Coordinated and Cooperative Control of Heterogeneous Mobile Manipulators

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Abstract. This paper proposes a multilayer scheme for the cooperative control of $n \geq 2$ heterogeneous mobile manipulators that allows to transport an object in common in a coordinated way; for which the kinematic modeling of each mobile manipulator robot is performed. Stability and robustness are demonstrated using the Lyapunov theory in order to obtain asymptotically stable control. Finally, the results are presented to evaluate the performance of the proposed control, which confirms the scope of the controller to solve different movement problems.

Keyklwords: cooperative control, kinematic modeling, Lyapunov method.

1 Introduction

The robotics nowadays has reached a high level of importance, since robots perform common tasks that require locomotion and manipulation capabilities [1,2,3]. Traditionally, the robots are used in the automotive, electrical, metallurgical, chemical and food industries, as well as in tasks of daily life, such as sweeping, vacuuming or mowing grass [4,5]. The tasks can be carried out individually or cooperatively in different areas, being of cooperative form more efficient in terms of manipulability, flexibility, accessibility and manoeuvrability, allowing greater efficiency in industrial processes. [6].

The cooperative control of mobile autonomous robots is widely studied due to its importance in applications of sensor networks, mobile robots, flight of formation of spaceships and in other areas [7]. The multirobot systems have two approaches: centralized and decentralized. The first approach, the lead unit plans and controls, determining the behaviour of the other robots [8,9]; while in the decentralised approach each robot makes its own decisions according to the local information available [10,11]. The centralized approach facilitates optimal global solutions and is vulnerable to failures, while the decentralized approach has the advantage of fault tolerance, robustness and reliability, for this reason it is considered the most suitable for implementation in robotics. [12,13].

The study of the cooperation of heterogeneous robots has evolved due to the fundamental capacities of each robot in the equipment, such is the case of a heterogeneous multirobot system composed of several UGV and a single UAV, in which different control schemes are realized with various degrees of cooperation [14]. In [15], they proposes the construction of a map through multiple cooperative aerial and terrestrial robots with the implementation of hardware, firmware and software of the frame of multirobot cooperation proposed. In [16], they proposes a method tolerant to aggression for the stabilization and navigation of compact formations of autonomous aerial and terrestrial robots that cooperate in surveillance scenarios. In [17], they presents astrategy of hybrid adaptive control and fixation to ensure that all heterogeneous robots in the cooperation-competition network follow a trajectory. In [18], they centres on the design, development and test of an Artificial Intelligence System that facilitates the cooperative behavior of teamwork of mobile heterogeneous robots.

In work [5] performs a cooperative control with up to two mobile robots unlike the present work that a multilayer scheme is developed for the cooperative control of $n \geq 2$ mobile heterogeneous manipulators that allow to transport an object in common in a coordinated way; for which it will have realize the the kinematic modeling of each mobile manipulator robot. Unlike [19], the design of the controller is based on a cascaded kinematic control, based on a virtual structure formed between the operating ends of the multiple mobile heterogeneous manipulator robots. The stability and robustness is demonstrated using the Lyapunov theory in order to obtain asymptotically stable control. Finally, the results are presented to evaluate the performance of the proposed control, which confirms the scope of the controller to solve different problems of movement.

2 Kinematic Model

2.1 Kinematic Model of Mobile Manipulator

The kinematic model of an mobile manipulator gives the location and orientation of the end-effector $\mathbf{h}(t)$ as a function of the robotic arm configuration and the mobile platform position, *i.e.,* $f : \mathcal{M}_p \text{ x } \mathcal{N}_{a1} \text{ x } \mathcal{N}_{a2} \text{ x} \ldots \mathcal{N}_{an} \rightarrow \mathcal{M}$, hence $(\mathbf{q}_\mathbf{p}, \mathbf{q}_{\mathbf{a}1}, \mathbf{q}_{\mathbf{a}2}, \ldots, \mathbf{q}_{\mathbf{a}n}) \mapsto \mathbf{h}(t) = f(\mathbf{q}_\mathbf{p}, \mathbf{q}_{\mathbf{a}1}, \mathbf{q}_{\mathbf{a}2}, \ldots, \mathbf{q}_{\mathbf{a}n})$, where, $\mathcal{N}_{a1}, \mathcal{N}_{a2} \ldots \mathcal{N}_{an}$ are the configuration space of the robotic arm, $\mathcal{M}_p$ is the operative space of the mobile platform and $\mathbf{h}(t)$ represents the position and orientation of the end effector of the mobile manipulator (see Fig.1).

