Cooperative Mobile Robot Control Architecture for Lifting and Transportation of any Shape Payload

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Abstract This paper addresses cooperative manipulation and transportation of any payload shape, by assembling a group of simple mobile robots (denoted m-bots) into a modular poly-robot (p-bot). The focus is made in this paper on the chosen methodology to obtain sub-optimal positioning of the robots around the payload to lift it and to transport it while maintaining a geometric multi-robot formation. This appropriate positioning is obtained by combining the constraint to ensure Force Closure Grasping (FCG) for stable and safe lifting of the payload and the maximization of the Static Stability Margin (SSM) during the transport. A predefined control law is then used to track a virtual structure in which each elementary robot has to keep the desired position relative to the payload. Simulation results for an object of any shape, described by a parametric curve, are presented. Additional 3D simulation results with a multi-body dynamic software validate our proposal.

Key words: Cooperative mobile robots, Control architecture, Payload transport and co-manipulation, Force closure grasping, Static stability margin.

1 Introduction

In recent years, many researches were oriented to survey and design collaborative mobile robotic systems [29, 26] gathering different engineering and science disciplines. This blend between those disciplines allows the design of autonomous systems able to interact with the environment without human mediation and also to achieve diverse complex tasks or infeasible by humans, such as exploring dangerous and/or unreachable areas [7] or navigation in formation for a group of autonomous robots [1]. Autonomous mobile robots have the ability for sensing and reacting in

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the environment by acquiring additional abilities. They can also collaborate when a task needs more than one robot, such as heavy objects co-manipulation or transport [2, 7, 13, 22]. The aim of our research is to co-manipulate and to transport objects using a group of mobile robots. We aim to design an innovative architecture for payload transport on structured environment. Collaborative robots behaviors may be also interesting for transporting tasks with mobile robots. Many robotic examples can be mentioned such as in [4, 13, 19, 23, 32]. Our goal in the C^3Bots project (Collaborative Cross and Carry mobile roBots) is to design several mobile robots with a simple mechanical architecture called m-bots that will be able to autonomously co-manipulate and transport objects of any shape by connecting together. The resulting poly-robot system, called p-bot, will be able to solve the so-called removal-man-task to transport object of any shape and mass repartition. Reconfiguring the p-bot by adjusting the number of m-bots allows to manipulate heavy objects with any shape, particularly if they are wider than a single m-bot. During the manipulation, the grasping task [3, 31] is a crucial phase for payload lifting and if it fails the whole task cannot be achieved.

To ensure the co-manipulation task, he group of m-bots must succeed to ensure the payload Force Closure Grasping (FCG) [3, 11, 20, 24, 31, 36] until putting it on their top platform. FCG refers to Newton laws which allows to ensure the payload immobility [31]. In the aim of ensuring object stability, which is the goal of any used grasping strategy, several methods have been developed using various approaches. Avoiding too large forces allows to reduce the power for the manipulator's actuation and the deformation of the manipulated object. A grasp is considered stable when a miniature disturbance on the position of the manipulated object or contact force, generates a restoring wrench that brings the system back to a stable configuration [3]. In [14], Nguyen presents an algorithm for stable grasps construction and he proved the possibility of making stable all 3D force closure grasps. According to [3, 31], a grasping strategy should ensure stability, task compatibility and adaptability to novel objects. Analytical and empirical approaches were developed in different literatures to ensure a stable grasping. The former approach choose the manipulator configuration and contact positions with kinematical and dynamical formulation whereas empirical approaches use learning to achieve a grasp depending on the task and on the geometry of the object. Diverse analytical methods were developed to find a force closure grasp [11, 20, 36]. The latter approach avoids the complexity of computation by attempting to mimic human strategies for grasping. Datagloves and map human hand were used by researchers for empirical approaches to learn the different joint angles [25, 30], hand preshape [16]. Vision based approach is also used to demonstrate grasping skills. A robot can track an operator hand for several times to collect sufficient data [10, 27].

