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Multi-robot manipulation using formation control and human-in-the-loop scheme

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***Abstract*—In this paper, we present a novel multi-robot manipulation system with human operator. We modify the formation control law, and apply it to the human-in-the-loop (HITL) scheme. We add a derivative term to the common formation control law to reduce the formation breakups in the transient state, which is one of difficult problems in the formation control. The HITL system is used to lead the formation while providing haptic feedback, such that the human can move the multi-robot with a desired prescribed formation. The method developed is applied to a platform to test the effectiveness and efficiency of the algorithm.**

I. Introduction

Formation control is a popular research topic in the field of multi-agent cooperative control due to the practical opportunities and theory challenges that arise in coordination and control of such systems [1], [2]. Applications of these systems include, for example, mobile robots, unmanned aerial vehicles, satellites, sensor networks, etc., however, the interaction of a team of cooperative robots and humans in manipulation tasks has been less explored.

Depending on the types of actively controlled variables to achieve a prescribed formation, the most common approaches to control multi-agent formations are position based [3], [4], distance-based [5], [6], displacement-based [7], [8], and bearing-based control laws [9], [10]. The prescribed formation is defined as a geometrical shape specified by a certain set of desired relative configurations. In distance-based approaches, each agent measures the relative positions of its neighboring agents with respect to its own local coordinate frame without any knowledge on a global coordinate system, therefore they do not share a common sense of orientation. Since no global information is used for the agents to obtain the relative positions to other agents, this is a decentralized approach control. The desired formation is given by the desired distances between every pair of agents. The agents achieve the desired formation by actively controlling the distances to their neighbors Since the only variable controlled is the inter-agent distance, the sensing graph that defines the desired formation needs to be rigid.

While the physical interaction of manipulators in cooperative tasks is been largely explored, the interaction of a group of cooperative robot and a human operator has been less explored. Cooperation os two or more agents often is crucial to improve the performance of physical tasks in terms of functionality and flexibility. Similar approaches have been reported, e.g., an interactive system of a human with a swarm of physically uncoupled cooperating robots can be found in [11]. The interaction between a human and a group of robots poses different challenges such as designing a control scheme to command the robots including a proper feedback to the human leader. In [12], it is presented a team of robots controlled by a human through a master robot. In [13], it is presented a team of robots controlled by a human using a motion capture system and a feedback through a band wrist that indicates the transient state of the robots response.

A interactive man-machine system where the human's role is central to the correct working of the system is refereed to as a human-in-the-loop control (HITL) system [14]. A HITL control can be used to combine human skills and robot properties to perform specific tasks such as co-manipulation [15], haptic operations [16], and learning from demonstration [17]. HITL has commonly two control loops: an inner loop to control the joint coordinates and an outer loop using impedance control in the task space. HITL provides an effective human-robot interaction method [18]. In the joint space, HITL needs the inverse kinematics model to compute the joints' desired positions given a position and orientation of the end-effector. However, it is well known that the inverse kinematics has multiple solutions for any point coordinates in the task space, thus requiring complete knowledge of the kinematics of the robot. On the other hand, in task space, HITL needs the Jacobian matrix to transform the control output to joint space which also implies full knowledge of the kinematic parameters [19].

In this paper, we present a modified formation based control law based on the typical gradient descent control law to control the formation of a multi-robot system using a HITL control scheme. We add a derivative component to reduce transient state error and compare the results with the normal gradient descent control law. The human operator is a part of the formation and controls the multi-robot system by manually moving a passive master robot. The human plays as the leader in a leader-followers formation where the robots performing the manipulation task are the followers. HITL system obtains the human leader desired position through the master robot, this allows to avoid the inverse kinematics problem issues since the position of the human is obtained using the forward kinematics of the robot. In order to provide haptic feedback to the human, we use an impedance control that retrieves information from the formation in order to let the leader know when the formation is in the transient state and when the formation might be broken.

II. Distance-based formation control

The motion and the desired position x_i of the manipulators need to be in compliance with the geometry of the object to be manipulated. In order to have desired trajectories geometrically consistent with the object geometry, the manipulator must follow a rigid formation so no excessive forces are applied on the object.