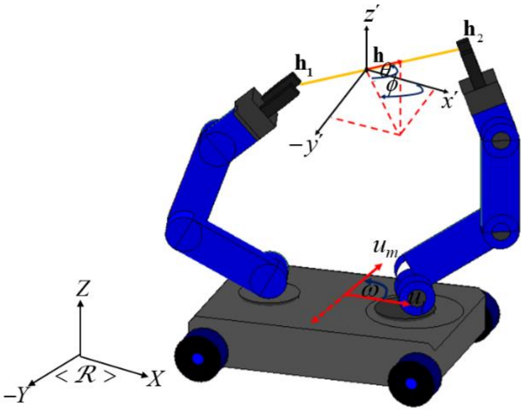


Fig 1. Mobile manipulator robot with two robotic arms.

For a mobile platform with two robotic arms located in the upper base of the mobile platform, it is considered that the generalized coordinates $h_1(t)$, $h_2(t)$, correspond to the end-effector of each robotic arm (1).

$$\begin{cases} h_{xi} = x \pm aC_{\Psi} + l_{2i}C_{q2i}C_{q1i,\psi} + l_{3i}C_{q2i,q3i}C_{q1i,\psi} + l_{4i}C_{q2i,q3i,q4i}C_{q1i,\psi} \\ h_{yi} = y \pm aS_{\Psi} + l_{2i}C_{q2i}S_{q1i,\psi} + l_{3i}C_{q2i,q3i}S_{q1i,\psi} + l_{4i}C_{q2i,q3i,q4i}S_{q1i,\psi} \\ h_{zi} = h_{alt} + l_{1i} + l_{2i}S_{q2i} + l_{3i}S_{q2i,q3i} + l_{4i}S_{q2i,q3i,q4i} \end{cases} \tag{1}$$

where, $i = 1,2$ represents each robotic arm mounted on the mobile platform; ψ is the orientation of the mobile platform. Derivate (1) with respect to the coordinates hx, hy, hz, the kinematic model of the mobile manipulator is obtained, defined as:

$$\dot{\mathbf{h}}_{\mathbf{n}}(t) = \mathbf{J}_{\mathbf{i}}\left(\mathbf{q}_{\mathbf{p}}, \mathbf{q}_{\mathbf{a}1}, \mathbf{q}_{\mathbf{a}2}\right)\mathbf{v}_{\mathbf{n}}(t) \tag{2}$$

where, $\dot{\mathbf{h}}_{\mathbf{n}}(t) = [\dot{h}_{i1} \quad \dot{h}_{i2}]^T$, is the velocity vector of the end-effectors of the double mobile manipulator, $\mathbf{v}_n = [\mathbf{v}_{\mathbf{q}}^T \quad \mathbf{v}_{\mathbf{a1}}^T \quad \mathbf{v}_{\mathbf{a2}}^T]^T$ is the control vector of mobility of the double mobile manipulator with dimension and $\mathbf{J}_n\left(\mathbf{q}_{\mathbf{p}}, \mathbf{q}_{\mathbf{a}1}, \mathbf{q}_{\mathbf{a}2}\right)$ is the Jacobian matrix that establishes a linear mapping between the velocities vector of the final effectors and the velocities vector of the mobile manipulator.