Payload stability during movement is evaluated according to developed metrics in literature. In the late sixties, stability margin metrics were developed and classified mainly in two categories: static [28]-[12] and dynamic [15]-[8] stability margins. We consider the Static Stability Margin (SSM) since our system evolves at low speed in a structured environment. This margin was defined by McGhee and Frank [28] as follows: "static stability margin is the shortest distance from the vertical projection of the centre of gravity to any point on the boundary of the support pattern". Considering the payload lifting and transport using mobile robots, stability is also ensured by coordinating the group of transporting robots which means multi-robot control problem.

The multi-robot navigation in formation is the main research area linked to the phase of payload transportation. A multitude of control architecture to deal with this task were proposed in the literature [1, 21, 34]. A multi-robot system control can be either centralized or distributed.

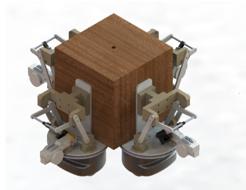
The control problem is discussed to provide a suitable control strategy for this task. Formation control can be classified according to recent literature, [1, 34], into three main approaches: the behavior-based approach, the leader-follower approach and the virtual structure approach.

This paper presents an algorithm allowing to determine an optimal positioning of m-bots around a general payload in order to maximize the Static Stability Margin (SSM) and to ensure Force Closure Grasping (FCG). A centralized control will be used for its higher calculation performances to calculate different desired positions according to a payload of any shape. For targets reaching and payload transport, the groups of robots will act according to centralized control approach. A predefined control law is then used to track a virtual structure in which each elementary robot has to keep the desired position relative to the payload. This paper is organized as follow: in Section 2 the paradigm of C^3Bots project is introduced and the general problem is presented for co-manipulation and transport using multi-robot system; Section 3 will present the robots positioning according to both criteria SSM and FCG computation and the multi-robot transport strategy. Simulation results for an object of any shape, described by a parametric curve, and 3D simulations with a multi-body dynamic software are also presented. Finally Section 4 provides a conclusion and future works.

2 Paradigm and problem statement

The paradigm of C^3Bots project is to co-manipulate and transport a common payload through collaboration between several similar elementary robots (see Fig. 1). Wheeled robots were selected for their versatility on various terrains and good efficiency on regular grounds compared to legs and tracks. The C^3Bots transport strategy takes inspiration from Army Ants [19] by laying the payload on top of robot's bodies, and from the structure given in [23], that has a rotative arm on top of it. The concept of modularity was also kept and each m-bot is built from two parts: a mobile platform and a manipulation mechanism [5]. The mobile platform is a single-axle Khepera robot and the manipulator is fixed on a rotary platform that lets the robot turn freely on itself when the object lays on the transporting platform. The manipulator has a parallelogram structure to bring the payload from the ground to the m-bot top platform with a circular trajectory [6].

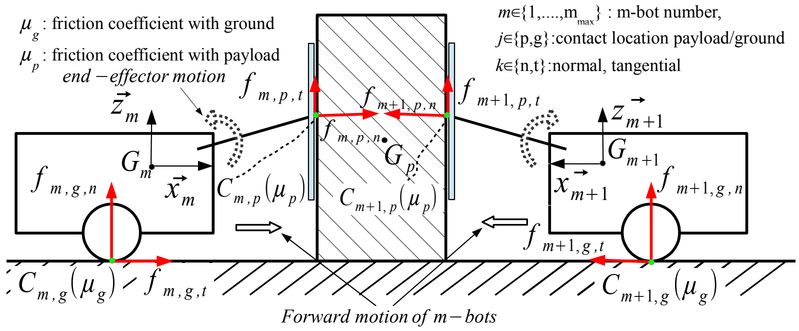
The resulting p-bot system (cf. Fig. 1(a), Fig. 1(c)) is thus allowed to translate along any direction and rotate around any point in the ground plane. Before starting the transport task, the m-bots have to achieve the co-manipulation process using the



(a) Prototype for object lifting and transport [5]

(b) Payload prehension by two m-bots

(c) Payload lifted by two m-bots



(d) Two M-bots pushing on the payload to elevate it with parallelogram manipulator [6]

