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Flexible co-manipulation and transportation with mobile multi-robot system

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Abstract

Purpose – The purpose of this paper is to address optimal positioning of a group of mobile robots for a successful manipulation and transportation of payloads of any shape.

Design/methodology/approach – The chosen methodology to achieve optimal positioning of the robots around the payload to lift it and to transport it while maintaining a geometric multi-robot formation is presented. This appropriate configuration of the set of robots is obtained by combining constraints ensuring stable and safe lifting and transport of the payload. A suitable control law is then used to track a virtual structure in which each elementary robot has to keep its desired position with respect to the payload.

Findings – An optimal positioning of mobile robots around a payload to ensure stable co-manipulation and transportation task according to stability multi-criteria constraints. Simulation and experimental results validate the proposed control architecture and strategy for a successful transportation task based on virtual structure navigation approach.

Originality/value – This paper presents a new strategy for co-manipulation and co-transportation task based on a virtual structure navigation approach. An algorithm for optimal positioning of mobile robots around a payload of any mass and shape is proposed while ensuring stability during the whole process by respecting multi-criteria task stability constraints.

Keywords Control architecture, Cooperative mobile robots, Navigation in formation, Payload co-manipulation and co-transportation, Robots positioning, Virtual structure approach

Paper type Research paper

1. Introduction

Compared with single-robot setups, multi-robot systems provide more efficient and robust task completion and enable behaviors having a higher degree of complexity and sophistication. To ease transportation tasks, the payload can be adequately distributed among a group of inexpensive robots because of the simpler kinematics and architecture, and the payload handling dexterity may be increased. The robots may be reconfigured to fit a payload of any shape and to adapt to the environment in which they evolve. Each of the robot can be rather simple and be manufactured at a low cost. Additionally, the failure tolerance of a multi-robot system can be very high provided that spare robots are available to replace damaged robots in the system. There have been a significant research studies related to payload transportation using multiple robots (Adouane and Le Fort-Piat, 2004; Abou-Samah and Krovi, 2002; Kernbach *et al.*, 2008).

Multi-robot transportation tasks can be seen as a navigation in formation control problem. This is a classical problem that has attracted the attention of the research community in the past decade (Dehghani *et al.*, 2016; Das *et al.*, 2015; Peng, 2013). The approaches proposed to solve it can be classified into three main groups, namely, behavior-based approach, leader–follower approach and virtual structure (VS) approach. In behavior-based approaches (Vilca *et al.*, 2013b; Benzerrouk *et al.*, 2010), a behavior or motion primitive for each entity is designed (e.g. obstacle avoidance, formation keeping, target seeking and trajectory tracking). Then, more complex motion patterns can be generated by using a weighted sum according to the relative importance of these behaviors. The main drawback of this approach is the complexity of the group dynamics, and as a consequence, the convergence to the desired formation configuration cannot be guaranteed. Leader–follower approach (Peng, 2013) is a strategy in which a robot is the

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leader, while others act as followers. The main advantage of using this approach is the reduction of the strategy to a tracking problem where stability of the tracking error is shown through standard control theoretic techniques; the leader has to track a predefined trajectory, and the followers track the leader with some prescribed offset. A disadvantage of this approach is that there is no feedback from followers to the leader, so that if a follower is perturbed, then the formation cannot be maintained, which characterizes a lack of robustness. The last approach is VS (Sadowska *et al.*, 2011; Mehrjerdi *et al.*, 2011) in which the entire formation is considered as a rigid body, and the notion of hierarchy does not exist. A control law for each entity is derived by defining the VS dynamics and then translated to the motion of the VS into the desired motion of each robot. The main advantages of this approach are its simplicity to prescribe the behavior of the group and its ability to maintain the formation during maneuvers. However, the potential application is limited by the VS rigidity, especially when the formation shape needs to be frequently reconfigured.

Our goal in the C^3Bots project (Collaborative Cross and Carry mobile roBots) is to design several mobile robots, called m-bots, with a simple mechanical architecture that will be able to autonomously co-manipulate and transport payloads of any shape. The resulting poly-robot system, called p-bot, will be able to solve the so-called removal-man-task to transport any payload on the top platform of m-bots (dorsal transport). Reconfiguring the p-bot by adjusting the number of m-bots allows to manipulate payloads of any mass, whereas modifying the poses of the m-bots inside the p-bot permits to adjust to any payload shape.