2.2 Kinematic Transformation

The method the cooperative coordinated proposed control considers two or more mobile manipulators. In the first case, two mobile manipulators are considered, to determine the kinematic transformation, the virtual point is fixed in the X-Y-Z plane between the midpoint of each final effector of the robotic arms; the virtual point is defined by. $\mathbf{P}_F = \frac{1}{2}\left[(h_{x1}+h_{x2})\quad(h_{y1}+h_{y2})\quad(h_{z1}+h_{z2})\right] \in \mathcal{R}^3$ that represents the position of its centroid on the inertial system $<\mathcal{R}>$ [6]; while, the vectorial structure of the virtual form is defined for,

$$\mathbf{S}_F = \left[\sqrt{(h_{x2}-h_{x1})^2+(h_{y2}-h_{y1})^2+(h_{z2}-h_{z1})^2}\quad \arctan\left(\frac{h_{y2}-h_{y1}}{h_{x2}-h_{x1}}\right)\quad \arctan\left(\frac{h_{y2}-h_{y1}}{h_{x2}-h_{x1}}\right)\right],$$

where d, is the distance between the position of the end-effector $\mathbf{h}_1$ y $\mathbf{h}_2$, θ_F and ϕ_F represents its orientation with respect to the *Y*-axis and the Z-axis, respectively in inertial frame $<\mathcal{R}>$. The point of interest of the system is denoted in a simplified way $\mathbf{r} = [\mathbf{P}_F \quad \mathbf{S}_F]$ [5].

Remark 1: $\mathbf{h}_i$ represent the position the end-effetor of the *n*-th mobile manipulator. The positions forward and inverse, give the relationship between the virtual structure pose-orientation-shape and the end-effector positions of the mobile manipulators, *i.e.*, $\zeta(t) = f(\mathbf{x})$ and $\mathbf{x}(t) = f^{-1}(\zeta)$, where $\zeta(t) = [\mathbf{P}_F \quad \mathbf{S}_F]^{\mathrm{T}}$ and $\mathbf{x} = [\mathbf{h}_1^T \quad \mathbf{h}_2^T]^T$.

When making the derivative of direct and inverse kinematic transformations with respect to a time variation of $\mathbf{x}(\mathbf{t})$ and $\zeta(\mathbf{t})$, obtained by the Jacobian matrix $\mathbf{J}_\mathbf{F}$, which is denote by

$$\dot{\zeta} = \mathbf{J}_\mathbf{F}(\mathbf{x})\dot{\mathbf{x}} \tag{3}$$

and when you apply the inverse you get

$$\dot{\mathbf{x}} = \mathbf{J}_\mathbf{F}^{-1}\dot{\zeta} \tag{4}$$

3 Scalability for the Cooperative Control

In this section the cooperation control of multiple heterogeneous mobile manipulators is described in a generalized way to the transport an object in common, usings the kinematic transformation presented in Section 2. The Fig.2, presents a multi-layer scheme for cooperative control in order to execute tasks of navigation and manipulation between multiple mobile heterogeneous manipulators. Each layer functions as an independent module that deals with a specific part of the problem of coordinated cooperative control the multi-layer scheme is defined by the task planning layer, the formation control layer, the kinematic control layer, the robot layer and the environment layer.

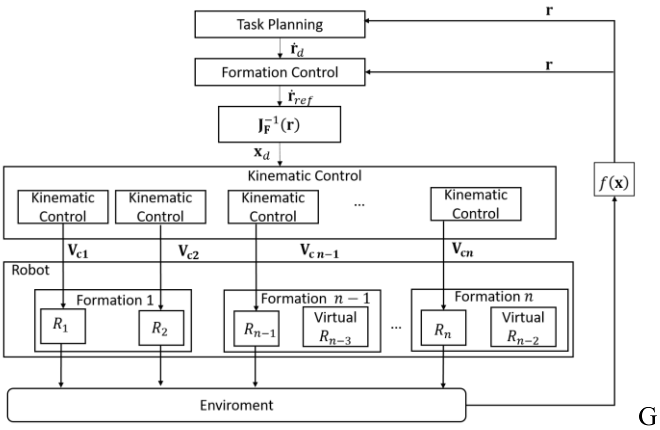


Fig. 2 Multi-layer control scheme.