Fig. 1 Co-manipulation of a box by a group of m-bots

mechanism presented in [5] and detailed in [6]. Its role is to hold firmly the payload and to ensure FCG [24] to lift the object by applying a sufficient normal force $f_{m,p,n}$ (cf. Fig. 1(d) and Fig. 4) which generates a vertical tangential lifting force $f_{m,p,t}$ (cf. Fig. 1(d)) with:

$$f_{m,p,n} \in [0, f_{max}] = [0, \mu_g m_m g] \text{ and } f_{m,p,t} \in [0, \mu_p \mu_g m_m g] \tag{1}$$

μ_p is the payload-end-effector friction coefficient; μ_g the wheel-ground friction coefficient; m_m is the robot mass and g is the gravity. The value of f_{max} is obtained while applying the well known resultant of the force/moment for the all system (First and Second principle of Newton). We obtained thus a simple formulation of f_{max} while taking into account the mentioned parameters. To improve the system efficiency in term of payload holding and avoiding its slipping, an additional mechanism, that ensures the payload tightening and avoids friction uncertainties, is under development.

The minimum number m_{min} of m-bots that have to be used to lift and transport the payload is obtained according to equation (2). The payload is considered in this paper as an homogeneous body, its shape and weight are known and its center of mass is predetermined.

$$\sum_{m=1}^{m_{min}} f_{m,p,t} = M_{pl} g \tag{2}$$

3 Cooperative mobile robot manipulation and transport

The proposed overall cooperative manipulation and transport strategy, for any payload 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. The details of the chosen criteria for cooperative manipulation and transportation are given respectively in sub-sections 3.1 and 3.2.

Step 1 (cf. Fig. 2) presents the first phase of the task and which consists on payload detection and estimation of its mass and gravity center position. Step 2 consists on determining the minimum number of m-bots (m_{min}) that could be used to ensure the payload lifting and transport with relative to (2). Step 3 presents the main contribution of this paper. It is detailed by the flowchart in the right side of Fig. 2 and will be discussed in sections 3.1.1 and section 3.1.2. Sasaki in [18] treated a similar problem for optimal robots positioning taking into account two criterion: the payload stability and the energy consumption. It was considered that the positioning is optimal when the payload is stable and the robots consume the minimum of energy (according to the data received from the robots sensors). In the proposed strategy, the m-bots positioning is optimal when FCG and SSM are ensured. Finally, Step 4 corresponds to multi-robot transport the payload toward the assigned final pose, this part will be detailed in section 3.2.

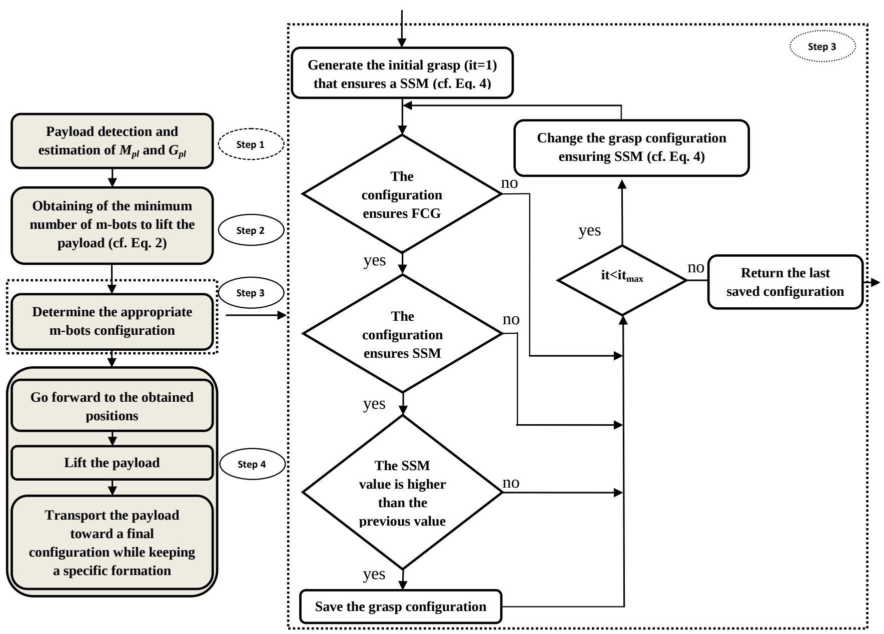


Fig. 2 Flowchart given the sequenced steps for the co-manipulation and transportation of any payload shape