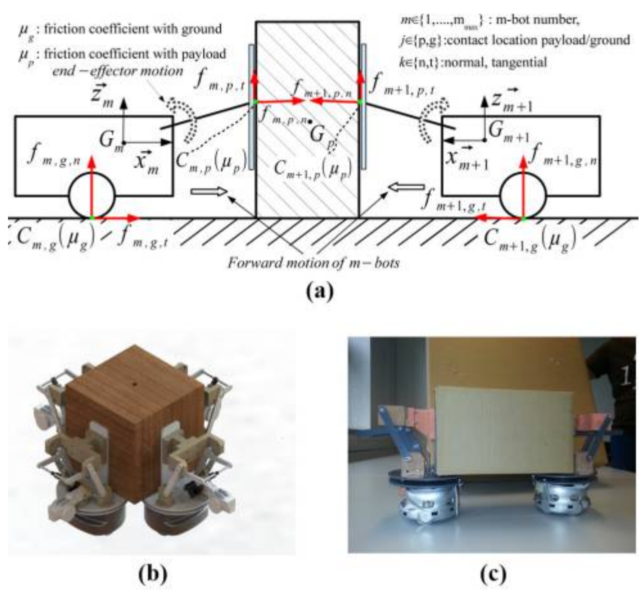
Many robotic systems used for objects manipulation and transport can be found in literature. Using different techniques, a group of similar (Adouane and Le Fort-Piat, 2004; Abou-Samah and Krovi, 2002) or heterogeneous robots (Dorigo *et al.*, 2013) can ensure payloads transport. Different strategies can be found in literature for multi-robot transportation. Pushing strategy proposed in Adouane and Le Fort-Piat's study (2004) was used, while a payload was on the ground. This strategy may face some difficulties depending on the friction generated by the contact surface with the ground, and it can also affect the quality of the transported object. Other robots are using grabbing tools (Khatib *et al.*, 1999) for transportation which limits the shape of objects that can be manipulated and requires geometries and shapes that could be gripped by the grippers. Some robots need human assistance for putting payload on their transport platform such as the Arnold robot presented in Abou-Samah and Krovi's study (2002). In the proposed work, a strategy based on tightening a payload by a multi-robot system to manipulate it, lift it and autonomously put it on the robots platform autonomously is proposed. To ensure the payload stability during the different phases, an optimal multi-criteria positioning of a set of m-bots around a payload of any shape and mass is proposed. The robots configuration ensures force closure grasping (FCG) which allows to ensure stability during the payload lifting and manipulation phase. It also ensures the static stability margin (SSM) which maintains the whole system's (m-bots and payload) stability during the transportation phase. These two criteria will be defined and detailed in Section 3.

This paper is organized as follows; Section 2 introduces the paradigm of the C^3Bots project; Section 3 presents the proposed multi-criteria optimization to achieve the targeted multi-robot tasks; Section 4 is dedicated to used control strategy that was used to achieve the tasks of stable manipulation and transport; Section 5 presents the results of the proposed algorithm, simulations and the manufactured prototypes illustrating the manipulation and lifting of the payload for the transportation. Finally, Section 6 is dedicated to conclusion and some prospects.

2. Paradigm and problem statement

As shortly introduced in the previous section, the paradigm of the C^3Bots project consists of co-manipulating and co-transporting of a common payload through collaboration between several similar elementary m-bots. Each m-bot is built by connecting a manipulation mechanism on the top platform of a single-axle mobile base (Hichri *et al.*, 2014b). The payload is supported on the edge of this transporting platform. The platform can rotate freely with respect to a central vertical axis on the mobile base. This mobility allows each robot to rotate around itself while maintaining the payload static on its top (Hichri, 2015a). The resulting p-bot system [Figures 1(b) and (c)] is thus allowed to rotate around any point on the ground, located at the intersection of all the axle axes, and to translate along any direction.

Figure 1 Co-manipulation of a box by a group of m-bots to achieve the co-lifting task



Notes: (a) Quasi-static model of two m-bots co-pushing on the payload to elevate it with their own manipulator (here simplified to a segment for the sake of clarity) (Hichri *et al.*, 2014b; Hichri, 2015a); (b) CAD view of four m-bots transporting a cubic payload on their top (Hichri *et al.*, 2014b); (c) payload lifted by two prototype m-bots

The manipulator has a parallelogram structure with a single degree of mobility to bring the payload from the ground to the m-bot top platform with a circular trajectory (Hichri *et al.*, 2015).

Before starting the transport task, the m-bots have to achieve the co-manipulation process using the mechanism presented in the study by Hichri *et al.* (2014b) and detailed in the study by Hichri *et al.* (2015). Its role is to hold firmly the payload and to ensure FCG (Yoshikawa, 2010; Liu, 1999) to lift the object by applying a sufficient normal force $f_{m,p,n}$ [Figure 1(a)] which generates a vertical tangential lifting force $f_{m,p,t}$ [Figure 1(a)].

3. Overall proposed multi-robot control architecture

3.1 Optimal positioning according to multi-criteria task constraints

The proposed overall cooperative manipulation and transport strategy, for payloads of any shape, by a group of m-bots is presented in Figure 2. This figure gives the most important steps to be achieved during this cooperative task. Step 1 allows the payload detection and the estimation of its mass and gravity center position. Step 2 helps in determining the minimum number of m-bots (m_{min}) that could be used to ensure the payload lifting and transport using the equations developed in the study by Hichri (2015a). Step 3 presents the main contribution of this paper. It is detailed by the flowchart in the right side of Figure 2 and will be precisely discussed later. The algorithm considers the external shape of the payload as a set of finite positions defined by the chosen step $\Delta\theta$. An initial grasp is then generated based on successive positions that respect inter-distances to avoid the collision of m-mbots. Then, the algorithm will run through all possible configurations to output a final optimal positioning of the robots (Hichri *et al.*, 2014a). In the proposed strategy, the m-bots positioning is optimal when FCG, *SSM* and restricted areas (RA) are ensured. Finally, Step 4 corresponds to target reaching phase and multi-robot transport of the payload toward the assigned final pose.

