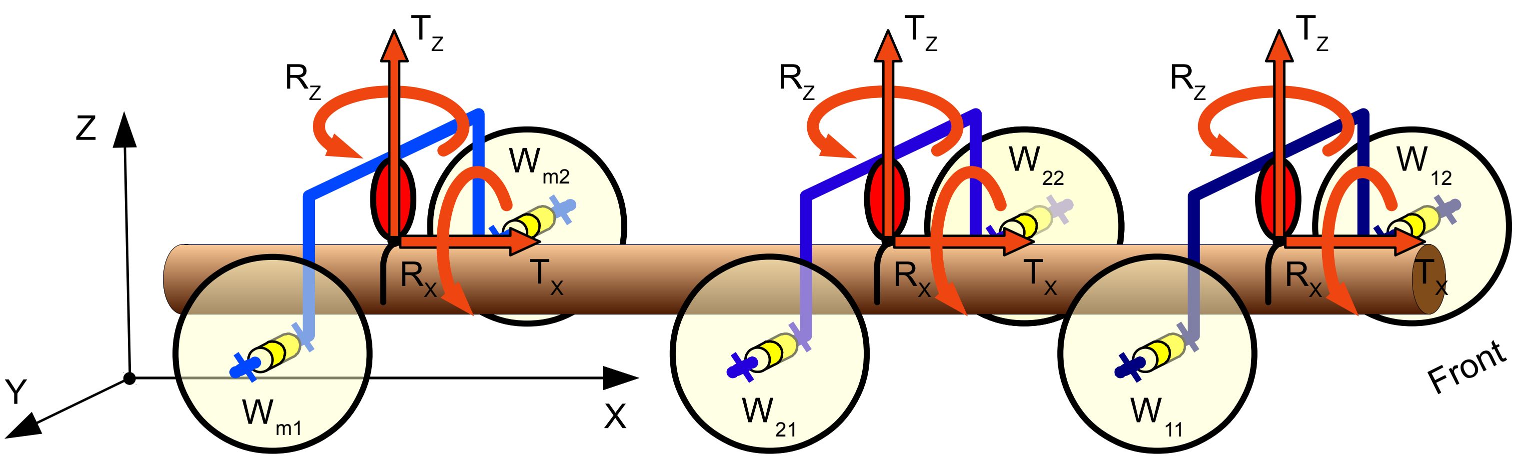
- T_x for **enhanced stabilization** (R3)

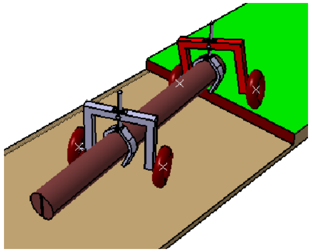
- R_x for **wheel elevation** during obstacle crossing & **fitting irregular grounds**

- T_z for **payload elevation**

- R_z for **steering** & **OpenWHEEL-like stabilization** (R3)

Kinematical conciseness





Kinematics of the mono-robot

A feasible solution with T_x generated by rollers

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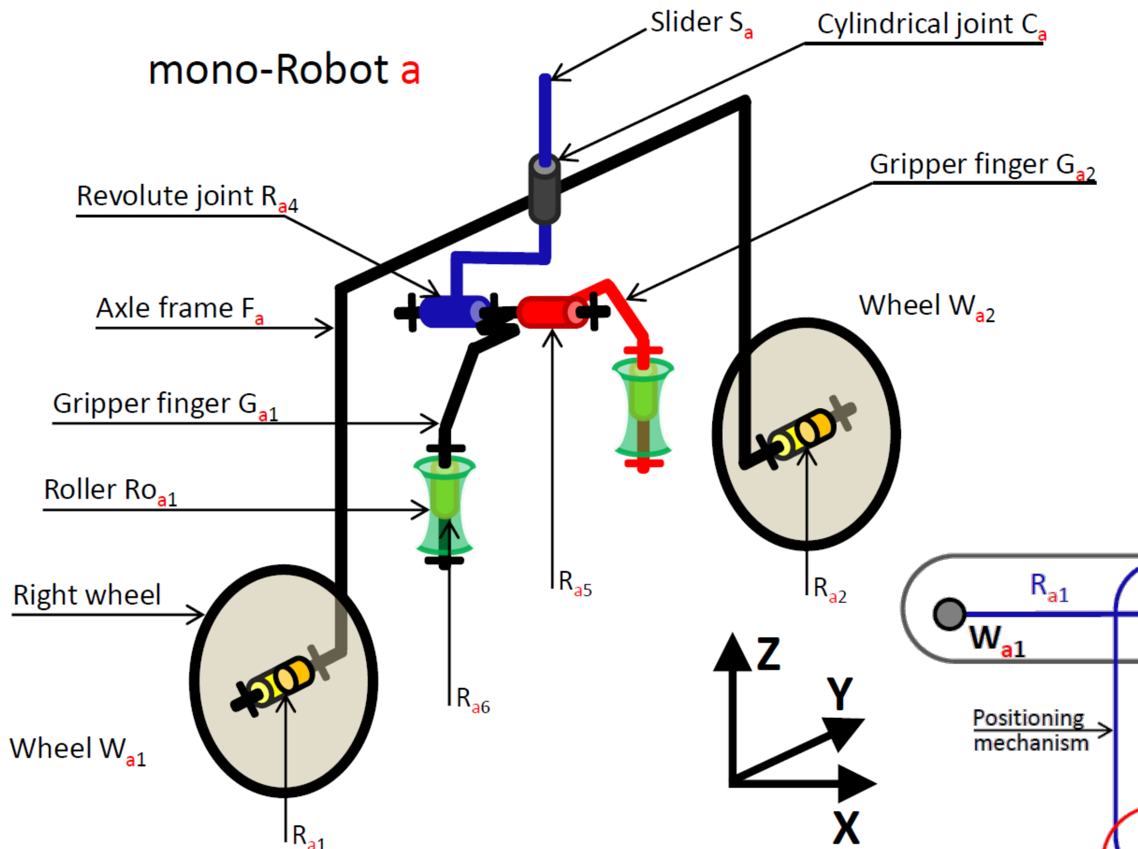

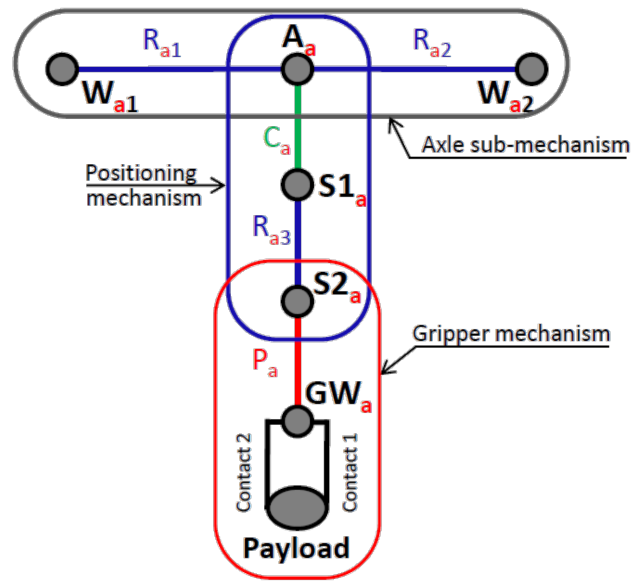

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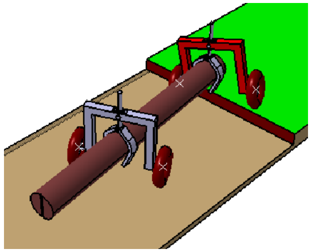
Kinematics of the mono-robot



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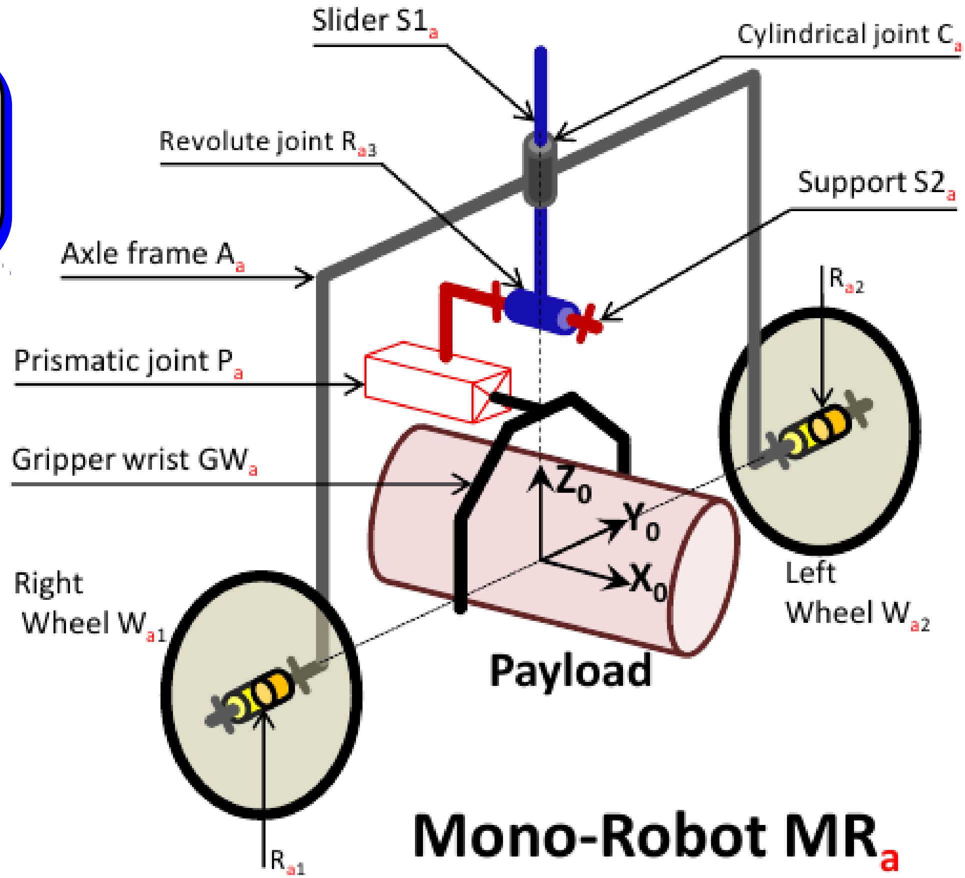
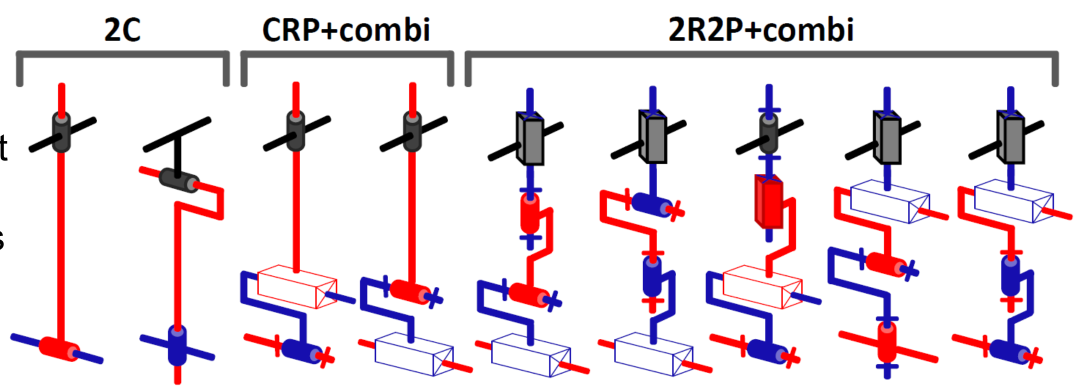
An alternative solution with a T_x slider



Alternatives

- 38 equivalent **serial** joint combinations to generate the 4 mobilities T_x, R_x, T_z, R_z
- 3 design rules → **15** sol.
- **Parallel** mechanisms...



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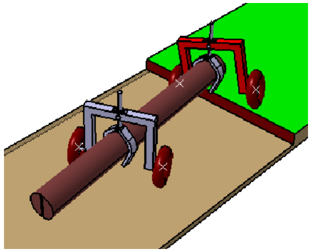

Kinematics of the poly-robot

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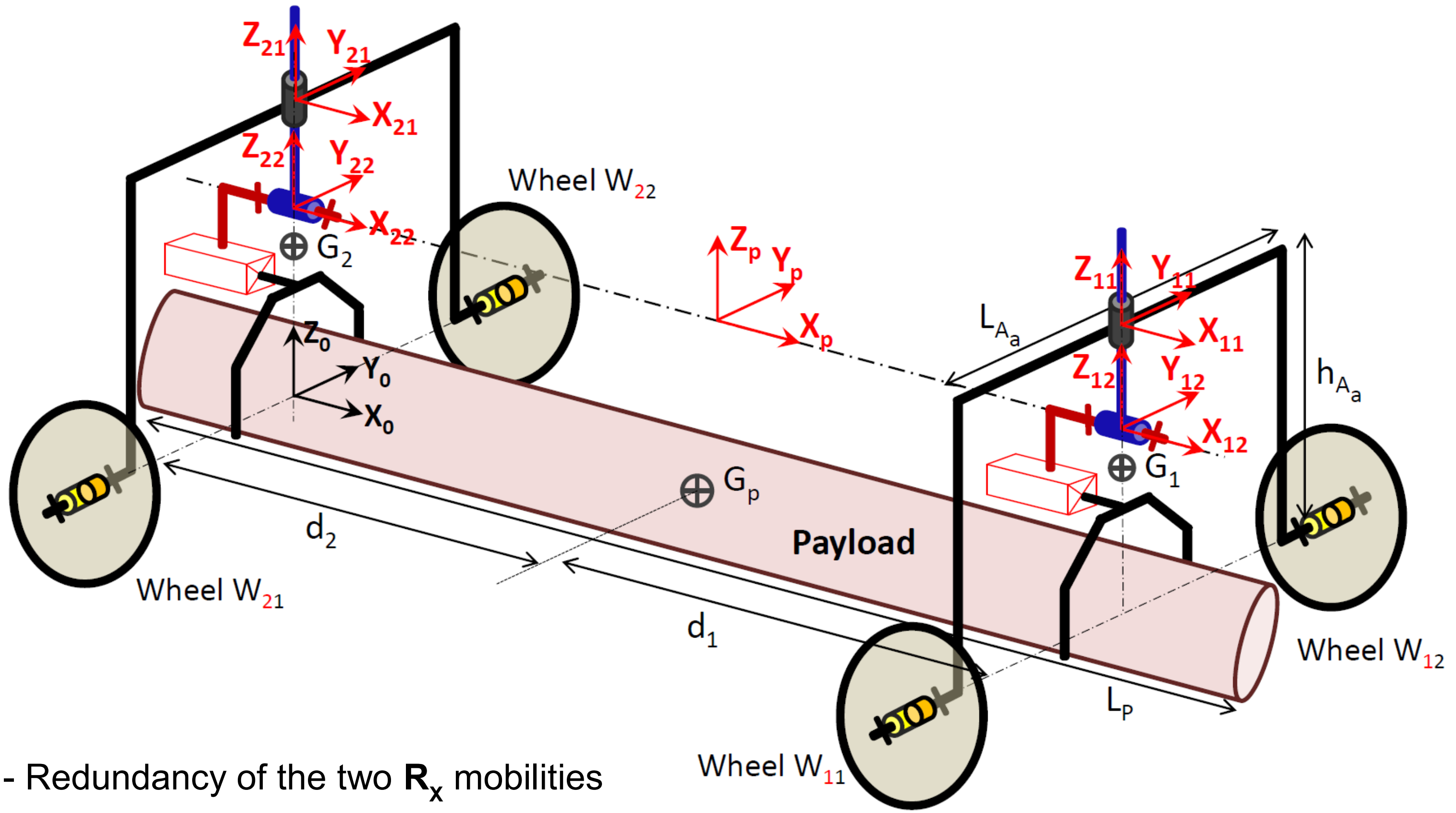
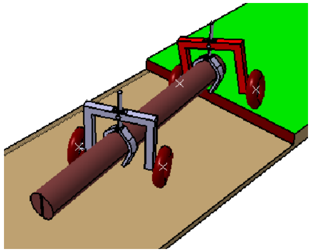
Case of 2 Mono-Robots



