Design and control of Collaborative, Cross and Carry mobile roBots «C³Bots»

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Outlines

- C³Bots
  - Introduction
  - State of the art

- Mobile robot design
  - Method
  - M-bot structure
  - Dimensional synthesis

- Global Control Architecture
  - M-bot positioning algorithm
  - Positioning criteria
  - Control architecture

- Simulations and experimental results

- Conclusion
C³Bots

Mobile Robots Design

Simulations and experimental Results

Introduction

State of the Art

Object transport on smooth ground

Obstacle crossing with heavy payload

Co-manipulation and transport with two operators

Object transport with several operators

Industrial logistics with several carts on flat ground

The C³BOTS poly-robot

Collaborative Cross and Carry mobile roBOTS

Collaborative

Cross

Carry

Obstacle crossing 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)

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

Co-transport of stretchers on irregular ground

Object transport on smooth ground

Obstacle crossing

Co-manipulation

Transport

Collaborative

Cross

Carry

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Introduction to the C³Bots project

General goal

C³Bots = Collaborative, Cross & Carry Mobile RoBots

- **Modularity**: Several m-bots that combine into a single p-bot
- **Reconfigurability**

- **Manipulation and transport**
- **Unstructured environments**
- **Obstacle avoiding**
- **Stability**
- **Payload of any mass & shape**

Scientific topics

- Design of a mechatronic system achieving the tasks with minimal DoF (→ simplicity)
- Flexible and reliable cooperative control of m-bots deployment, payload collaborative manipulation and transport
Structured environment mobile robots

- Alice [EPFL, 2004]
- Khepera [K team]
- Pioneer [siegwart, 2004]

All terrain mobile robots

- Nomad [Wettergreen, 1997]
- Micro 5 [Kubota, 2003]
- Crab [Krebs et al, 2008]

Obstacle climbing mobile robots

- Rocky 7 [Volpe, 1997]
- Shrimp [Siegwart, 2002]
- OpenWHEEL [Fauroux et al, 2006]

Modular robots

- M-tran [Yim, 2007]
- Atron [Jorgensen, 2004]
- Swarm agents [Kernbach, 2008]
Collaborative Robots that carry objects

Dorsal payload transport
Army-Ant [Bay, 1995]:

Cooperative object transfer
by legged robots [Aiyama, 1999].

Collaborative transport using robot arms
Stanford robotic platform [Khatib, 1999]

Collaborative stick-pulling
Khepera [Ijspeert, 2001]

Collaborative pushing
Alice [Adouane, 2005]:

Heterogeneous fleet of robots
Swarmanoïd [Dorigo, 2012]
Relative to the state of the art our contribution consists on:

- Proposing a new strategy that ensures payload co-manipulation and transport
- Making an innovative design with simple architecture dedicated to structured grounds and ensuring stable co-manipulation and transport.
- Optimal positioning for permanent stability and successful task achievement

- Post-Doctoral period of Mohamed KRID (2013-2014)
- Transport of heavy long payloads → ventral storage, between wheels
- Unstructured grounds and obstacle crossing
Co-manipulation and transportation method

Co-manipulation by using forks

Co-manipulation by tightening the payload

Co-manipulation by tightening the payload and putting it on robot bodies
Co-manipulation and transportation method

1- M-bot positioning

Desired position
End-effector
Wheel
Mobile platform

2- Payload co-pushing for lifting

3- Lifted payload for transport

4- Collaborative transport

B. HICHRI,
[ModTECH 2013]
- The **p-bot lifting capacity**
  - Increases with the number of used m-bots
  - Depends on the friction coefficient $\mu_g$ wheel / ground
  - Depends on the friction coefficient $\mu_p$ end-effector / payload

- $\mu_p$ and $\mu_g$ may be unknown or variable → by **interconnecting the m-bots**, the normal force $f_{m,p,n}$ becomes constant and do not depend anymore on $\mu_p$. 

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Method
- Dimensional synthesis
- Manufactured prototypes
Structural choice

Patient lifting device:
US2013/0269103 A1

Lifting mechanism for a storage bed base:
EP 2 462 842 A1

Lifting mechanism for articulated bed:
EP 2 108 288 A1

2 DOF lifting mechanism
1 DOF lifting mechanism
1 DOF lifting mechanism

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Specification:
- Landing position $P_2$
- Intermediate position for collision avoidance $P_3$
- Landing width $l$
- Platform height $h$
- Initial pushing angle $\alpha_0$

Constraints:
- Non flat parallelogram mechanism
- Stability condition

Goal:
- Determine the parallel bar length which corresponds to the trajectory radius $r$
- Linkage position $(x_A, y_A)$
- Linkage orientation $\gamma$
- Over hanging distance $c$
Specification:
- Landing position \( P_2 \)
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- Initial pushing angle \( \alpha_0 \)
- Platform height \( h \)
- Landing width \( l \)

Constraints:
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- Determine the parallel bar length which corresponds to the trajectory radius \( r \)
- Linkage position \((x_A, y_A)\)
- Linkage orientation \( \gamma \)
- Overhanging distance \( c \)

Specification:
- \( \alpha \)
- \( \gamma \)
- \( \beta \)

Method:
- Dimensional synthesis
- Manufactured prototypes

Conclusion:
- Simulations and experimental results
End-effector circular trajectory for payload lifting.