3.2 Force closure grasping

A grasp is considered stable when a small disturbance on the position of the manipulated object or contact force generates a restoring wrench that brings the system back to a stable configuration. FCG problem is extensively studied for objects manipulation using multi-fingered robotic hands (Yoshikawa, 2010). This problem was adapted for mobile robots to ensure stable lifting and transport task of payloads.

In the proposed strategy, the co-manipulation problem is restricted to a 2D problem in plane, while robots are acting simultaneously and applying tightening forces with all contact points in the same plane (Figure 3).

A necessary and sufficient condition to have force closure is that the intersection of all the friction cones is not empty (Li *et al.*, 2003). The proposed algorithm aims to ensure force closure if forces and moments equilibrium are satisfied and when the payload center of mass G_{pl} is inside the friction cones intersection. The latter condition allows to reduce the momentum generated around the payload center of mass by the m-bots while applying the pushing forces to tighten the payload and to lift it.

Figure 2 Flowchart given the sequenced steps for the co-manipulation and co-transportation of any payload shape

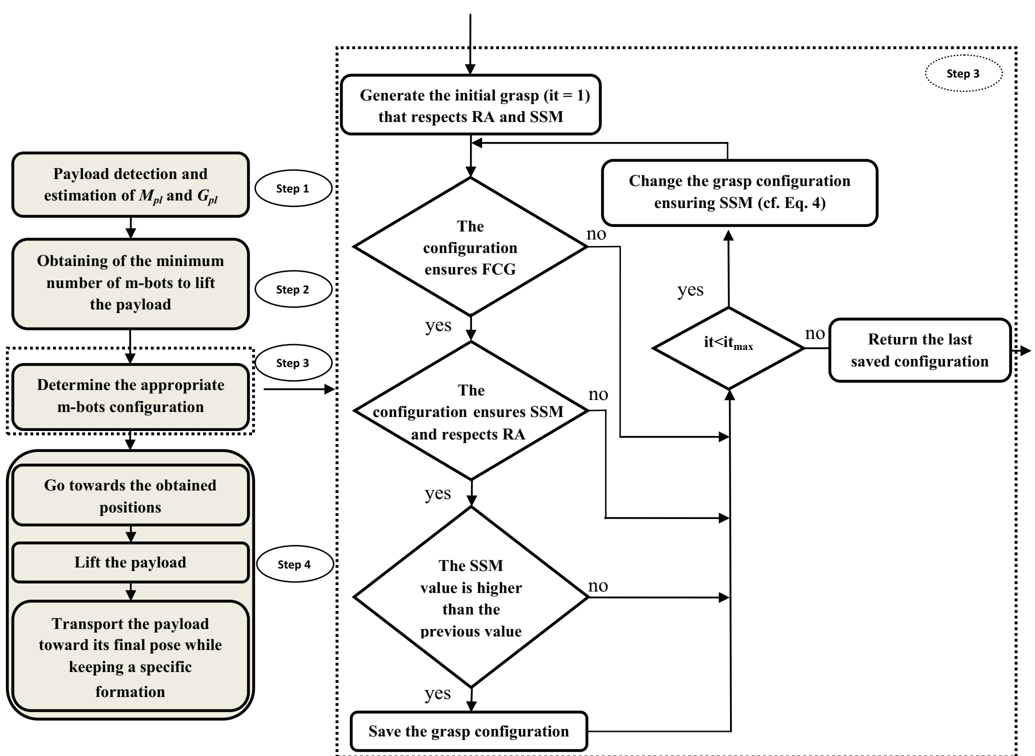
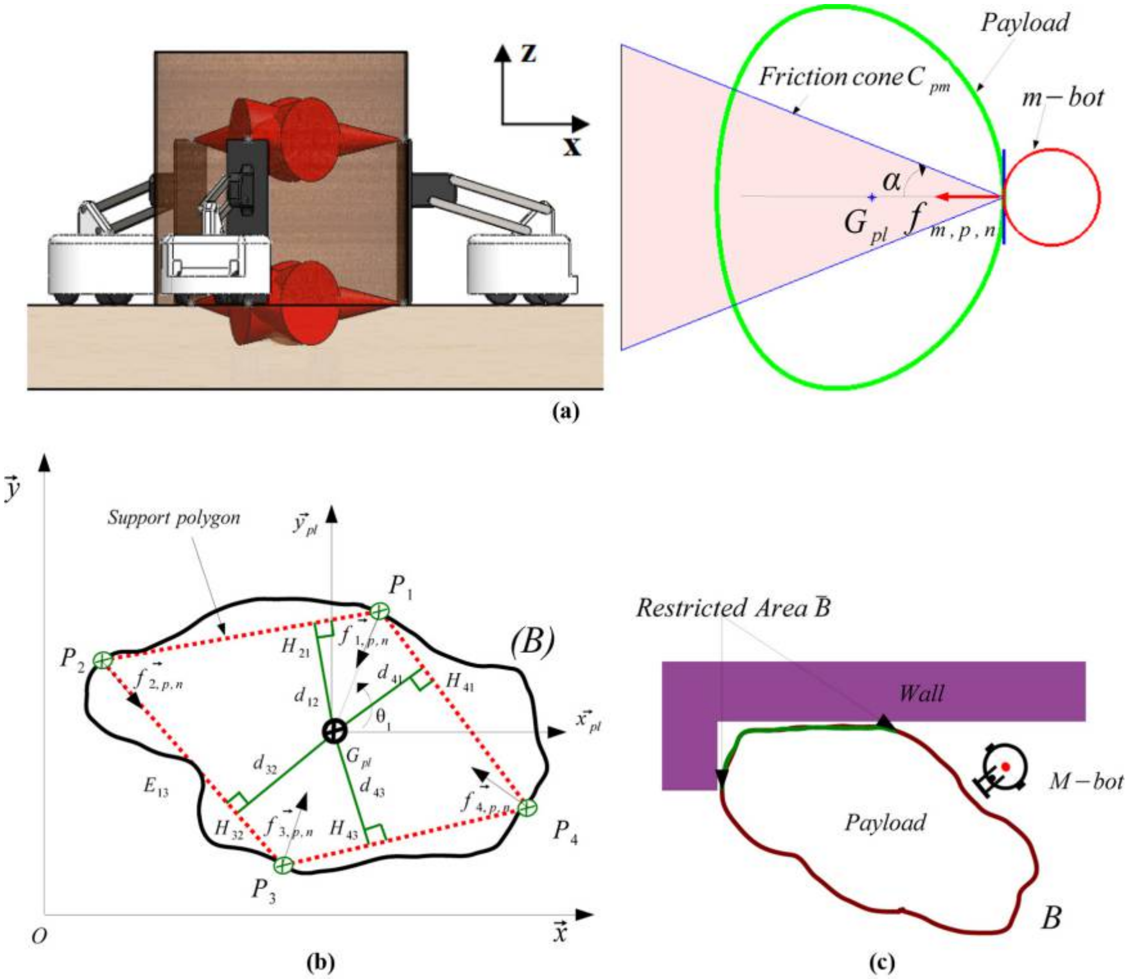