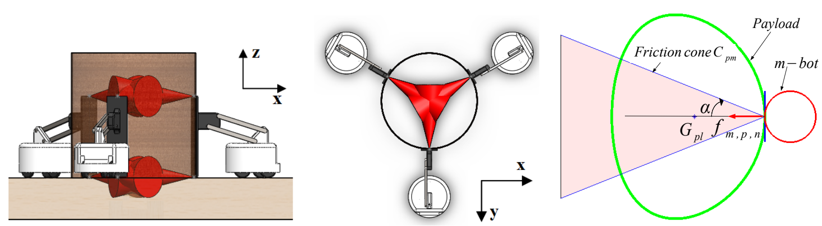
3.1 Cooperative m-bots positioning and co-manipulation

Since the features of the payload are known (step 1 in Fig. 2) the minimum number of m-bots (m_{min}) is obtained while using equation 2 (step 2), the group of m-bots must be well positioned around the payload (step 3) to permit to safely lift it and to maintain a well stability of the payload in the top of the p-bot during the transportation phase (step 4). During this manipulation phase (sub-step 2 in step 4), FCG (cf. sub-section 3.1.1) as well as SSM (cf. sub-section 3.1.2) must be thus ensured to lift and transport safely the object (cf. details given for Step 3 in Figure 2).

3.1.1 Force Closure Grasping

Force closure grasping problem is extensively treated and studied for objects manipulation using multi fingered robotic hand [35, 37]. This problem was adapted to mobile robot co-manipulation and transport in C^3Bots project to ensure lifting and transport task.

The co-manipulation problem (cf. section 2) is restricted to a 2D problem in plane $(O, \mathbf{x}, \mathbf{y})$ while robots are acting simultaneously and applying a tightening forces on the payload on the same plane (Fig. 3).



(a) Side view (b) Top view (c) m-bot planar contact

Fig. 3 Applied tightening forces on the payload

The aim of this part is to ensure force closure grasping when choosing the m-bots positions which returns to fully constraint the payload motion with m_{min} m-bots. In other words, the static equilibrium must be ensured while positioning the group of mobile robots. The problem of force closure grasping is studied under the following assumptions (cf. Fig. 3(c)):

- A contact force lies inside the friction cone centred about the normal direction to the contact surface with half angle α.
- The tangent of α represent the friction coefficient.
- The friction cone of the m^{th} contact is denoted C_{pm}.

A necessary and sufficient condition to have force closure is that the intersection of three friction cones is not empty [36]. This condition was extended to m_{min} m-bots.

In [36], the treated problem concerns multi fingered hand grasping although the problem treated in this paper focuses on co-manipulation using a group of modular mobile robots. The proposed algorithm is based on ensuring force closure if forces and moments equilibrium satisfy (3) and when the payload center of mass is inside the friction cones intersection (4). The later condition allows to reduce the moments generated on the payload by the m-bots because the direction of the applied force on the plane is closer to the gravity center.

$$\sum_{m=1}^{m_{min}} (P_m G_{pl} \otimes f_{m,p,n}) = 0; \sum_{m=1}^{m_{min}} f_{m,p,n} = 0 \tag{3}$$

$$G_{pl} \in Convexhull(\cap C_{pm}) \mid m = 1..m_{min} \tag{4}$$

Where C_{pm} presents the friction cone for the contact force on P_m and $f_{m,p,n}$ is the applied normal on the payload (cf. Fig. 3(c)).

