Multi-robot manipulation controlled by a human with haptic feedback

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Abstract— **The interaction of a single human with a team of cooperative robots, which collaboratively manipulate an object, poses a great challenge by means of the numerous possibilities of issuing commands to the team or providing appropriate feedback to the human. In this paper we propose a formation-based approach in order to avoid deformations of the object and to virtually couple the human to the formation. Here the human can be interpreted as a leader in a leader-follower formation with the robotic manipulators being the followers. The results of a controllability analysis in such a leader-follower formation suggest that it is beneficial to measure the state of the human (leader) by all physically cooperating manipulators (followers). The proposed approach is evaluated in a full-scale multi-robot cooperative manipulation experiment with humans.**

I. Introduction

While the physical cooperation of several manipulators to achieve a common task is a popular research topic in recent years [1]–[3], the interaction between a team of physically cooperating robots and humans has been less explored. For physical tasks the cooperation of two or more partners is often crucial to enhance functionality and flexibility. A specific related research direction concerns the interaction of a single human with a swarm of multiple cooperating - however physically uncoupled - robots [4]. This setting is particularly attractive as the multi-robot team typically outperforms the human at repetitive and exhausting tasks but not at cognitive reasoning in everyday tasks in unstructured environments. The interaction between a human and a group of robots poses two fundamental issues: the choice of a suitable and natural way to command multiple robots [5] and providing the appropriate feedback to the human operator [6]. A related problem is explored in multi-robot teleoperation [7] where a group of slave robots is controlled by the human through a master robot. The main focus has been here on stability by exploiting passivity. Vibrotactile feedback is employed in [8] to solve a cooperative navigation task, without physical coupling between the robots. Largely unexplored question is, how the human command should be mapped into the action space of the robots in a cooperative manipulation task.

We investigate the prototypical task where a single human operator commands several robotic manipulators which cooperatively manipulate a common object such that no excessive force is exerted on the manipulated object. We formulate this as a formation control framework for impedance controlled manipulators. The human operator is considered as part of the formation and controls the team with the movement of his/her hand, see Fig. 1. The human can be interpreted as the virtual leader and the robots can be interpreted as the followers in a leader-follower formation. One of the crucial questions is, which variable/state of the robotic team the human should control. This question can be formally posed within controllability analysis. Controllability in our context indicates if it is possible to drive the follower system states to any configuration, i.e. which subspaces can be independently controlled by the leader [9]. The relation of controllability of a larger swarm and the perceived rating of users is investigated based on a user study [10]. So far, however, the relevance of controllability for guiding a cooperative manipulation task has not been explored in depth.

In this paper we present a control scheme for multi-robot cooperative manipulation which is controlled by a single human. Our work employs a human operator as the explicit leader in a multi-robot manipulation task based on the widely-used leader-follower formation paradigm. The contribution of this paper is two-fold: i) we present a controllability analysis of the human-robot team interaction in a cooperative manipulation task. We investigate the controllable eigenmodes of the robot formation and show that every robot needs the state information of the human leader. As a result the desired trajectories are in accordance with the object geometry during the transient phase and no internal force acts on the object. Based on these results we devise a control strategy for human-controlled formations of physically cooperating robots; ii) we further propose a feedback strategy to the human operator where the formation state is displayed to the human via vibrotactile feedback.

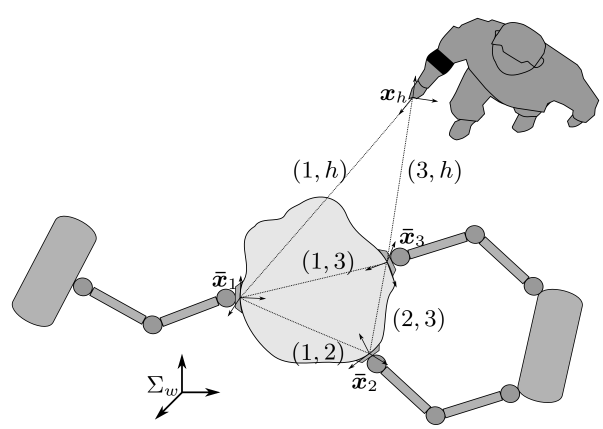

Fig. 1. Three robotic manipulators perform a cooperative positioning task under a formation-preserving control law. A human operator is the leader of this formation and controls the robots.