Figure 3 Multi-criteria task constraints



Notes: (a) Force closure grasping (FCG) condition of several m-bots co-pushing on the payload to elevate it; (b) support polygon formed by four robots positioned at $Pm \mid m = 1.4$; (c) condition on restricted areas (RA) unreachable for the m-bots

$$\sum_{m=1}^{m_{min}} (P_m G_{pl} \otimes f_{m,p,n}) = 0; \sum_{m=1}^{m_{min}} f_{m,p,n} = 0 \quad (1)$$

$$G_{pl} \in Convexhull(\cap C_{pm}) \mid m = 1..m_{min} \quad (2)$$

where C_{pm} denotes the friction cone for the contact force on P_m and $f_{m,p,n}$ is the applied normal on the payload [Figure 3(a)].

3.3 Static stability margin

Stability margins were extensively studied for walking mobile robots (Wang *et al.*, 2011). In the investigated work, to ensure a stable payload transport, SSM is a crucial criterion for a successful task achievement.

For the SSM problem, let us assume that the payload shape from the top view is a closed curve (B) that is parametrized in polar coordinates by $P(\theta)$; $\theta \in [0, 2\pi]$ [Figure 3(b)].

Let $R\left(G_{pl}, \vec{x}_{pl}, \vec{y}_{pl}, \vec{z}_{pl}\right)$ be the frame linked to the payload with respect to the reference frame $R\left(O, \vec{x}, \vec{y}, \vec{z}\right)$. $P_{m|(m=1..m_{min})}$ are the positions of the contact points of the m-bots; $H_{m,m+1}$ is the projection of the payload center of mass G_{pl} on the edge linking two consecutive points P_m and P_{m+1}; and $d_{m,m+1}$ is the stability margin (the distance from G_{pl} to segment P_mP_{m+1}) on the same edge. P_1 and $P_{m_{min}+1}$ are confounded, and as a consequence, $d_{1,m_{min}+1}$ is equal to $d_{m_{min},1}$.

The idea behind the algorithm is to run through (B) and to find the set of points P_m ensuring a maximal SSM while maximizing the objective function in equation (3). The constraint imposed by equation (4) must be satisfied for m_{min} m-bots ≥ 3 which gives a necessary condition to keep the center of mass G_{pl} inside the polygon ($P_1 . P_m$):

$$f(\theta_m, ..\theta_{m_{min}}) = \text{Min}(d_{m,m+1}) \mid m = 1..m_{min} \quad (3)$$

$$\theta_{m+1} - \theta_m < \pi \mid m = \{1...m_{min}\} \quad (4)$$

In the case where we have only two m-bots to co-manipulate the object, the constraint expressed by equation (4) is not considered, and the robots are positioned in opposite positions which means $\theta_2 - \theta_1 = \pi$. For each configuration where the minimum number of used m-bots $m_{min} \geq 3$, the algorithm aims at determining the equation of the line $P_m P_{m+1}$ and at computing the shortest distance of $G_{pl}(x_{G_{pl}}, y_{G_{pl}})$ from it.