- Redundancy of the two $\mathbf{R_x}$ mobilities can be used for lateral balancing of the payload

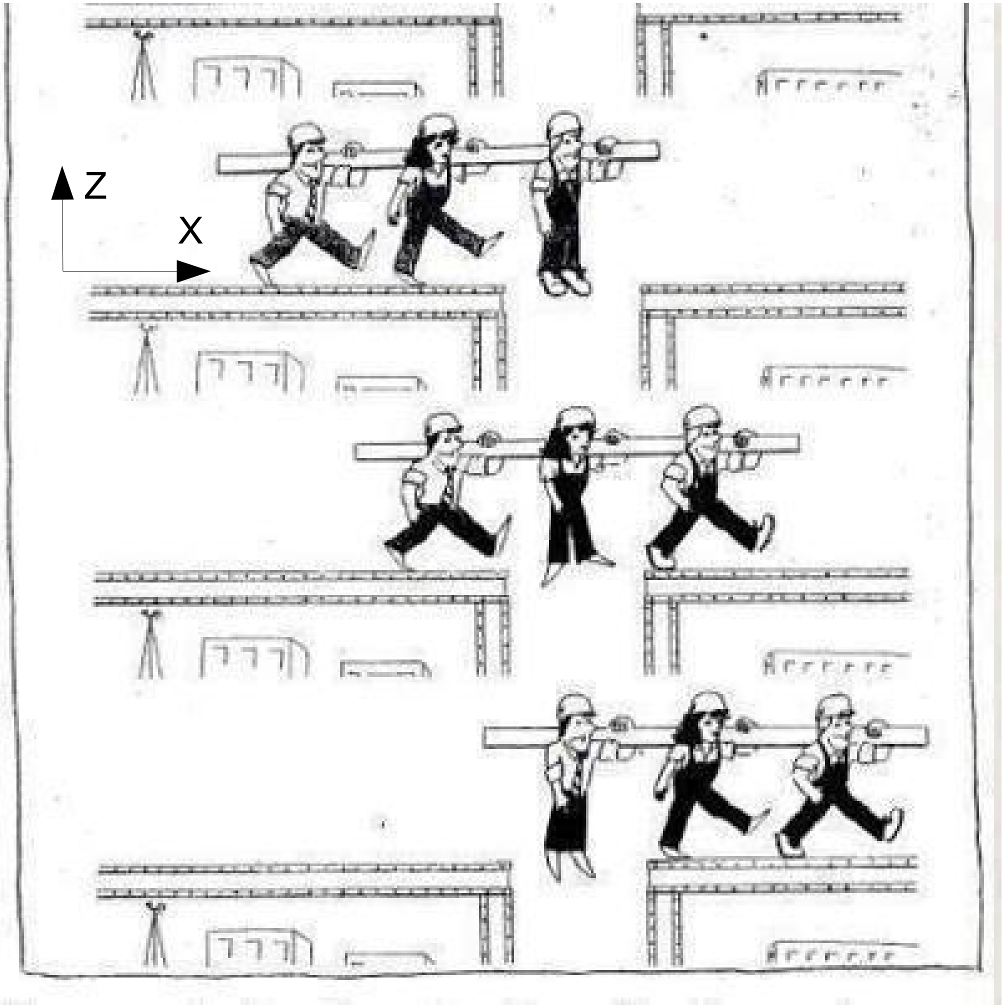
3+ axles: 2D crossing mode

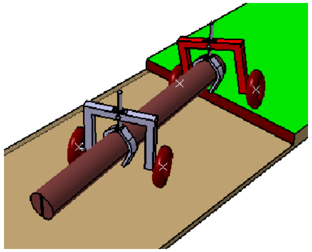


2D crossing mode

C³Bots = Collaborative Cross & Carry Mobile RoBots

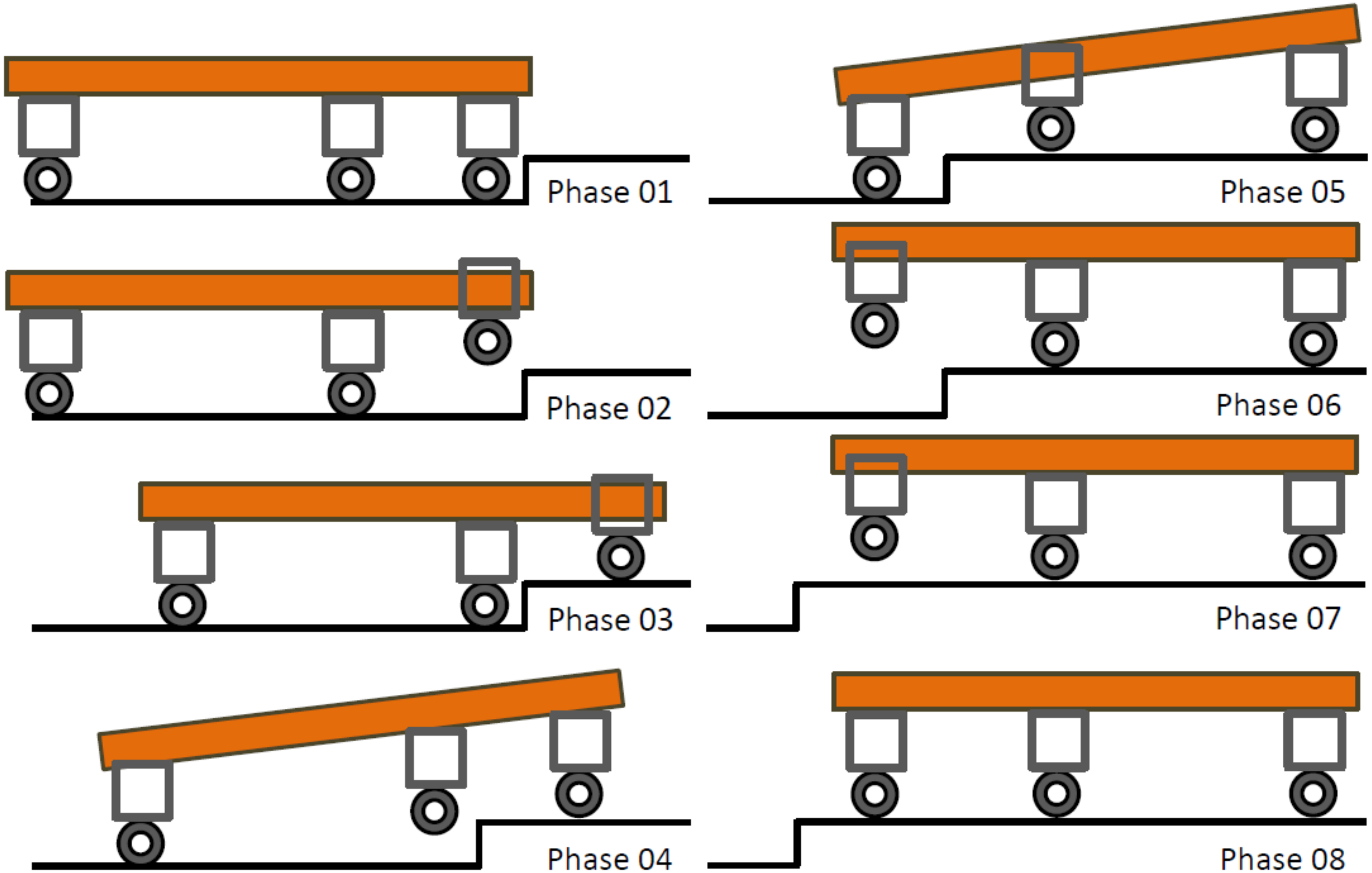
- Obstacle-crossing is easy with three axles and more
- Plane motion of parts in plane XZ



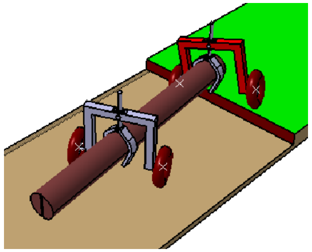


3+ axles: 2D crossing mode

2D crossing mode



2 axles: 3D serpentine crossing mode



C^3Bots = Collaborative Cross & Carry Mobile RoBots

- C^3Bots context
- C^3Bot AT/VLP
  - Requirements
  - Kin. synthesis
  - Control synth.
- C^3Bot DGP
- Conclusion

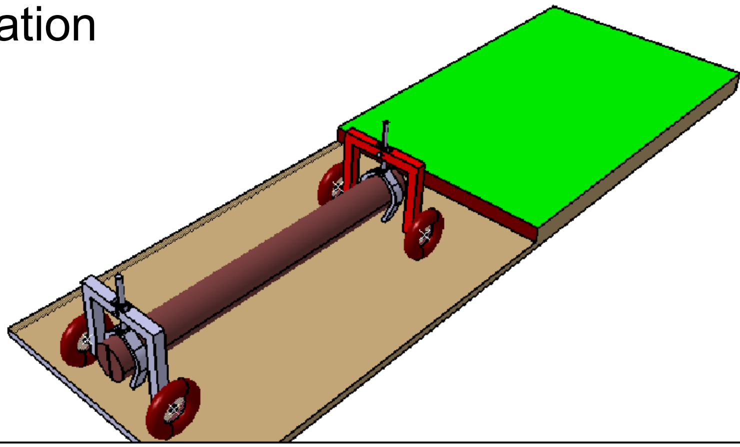
Process description

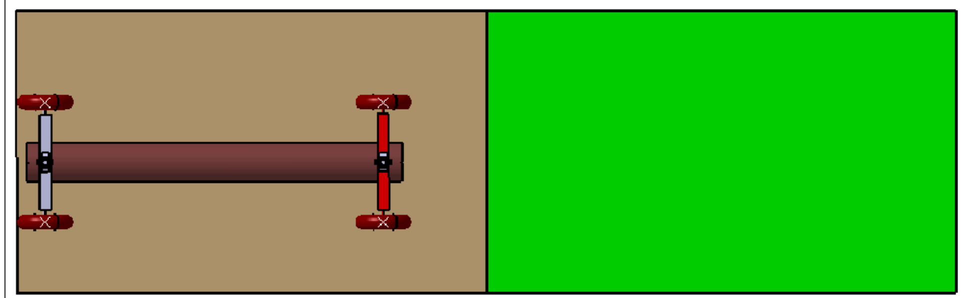
- Inspired form OpenWHEEL i3R locomotion mode
- **20** stages or manoeuvers
- **4 phases** (one per wheel) and intermediate manoeuvres
- Obstacle crossing of wheel W_{as} (a=axle number, s=side number) takes **4 manoeuvres**
  - Manoeuvre M_{01}: **Stabilization** (motion of axles other than a)
  - Manoeuvre M_{02}: W_{as} **elevation T_{Z+}**
  - Manoeuvre M_{02}: W_{as} **progression T_X**
  - Manoeuvre M_{03}: W_{as} **landing T_{Z-}**

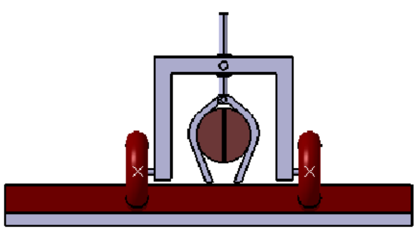
Video CAD

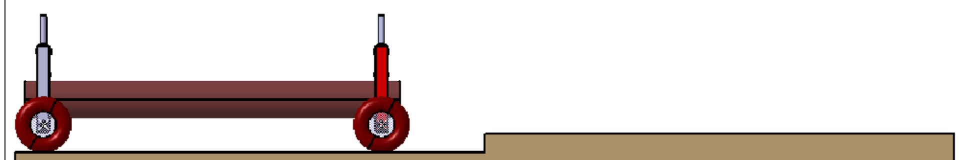
2 axles: 3D serpentine crossing mode
Stage 00

Poly-robot
Preparation

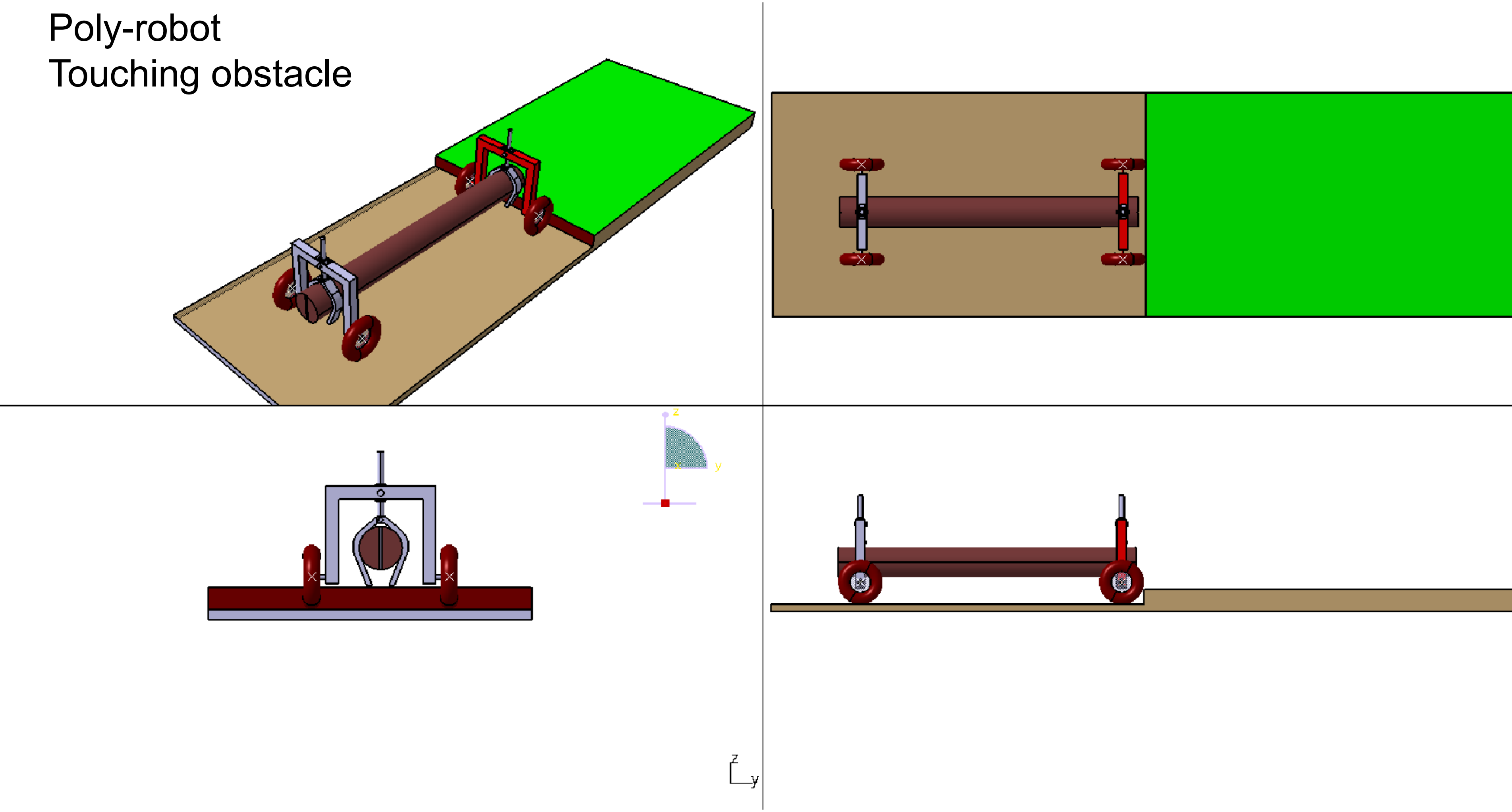






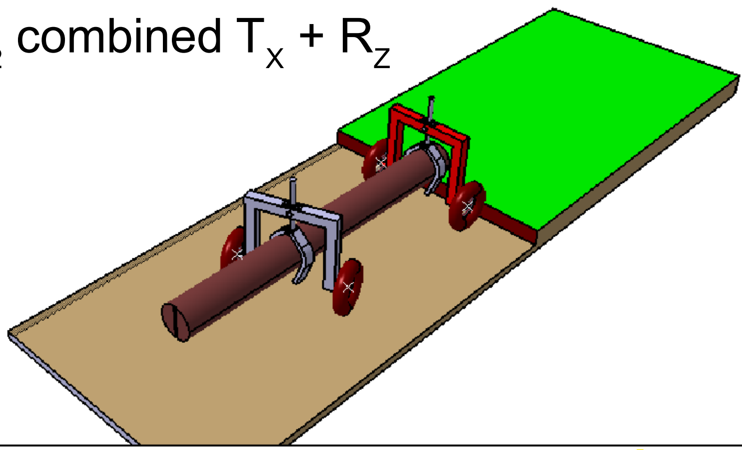


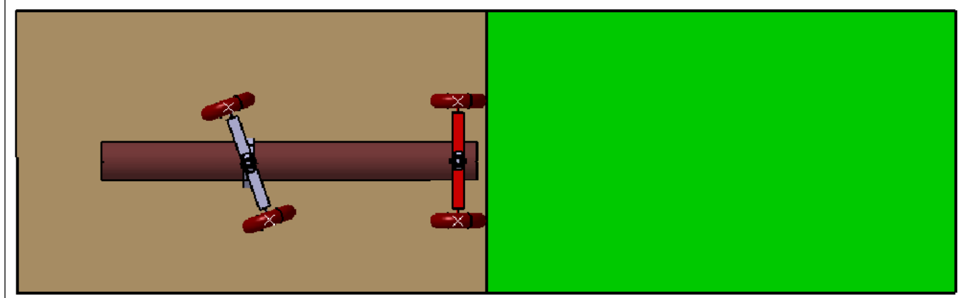
2 axles: 3D serpentine crossing mode
Stage 01