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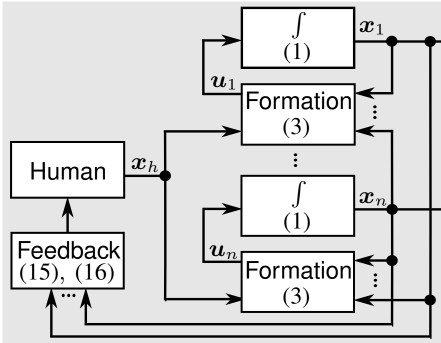

Fig. 2. General control approach for the human robots team

The approach is validated in a preliminary human user study involving three manipulators and a human.

The remainder of this paper is organized as follows. Section II describes formally the group of cooperating robots and Section III the interaction of a single human operator with a cooperative robot team. The feedback given to the human by the robot team is presented in Section IV. The experimental evaluation is presented in V.

Notation: Bold symbols denote vectors. $|\boldsymbol{a}|$ represents the absolute-value norm of a. N denotes the number of robots. $\boldsymbol{a}_i$ relates the variable to ith manipulator. $\boldsymbol{a}_{i,k}$ relates the variable to the kth state of manipulator i. The identity matrix of dimension n is signified by I_n. $\mathbf{1}$ denotes a vector with ones of appropriate size.

II. Formation control for Cooperative manipulation

This section describes the system model used for the physically coupled cooperative multi-robot team, which is feedback-controlled by a cooperative formation term. The general setup can be seen in Fig. 2. The cooperative term establishes a formation of the robotic manipulators in order to generate desired trajectories for the impedance-controlled manipulators.

A. Formation Control Scheme

The motion and accordingly the desired positions $\boldsymbol{x}_i$ for each of the N manipulators need to be in compliance with the geometry of the object. Then the desired trajectories are called geometrically consistent with the object geometry and so no extensive force is exerted on the manipulated object by the manipulators. For the sake of exposition we only consider translational movements for the end-effector of each robotic manipulator for the system analysis. The desired position $\boldsymbol{x}_i \in \mathbb{R}^3$ of the ith end-effector in task space is denoted as $\boldsymbol{x}_i = [x_{i,1}, x_{i,2}, x_{i,3}]$, where $x_{i,1}, x_{i,2}, x_{i,3}$ denote the components along each translational direction in Cartesian space. We argue that it is sufficient to consider only translational states $\boldsymbol{x}_i \in \mathbb{R}^3$ for the end-effector of each robotic manipulator as the position and orientation of the object is relevant here: both can be uniquely determined in a multi-robot ($N \geq 2$) manipulation task by considering only positions of the robotic end-effectors. Additionally, since the representation spaces of rotations are nonlinear the complexity of the problem increases significantly. The desired position $\boldsymbol{x}_i$ for each individual end-effector is the output of the formation control approach and by definition evolves according to

$$\dot{\boldsymbol{x}}_i = \boldsymbol{u}_i, \tag{1}$$

where $\boldsymbol{u}_i = [u_{i,1}, u_{i,2}, u_{i,3}]$ is the system input. Since we only consider translational motions for each manipulator, the dynamics $\dot{x}_{i,k} = u_{i,k}$ for each translational degree of freedom $k \in \{1, 2, 3\}$ is considered decoupled.

We propose to employ a formation control term to generate the desired trajectories $\boldsymbol{x}_i$. This formation is presented by a desired displacement $\boldsymbol{d}_{ij} = [d_{ij,1}, d_{ij,2}, d_{ij,3}]$ among the cooperating manipulators i and j, which needs to be established and maintained throughout the complete task execution. Artificial Potential Fields (APF) are widely used in formation control in order to establish and maintain a desired displacement $\boldsymbol{d}_{ij}$ between two agents i and j [11]. It is common to consider a quadratic potential field $V_{ij,k}\left(|x_{i,k} - x_{j,k}|\right)$ which has its global minimum at the desired displacement $d_{ij,k}$

$$V_{ij,k}\left(|x_{i,k} - x_{j,k}|\right) = \frac{1}{2}\left(|x_{i,k} - x_{j,k}| - d_{ij,k}\right)^2. \tag{2}$$