Then, $d_{m,m+1}$ is calculated using equation (5) which represents the stability margin with respect to each edge and the SSM given by equation (3). The coordinates of P_m (x_{P_m}, y_{P_m}) are expressed in $R\left(G_{pl}, \vec{x}_{pl}, \vec{y}_{pl}, \vec{z}_{pl}\right)$ [Figure 3(b)]:

$$d_{m,m+1} = d\left(G_{pl}, (P_m P_{m+1})\right) = \frac{x_{G_{pl}} \dfrac{y_{P_{m+1}} - y_{P_m}}{x_{P_{m+1}} - x_{P_m}} - y_{G_{pl}} + y_{P_m} - x_{P_m} \dfrac{y_{P_{m+1}} - y_{P_m}}{x_{P_{m+1}} - x_{P_m}}}{\sqrt{\left(\dfrac{y_{P_{m+1}} - y_{P_m}}{x_{P_{m+1}} - x_{P_m}}\right)^2 + 1}} \quad (5)$$

3.4 Restricted area

In some cases, the payload could be positioned in a manner that the m-bots could not reach all the positions around it [Figure 3(c)]. The proposed algorithm takes into consideration this constraint and allows to find the optimal robots' positions that ensures the previous constraints and the task achievement without loss of stability. The RA is presented by a portion of the payload curve, and it is not considered while searching the optimal positions. This forbidden portion is denoted by $\overline{B}$.

4. Target reaching and virtual structure navigation

At any moment of the formation motion, we can determine the robots positions with respect to the object position and orientation. During the transportation phase, the robots have to track a dynamic target defined with respect to the payload center of mass.

4.1 Control law

Considering a unicycle mobile robot, the state vector $X_m = (x_m, y_m, \theta_m)^T$ denotes the position of the mth robot center of mass $G_m(x_m, y_m)$ and the orientation θ_m of the robot with respect to $\vec{x}$ axis of the global reference frame. The m-bot control inputs are the forward velocity V and the angular velocity ω.

Let e be the error between the m-bot current pose and the desired pose $X_{dm} = (x_{dm}, y_{dm}, \theta_{dm})^T$ defined by $e = X_{dm} - X_m$.

The used control law (Benzerrouk et al., 2014) is given by equation (6):

$$\begin{aligned} V_m &= V_{max} - (V_{max} - V_d) e^{-\left(d_m^2/\sigma^2\right)} \\ \omega_m &= \omega_{Sm} + k\theta_m \end{aligned} \quad (6)$$

- V_m and ω_m are the linear and angular velocities of the m-bot;
- V_{max} is the maximum linear speed of the m-bot;
- V_d is the desired velocity of the p-bot, and it is considered as constant;
- $d_m = \sqrt{e_x^2 + e_y^2}$ is the current distance between the mth robot and its desired target;
- ω_{Sm} is the angular velocity of set-point angle θ_{Sm} applied to the robot to reach the desired goal: $\omega_{Sm} = \dot{\theta}_{Sm}$; and
- σ and k are the control law gains (positive constants).

4.2 Limit-cycle method for target reaching and navigation in formation

Control law used to simulate the obstacle avoidance for desired targets reaching in the proposed work uses the limit-cycle method [Figure 4(a)] (Vilca et al., 2014; Vilca et al., 2013a; Adouane, 2009) which is a path planning method developed initially for obstacle avoidance behavior, and it is one of the trajectory methods defined by differential equations (Stuart and Humphries, 1998). This technique has been adopted in this paper to perform both: target reaching phase and virtual structure navigation [Figure 4(b)]. The differential equations of the elliptic limit-cycles are:

$$\begin{aligned} \dot{x}_s &= m(By_s + 0.5Cx_s) + x_s\left(1 - Ax_s^2 - By_s^2 - Cx_s y_s\right) \\ \dot{y}_s &= -m(Ax_s + 0.5Cy_s) + y_s\left(1 - Ax_s^2 - By_s^2 - Cx_s y_s\right) \end{aligned} \quad (7)$$

With $m = \pm 1$ according to the avoidance direction (clockwise or counter-clockwise, Figure 4). (x_s, y_s) corresponds to the position of the m-bot according to the center of the ellipse. The variables A, B and C are given by:

$$A = \left(\sin(\Omega)/b_{lc}\right)^2 + \left(\cos(\Omega)/a_{lc}\right)^2 \quad (8)$$

$$B = \left(\cos(\Omega)/b_{lc}\right)^2 + \left(\sin(\Omega)/a_{lc}\right)^2 \quad (9)$$

$$C = \left(1/a_{lc}^2 - 1/b_{lc}^2\right)\sin(2\Omega) \quad (10)$$

where a_{lc} and b_{lc} characterize, respectively, the major and minor elliptic semi-axes, and Ω gives the ellipse orientation when it is not equal to 0.

The set-point angle that the robot must follow to avoid the obstacle is given by:

$$\theta_{S0a} = \arctan\left(\frac{\dot{y}_s}{\dot{x}_s}\right) \quad (11)$$

The control architecture for the m-bot navigation is presented in Figure 5. This architecture, with specific elementary controller blocks (attraction to the target, obstacle avoidance), aims to manage the interactions among elementary controllers while guaranteeing the stability of the overall control to obtain safe and smooth navigation.