Free steering motion of the mobile platform relative to the manipulation mechanism.
Calculation of the landing zone width $l$

$$l = d_1 + W_b - s_1 + \epsilon = d_1 + W_b - \frac{W_b T}{2\sqrt{4W_b^2 + T^2}} + \epsilon \quad | \quad \epsilon \geq 0$$

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### Assumptions

- $f_{mpt} < \mu_p f_{mpn}$
- $\tan(\alpha) = \mu_p$
- The friction cone of the $m^{th}$ contact is denoted $C_{pm}$.
Passive mechanism

Payload mass $M_1$ (small).

Payload mass $M_2 > M_1$

Generated lifting force:

$$f_{m,p,t} = \frac{P_{mm}x_{G_{mm}}}{r_1 \cos \alpha + c}$$

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Mechanism with compliant organs

 Generated lifting force:

\[ f_{m,p,t} = \frac{P_{mm}x_{G_{mm}} + F_{spr} \frac{r \sin \alpha + r_2 \sin \alpha}{\sqrt{r^2 + r_1^2 - 2rr_1 \cos(\alpha + \gamma)}} (r \cos \alpha - r_1 \cos \alpha)}{r \cos \alpha + c} \]

Generated lifting force:

\[ f_{m,p,t} = \frac{P_{mm}x_{G_{mm}} + M_{tor-spr}}{r \cos \alpha + c} \]
Mechanism with springs

Low stiffness
Compliant organs.

High stiffness
Compliant organs.

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Passive mechanism with interconnection system

Actuated mechanism with interconnection system

Generated lifting force: \( f_{m,p,t} = \mu_p \mu_g M g \)

Generated lifting force: \( f_{m,p,t} = \frac{M_m - P_{mm} x_{Gmm}}{r \cos \alpha + c} \)
Co-manipulation and transportation method

1- M-bot positioning

- Desired position
- End-effector
- Wheel
- Mobile platform

2- Payload co-pushing for lifting

3- Lifted payload for transport

4- Collaborative transport

B. HICHRI, [ModTECH 2013]
Input parameters

- The payload curve \((B)\)
- The number of used m-bots
- The payload center of mass \(G_{pl}\)

Objective

- Ensuring the payload prehension without slipping
- Ensuring stability of the whole system (m-bots+payload)

Force Closure Grasping FCG

- Common concept for manipulation
- Used here for ensuring the stable contact payload/end-effector

Static Stability Margin SSM

- Common concept generally used for stability during locomotion
- Used here for ensuring a stable contact wheel/ground
Payload detection and estimation of \( M_{pl} \) and \( G_{pl} \)

Obtaining the minimum number of m-bots to lift the payload

Determine the appropriate m-bots configuration

Go to the obtained positions

Lift the payload

Transport the payload toward a final configuration while keeping a specific formation

Generate an initial grasp that ensures SSM

If the config ensures FCG

If the config ensures SSM

If the SSM is higher than the previous one

Save the grasp config

Change config

Return the last saved config

If \( it \lt it_{max} \)
Force Closure Grasping

Stable configuration

Unstable configuration

\[
\sum_{m=1}^{m_{\text{min}}} (P_m G_{pl} \wedge f_{m,p,n}) = 0; \quad \sum_{m=1}^{m_{\text{min}}} f_{m,p,n} = 0
\]

\[G_{pl} \in \text{Convexhull}(\cap C_{pm}) \mid m = 1..m_{\text{min}}\]

J-W Li, [ICRA 2003]

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Goal: maximize the objective function $f$:

$$f(\theta_m, \ldots \theta_{m_{\text{min}}}) = \text{Min}(d_{m,m+1}) \mid m = 1 \ldots m_{\text{min}}$$

$$d_{m,m+1} = d(G, (P_mP_{m+1})) = \frac{y_{P_{m+1}} - y_{P_m} - y_G + y_{P_m} - x_{P_m}x_{P_{m+1}} - x_{P_m}}{\sqrt{(x_{P_{m+1}} - x_{P_m})^2}}$$

Stability margin

Support polygon

Global Control Architecture

Simulations and experimental Results

Method

Positioning criteria

Conclusion

M-bot positioning

Control architecture

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Restricted Area (RA)

Restricted Area $\overline{B}$

Wall

Payload

$M$-bot

Restricted Area $\overline{B}$

Wall

Payload

$M$-bot
Control architecture

- Designed for a group of unicycle robots.
- Safe and smooth navigation in formation

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Vehicle and target configuration

Navigation in formation

\[ x_{dm} = x_{G_{pl}} + l_{xm} \cos \theta_{dm} - l_{ym} \sin \theta_{dm} \]
\[ y_{dm} = y_{G_{pl}} + l_{xm} \sin \theta_{dm} + l_{ym} \cos \theta_{dm} \]