From the potential field, a control signal $u_{i,k}$ for the i-th end-effector (agent) along the kth Cartesian direction is derived based on the gradient descent

$$\begin{aligned} u_{i,k} &= -\sum_{j\in N_i} \delta_{ij} \frac{\partial V_{ij,k}\left(|x_{i,k} - x_{j,k}|\right)}{\partial x_{i,k}} \\ &= -\sum_{j\in N_i} \delta_{ij} \frac{x_{i,k} - x_{j,k}}{|x_{i,k} - x_{j,k}|}\left(|x_{i,k} - x_{j,k}| - d_{ij,k}\right), \end{aligned} \tag{3}$$

where $k \in \{1, 2, 3\}$ and $\delta_{ij} > 0$ is a scalar gain used to adapt the convergence rate to the desired formation. N_i describes the neighbors of agent i. Note that from a formation-control perspective, this approach is characterized as a displacement-based control approach [12] where the particular robots have to sense the relative positions of their neighbors. Under the control law (3) the robots converge to the desired formation if the underlying interaction topology resulting from the N_is is connected or if there exists a spanning tree [12]. Typically multiple stable equilibria exist [12]. By practically choosing the initial values of $\boldsymbol{x}$ close to the desired formation, we avoid the undesired equilibrium points. In a displacement-based approach the robots need to know the orientation of the world coordinate system, but not their positions in the world coordinate system. For the sake of exposition we assume all desired positions $x_{i,k}$ are expressed in a world coordinate system Σ_w which demands that each end-effector is aware of its rotation to that common reference frame. All formation-based approaches are suitable for outdoor applications by using appropriate sensing technologies such as GPS or a compass. Furthermore, the distributed formation control law (3) assumes that each manipulator knows the current displacement to its neighbors N_i by measurement. Compared to a distance-based approach, where the coupling between the state occurs along all dimension in $\mathbb{R}^3$, in a displacement-based approach more advanced sensing capabilities are required but the requirements on the interaction topology are less. Since (1) and (3) are fully decoupled with respect to the translational directions, the dynamics for the individual directions can be analyzed separately. The extension of L_c to the multi-dimensional case is straightforward using the Kronecker product. Following the argumentation in [13], (1) and (3) can be compactly rewritten as

$$\dot{\boldsymbol{x}} = -L_c(\boldsymbol{x})\boldsymbol{x} = -D_\sigma C(\boldsymbol{x}) D_\sigma^\intercal \boldsymbol{x}, \tag{4}$$

where $\boldsymbol{x} = [x_{1,k}, \ldots, x_{N,k}]^\intercal$ is the concatenated state vector along one dimension $k \in \{1, 2, 3\}$ and $L_c \in \mathbb{R}^{N\times N}$ is the weighted graph Lacplacian. The coupling matrix C is $C = \mathrm{diag}(c_{ij}) \in \mathbb{R}^{M\times M}$, where

$$c_{ij} = \frac{|x_{i,k} - x_{j,k}| - d_{ij,k}}{|x_{i,k} - x_{j,k}|}, \tag{5}$$

resulting from (3) and M is the number of all neighborhoods between any robots i and j. $D_\sigma \in \mathbb{R}^{N\times M}$ is the oriented incidence matrix of an undirected graph [13]. Note that the potential function (2) does not guarantee collision avoidance among the manipulators. It is straightforward to extend it with collision avoidance terms as e.g. defined in [12].

Remark 1: Graph theory is mostly used for large swarms with many agents. We will still employ this formalism here for the few agents as representation and standard results from graph theory can be carried over. Beneficially, by using the weighted graph Laplacian matrix L_c, the integration of the human into the formation and the controllability analysis can be expressed in a more convenient manner. The interested reader is referred to [13] and [14].

The output of the formation control is the desired trajectory for the local impedance control laws.