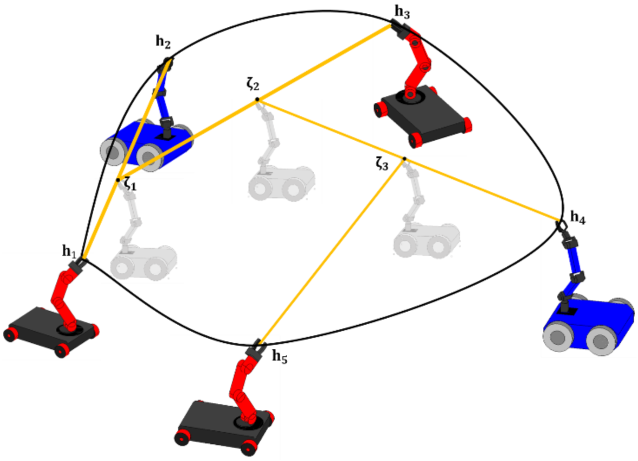


Fig. 3 Multiple heterogeneous mobile manipulators.

To perform scalability, projections are made between the operating ends of a pair of robots, which form a virtual operator (see, Fig.3). In this way, according to the analysis presented, the point of interest of the object transported by two mobile manipulators based on the training is $\zeta_1 = \begin{bmatrix} h_{x1} & h_{y1} & h_{z1} & d_{F1} & \theta_{F1} & \phi_{F1} \end{bmatrix}^T \in \mathcal{R}^5$ which is a virtual robot that is located at the midpoint formed by the first end-effector $\mathbf{h}_1$ and the second end-effector $\mathbf{h}_2$. Adding another robot to perform the cooperation task defines another point of interest $\zeta_2 = \begin{bmatrix} h_{x2} & h_{y2} & h_{z2} & d_{F2} & \theta_{F2} & \phi_{F2} \end{bmatrix}^T$, which is formed by the virtual robot ζ_1 and and the third end-effector $\mathbf{h}_3$. For $n \geq 2$ heterogeneous mobile robots, is formed by the virtual robot $n-2$ with point of interest ζ_{n-2} and the *n-th* heterogeneous robot. They define the characteristics of the object transported by the position, distance and the desired angles that exist between the robots.

4 Control Strategy

In this section proposed a control algorithm based on inverse kinematics. By means of the derivation in time of the forward and inverse kinematic transformations, the relation between the time variations of $\mathbf{x}(\mathbf{t})$ and $\mathbf{r}(\mathbf{t})$, represented by the Jacobian matrix $\mathbf{J}_{\mathbf{F}}$ and $\mathbf{J}$ is the Jacobian matrix that establishes a linear mapping between the velocities vector of the final effectors and the velocities vector of the mobile manipulator. The implementation of the control of multiple heterogeneous mobile manipulators, it is based on the formation of the control and kinematic control of mobile manipulators.

The structure of the formation controller is similar that kinematic controller, therefore the following control law is proposed (5).

$$\upsilon = \boldsymbol{\mu}^{-1}\left(\dot{\xi}_d + \mathbf{M}\tanh\left(\tilde{\xi}\right)\right) \tag{5}$$

Where, $\boldsymbol{\mu}^{-1}$ is the inverse $\boldsymbol{\mu}$ matrix; $\dot{\xi}_d$ is the vector of desired velocities; $\mathbf{M}$ a definite positive matrix that weighs the control actions of the system; ξ is the vector of control errors with $\tilde{\xi} = \xi_{\mathbf{d}} - \xi$.