For a formation in $\mathbb{R}^m$, $m = 2$ or 3, with $n \geq 2$ manipulators labeled by $1, ..., n$, the neighbors relationships are described by an undirected graph $\mathbb{G}$ [20]. An undirected graph is a pair $\mathbb{G} := (\nu, \varepsilon)$, where ν is the set of nodes or vertices such that $\nu = \{1, ..., n\}$ and $\varepsilon \subseteq \nu \times \nu$ is the set of pairs of nodes, called edges. We assume that there is no self-edge, i.e., $(i, i) \notin \varepsilon$ for $i \in \nu$. The set of neighbors of $i \in \nu$ is defined as $N_i := \{j \in \nu : (i, j) \in \varepsilon\}$.

Let k_{ij} be the label of the edge between the vertices i and j of the ordered pair (i, j), then $k_{ij} \neq k_{ji}$. Let ε_i denote the set of labels k_{ij} of all the edges associated to vertex i. In order to keep a desired formation shape, each agent i is assigned the task of keeping a prescribed distance $d_{k_{ij}}$ relative to every neighbor j. The distance constraints $d_{k_{ij}}$ are assumed to be realizable in $\mathbb{R}^m$.

The graph containing the prescribed desired formation is contained in $\mathbb{R}^m$ by assigning a cartesian coordinate $x_i \in \mathbb{R}^m$ to each vertex i. A framework is a pair $(\mathbb{G}, x)$ where $x = \left(x_1^T, ..., x_n^T\right)^T \in \mathbb{R}^{m \times n}$ is the set of all the vertices' cartesian coordinates. For any framework $(\mathbb{G}, x)$, we can define the edge function $f_{\mathbb{G}}$ as

$$f_{\mathbb{G}}(x) = \underset{\forall k_{ij} \in \varepsilon}{\mathrm{col}} (\left\| z_{k_{ij}} \right\|^2) \tag{1}$$

where $z_{k_{ij}} = x_i - x_j$ is the relative position vector between vertices i and j for the edge k_{ij} in the framework, $\|\cdot\|$ is the Euclidean norm and $\mathrm{col}(\cdot)$ is the column vector formed by the length of all the edges.k_{ij} of the framework.

A formation is said to be rigid if it is not possible to move slightly some vertices of the framework $(\mathbb{G}, x)$ without moving the other vertices while maintaining the edge lengths given by the edge function (1) (see Fig. 1).

A general formation control problem for N-agents can be described as follows [2]

$$\left\{ \begin{array}{ll} \dot{x}_i = f_i(x_i, u_i) & \\ \dot{y}_i = g_i(x_i, ..., x_N), & i = 1, ..., N \\ z_i = h_i(x_i, u_i) & \end{array} \right. \tag{2}$$

where $x_i \in \mathbb{R}^{n_i}$, $u_i \in \mathbb{R}^{p_i}$, $y_i \in \mathbb{R}^q$, $z_i \in \mathbb{R}^r$, are the state, control input, measurement and the output of the agent i,

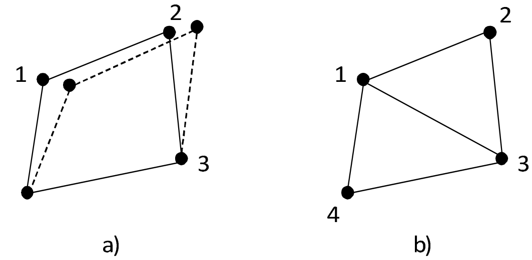

Fig. 1. Examples of undirected graphs: a) not rigid, b) rigid.

respectively. Defining $z = (z_1^T, ..., z_N^T)^T \in \mathbb{R}^{r \times N}$, the desired formation for the agents can be defined by M-constraints as

$$F(z) = F(z^*) \tag{3}$$

where $F : \mathbb{R}^{r \times N} \to \mathbb{R}^M$, for some given $z^* \in \mathbb{R}^{r \times N}$. Then, a formation control problem can be stated as: design a control law u_i such that the formation

$$E_{z^*} = \{\left(x_1^T, ..., x_n^T\right)^T : F(z) = F(z^*)\} \tag{4}$$

becomes asymptotically stable under such control law. In a distance-based approach, the constraints (3) are the desired distances between the agents.