After positioning the m-bots, they must keep their desired position (x_{dm}, y_{dm}) with respect to the payload center of mass G_{pl} and must respect the following conditions during the task achievement:

$$\begin{aligned} x_{dm} &= x_{G_{pl}} + l_{xm}\cos\theta_{dm} - l_{ym}\sin\theta_{dm} \\ y_{dm} &= y_{G_{pl}} + l_{xm}\sin\theta_{dm} + l_{ym}\cos\theta_{dm} \end{aligned} \quad (12)$$

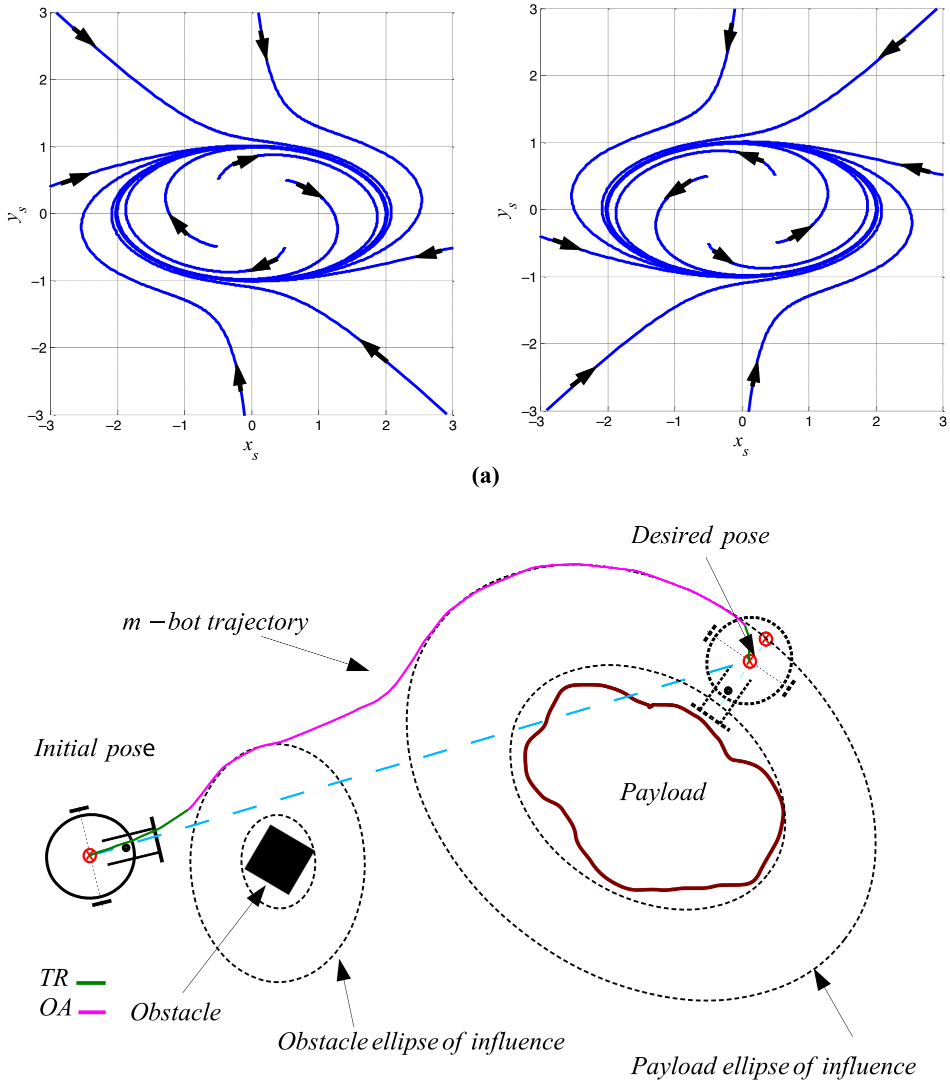
where l_{xm} and l_{ym} are the relative distances $G_m G_{pl}$ according the axis $\vec{x}_m$ and $\vec{y}_m$, respectively. These two distances define rigid links maintaining the robot position with respect to G_{pl}.

5. Proposal validation

5.1 Simulation results

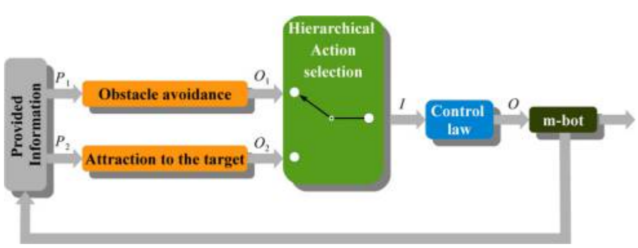
The algorithm was simulated by using an Intel Core i5 2400 CPU 3.1 GHz system. Figure 6(a) presents the simulation

Figure 4 Target reaching strategy with obstacle avoidance using limit-cycle method



Notes: (a) Limit-cycle possible directions (Adouane, 2009; Adouane *et al.*, 2011): clockwise direction and counter-clockwise direction; (b) target reaching of m-bot using limit-cycle strategy