3.1.2 Static Stability Margin (SSM)

In this part, Static Stability Margin (SSM) is considered to ensure the payload stability during the transporting phase. Stability margins were extensively studied for walking mobile robots [9, 17, 38]. In C^3Bots project, to ensure a stable payload transport, the Static Stability Margin (SSM) is a crucial criterion for a successful task achievement. Before describing the proposed algorithm for m-bots positioning ensuring an optimal SSM during object transport using m-bots, let's detail the following assumptions (cf. Fig. 4):

- The payload shape from the top view is a closed curve (B) and defined by polar curve defined by $P(\theta)$; $\theta \in [0, 2\pi]$.
- In function of the payload mass M_p, m_{min} is the minimum number of m-bots allowing to lift and transport the object.
- The payload center of mass is denoted G_{pl}.

Let $R(G_{pl}, \mathbf{x}_{pl}, \mathbf{y}_{pl}, \mathbf{z}_{pl})$ be the frame linked to the payload with respect to the reference frame $R(O, \mathbf{x}, \mathbf{y}, \mathbf{z})$ (cf. Fig. 4). Cartesian coordinates will be used in the proposed algorithm. As given in section 2, $P(\theta)$ be the parametric description of the payload closed boundary (B). $P_{m|m=1..m_{min}}$ are the m-bots positions, $H_{m,m+1}$ is the projection of the payload center of mass G on the edge linking two consecutive points P_m and P_{m+1} and $d_{m,m+1}$ is the stability margin on the same edge. P_m and $P_{m_{min}+1}$ are confounded and as a consequence $d_{m,m_{min}+1}$ 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 (5). The constraint imposed by (6) must be satisfied for m_{min} m-bots$\geq$3 which gives a necessary condition to keep the center of mass G_{pl} inside the polygon $(P_1..P_m)$

$$f(\theta_m, ..\theta_{m_{min}}) = \text{Min}(d_{m,m+1}) \mid m = 1..m_{min} \tag{5}$$

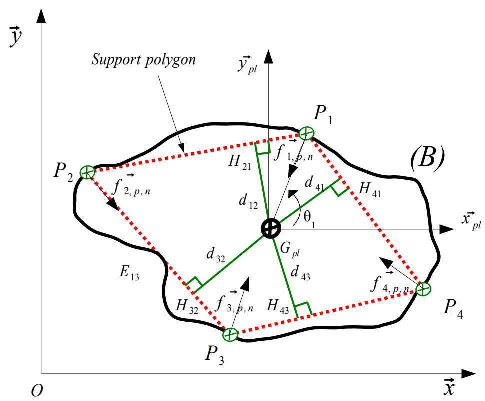


Fig. 4 Support polygon formed by four robots positioned at $P_{m|m=1..4}$

$$\theta_{m+1} - \theta_m < \pi \; |m = \{1...m_{min}\} \tag{6}$$

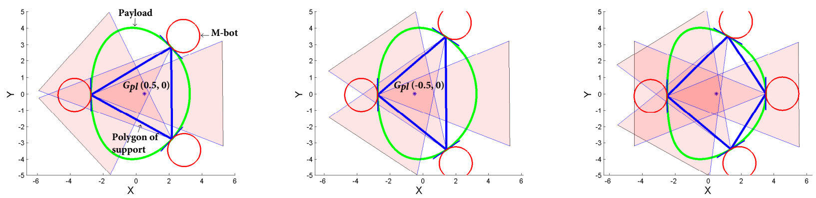
In the case where we have only two m-bots to co-manipulate the object, the constraint expressed by (6) is not considered and the robots are positioned in opposed positions which means $\theta_{m+1} - \theta_m = \pi$. For each configuration where n m-bots ≥ 3, the algorithm aims at determining the equation 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 by (7) which represent the stability margin relative to each edge and the static stability margin SSM given by (5). P_m coordinates are expressed in $R(G_{pl}, \mathbf{x}_{pl}, \mathbf{y}_{pl}, \mathbf{z}_{pl})$ (cf. Fig. 4).

$$d_{m,m+1} = d(G, (P_m P_{m+1})) = \frac{x_G \frac{y_{P_{m+1}} - y_{P_m}}{x_{P_{m+1}} - x_{P_m}} - y_G + y_{P_m} - x_{P_m} \frac{y_{P_{m+1}} - y_{P_m}}{x_{P_{m+1}} - x_{P_m}}}{\sqrt{(\frac{y_{P_{m+1}} - y_{P_m}}{x_{P_{m+1}} - x_{P_m}})^2 + 1}} \tag{7}$$

