Modular Cooperative Mobile Robots for Ventral Long Payload Transport and Obstacle Crossing

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Introduction to the C³Bots project

C³Bots = Collaborative Cross & Carry Mobile RoBots

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General goal

- 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 poly-robot/payload
- Optimal **reconfiguration** of the mono-robots for the task (number, poses, cooperation strategies)

Scientific topics

- **Modularity**: Several mono-robots that combine into a single poly-robot
- **Reconfigurability**
- Unstructured environments
- **Obstacle** crossing
- **Stability**
- **Manipulation and transport**
- **Payloads of any mass & shape**
- **Removal man task**

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The C3Bots project – Examples of tasks

C3Bots = Collaborative Cross & Carry Mobile RoBots

Object transport on smooth ground
Object transport with several operators
Industrial logistics with several carts on flat ground

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

Obstacle crossing with heavy payload
Co-manipulation and transport with two operators
Bio-inspired co-manipulation

Co-manipulation of a heavy payload on flat ground
Co-manipulation of a heavy payload with obstacle crossing
Co-manipulation of compliant bars on a flat but unstructured environment (building area)

The C3BOTS poly-robot
Collaborative Cross and Carry mobile RoBOTS

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**C³Bots project: two general architectures**

**C³Bots DGP**  
Dorsal General Payload

- PHD of Bassem HICHRI  
- Structured terrain (for the moment)  
- Payload of any shape  
- Dorsal storage  
- Described in a separate paper at EUCOMES 2014

**C³Bots AT VLP**  
All-Terrain Ventral Long Payload

- Post-Doctoral period of of Mohamed KRID  
- Described in this paper  
- Heavy long payloads should be stored lower → ventral storage, between axle wheels  
- Which kinematic chain to connect the payload to the mono-robots?
Existing devices: mobile robots

Robots that carry objects

C³Bots = Collaborative Cross & Carry Mobile RoBots

- Introduction
- Devices
- OpenWHEEL

Kinematics

Locomotion

Conclusion

Mars rover pair cooperatively transporting a long payload [1]


Existing devices: mobile robots

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Collaborative robots

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

Swarmanoid [5]


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
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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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


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OpenWHEEL i3R

Locomotion mode in 19 stages

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Video

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Design Requirements from OpenWHEEL i3R

**Requirement R1 = Adding modularity to OpenWHEEL i3R**

- C³Bots = Collaborative Cross & Carry Mobile RoBots
- Poly-robot = Mono-robot 2 + 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 \( a = 1 \ldots m \)
  - Kinematical conciseness

- Design req.
- Mobilities
- Kin. Solution
Required mobilities

**Requirement R3**

**Stability condition**

- 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
  \[ T_z \text{ elevation translation} \]
  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 & **focusing irregular grounds**
- \( T_z \) for **payload elevation**
- \( R_z \) for **steering & OpenWHEEL-like stabilization** (R3)
Kinematics of the mono-robot

A feasible solution with $T_x$ generated by rollers

$C^3Bots =$
- Collaborative
- Cross & Carry
- Mobile RoBots

$C^3Bots$

$Kinematics$
- Design req.
- Mobilities
- Kin. Solution

$Locomotion$

$Conclusion$

mono-Robot a

Slider $S_a$
- Cylindrical joint $C_a$

Revolute joint $R_{a4}$

Axle frame $F_a$

Gripper finger $G_{a1}$

Roller $R_{a1}$

Right wheel

Wheel $W_{a1}$

Wheel $W_{a2}$

Gripper mechanism

Axle sub-mechanism

Positioning mechanism

Payload

Contact 1

Contact 2

$GW_a$

$P_a$

$R_{a3}$

$S_1$

$S_2$

$A$

$R_{a1}$

$R_{a2}$

$R_{a3}$

$R_{a4}$

$R_{a5}$

$R_{a6}$
Kinematics of the mono-robot

Alternatives

- Equivalent joint combinations to generate the 4 mobilities $T_x, R_x, T_z, R_z$
- Parallel mechanisms could also be used
Kinematics of the poly-robot

Case of 2 Mono-Robots

- Redundancy of the two $R_x$ mobilities can be used for lateral balancing of the payload
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

C³Bots = Collaborative Cross & Carry Mobile RoBots

- C³Bots
- Kinematics
- Locomotion
  - 3+ axles
  - 2 axles
- Conclusion

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2 axles: 3D serpentine crossing mode

- Inspired form OpenWHEEL i3R locomotion mode
- 20 stages or manoeuvres
- 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 \( T_z^- \)
Poly-robot Preparation

2 axles: 3D serpentine crossing mode
Stage 00
2 axles: 3D serpentine crossing mode
Stage 01

Poly-robot
Touching obstacle
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}
2 axles: 3D serpentine crossing mode
Stage 04 - PW_{11} M_{03}
2 axles: 3D serpentine crossing mode
Stage 05 - PW$_{11}$M$_{04}$
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}
2 axles: 3D serpentine crossing mode
Stage 08 - PW_{12}M_{03}
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
MR₂ moving backward
2 axles: 3D serpentine crossing mode
Stage 11 - PW_{21}M_{01}

\( W_{21} \) stabilization
by MR_{1} combined \( T_{X} + R_{Z} \)

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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\textsubscript{21}M\textsubscript{03}

\[ W_{21} T_x \]
2 axles: 3D serpentine crossing mode
Stage 14 - $PW_{21} M_{04}$
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$_{03}$
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 $T_x R_z$
Conclusion

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- C³Bots
- Kinematics
- Locomotion
- 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**


**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