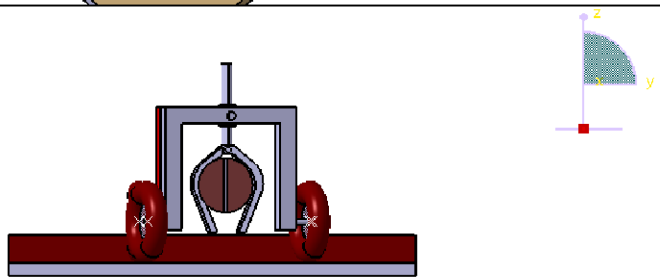


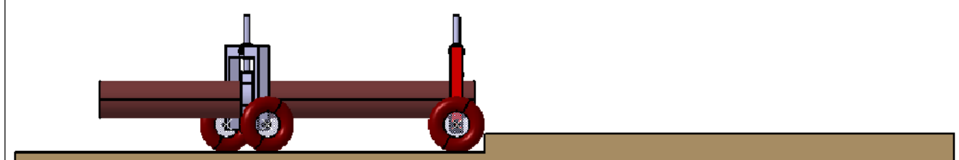
2 axles: 3D serpentine crossing mode
Stage 02 - $PW_{11}M_{01}$

W_{11} stabilization
by MR_2 combined $T_X + R_Z$



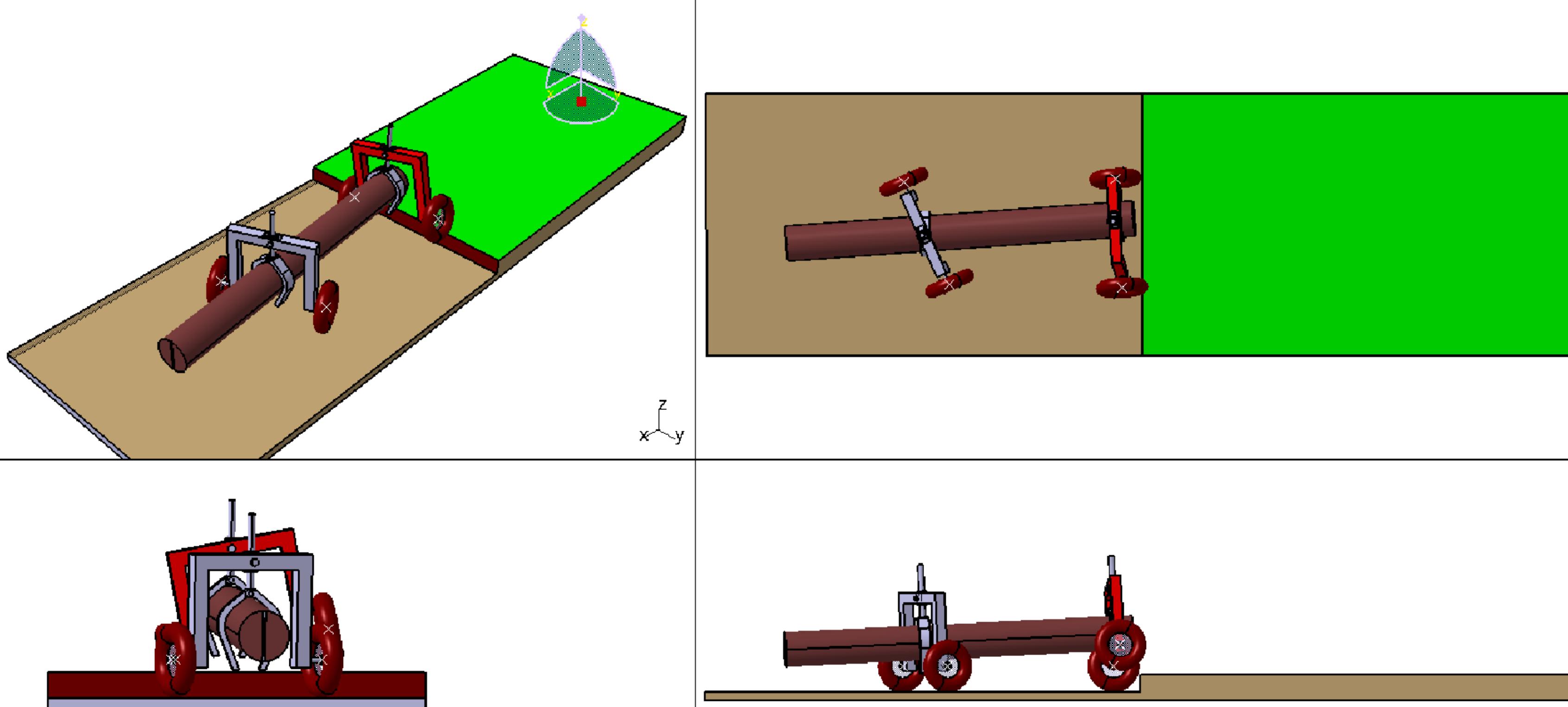






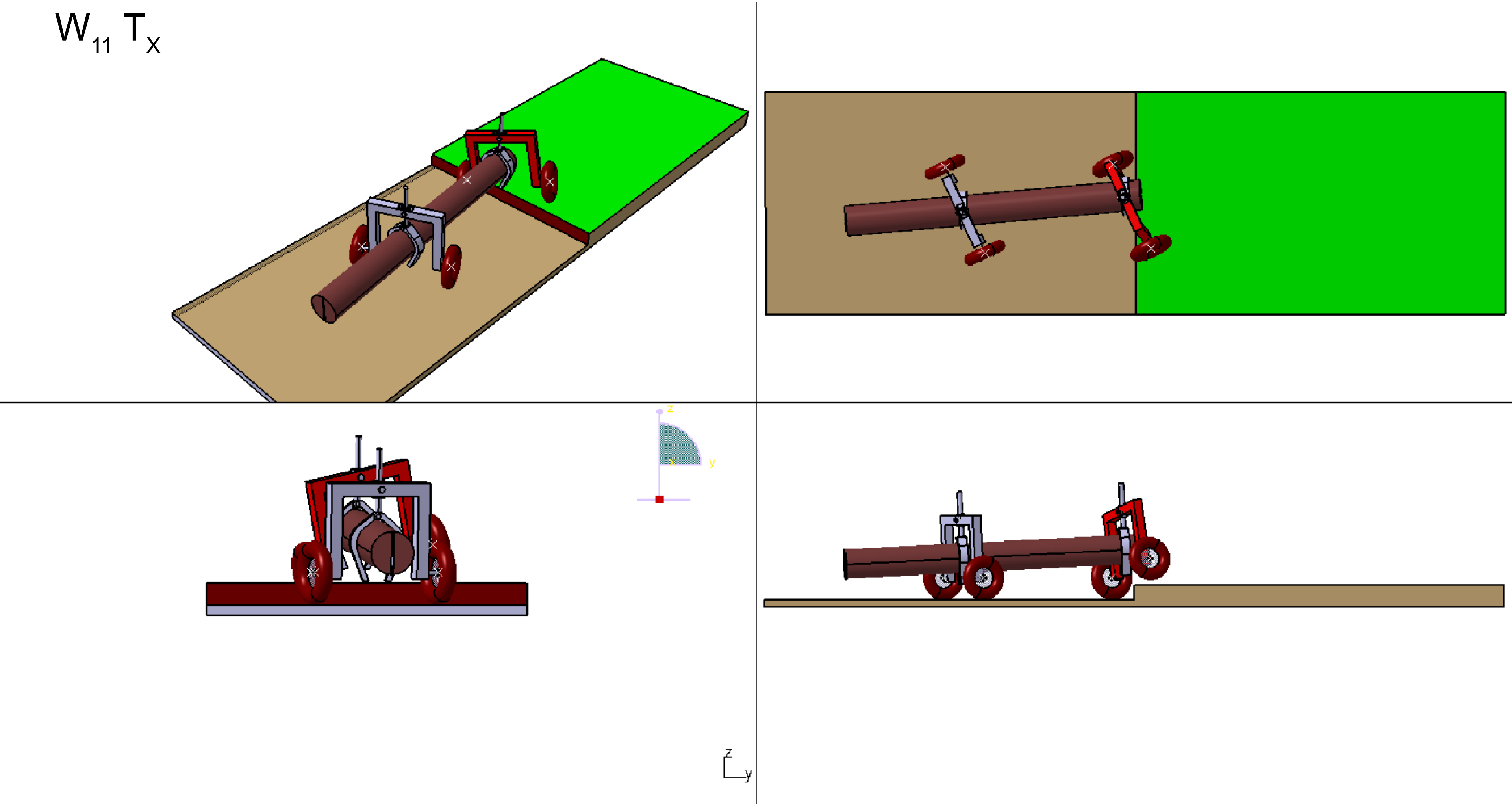
2 axles: 3D serpentine crossing mode
Stage 03 - $PW_{11}M_{02}$