Error variables for target reaching controller

\[ e_{xm} = x_d - x_m = e \cos \gamma_m \]
\[ e_{ym} = y_d - y_m = e \sin \gamma_m \]
\[ e_{\theta} = \theta_d - \theta_m \]
Obstacle avoidance controller [ADOUANE IFAC WC’11]

\[
\begin{align*}
\dot{x}_s &= m(By_s + 0.5Cx_s) + x_s(1 - Ax_s^2 - By_s^2 - Cx_sy_s) \\
\dot{y}_s &= -m(Ax_s + 0.5Cy_s) + y_s(1 - Ax_s^2 - By_s^2 - Cx_sy_s)
\end{align*}
\]

\[
A = \left(\frac{\sin(\Omega)}{b_{lc}}\right)^2 + \left(\frac{\cos(\Omega)}{a_{lc}}\right)^2
\]

\[
B = \left(\frac{\cos(\Omega)}{b_{lc}}\right)^2 + \left(\frac{\sin(\Omega)}{a_{lc}}\right)^2
\]

\[
C = \left(\frac{1}{a_{lc}^2} - \frac{1}{b_{lc}^2}\right)\sin(2\Omega)
\]
Limit-cycle trajectories

\[
a_{\text{inf}} = a_{\text{sur}} + R + M_{\text{arg}}
\]

\[
b_{\text{inf}} = b_{\text{sur}} + R + M_{\text{arg}}
\]
M-bots positioning

Restricted area

M-bots positioning while respecting the restricted area criterion
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Robot trajectory in \([O,X,Y]\) reference.

- **Initial position**
- **Desired position**

Robots Objective distances evolution

**C^3Bots**

**Global Control Architecture**

**Mobile Robots Design**

**Simulations and experimental Results**

**Conclusion**
Robot and payload trajectories in [O,X,Y] reference

Robots Objective distances and angles evolution
Robot and payload trajectories in \([O,X,Y]\) reference

Robots Objective distances and angles evolution

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Robot and payload trajectories in [O,X,Y] reference

Robots Objective distances evolution
Robot and payload trajectories in \([O,X,Y]\) reference

Robots Objective distances evolution
Lifting testbench

Prototypes

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Lifting testbench

<table>
<thead>
<tr>
<th>Type of contact</th>
<th>Type of actuation</th>
<th>Lifting capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic-composite</td>
<td>Passive mechanism</td>
<td>0.07kg</td>
</tr>
<tr>
<td>Plastic-composite</td>
<td>Helical spring mechanism</td>
<td>0.18kg</td>
</tr>
<tr>
<td>Rubber-composite</td>
<td>Passive mechanism</td>
<td>0.17kg</td>
</tr>
<tr>
<td>Rubber-composite</td>
<td>Helical spring mechanism</td>
<td>0.5kg</td>
</tr>
<tr>
<td>Rubber-rubber</td>
<td>Passive mechanism</td>
<td>0.6kg</td>
</tr>
<tr>
<td>Rubber-rubber</td>
<td>Helical spring mechanism</td>
<td>0.82kg</td>
</tr>
</tbody>
</table>
Testbench
Conclusion

- Topic: **transporting** generic payloads (any shape & mass) in structured environments with **collaborative** elementary robots.

- Innovative strategy of payload **co-lifting** and **co-transportation** using a **homogenous group** of **simple** robots.

- **Mechanical model** and **design** of robot structure:
  - Force model: **robot/ground** and **robot/payload contacts**
  - A general structure compatible with the **cooperative task** achievement:
    - A **turret** connecting a **standard mobile base** to a simple **manipulator + end-effector**

- **Dimensional synthesis** of the **lifting mechanism** based on parallelogram structure

- Evaluation of the **lifting force** according to mechanism actuation
Conclusion

- Global control architecture
  - Global deployment strategy for the multi-robot system
  - Find sub-optimal robots positions around the payload to maximize stability:
    - Force Closure Grasping during co-manipulation
    - Static Stability Margin during co-transportation
  - Limit-Cycle approach for 3 sub-tasks achievement: hidden target reaching, obstacle avoidance for m-bot and virtual structure navigation for p-bot

- Simulation
  - Multi-body dynamic simulation (Adams/SolidWorks)
  - Evaluation of the overall navigation strategy (Matlab/Simulink)

- Prototyping and experimenting
  - Testbench for payload lifting with contact
  - Manufacturing of two prototypes
  - First lifting experiment using two m-bots
Future work

- Developing **new strategies** of collaboration between robots by inspiring from human beings
- Designing an interconnection **mechanism** between robots for adjusting the tightening force independently from the friction coefficient $\mu_p$
- Developing a **compliant end-effector** that allows to adapt the payload shape and ensures a higher contact surface
- Fitting an **industrial application** at bigger scale (dimensions and number)
- Adding mobilities to m-bots such that the p-bot can maintain its **stability** on various environments
- Implementing a **distributed control architecture** giving more autonomy to each m-bot
Thank you for your attention

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