Let the agent i's motion be described by the first order kinematic point model

$$\dot{x}_i = u_i, \qquad i = 1, ..., n \tag{5}$$

where $u_i \in \mathbb{R}^m$ is the control input for the agent i.

In [5], it is presented the gradient descent control law using $z_{k_{ij}}$

$$u_i = -\sum_{k_{ij} \in \varepsilon_j} \delta_{k_{ij}} z_{k_{ij}} e_{k_{ij}} \tag{6}$$

where $\delta_{k_{ij}} > 0$ is a scalar gain used to adapt the convergence rate to the desired formation and $e_{k_{ij}}$ is the error between the square of the real distance $\bar{d}_{k_{ij}}$ and the square of the prescribed distances $d_{k_{ij}}$ between the agents i and j associated to the edge k_{ij}, i.e.,

$$e_{k_{ij}} = \left\| \bar{d}_{k_{ij}} \right\|^2 - d_{k_{ij}}^2 \tag{7}$$

As demostrated in [5], when $\bar{d}_{k_{ij}} = \bar{d}_{k_{ji}}$ and $d_{k_{ij}} = d_{k_{ji}}$, the control law (2) makes the solution of the multi-agents system to follow the direction of the gradient of the system's potential function given by

$$V = \frac{1}{4} \sum_{k_{ij} \in \varepsilon} e_{k_{ij}}^2 \tag{8}$$

Note that from a formation control perspective, this is a distance based control approach where the agents have to sense the relative positions of their neighbors. In a multi-robot manipulation system, we assume that all desired positions x_i

are expressed in a world coordinate system, thus the relative positions of each pair of robots can be computed using the forward kinematics model K_F, i.e., $x_i = K_F(q_i)$ where q_i is the vector of joint coordinates of the robot i.

The gradient control law (2) does not consider any motion constraints. In real applications, the robots may not be able to follow the gradient of the potential function (8) exactly due to certain motion constraints such as velocity saturation or dynamic effects causing $\bar{d}_{k_{ij}} \neq \bar{d}_{k_{ji}}$ or $d_{k_{ij}} \neq d_{k_{ji}}$, and thus $e_{k_{ij}} \neq e_{k_{ji}}$ leading to unknown distorted formation shape or steady state collective motion induced by inconsistency [21]. As a result, the convergence of the entire multi-robot system to the prescribed formation may not be guaranteed. In order to avoid formation breakups, we propose a modified gradient control law with an additional derivative action to control the multi-robot manipulation system while preserving the formation prescribed.

The modified control law is

$$u_i = -\sum_{k_{ij} \in \varepsilon_j} \left(\delta_{k_{ij}} z_{k_{ij}} e_{k_{ij}} + \eta_{k_{ij}} z_{k_{ij}} \dot{e}_{k_{ij}} \right) \tag{9}$$

where $\eta_{k_{ij}} \geqslant 0$ is the derivative gain used to smooth the system response and $\dot{e}_{k_{ij}}$ is the time derivative of the error $e_{k_{ij}}$.

Similar approaches including a velocity term known as distance-based control of double-integrator modeled agents can be found in [23], [24].A N multi-agent system modeled as double-integrator in n-dimensional space has the following form

$$\begin{cases} \dot{p}_i = v_i \\ \dot{v}_i = u_i \end{cases}, \qquad i = 1, ..., N \tag{10}$$

where $p_i \in \mathbb{R}^n$, $v_i \in \mathbb{R}^n$, and $u_i \in \mathbb{R}^n$ denote the position, the velocity, and control input, respectively, of agent i with respect to the global coordinate system ${}^g\sum$. We assume that each agent is able to measure its own velocity and the relative position to its own coordinate frame. Then, the desired formation E_{p^*,v^*} is defined as

$$E_{p^*,v^*} := \{ \begin{pmatrix} p^T & v^T \end{pmatrix}^T \in \mathbb{R}^{2n \times N} : \|p_j - p_i\| = \left\|p_j^* - p_i^*\right\| \\ , v = 0, \forall (i,j) \in \nu \} \tag{11}$$