W_{11} T_{Z+}



2 axles: 3D serpentine crossing mode
Stage 04 - $PW_{11}M_{03}$

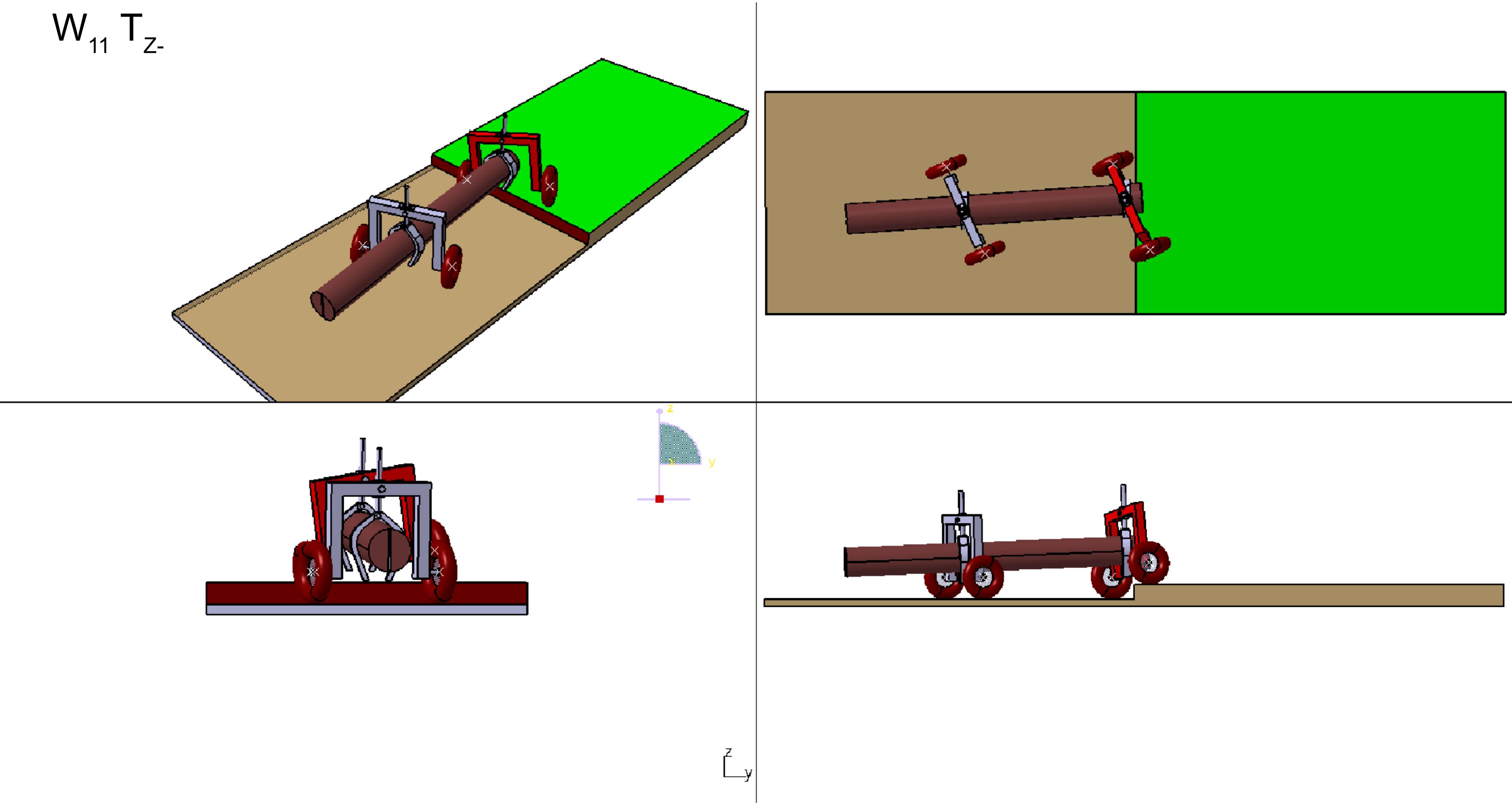
W_{11} T_X



2 axles: 3D serpentine crossing mode

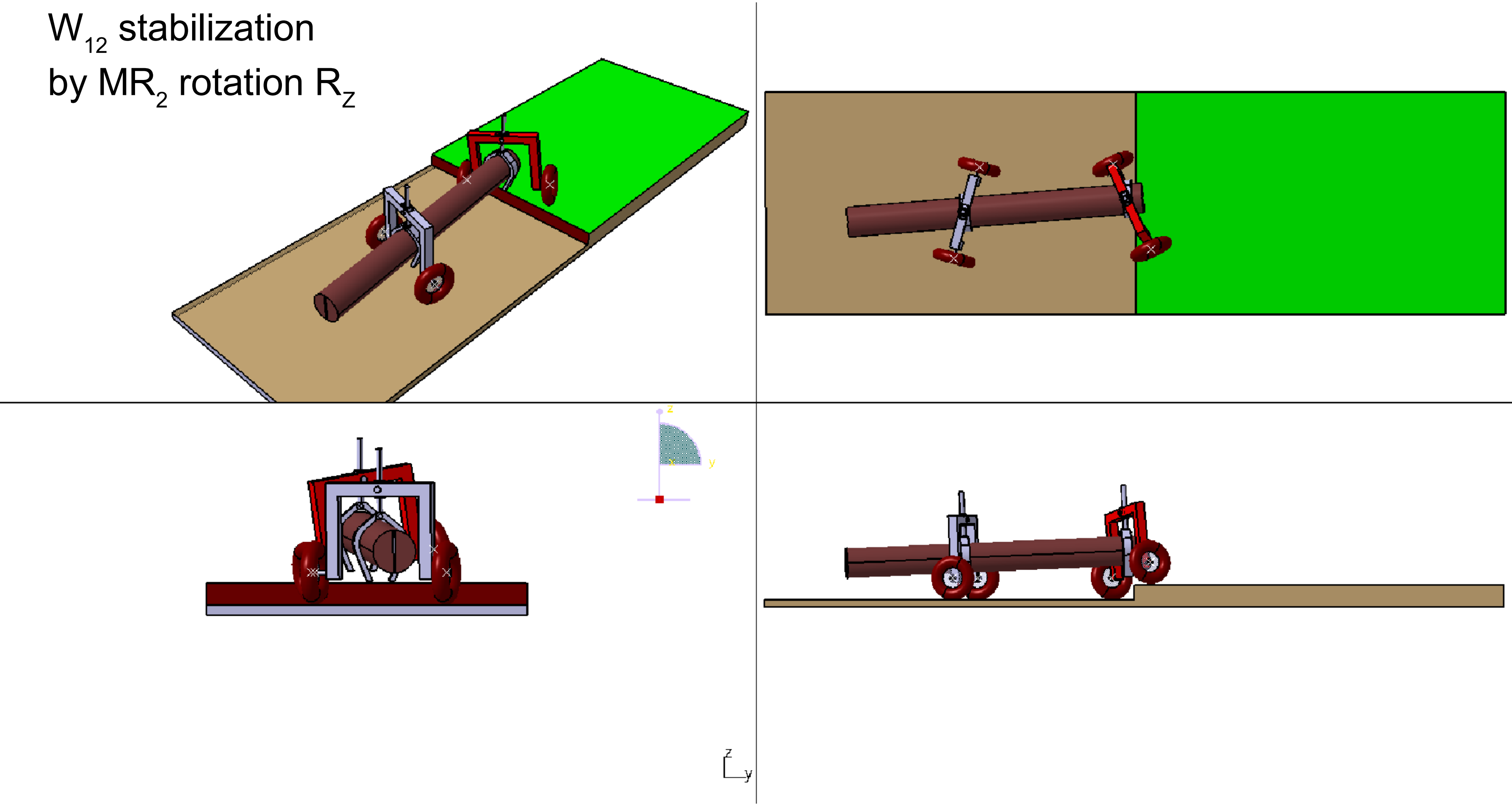
Stage 05 - $PW_{11}M_{04}$

W_{11} T_{Z-}



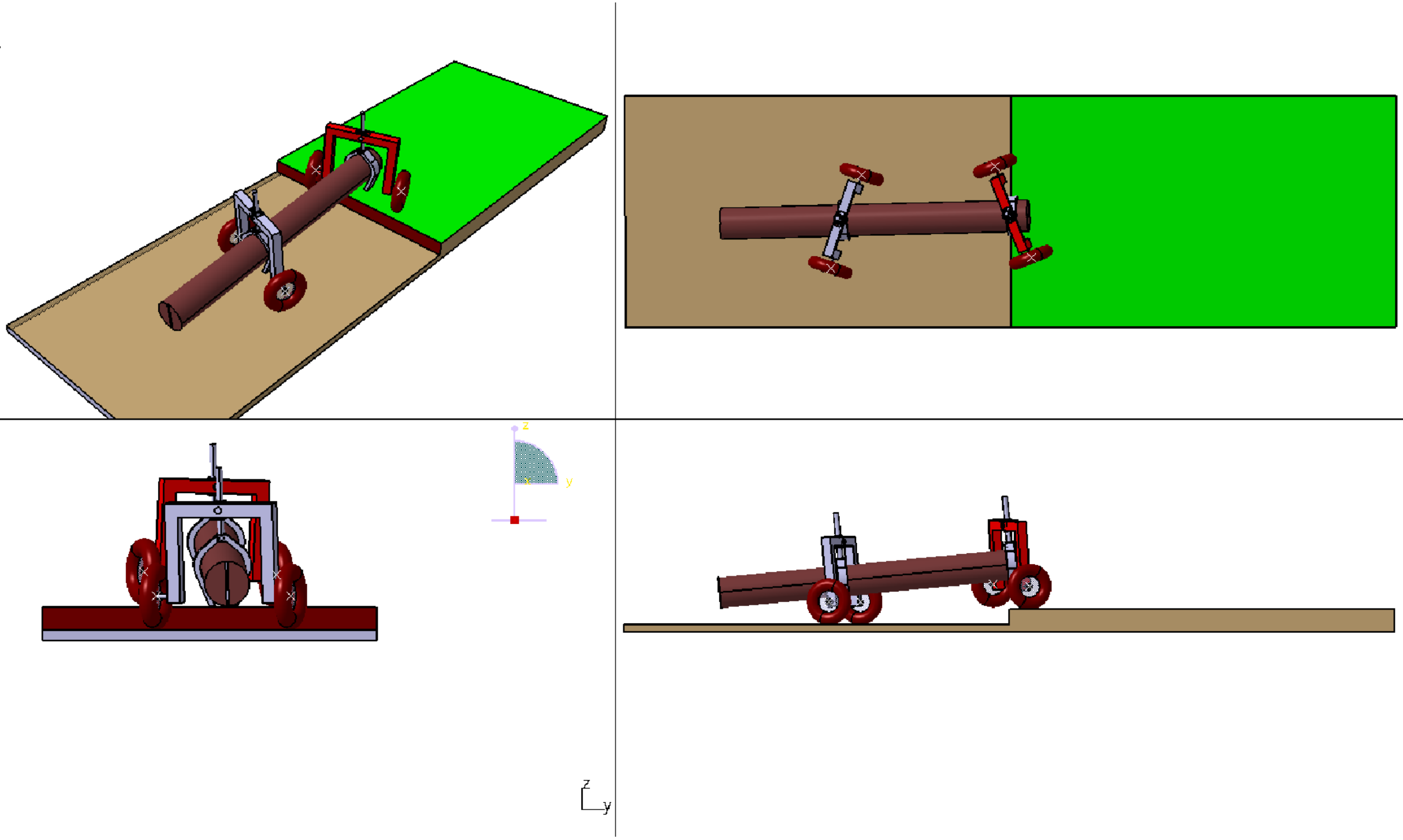
2 axles: 3D serpentine crossing mode
Stage 06 - $PW_{12}M_{01}$

W_{12} stabilization
by MR_2 rotation R_Z



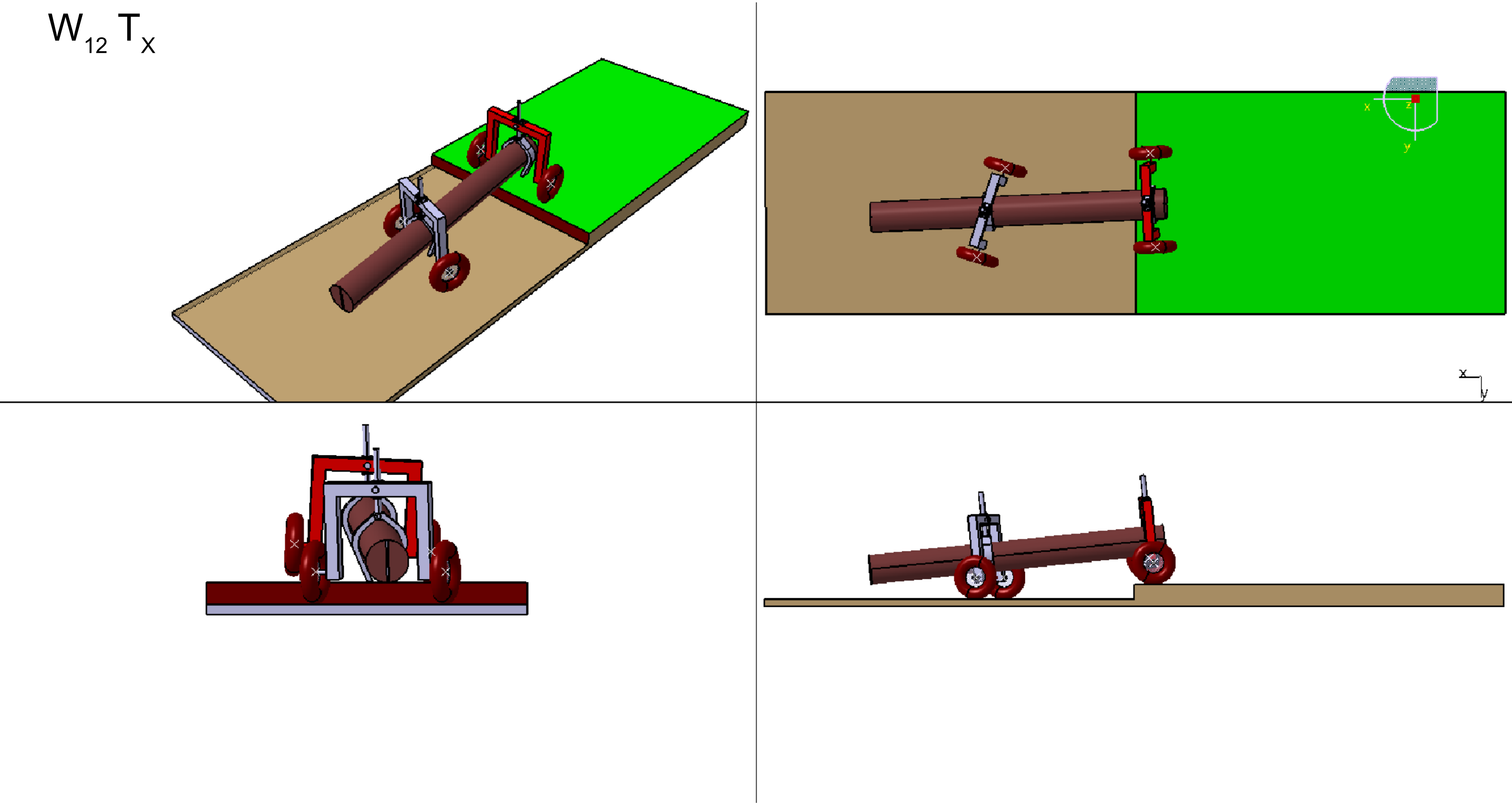
2 axles: 3D serpentine crossing mode
Stage 07 - $PW_{12}M_{02}$

$W_{12}\ T_{Z+}$



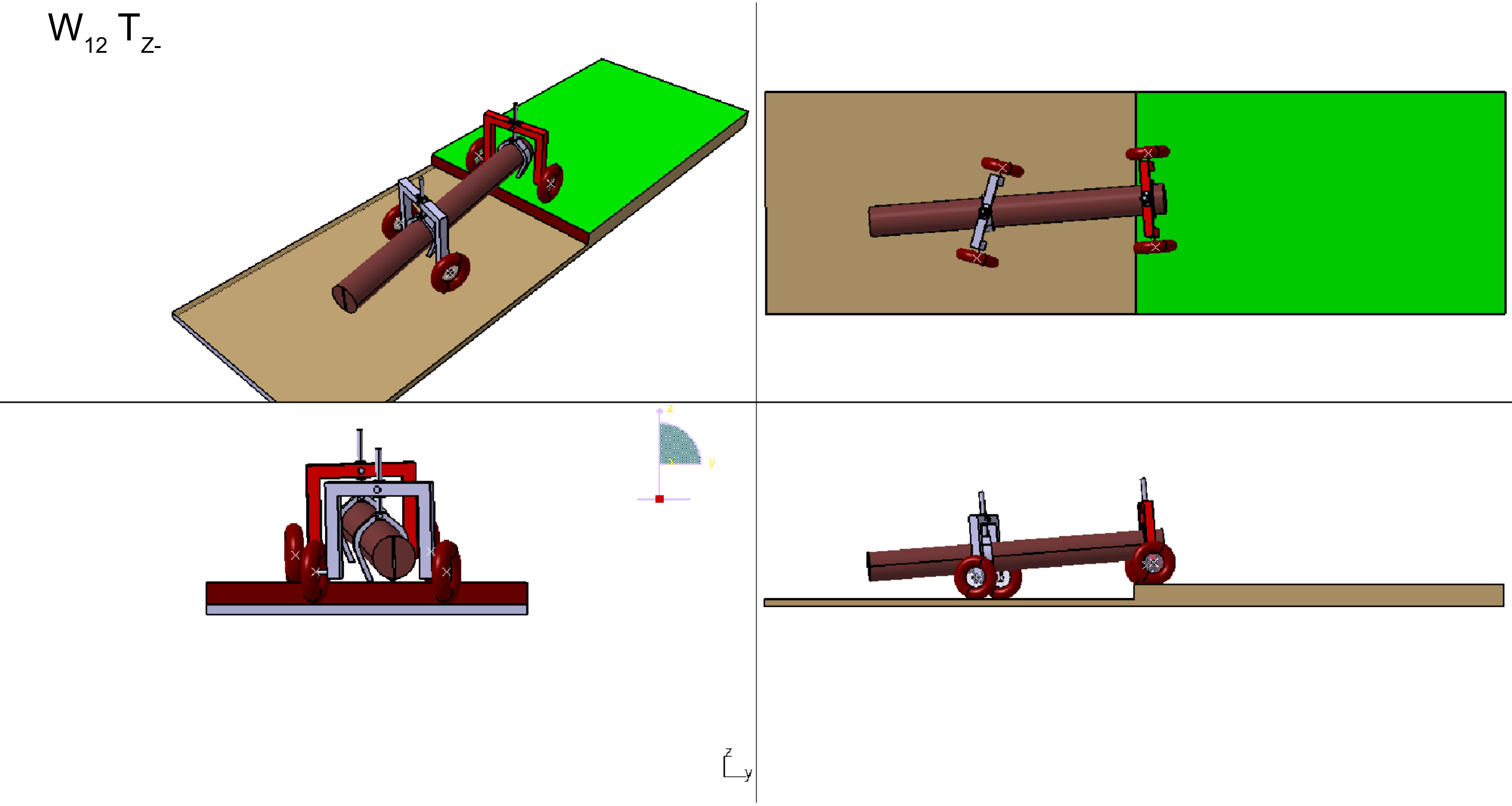
2 axles: 3D serpentine crossing mode
Stage 08 - $PW_{12}M_{03}$