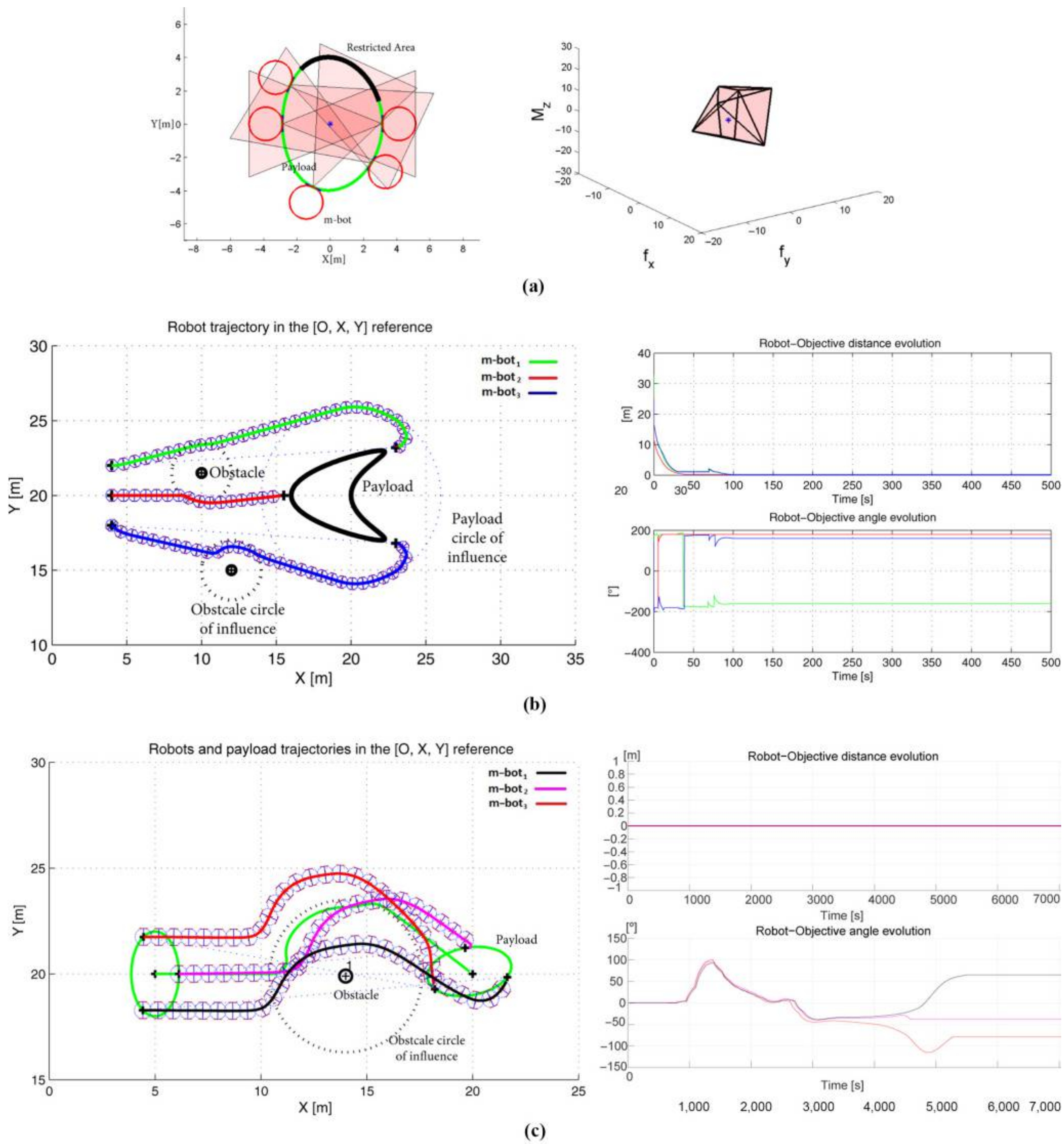
Figure 5 Control architecture for mobile robot navigation during the target reaching phase (the first phase of step 4 in Figure 2)



results for the developed algorithm for robots positioning to guarantee an optimal static stability margin respecting the force closure condition. The friction cones sides are drawn with thin lines, and the intersection can be seen with the contrasted area resulting from the superposition of friction cones [Figure 6(a) on the left side]. It is shown how the algorithm keeps the payload center of mass G_{pl} inside the intersection area, and it allows building a polygon of support that ensures the payload stability during the transport. The computing duration depends on the chosen steps of θ_m to run through the payload curve but never exceeds 10 s. The results were also checked using the developed criterion of Liu in the study of Li *et al.* (2003). It was demonstrated that for each configuration, the origin of the wrench space is inside the convex hull of intersection of the wrench spaces of each contact force [Figure 6(a)].

The controller parameters are set to $k = 22$ and $\sigma = 0.1$. These parameters were chosen to obtain a safe and smooth trajectory, fast response and velocity value within the limits of the m-bots capacities.

Figure 6 Simulation results



Notes: (a) Robots positioning simulation around a payload and corresponding system of wrenches; (b) target reaching simulation of three m-bots and their objective distances and orientations evolution; (c) collective payload co-transportation and their objective distances and orientations evolution

Figures 6(b) and (c) show, respectively, the trajectories of the mobile robots during target reaching and the transportation phases. It can be noted that the smoothness of the vehicle trajectories along the navigation and the non-collision with obstacles owing to the limit-cycle method.

The right graph of Figure 6(b) shows (from top to down) the values of the position errors e_m between each m-bot and its assigned virtual target around the payload; the value of the angular set-point θ_{Sm} which is tracked with a stable way by each m-bot [equation (6)]. It shows the convergence of the position error to zero, and it shows the evolution of the robot trying to reach its target. Figure 6(c) illustrates the navigation in formation of the whole structure while maintaining the assigned desired position of each m-bot with respect to the payload [according to equation (12)] to ensure the whole system stability and to avoid the transportation task failure. The position error evolution is kept close to zero. For both target reaching and transportation, the ellipse of influence was considered as a circle ($a_{lc} = b_{lc}$), as the obstacles have a circular shape. The radius of the circle of influence was chosen in a manner that the obstacle avoidance is guaranteed by keeping a safety margin.