For agents on a plane, in [24] propose a control law $u = f(p, v)$ that guarantees local stability of E_{p^*,v^*} with respect to (10). In [23], it is proposed a gradient based control law that resembles a PD controller, the local asymptotic stability proof can be found in [25].

However, the stability analysis of the modified gradient law proposed in this work still remains to be made.

III. Human-in-the-loop system

The most distinguishing factor of a HITL controller from traditional controllers is the direct involvement of a human operator. Unlike other HITL controllers that are mostly autonomous and only require occasional intervention by the human operator [14], [22], the multi-robot manipulation system requires the human to be actively controlling the motion of the followers manipulating the object.

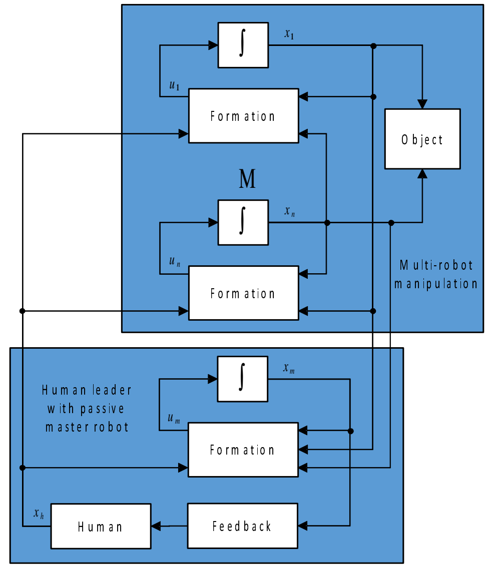

Fig. 2. Control scheme for multi-robot manipulation using distance-based formation control and HITL.

The control scheme of the HITL multi-robot system is shown in Fig. 2. Two main sections can be identified in the diagram. The first one refers to the followers of the formation that manipulate the object of interest. The second one includes the human leader with the passive master robot. In this section, the robot is also affected by the formation control law in order to provide feedback to the human to improve the performance through the manipulation task.

Proper haptic feedback can be given to the human by using the mechanical impedance of the robot's end-effector given by

$$F_d(s) = \left(M_d s^2 + D_d s + K_d\right) x(s) \tag{12}$$

or equivalently

$$F_d(s) = \left(M_d s + D_d + \frac{K_d}{s}\right) \dot{x}(s) \tag{13}$$

$$\dot{x}(t) = \frac{d}{dt} x(t) \tag{14}$$

where x is the end effector's position, $\dot{x}$ is the end effector's velocity, M_d, D_d and K_d are the mass, damping and stiffness for a desired dynamics of the system, and F_d is the reaction force exerted by the end effector on its environment.

The eq. (13) has the form of a PID controller where D_d, K_d and M_d are equivalent to the proportional, integral y derivative gains of the PID controller, respectively. Thus, the impedance control can be considered as a PID controller in which the reference desired velocity error is zero, i.e., in order to have a reaction force, we must take the derivative of the error between the desired end effector's position and the real position as input of the impedance control to generate such output force.

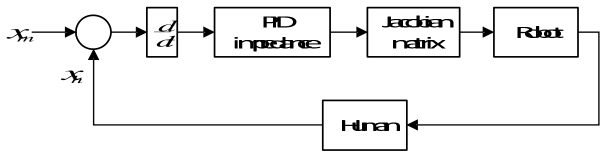

Fig. 3. HITL control diagram with impedance control with reference from the formation control.

Fig. 4. 3-DOF robots used in the experimental setup.