$W_{12}\ T_X$



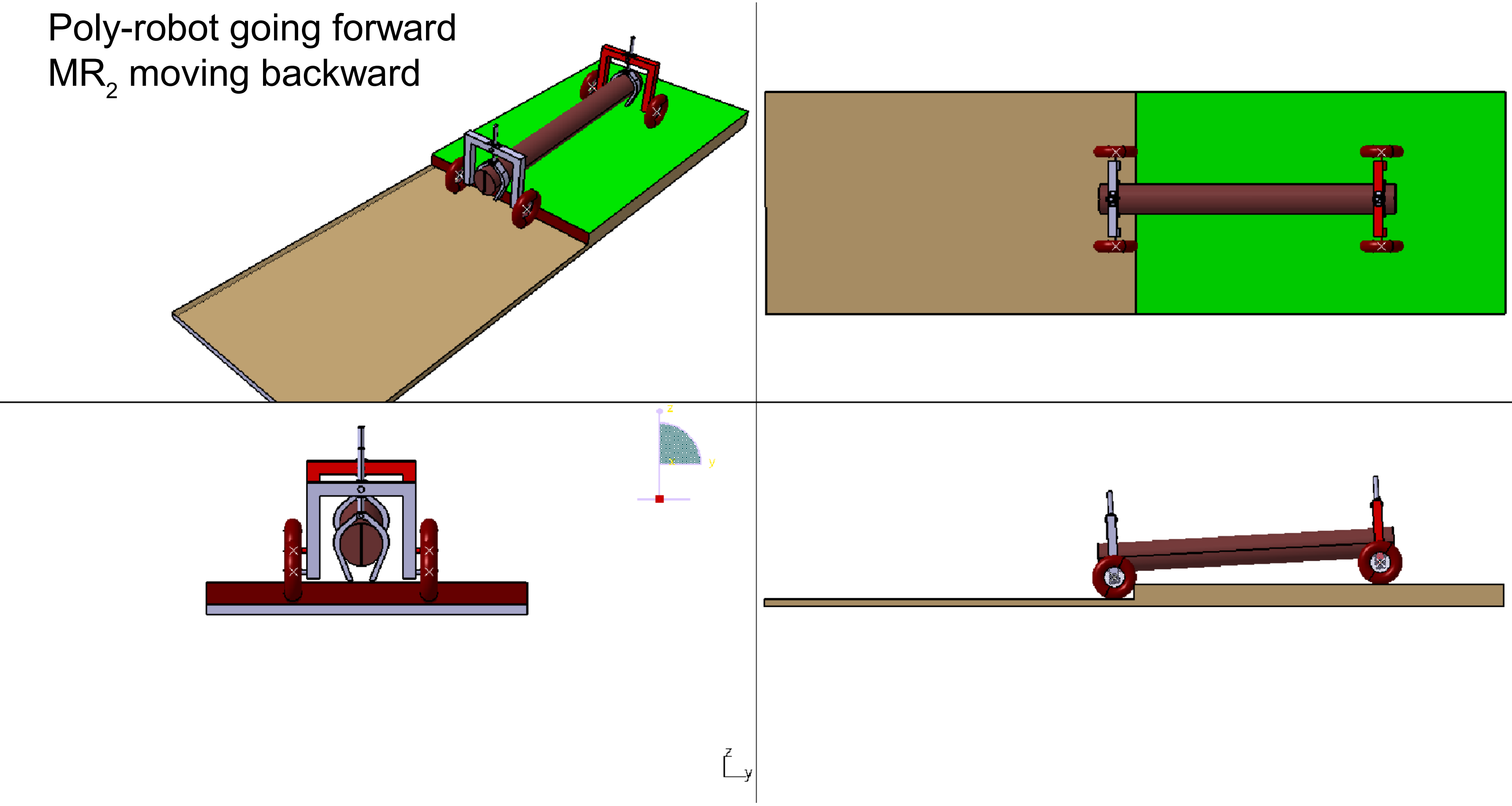
2 axles: 3D serpentine crossing mode
Stage 09 - $PW_{12}M_{04}$

$W_{12}\ T_{Z-}$



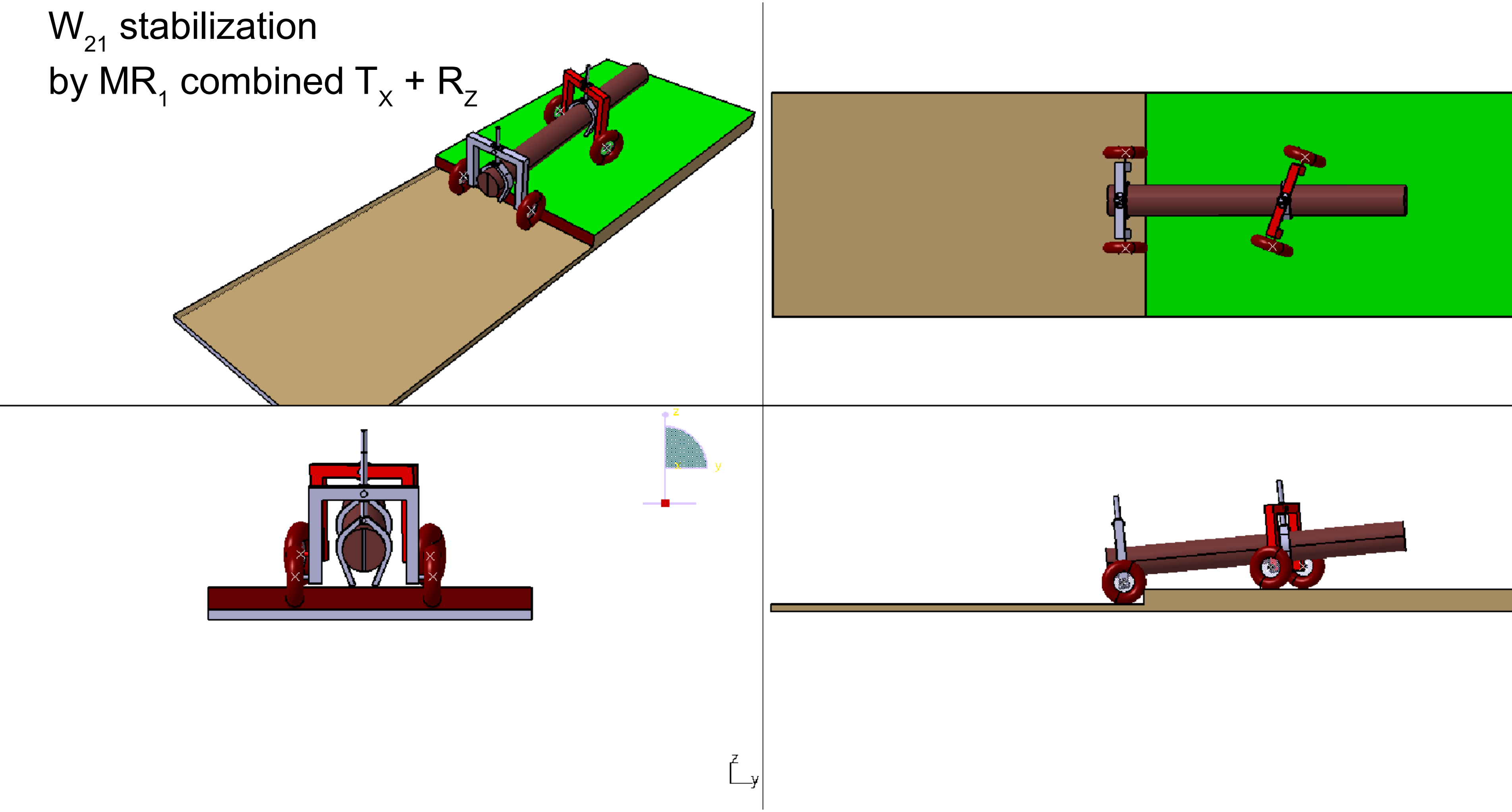
2 axles: 3D serpentine crossing mode
Stage 10

Poly-robot going forward
MR_2 moving backward



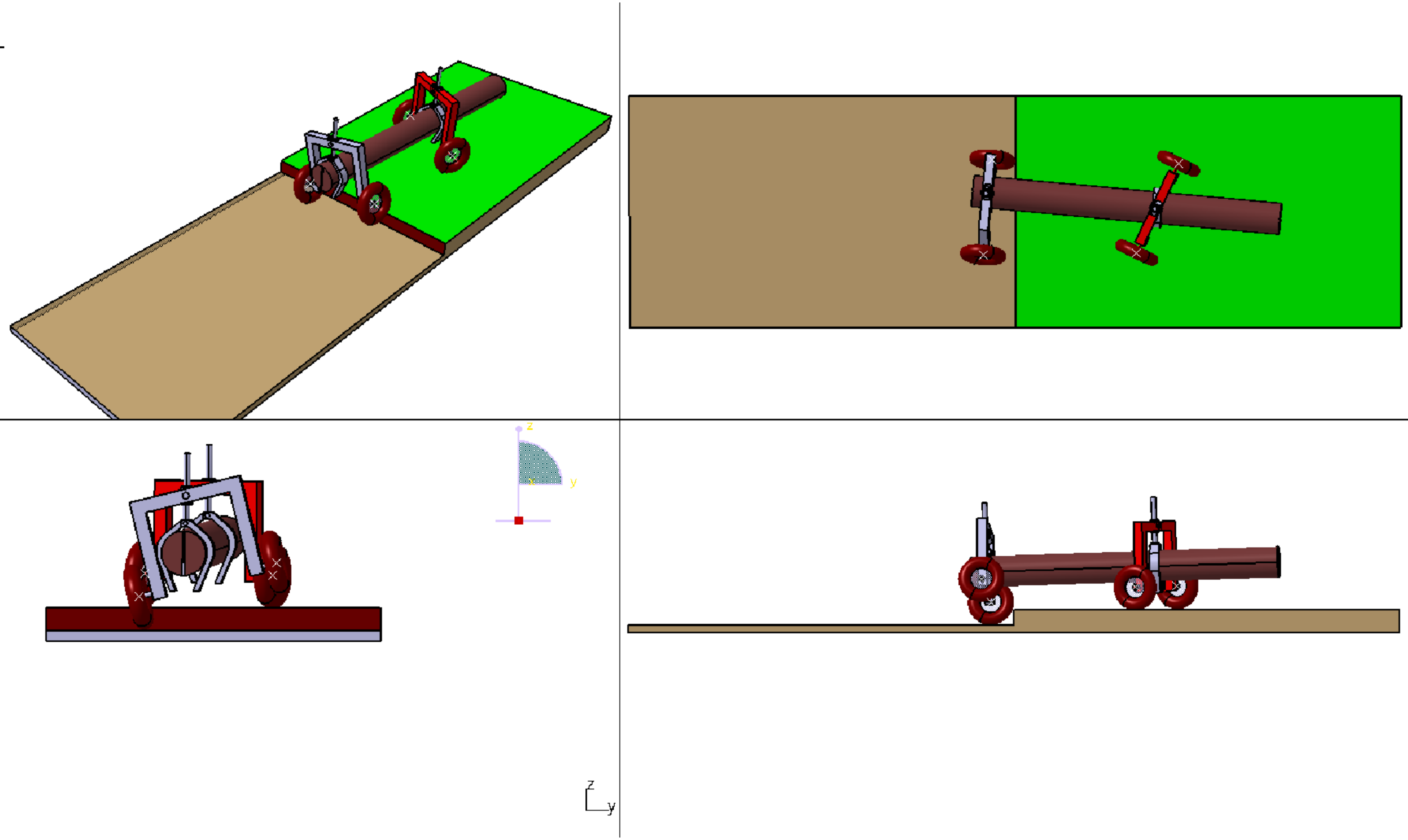
2 axles: 3D serpentine crossing mode
Stage 11 - $PW_{21}M_{01}$

W_{21} stabilization
by MR_1 combined $T_X + R_Z$



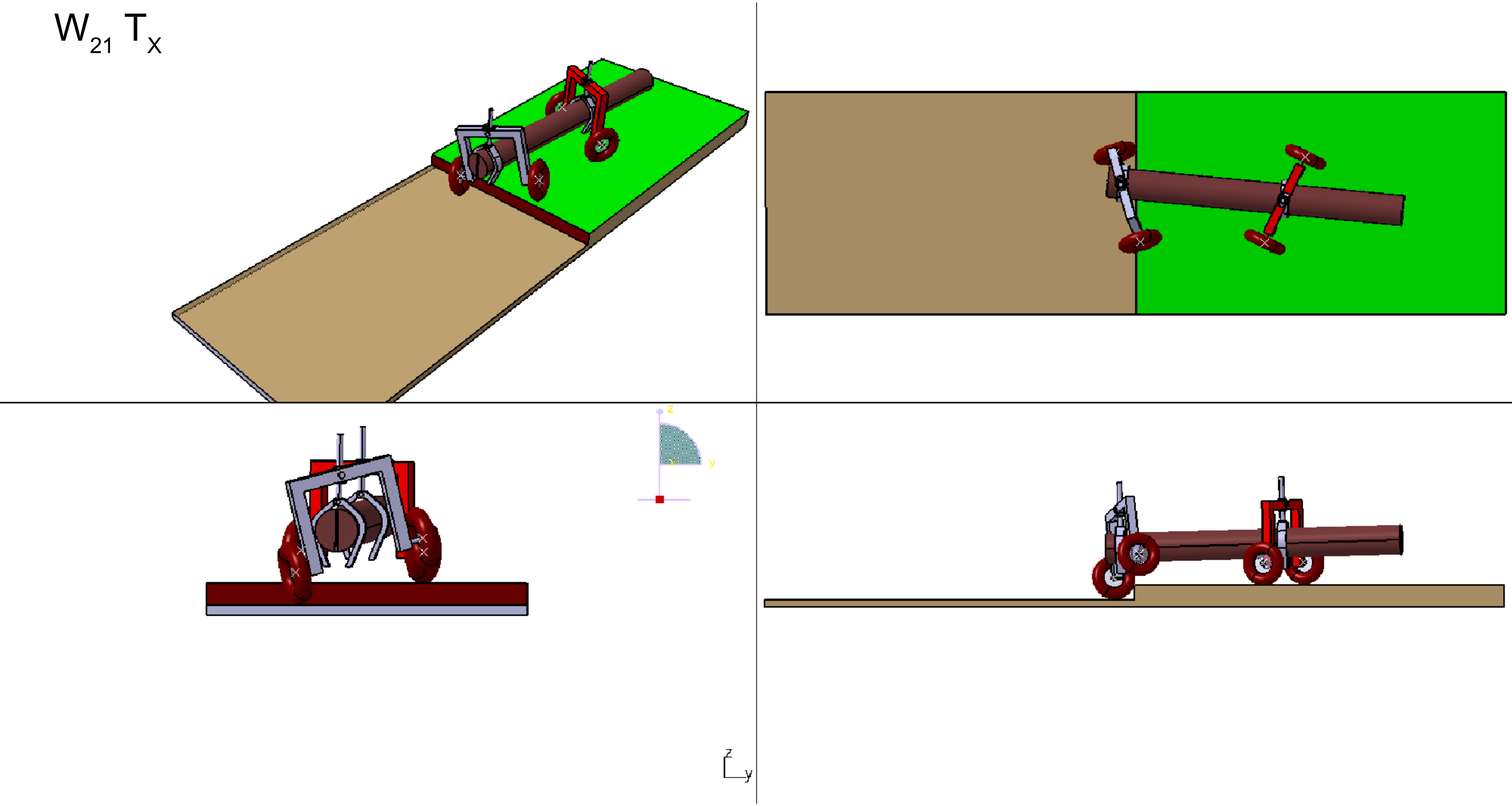
2 axles: 3D serpentine crossing mode
Stage 12 - $PW_{21}M_{02}$