3.1.3 Simulation results

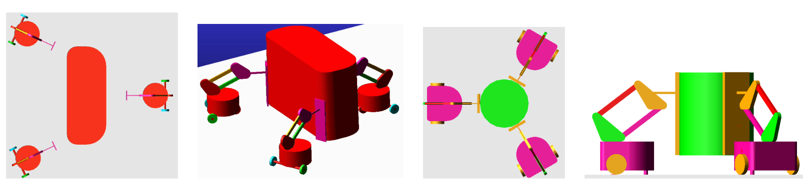
The proposed algorithm allows to determine a sub-optimal configuration for a group of mobile robots in order to lift and transport a payload of any shape. Two criteria have been respected (FCG and SSM) which reduces the total configurations to be tested by the algorithm taking into consideration (3) and (4). The Algorithm was simulated by using an Intel Core i5 2400 CPU 3.1 GHz system. Fig. 5 presents the simulation results for the developed algorithm for robots positioning in order to guarantee an optimal static stability margin respecting the force closure condition. The blue bold polygon presents the polygon of support ensuring the optimal SSM (cf. subsection 3.1.2), the thin blue lines presents the friction cones sides and the intersection is presented by contrasted area resulted by the superposition of friction cones. It is shown how the algorithm keeps the payload center of mass G_{pl} inside the intersection area and it allows to build a polygon of support ensuring the payload stability during the transport. The duration to find results depends on the chosen steps of θ_m to run throw the payload curve.



(a) (b) (c)

Fig. 5 Simulation results: a-b) 3 m-bots positioning with different configuration according to the localization of the payload center of mass; c) 4 m-bots positioning

The payload stability during the lifting phase was simulated with respect to both criteria (SSM and FCG) using ADAMS multi-body dynamic software to validate the proposed algorithm (cf. Fig. 2) while testing the m-bots performances when they are positioned to co-manipulate the object. Fig. 6 shows that the robots ensure the payload lifting without loss of stability of the lift. Videos for simulation are visible under [33].



(a) (b) (c) (d)

Fig. 6 Multibody simulation results with ADMAS software: Top view (a and c), and 3D lifting phase (b and d).

3.2 Multi-robot transport

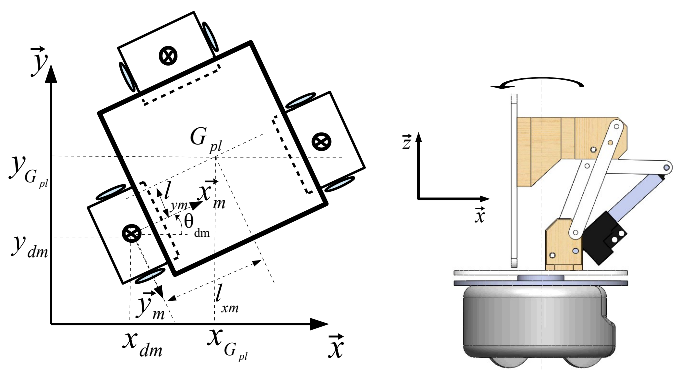
After lifting the payload, which is positioned now on the top of the p-bot, the group of m-bots must transport the payload toward a final configuration. During this last phase (Step 4 in Fig. 2), and in order to guarantee the payload stability, the p-bot should navigate as rigid formation shape and for this, a virtual structure architecture was used [1]. After the end of Step 3, each m-bot receives its attributed position which insures the sub-optimal p-bot positioning that permits to ensure Force Closure Grasping (FCG) and to maximize the Static Stability Margin (SSM) during the transport. For transport task, the m-bots have to reach their goals, computed using the algorithm presented in the previous section (cf. Step 4 in Fig. 2). After reaching the desired positions, the transport task starts considering that the payload lays on robots bodies. To avoid payload slippage, the group of m-bots has to track a fixed position relative to the object when it follows a trajectory. In this section, a control law is proposed to solve the goal reaching problem (P_m in section. 3.1.2) and the navigation as Virtual Structure (VS) of the set of m-bots. In VS approach [34] [1], the entire formation is considered as a rigid body and the notion of hierarchy do not exist. The control law for each entity is derived by defining the VS dynamics and then translate the motion of the VS into the desired motion of each elementary robot. The main advantages of this approach are its simplicity to prescribe the coordinate behavior of the group and the maintaining of the formation during manoeuvres.