B. Impedance Control

In order to allow minor deviations of the desired position trajeectories from the formation constraints which result from model and geometric uncertainties or external disturbances we propose to employ impedance control for each of the N manipulators here. Due to the use of impedance control, those small deviations will not result in high internal forces exerted on the object. The Cartesian impedance control for each manipulator is described as following

$$M_i \ddot{\boldsymbol{p}}_i + D_i \dot{\boldsymbol{p}}_i + K \boldsymbol{e}_i = \boldsymbol{f}_i, \tag{6}$$

where $\boldsymbol{f}_i \in \mathbb{R}^3$ is the applied force to the i-th manipulator and $\boldsymbol{e}_i = \boldsymbol{p}_i - \boldsymbol{x}_i$ is the deviation of the current end-effector position $\boldsymbol{p}_i \in \mathbb{R}^3$ from the desired position $\boldsymbol{x}_i \in \mathbb{R}^3$. $M_i, D_i, K_i \in \mathbb{R}^{3\times 3}$ are the positive definite mass, damping, and stiffness matrices, respectively. The architecture can be seen in Fig. 2. Here, (1) and (3) provide the desired trajectories for the cooperative robotic system. Since we are mostly interested in the desired trajectories for the robots given by the human, we neglect the impedance control law (6) in the following analysis.

III. Human input as leader

The purpose of this section is to characterize the mathematical model for the human as a leader for the cooperative multi-robot team as depicted in Fig. 1. The cooperative robots manipulate an object under a formation-preserving control law while a desired trajectory is given to the robots by the human operator.

A. How can a human control multiple robots explicitly?

As illustrated in Fig. 1 the human becomes an active member of the formation without being in touch with the manipulated object. Therefore, the Cartesian position $\boldsymbol{x}_h$ of the human is required in the world frame Σ_w. In our task $\boldsymbol{x}_h$ is a position on the human hand. Since we only consider a single dimension $k \in \{1, 2, 3\}$ for (4), the human state is given by $x_{h,k}$. The human state $x_{h,k}$ is appended to the concatenated robot state $\boldsymbol{x}$ to $\bar{\boldsymbol{x}} = [\boldsymbol{x}^\intercal, x_{h,k}]^\intercal$. Hence, the human-extended weighted Laplacian matrix $\bar{L}_c(\bar{\boldsymbol{x}})$ which involves the state of the human is given by

$$\bar{L}_c(\bar{x}) = -\left[\begin{array}{c|c} L_r(\bar{\boldsymbol{x}}) & \boldsymbol{l}_h(\bar{\boldsymbol{x}}) \\ \hline \boldsymbol{l}_h(\bar{\boldsymbol{x}})^\intercal & \gamma(\bar{\boldsymbol{x}}) \end{array}\right], \tag{7}$$

where $L_r(\bar{\boldsymbol{x}}) \in \mathbb{R}^{N\times N}$ is the principal submatrix of $\bar{L}_c(\bar{x})$ and reflects the influence of the cooperating robots on each other. Accordingly, $\boldsymbol{l}_h(\bar{\boldsymbol{x}}) \in \mathbb{R}^N$ represents the influence of the human leader on the team of robots. Similar to (4), (7) characterizes the interaction in one dimension k.

Since there is no direct physical contact between the human and the robot team, the human only imposes movements on the robot-formation by his/her arm movement. From a control theoretic perspective the human has a directed influence on the states of the robot team and so the leader-follower dynamics which describe the human-to-robots interaction is given by

$$\dot{\boldsymbol{x}} = L_r(\bar{\boldsymbol{x}})\boldsymbol{x} + \boldsymbol{l}_h(\bar{\boldsymbol{x}}) x_{h,k}. \tag{8}$$

We are now ready to discuss the structure of $\boldsymbol{l}_h$ in (8), i.e.which of the robots have to know the human state $\boldsymbol{x}_h$ or equivalently what is N_h.

B. Which robots need to sense the human command?

When a human operator issues commands to a team of cooperative robots by (8), it is essential that all robots move in a coordinated way simultaneously, i.e. in formation, such that no undesired internal stress is applied to the object based on the human command $\boldsymbol{x}_h$. Hence, if the multi-robot cooperative team consists of more than two manipulators, the question arises whether the human state $\boldsymbol{x}_h$ excites all robots simultaneously or if particular robots are excited independently from each other. The number of robots which can be independently influenced by the human is closely related to the controllability of a system.