Assuming the velocity is constant, then $\dot{\tilde{\xi}} = \dot{\xi}_{\mathbf{d}}$. For the stability analysis the following Lyapunov candidate function is considered $\mathrm{V}(\tilde{\xi}) = \frac{1}{2}\tilde{\xi}^T\tilde{\xi} > 0$. Its time derivate on the trajectories of the system is

$$\dot{\mathrm{V}}\left(\tilde{\xi}\right) = -\tilde{\xi}^T\mathbf{M}\tanh\left(\tilde{\xi}\right) < 0 \tag{6}$$

This implies that the equilibrium point of the closed loop (8) is asymptotically stable, $\dot{\tilde{\xi}}(t) \to 0$ asymptotically with $t \to \infty$.

Remark 2: By means of the control analysis (5) the following control laws are obtained for the formation controller (7) and kinematic controller (8).

$$\dot{x}_d = \mathbf{J}_{\mathbf{F}}^{-1}\left(\dot{\zeta}_d + \mathbf{K}_1\tanh\left(\mathbf{K}_2\tilde{\zeta}\right)\right) \tag{7}$$

$$\mathbf{v}_n = \mathbf{J}_n^{\#}\left(\mathbf{h}_{\mathbf{d}n} + \mathbf{K}_n\tanh\left(\mathbf{K}_n\tilde{\mathbf{h}}_n\right)\right) \tag{8}$$

5 Results and Discussion

A 3D simulator was developed in Matlab to evaluate the performance of the proposed control scheme, in which the uniciclo, car-like and omnidirectional robots are considered, which are composed of a mobile platform and one or two robotic anthropomorphic. The Fig. 5 shows the stroboscopic movement in the XYZ space of the reference system $<\mathcal{R}>$, which makes it possible to check that the proposed controller is performing adequately when carrying out cooperation and coordination tasks when a common object is transported cooperatively between the mutiple heterogeneous mobile manipulators.

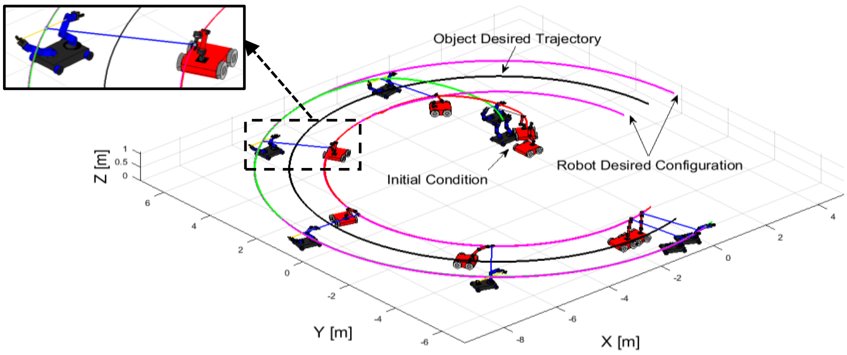


Fig. 5 Stroboscopic movement of the mobile manipulator.

The Fig. 6 indicates the control errors of the position between the ends of the robotic arms; the form and orientation errors, i.e. the distance between the operating ends and the angles that form the object with the arms on the planes XY and YZ with respect to the reference system, is presented in Fig. 7 illustrates; in the two graphs it can be seen that the control errors tend to zero asymptotically when . $t \rightarrow \infty$.

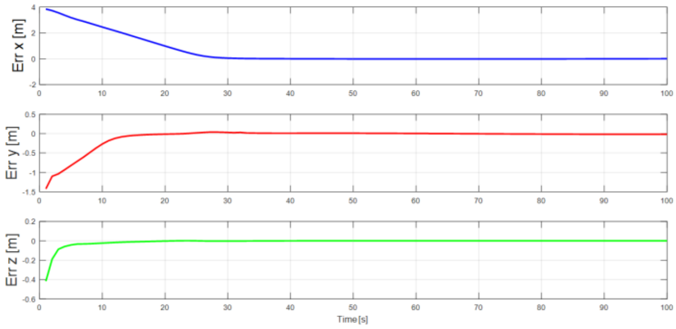


Fig. 6 Errors of position of the point of interest or midpoint of the operative ends.