The result of the algorithm for a given object shape described by a parametric curve (B) is a set of n targets to be reached by the m-bots. Considering a unicycle mobile robot, the state vector $X_m = (x_m, y_m, \theta_m)^T$ denotes the position of the m^{th}robot center of mass $G_m(x_m, y_m)$ and its orientation θ_m with respect to $\mathbf{x}$ axis of the global frame. The m-bots 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 defined by $X_{dm} = (x_{dm}, y_{dm}, \theta_{dm})^T$: $e = X_{dm} - X_m$.

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:

$$\begin{aligned} x_{dm} &= x_{G_{pl}} + l_{xm}\cos\theta_{dm} - l_{ym}\sin\theta_{dm} \\ y_{dm} &= y_{G_{pl}} + l_{xm}\sin\theta_{dm} + l_{ym}\cos\theta_{dm} \end{aligned} \tag{8}$$



(a) (b)

Fig. 7 M-bot position and mobility during payload transport: a) Desired position of the robot relative to the payload; b) Free steering of the mobile platform relative to the manipulator

where l_{xm} and l_{ym} (cf. Fig. 7(a)) are the relative distances G_mG_{pl} according the axis $\mathbf{x}_m$ and $\mathbf{y}_m$ respectively. These two distances define rigid links maintaining the robot position with respect to G_{pl}. It is to be noted that the mobile platform has a steering mobility around its vertical axis z (cf. Fig. 7(b)). This mobility allows to each robot to rotate around itself ($V_m = 0$ and ω_m=Constant (cf. equation (9))) while maintaining the payload static on its top. According to this effector new degree of freedom, the group of mobile robots could ensure easily the payload approach, lifting and transportation.