W_{21} T_{Z+}



2 axles: 3D serpentine crossing mode
Stage 13 - $PW_{21}M_{03}$

W_{21} T_X



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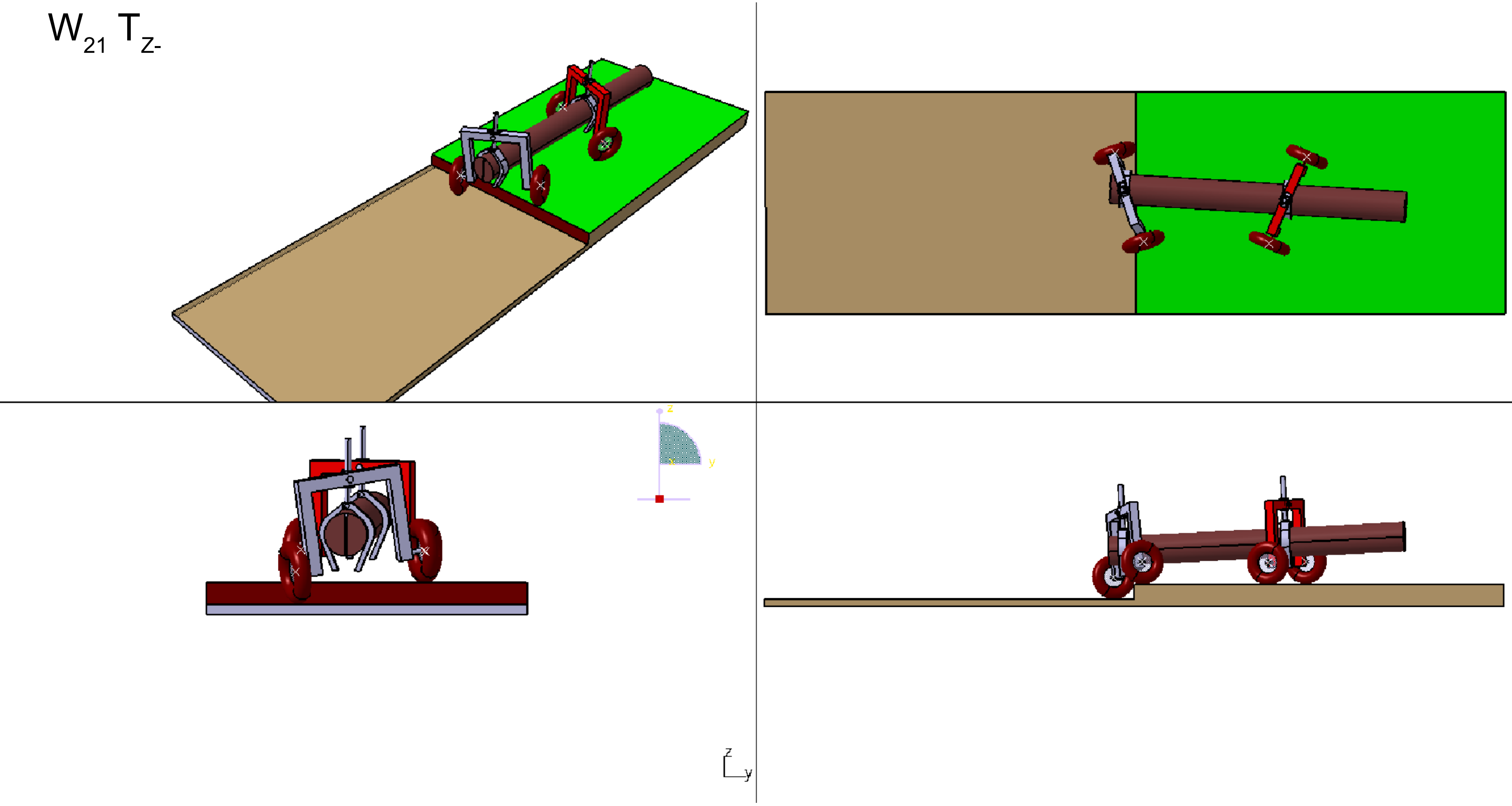
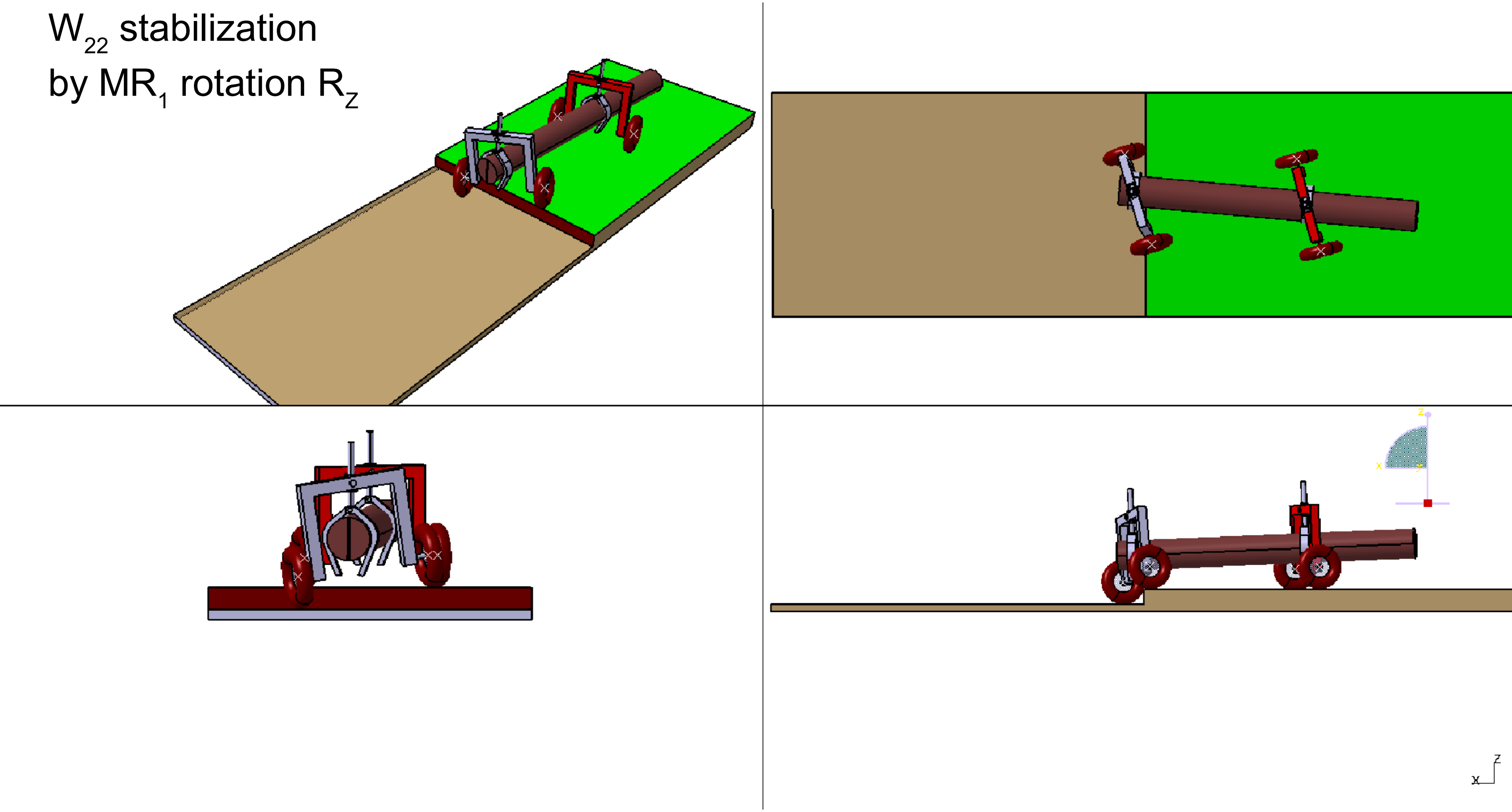
2 axles: 3D serpentine crossing mode
Stage 14 - $PW_{21}M_{04}$

W_{21} T_{Z-}



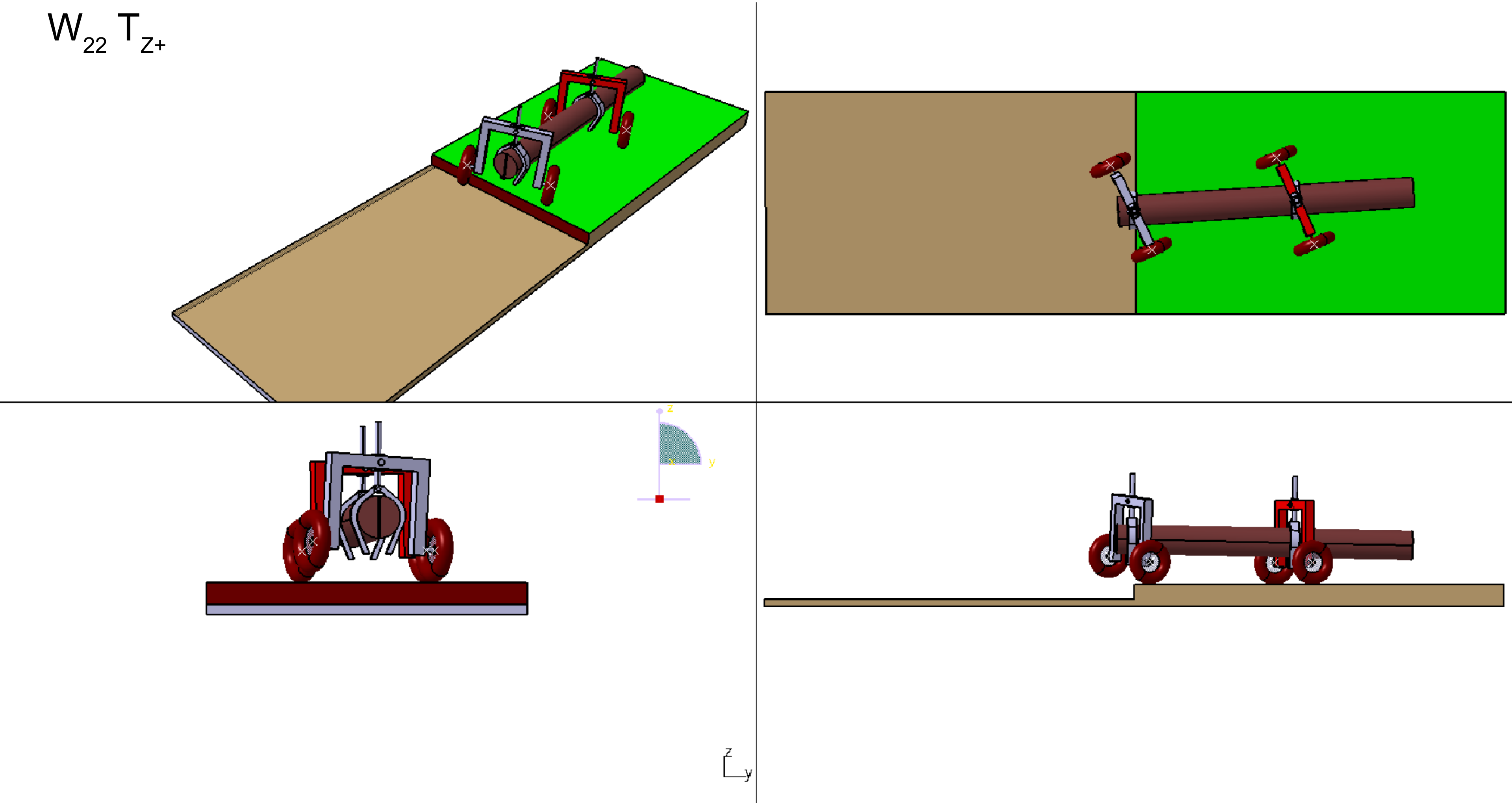
2 axles: 3D serpentine crossing mode
Stage 15 - $PW_{22}M_{01}$

W_{22} stabilization
by MR_1 rotation R_Z



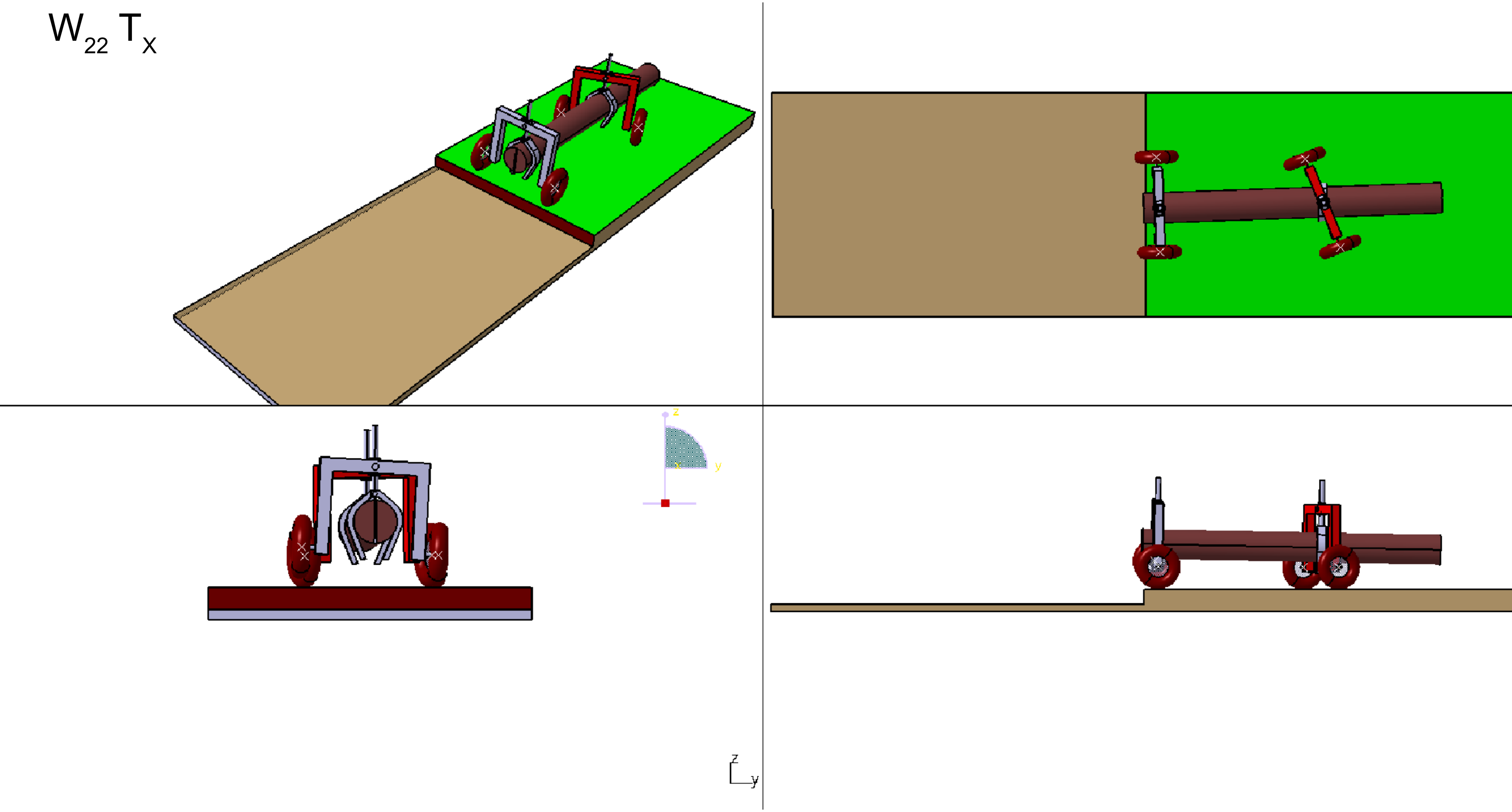
2 axles: 3D serpentine crossing mode
Stage 16 - $PW_{22}M_{02}$