5.2 3D simulations and manufactured prototypes results

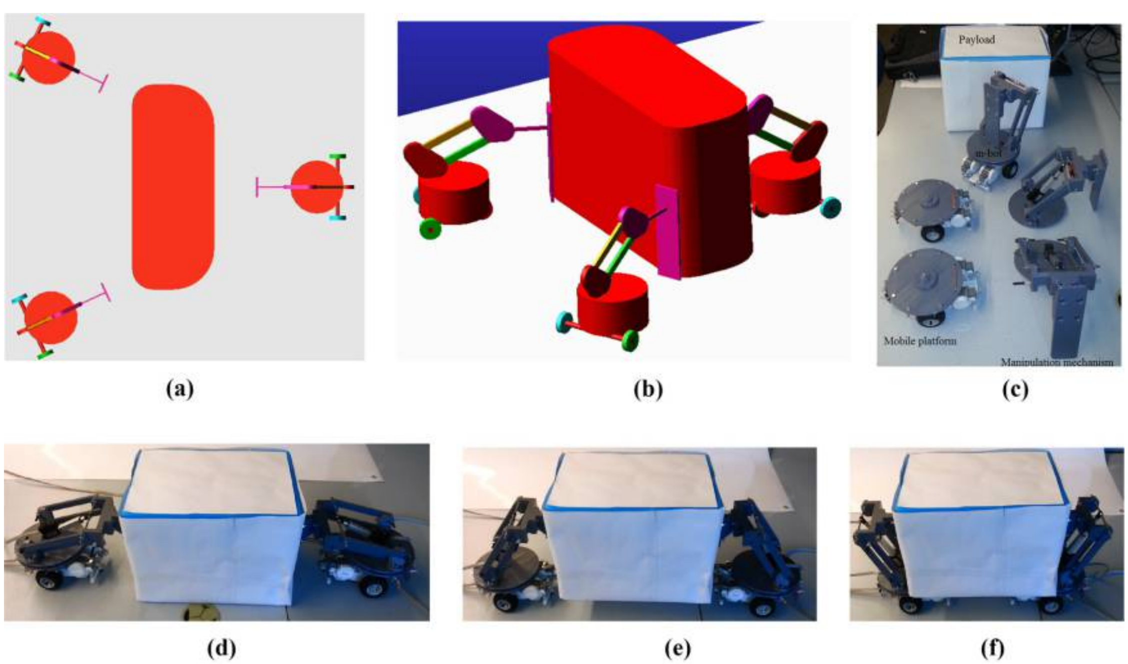
Using ADAMS multi-body dynamic software, the m-bots were positioned with respect to their desired positions according to the proposed algorithm (Figure 2). Three robots were positioned around a payload while guaranteeing FCG and SSM. The results are shown in Figures 7(a) and (b). Videos for simulation are visible under the study by Hichri (2015b). In case of using two robots that do not respect FCG, the payload stability is not ensured during the lifting process and the co-manipulation fails (Hichri, 2015b).

The mechanism that ensures the co-lifting process is illustrated in Figures 7 (c-f) based on parallelogram structure that ensures a circular trajectory to lift the payload from the ground and put it on robots platform. Manufactured prototypes allow to experiment the proposed strategy of co-manipulation and co-transportation. Figure 7(c) presents prototypes tested for co-lifting and co-transport for both m-bot and p-bot. The lifting and transport process by two m-bots is presented in Figures 7 (d), (e) and (f). Several simulations and experimental validations for lifting are given in the study by Hichri (2015b). These developed systems will be used for future experiments and validation of the global strategy for co-manipulation and co-transportation proposed in this work.

6. Conclusion

The main challenge addressed in this paper is to estimate the optimal robots' configuration around payload to achieve its co-manipulation and the co-transportation while maximizing the stability of the resulting poly-robot (or p-bot) during the task (Hichri *et al.*, 2014b). The p-bot stability is guaranteed, when the m-bots are positioned with respect to accessible area and RA, using the FCG criterion which ensures the payload stability during the co-manipulation phase, and the SSM criterion which ensures payload stability during the co-transportation phase. Several elementary navigation functions have been used to deal with this cooperative task. Among them, the obstacle avoidance controller, based on limit-cycles, which is used for two aspects: first, when each m-bot aims to reach its position around the payload (the robot may need to avoid other robots or any other obstacles to reach its assigned pose); second, when the p-bot is in the navigation

Figure 7 (a, b) Multi-body 3D simulation; (c) m-bot prototyping; and (d, e, f) payload co-lifting



Notes: (a) Multi-body simulation (top view); (b) multi-body simulation results (perspective View); (c) prototype obtained with 3D printer; (d) payload prehension; (e) payload lifting; (f) payload transport phase and has to avoid any obstructing obstacle. The p-bot navigation also raises interesting issues related to multi-robot navigation in formation. It is planned in near future to perform more experiments of the overall defined strategy for cooperative payload co-lifting and co-transportation.

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