Controllability in a leader-follower formation depends on the interaction topology and the interaction topology is defined by the neighbors N_h of the human operator in the formation. Although our leader-follower system (8) is nonlinear by design, we investigate the first-order local controllability of (8) in order to employ methods such as Kalman decomposition and eigenvalue analysis. Formation equilibria are the positions of the robots such that the edge distances meet the desired ones. Furthermore, let $\delta_{ij} = 1$. We now linearize the system (8) about the formation equilibria:

$$\begin{aligned}\dot{\tilde{\boldsymbol{x}}} &= \frac{\partial L_r(\bar{\boldsymbol{x}})\boldsymbol{x} + \boldsymbol{l}_h(\bar{\boldsymbol{x}})x_{h,k}}{\partial \bar{\boldsymbol{x}}}\tilde{\boldsymbol{x}} + \frac{\partial L_r(\bar{\boldsymbol{x}})\boldsymbol{x} + \boldsymbol{l}_h(\bar{\boldsymbol{x}})x_{h,k}}{\partial x_{h,k}}x_{h,k} \\ &= A\tilde{\boldsymbol{x}} + \boldsymbol{b}x_{h,k}. \end{aligned} \tag{9}$$

Similar to [10] $A \in \mathbb{R}^{N\times N}$ and $\boldsymbol{b} \in \mathbb{R}^N$ are the system and input matrices of the controlled consensus problem resulting from the graph Laplacian:

$$L = -\left[\begin{array}{c|c} A & \boldsymbol{b} \\ \hline \boldsymbol{b}^\intercal & \gamma \end{array}\right]. \tag{10}$$

The controlled consensus problem (9) is the linear version of (8), where A and $\boldsymbol{b}$ are the submatrices of the graph Laplacian L without nonlinear weights, i.e. $C(\boldsymbol{x}) = I_M$ in (4) . The controllability matrix Q_c of the matrix pair $(A, \boldsymbol{b})$ is defined as:

$$Q_c = \begin{bmatrix}\boldsymbol{b} & A\boldsymbol{b} & A^2\boldsymbol{b} & \dots & A^{N-1}\boldsymbol{b}\end{bmatrix}. \tag{11}$$

The rank of Q_c characterizes the number of independently controllable states of $\boldsymbol{x}$. If Q_c is rank deficient the co-operating multi-robot system (9) can be decomposed into its controllable and uncontrollable part by the Kalman decomposition [15]. The similarity transformation of the Kalman decomposition is given by $T = \left[Q_c^{\|} \mid Q_c^{\perp}\right]$, where $Q_c^{\|} = \mathrm{span}(Q_c) \in \mathbb{R}^{N\times \operatorname{rank} Q_c}$ indicates the range of the controllable subspace and $Q_c^{\perp} = \mathrm{null}(Q_c)$ the range of the uncontrollable subspace. In the following, $Q_c^{\|}$ and $Q_c^{\perp}$ are composed of the set of eigenvectors ν^A of A, where the Hautus criterion [9] determines whether one eigenvector is a controllable eigenvector $\nu_i^{A_c} \subset \nu^A$ belonging to $Q_c^{\|}$ or whether it is an uncontrollable one $\nu_i^{A_{\bar{c}}} \subset \nu_A$ belonging to $Q_c^{\perp}$. The similarity transformation results in

$$T^\intercal A T = \begin{bmatrix} A_c & 0 \\ 0 & A_{\bar{c}} \end{bmatrix}, \quad T^\intercal \boldsymbol{b} = \begin{bmatrix} \boldsymbol{b}_c \\ 0 \end{bmatrix}, \text{ and} \\ \begin{bmatrix} \tilde{\boldsymbol{x}}_c \\ \tilde{\boldsymbol{x}}_{\bar{c}} \end{bmatrix} = T^\intercal \tilde{\boldsymbol{x}}, \tag{12}$$