The control loop for the haptic feedback is shown in Fig 3. Note that this control scheme regulates the position error between the master robot's position x_m given by the formation control (9) and the human operator's position x_h, i.e., $e = x_m - x_h$. Then, the time derivative of the error e is used to compute the reaction forces F_d of the robot in the task space through the impedance control (13). To transform this forces to joint space torques τ, we use the Jacobian matrix of the robot as follows

$$\tau = J^T(q)F_d \tag{15}$$

Finally, the robot will apply the reaction forces to the human. This haptic feedback allows the operator to lead the formation in compliance with the position of the master robot given by the formation control in such way that $F_d \approx 0$.

IV. Experimental Results

To test the multi-robot manipulation system with HITL feedback control we use the 3-degrees-of-freedom (DOF) robots shown in Fig. 4. First, we simulated the system from Fig. 2 with two followers and without feedback in order to verify the performance of the modified gradient descent distance-based formation control compared to the regular gradient descent control law. The human leader desired position is modelled as

$$x_h = x_{offs} + A\sin(\varpi t) \tag{16}$$

where x_{offs} is an offset point from the origin of the world coordinate frame, A and ϖ are the vectors of amplitude and frequency of the desired oscillations, respectively.

The response of followers robots 1 and 2 shown in Fig. 5 and Fig. 6, respectively, correspond to the normal gradient

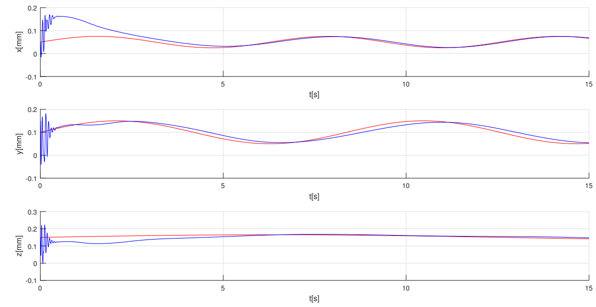

Fig. 5. Desired end-effector's position given by the formation for follower robot 1 (red) and position using the formation control (6) (blue).

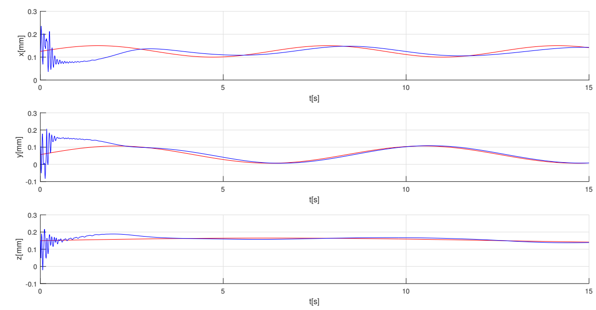

Fig. 6. Desired end-effector's position given by the formation for follower robot 2 (red) and position using the formation control (6) (blue).

control (6). Using the modified formation control (9), the robots' trajectories are illustrated in Fig. 8 and Fig. 9. Now, from Fig. 9 and Fig. 10, it can be verified that the transient state error lessens by adding the derivative term, which roughly speaking, it means that the formation is followed in a better way.

Now, if we add the HITL control (13), we obtain the error responses for the formation control (9) shown in Fig. 11. Since the followers' error are smaller using the HITL in the loop controller compared to the normal distance-based control

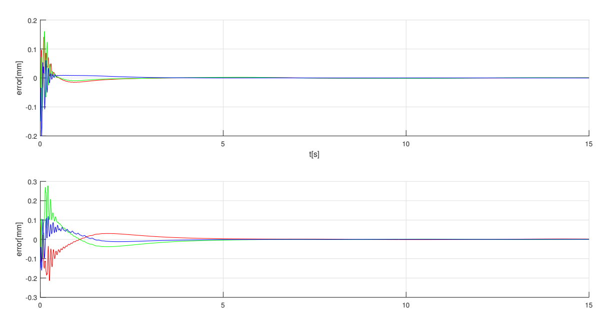

Fig. 7. Response error of follower robot 1 (up) and robot 2 (down) using the formation control (6): coordinates x(red), y(blue) and z(green).