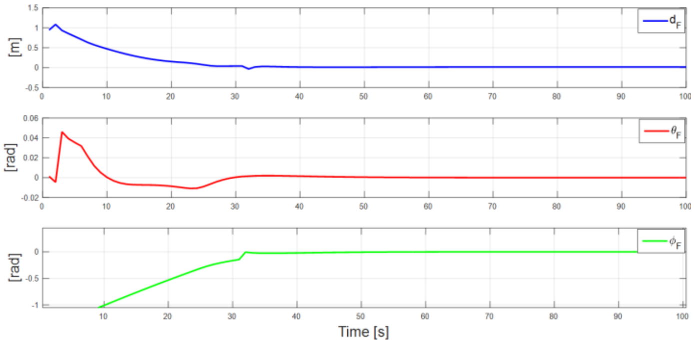
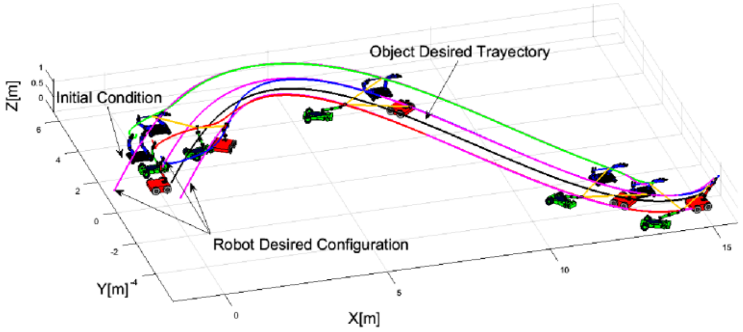
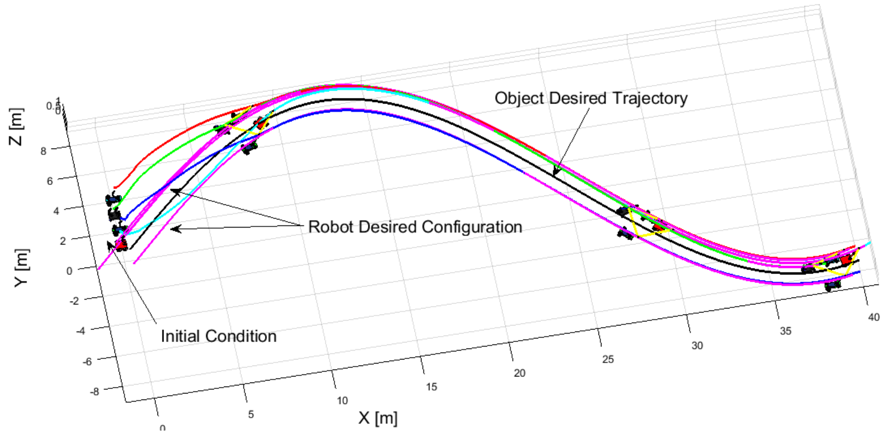


Fig. 7 Errors of shape of the object to be transported

Fig.8 shows the stroboscopics movements of $n \geq 2$ heterogeneous mobile robots, confirming that the implemented control is adequate as the robots followed the desired trajectory.



(a) Coordinated cooperative control of three mobile manipulators



(b) Coordinated cooperative control of four mobile manipulators
Fig. 8 Stroboscopic movement of the mobile manipulator.

6 Conclusions

In this work, the design of a multilayer scheme was presented for the coordinated cooperative control of $n \geq 2$ heterogeneous mobile manipulators for trajectory tracking that allows to transport an object in common. In the controller design employs a kinematic cascading control implemented on a virtual structure formed between the operating extremes of multiple heterogeneous mobile manipulator robots. Stability and robustness are verified with the Lyapunov method. The simulation experiments using a virtual structure allow to determinate the performance of the proposed control scheme, validating the the efficiency of the controller in solving different motion problems through a choice of control references.

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