W_{22} T_{Z+}



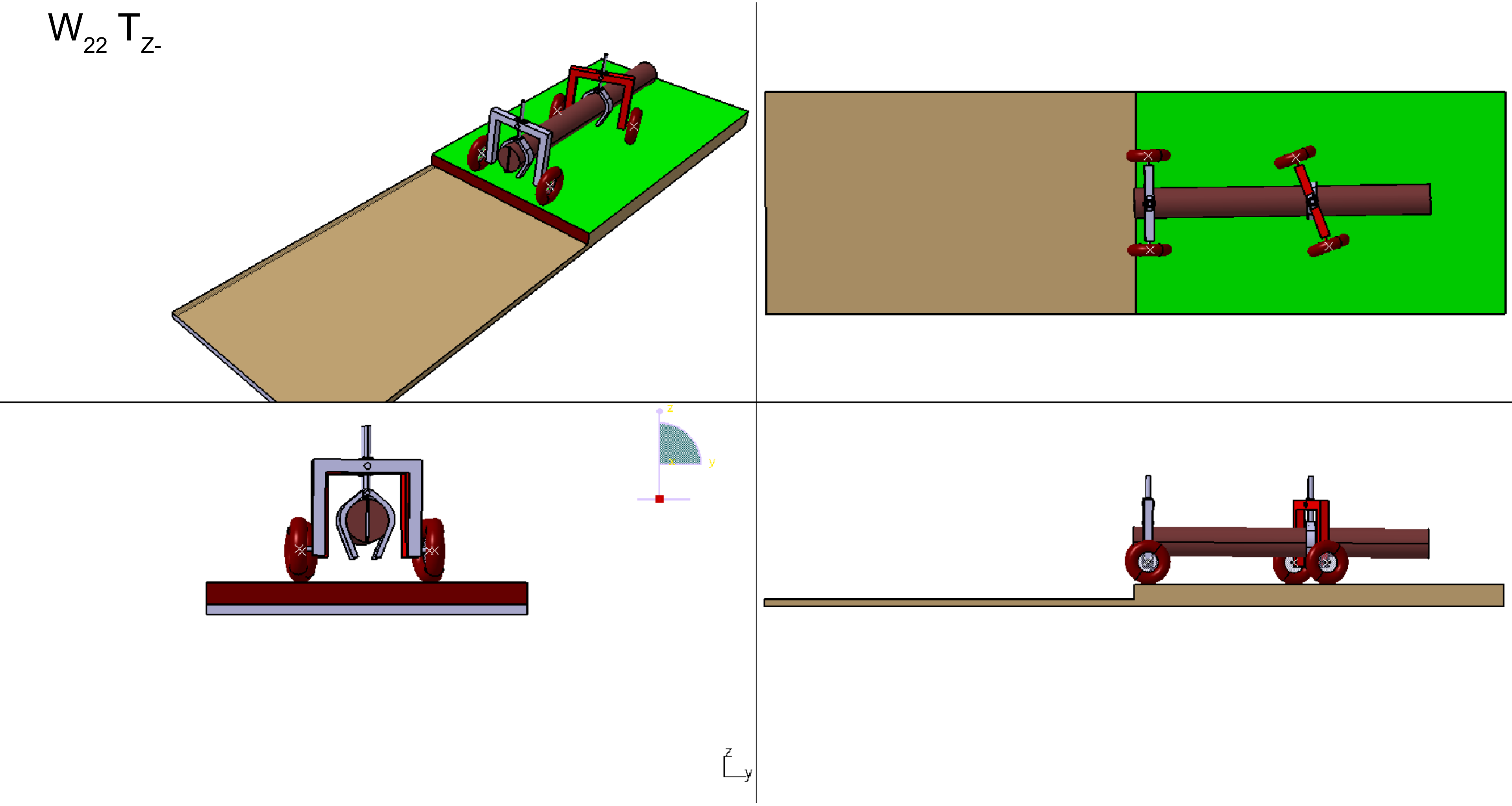
2 axles: 3D serpentine crossing mode
Stage 17 - $PW_{22}M_{03}$

$W_{22}\ T_X$



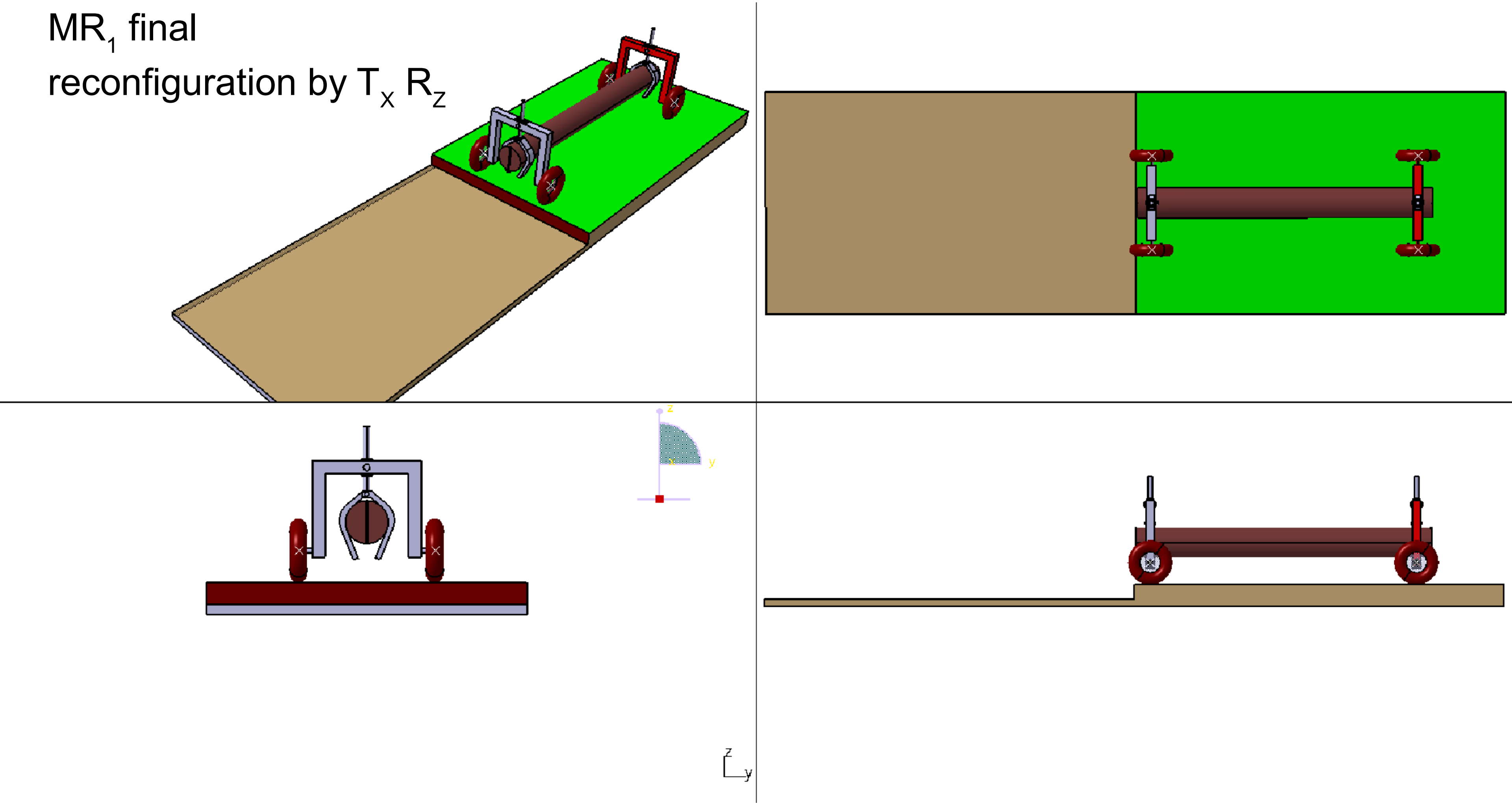
2 axles: 3D serpentine crossing mode
Stage 18 - $PW_{22}M_{04}$

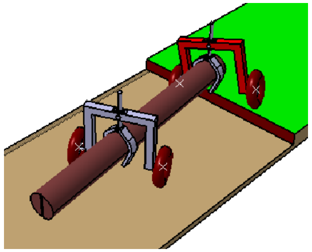
W_{22} T_{Z-}



2 axles: 3D serpentine crossing mode
Stage 19

MR_1 final
reconfiguration by T_X R_Z





Partial conclusion on C³Bots VLP

C³**Bots =**
Collaborative
Cross &
Carry
Mobile RoBots

- C³Bots context
- C³Bot AT/VLP
  - Requirements
  - Kin. synthesis
  - Control synth.
- C³Bot DGP
- Conclusion

Conclusion

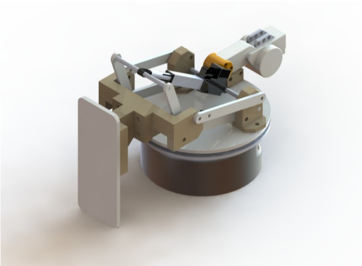
- ✔ Topic: transporting long payloads in unstructured environments with collaborative mono-robots
- ✔ Problem reformulation to extract the **four required mobilities (T_x, R_x, T_z, R_z)**
- ✔ Several **new** corresponding **kinematics**
- ✔ Kinematical **conciseness**
- ✔ **Two locomotion modes** for obstacle-crossing
  - ✔ For 3 axles and more: 2D mode
  - ✔ For 2 axles: a 3D serpentine mode
- ✔ The C³Bots AT/VLP kinematics have been **patented**

[**PAT14**] Jean-Christophe FAUROUX, Belhassen-Chedli BOUZGARROU and Mohamed KRID, « Unité robotique de transport de charges longues », Brevet français N°14/51661, 28 février 2014, 29p.

[**PAT15**] Jean-Christophe FAUROUX, Belhassen-Chedli BOUZGARROU and Mohamed KRID. " Unité robotique de transport de charges longues ", PCT patent WO 2015128594, Institut Français de Mécanique Avancée (IFMA), February 27th, 2015, 34p.

Future work

- ✔ A **new stability margin** developed for stability on 3 wheels
- ✔ **Maximization of the stability margin** along the locomotion stages
- ✔ Both **structural** and **joint** variables can be simultaneously optimized



C³Bots DGP: General principle

[MODTECH 2013]
[EUCOMES 2014]
[DARS 2014]

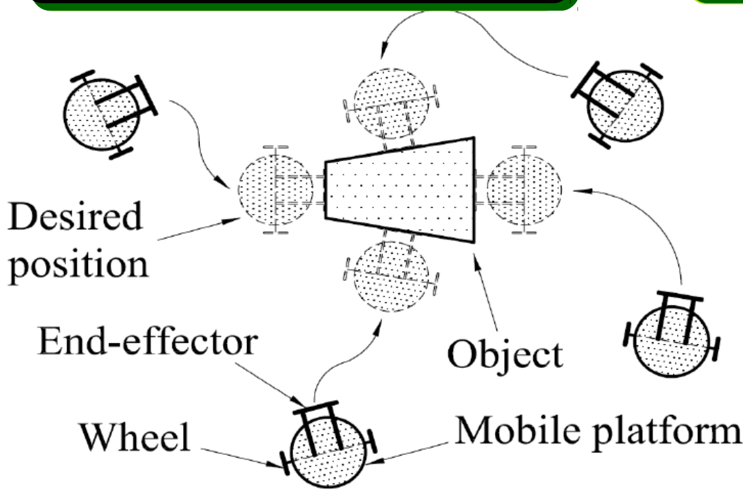
C³Bots =
Collaborative
Cross &
Carry
Mobile RoBots

- C³Bots context
- C³Bot AT/VLP
- C³Bot DGP
  - Principles
  - Kinematics
  - Control
- Conclusion

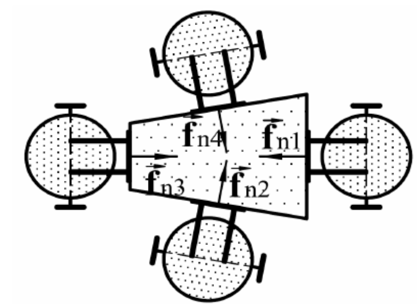
Co-manipulation and transportation method

- Motions of the **mono-robots** (in top view)
- Optimal position around the payload →
  - Optimal stability by pre-weighing
  - Avoiding collisions
  - Poly-robot dimensionning for doors
- **Poly-robot** = Payload U Mono-robots

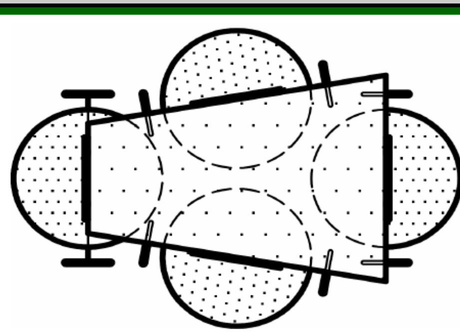
1 - M-bot positioning



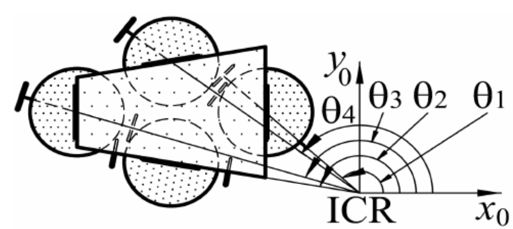
2 - Payload tightening for lifting



3 - Payload posing for transport



4 – Collaborative transport



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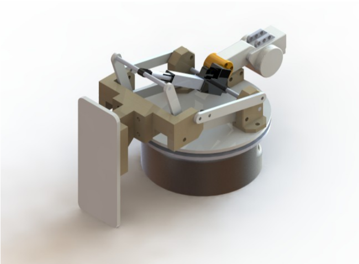
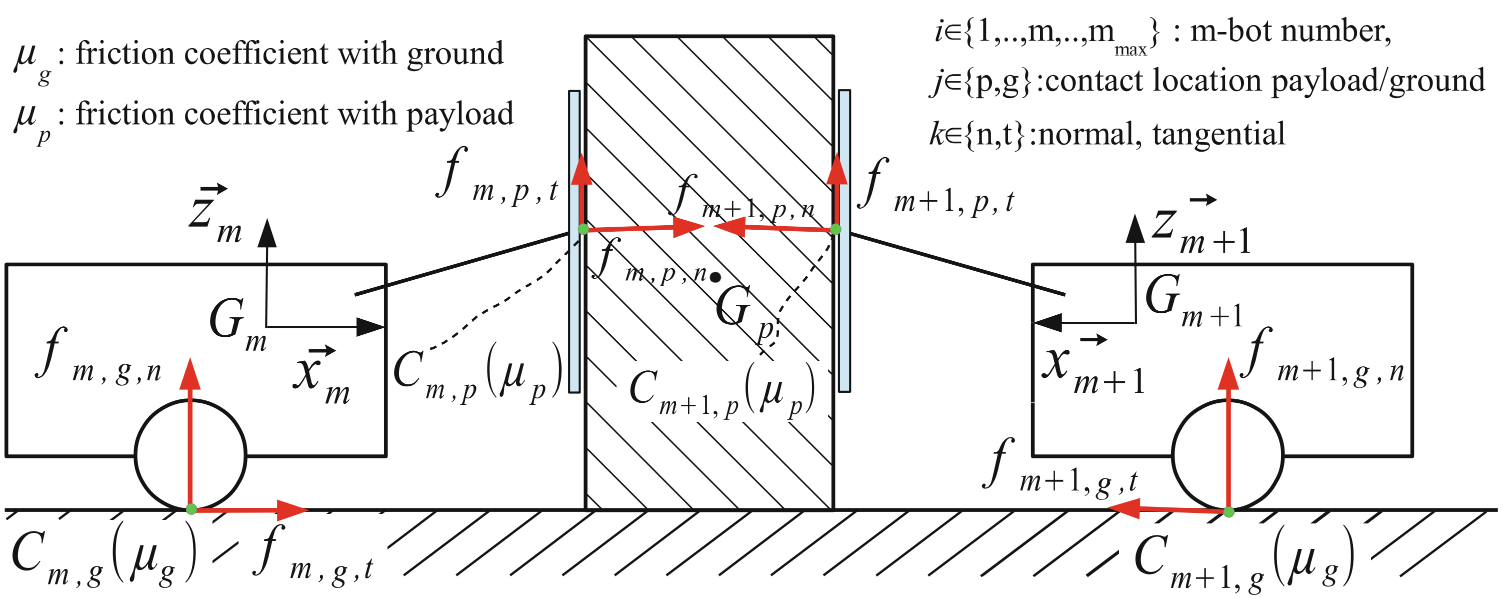


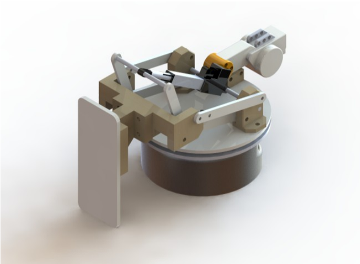
C³Bots DGP: Contact forces

- **Two types of contact**
  - Contact ground-robot → μ_g
  - Contact robot-payload → μ_p

$$f_{m,p,t} = \mu_p f_{m,p,n} = \mu_p f_{m,g,t} = \mu_p(\mu_g f_{m,g,n}) = \mu_p(\mu_g Mg) \quad (1)$$

The maximal total lifting force is $f_{p,t} = \sum_{m=1}^{m_{max}} f_{m,p,t} = m_{max}\mu_p(\mu_g Mg) \quad (2)$