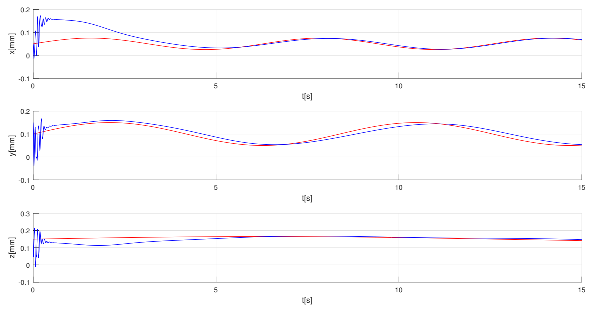

Fig. 8. Desired end-effector's position given by the formation for follower robot 1 (red) and position using the modified formation control (9) (blue).

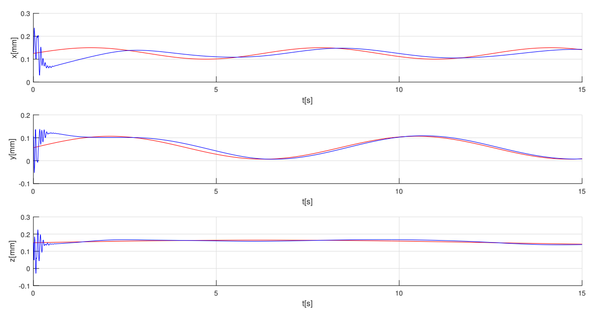

Fig. 9. Desired end-effector's position given by the formation for follower robot 2 (red) and position using the modified formation control (9) (blue).

(6), the system tends to keep a better formation in terms of less deviation from the prescribed framework compared to the system without feedback.

V. Conclusions

In this paper, we present a multi-robot manipulation system controlled by a human through the human-in-the-loop (HITL) scheme. We use the distance-based control and the leader-follower formation paradigm. The distance-based formation control modifies the common gradient descent method with

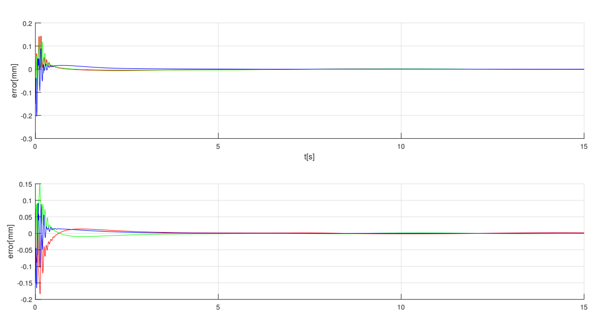

Fig. 10. Response error of follower robot 1 (up) and robot 2 (down) using the modified formation control (9): coordinates x(red), y(blue) and z(green).

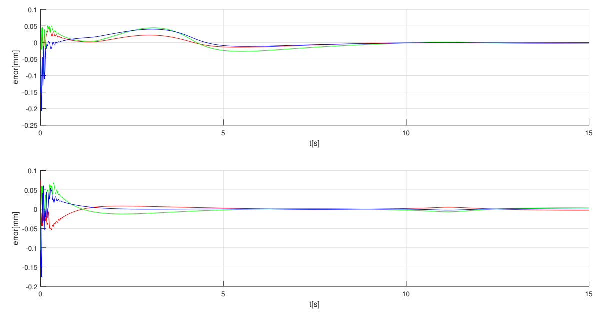

Fig. 11. Position error of robots 1 (up) and 2 (down) from using the modified control law (9) and the HITL feedback system.

an additional term corresponding to the derivative of the error. The proposed control law has better performance in reducing the transient state error. The novel method has better formation and less forces. This is one of difficult problems in multi-agent formation control. Additionally, we designed a haptic feedback control for the human operator using the impedance control law. It allows the human to control the multi-robot manipulation system in compliance with the formation of the followers.

Further work will include stability analysis of the proposed formation control and the integration of force control in the multi-robot followers, such that the forces on the object can be reduced further.

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