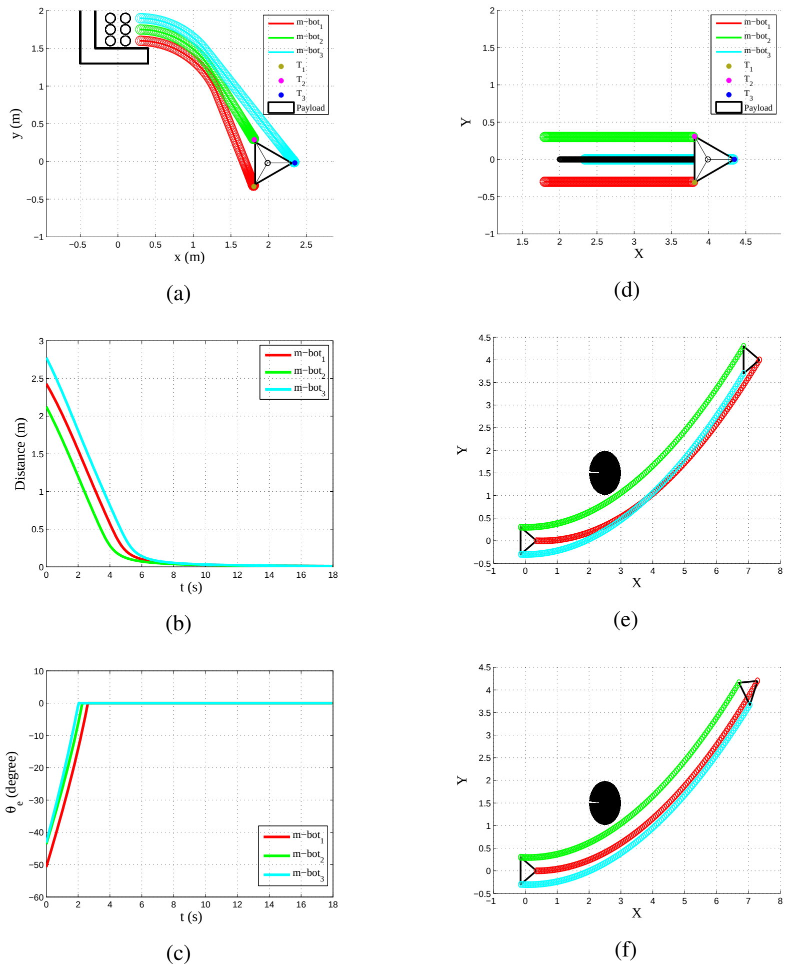


Fig. 8 M-bots target reaching (TR) and Virtual structure (VS) navigation: a) Trajectories of the m-bots reaching the desired positions; b) Position error for TR; c) Angle Error for TR; d) The p-bot is navigating as a rigid Virtual Structure (VS); e) The p-bot avoids the obstacle and keeps the same orientation; f) The p-bot avoids obstacle and changes the payload orientation.

The used control law [1] is given by (9):

$$\begin{aligned} V_m &= V_{max} - (V_{max} - V_d)e^{-(d_m^2/\sigma^2)} \\ \omega_m &= \omega_{Sm} + k\theta_m \end{aligned} \tag{9}$$

- 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 considered to be constant.
- $d_m = \sqrt{e_x^2 + e_y^2}$ is the current distance between the m^{th} robot and its desired target.
- ω_{Sm} is the angular velocity of set point angle θ_{Sm} applied to the robot in order to reach the desired goal: $\omega_{Sm} = \dot{\theta}_{Sm}$
- σ, k are positive constants (control law gains).

The control law was simulated for a group of three m-bots transporting an object. Fig. 8(a) presents the goal reaching problem with k=22 and $\sigma = 0.1$. In order that the m-bots reach the desired positions, the desired speed when reaching the goal is set to zero and then the whole structure will navigate with a speed of 10 cm/s (Fig. 8(d), 8(e) and 8(f)). The payload lays on robot bodies during transport and the group of m-bots is navigating while maintaining constant distances. Fig. 8(b) shows the convergence of the position error e to zero during target reaching phase. Fig. 8(c) presents the angular error for each robot. One can note the convergence to zero of the error which shows the target reaching achievement. Fig. 8(d), 8(e) and 8(f) show respectively the payload transport in a straight line, considering obstacle avoidance while keeping the payload orientation and finally with a new payload orientation. One can note that all m-bots keep a null position errors which means that the formation is properly maintained and that slippage avoidance and task performance are ensured. It is important to notice, that in this paper, we suppose a centralized control of the fleet of robots, thus, the movement of the virtual structure is already defined according to the configuration of the environment. Indeed, the focus of this paper is on the presentation of the virtual structure and the way how each elementary robot keeps the desired position relative to the payload.

4 CONCLUSIONS AND FUTURE WORK

This work takes place within the C^3Bots project, that aims to design simple robot entities (m-bots) able to co-manipulate and transport payloads of any shape by aggregating in a modular way into a poly-robot (p-bot). This work has the ambition to combine two criteria in an original way:

- On one side, the Static Stability Margin (SSM), generally used for legged locomotion.
- On the other side, Force Closure Grasping (FCG), used for stable multi-finger manipulation.

The m-bots used in this work include in their lower part a wheeled-axle, which is similar to a foot of a multi-leg mobile robot, and in their top part a manipulator acting like the finger of a robotic hand. The resulting p-bot ensures the stable payload grasping and transport. An algorithm was developed in order to search the optimal positions of n unicycle m-bots that ensure force closure grasping and maximize the static stability margin for the transport of a payload of any shape, defined by its closed curve boundary. Simulation results using a multi-body dynamic software validates our proposal and shows the ability of robots to maintain the payload stability during lifting process. A flexible control architecture was used to validate the target reaching problem while maintaining the chosen formation. This navigation was considered in a flat structured environment. Future works will consider the problem of payload manipulation and lifting in all terrain. Unreachable areas on the payload boundary will also have to be taken into consideration (as for example one side of a square object opposed to a wall).

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