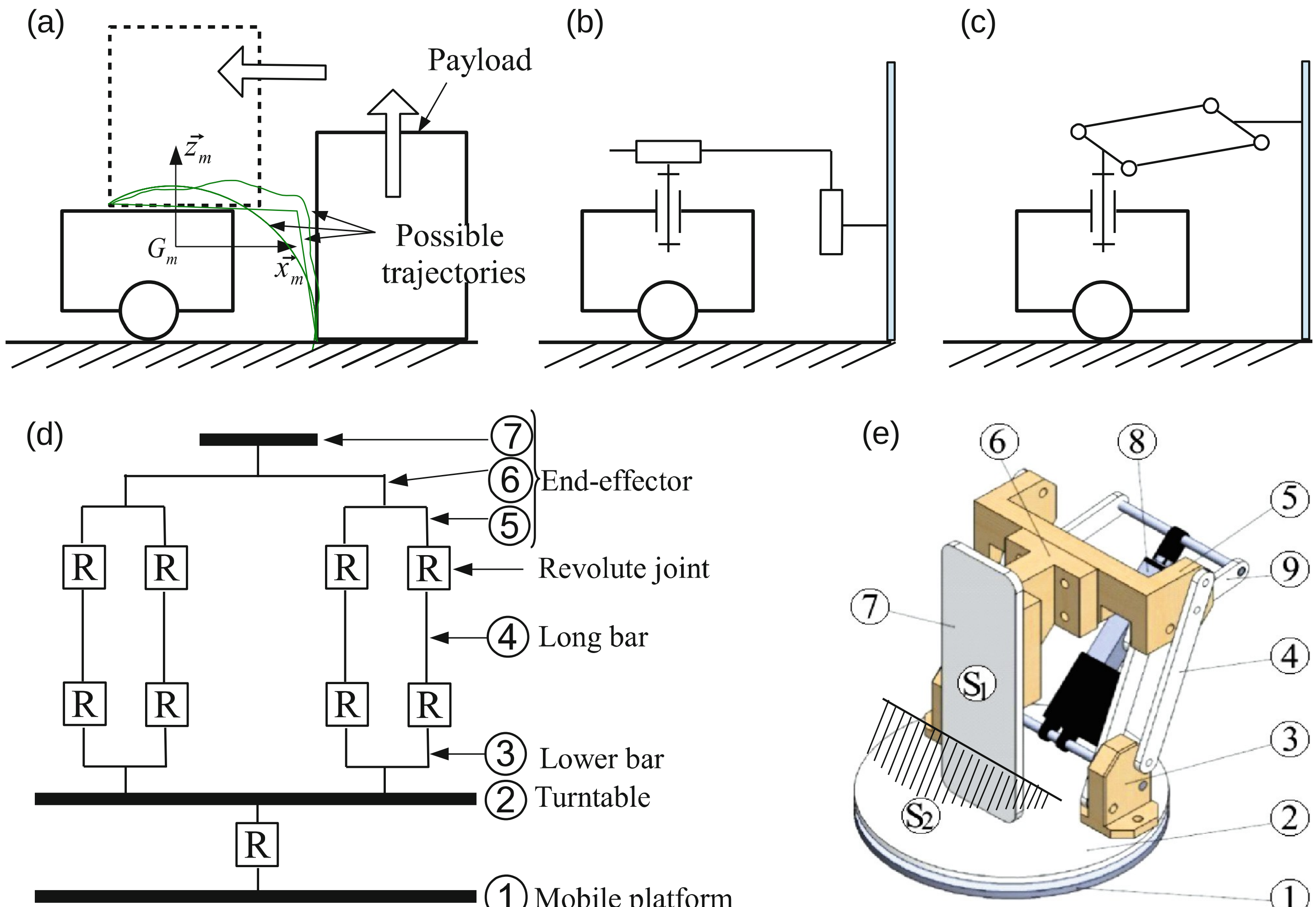
C³Bots DGP: Choosing a structure

C³Bots =
Collaborative
Cross &
Carry
Mobile RoBots

- C³Bots context
- C³Bot AT/VLP
- C³Bot DGP
  - Principles
  - Kinematics
  - Control
- Conclusion

From displacements to structure

- Trajectories coupling elevation and horizontal motion
- Parallelogram for keeping end-effector orientation
- Turret for steering under the payload



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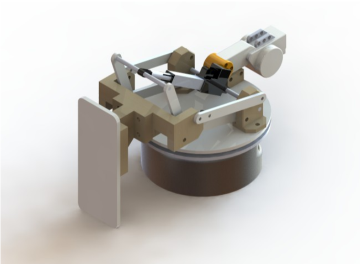
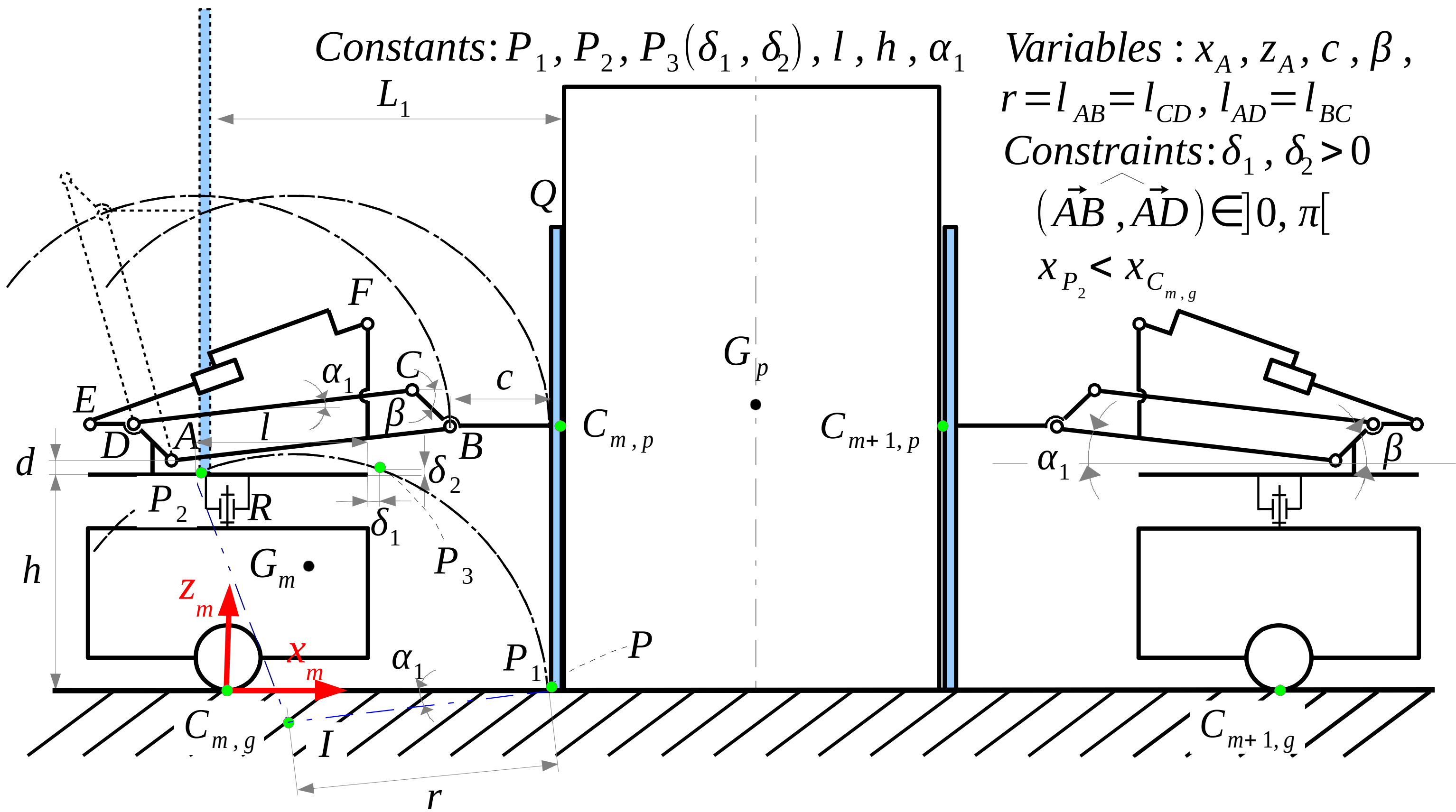


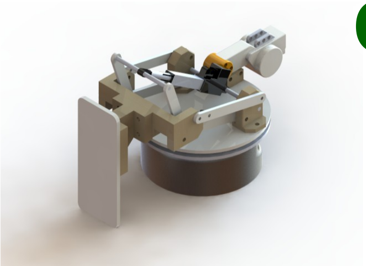
C^3Bots DGP: Dimensional synthesis

C^3Bots = Collaborative Cross & Carry Mobile RoBots

- C^3Bots context
- C^3Bot AT/VLP
- C^3Bot DGP
  - Principles
  - Kinematics
  - Control
- Conclusion

- **Synthesis of the parallelogram mechanism**
  - **Variables**: positions & dimensions of the #
  - **Constraints**: sufficient clearance, avoiding singular flat #, stability
  - **Constants**: depending of the environment and the rest of the mono-robot

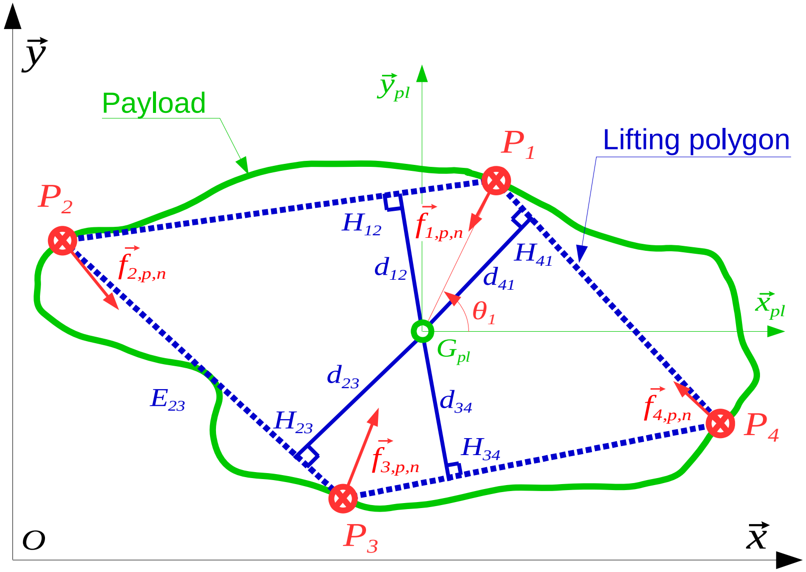


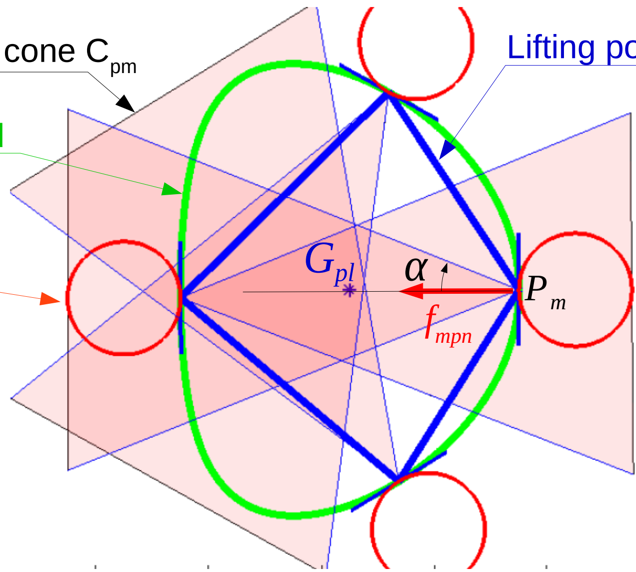


C^3Bots DGP: Optimal control during lifting

C^3Bots = Collaborative Cross & Carry Mobile RoBots

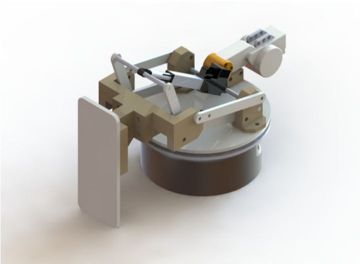
- **Static Stability Margin**
  - Optimal positioning of m-bots P_i with the angles θ_i
  - Maximise the shortest length between G_{pl} and the edges of the lifting polygon





- **Force Closure Grasping**
  - Keep G_{pl} inside the intersection of the friction cones

C^3Bots DGP: Testing & Conclusion

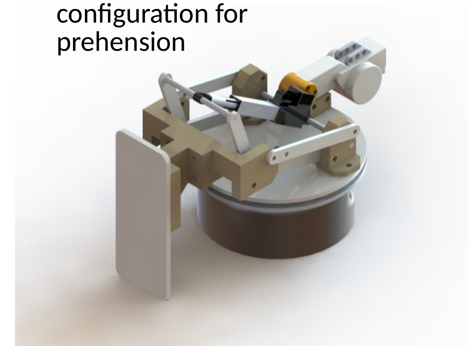


C^3Bots = Collaborative Cross & Carry Mobile RoBots

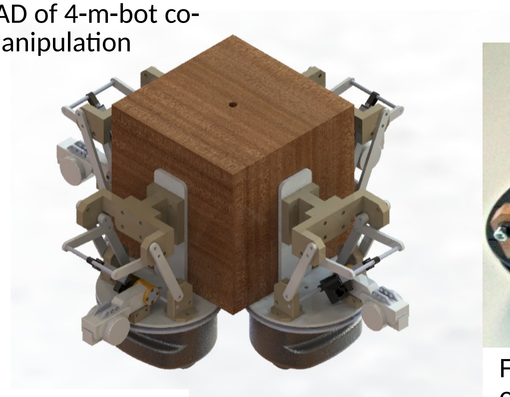
Conclusion on C^3Bots DGP

- Dorsal transport of generic payloads of any shape
- Design of m-bots with a parallelogram lifting mechanism
- Control combining Static Stability Margin & Force Closure Grasping

CAD of a m-bot in configuration for prehension

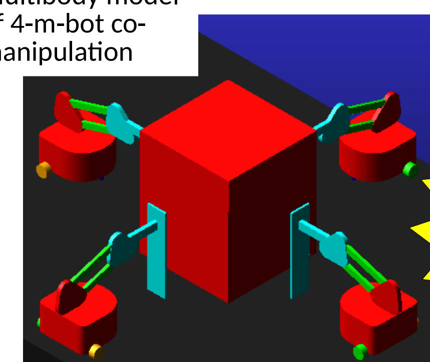


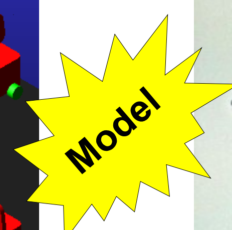
CAD of 4-m-bot co-manipulation



First experimentation on customised Khepera platforms

Multibody model of 4-m-bot co-manipulation





General conclusion on C³Bots

C³Bots =
Collaborative
Cross &
Carry
Mobile RoBots

- C³Bots
- Kinematics
- Locomotion
- Conclusion

Conclusion

- Structural synthesis of 2 original kinematics of **reconfigurable modular mobile manipulators**
  - **AT/VLP** : low centre of mass of the payload → long payloads & **obstacle crossing**
  - **DGP** : payloads of **any shape and mass** on the back of the robot
- Design of varied associated **control modes**
  - **Mono-robot locomotion** as separate entities
  - **Poly-robot locomotion**: several modes requiring to coordinate the motions of the mono-robots
    - Payload loading / unloading
    - Moving on flat ground
    - Steering
    - Obstacle crossing (including 2 locomotion modes)
- Control can be **centralized** or **dispatched** in every unit

Future work

- Towards a **systematic modularization** of industrial AGVs and mobile manipulators
  - Bots2ReC European project about collaborative robotized asbestos removal
- Solutions must be found for better **integration into** existing **logistics**