where c and $\bar{c}$ correspond to the controllable and uncontrollable parts of the robotic system and result in two decoupled subsystems. Due to the similarity transformation T the eigenvalues denoted as spectrum $\{\lambda_i^A\}$ of A and of $T^\intercal AT$ are the same. The spectrum of A is $\{\lambda_i^A\} = \{\lambda_i^{A_c}\} \cup \{\lambda_i^{A_{\bar{c}}}\}$ where $A_c = \mathrm{diag}(\lambda_i^{A_c}) \in \mathbb{R}^{\operatorname{rank} Q_c \times \operatorname{rank} Q_c}$ and $A_{\bar{c}} = \mathrm{diag}(\lambda_i^{A_{\bar{c}}}) \in \mathbb{R}^{N-\operatorname{rank} Q_c \times N - \operatorname{rank} Q_c}$.

From a shared control perspective the uncontrollable subsystem $\dot{\tilde{\boldsymbol{x}}}_{\bar{c}} = A_{\bar{c}}\tilde{\boldsymbol{x}}_{\bar{c}}$ can be interpreted as the autonomous sub-task of the overall robotic system. Uncontrollability means that the human has no influence on states $\boldsymbol{x}_{\bar{c}}$, i.e. the movement of the human hand has no effect on the transformed robot states. Since the human has no influence on the uncontrollable subsystem, the eigenmodes $\{\lambda_i^{A_{\bar{c}}}\} \subset \{\lambda_i^A\}$ are masked from the human. Analogously, the controllable subsystem $\dot{\tilde{\boldsymbol{x}}}_c = A_c\tilde{\boldsymbol{x}}_c + \boldsymbol{b}_c x_{h,k}$ can be interpreted as the sub-task controlled by the human operator. Note that the eigenvalues $\lambda_i^{A_c}$ of the controllable subsystem are always distinct from each other, i.e. $\forall i, j,\ \lambda_i^{A_c} \neq \lambda_j^{A_c}$. To show that let us assume that the spectrum of A has an eigenvalue with geometric multiplicity greater than one, i.e. $\lambda_i^A = \lambda_j^A$. Then we can always find a linear combination of the two eigenvectors belonging to λ_i^A and λ_j^A that produces a zero entry at the position of the leader [13, Prop 10.3]. A zero entry in the eigenvector at the position of the leader leads to an uncontrollable subspace [13]. All except one of the eigenvalues with geometric multiplicity greater than one can be in $\lambda_i^{A_c}$. In other words, all eigenvalues $\lambda_i^{A_c}$ are different.

The human operator has direct influence on the controllable eigenmodes $\lambda_i^{A_c}$ which correspond to the rate of convergence. The ith locally controllable state trajectory $\tilde{x}_{c,i}(t)$ of the robots evolves according to the solution of the ordinary differential equation given by

$$\tilde{x}_{c,i} = e^{\lambda_i^{A_c} t}\tilde{x}_{c,i}(t_0) + \int_{t_0}^{t_1} e^{\lambda_i^{A_c}(t-\tau)} b_{c,i} x_{h,k}(\tau)\mathrm{d}\tau, \tag{13}$$

where $b_{c,i}$ is the ith component of $\boldsymbol{b}_c$. If there exist n different controllable eigenmodes for the human, then the human can locally control n different controllable states $\tilde{x}_{c,i}$. Since $\lambda_i^{A_c} \neq \lambda_j^{A_c}$, the human input $x_{h,k}(t)$ drives the trajectories of the controllable states $\tilde{\boldsymbol{x}}_c(t)$ of (13) differently:

$$\tilde{x}_{c,i}(t) \neq \tilde{x}_{c,j}(t), \quad \forall i, j \text{ and } t \in [t_0, t_1]. \tag{14}$$

Since the local trajectories (13) are different in the transient phase due to (14) for $\operatorname{rank}(Q_c) > 1$, we result in a break-up of the formation during the transient phase of the dynamical system (8). Hence, in the transient phase the desired positions are not geometrically consistent with the object geometry any more. Desired trajectories which are not geometrically consistent with the object geometry result in an undesired internal force acting on the object [2]. This must be strictly avoided in a cooperative manipulation task.

In the following we want to describe the meaning of the controllable subspace in case of a multi-robot formation. i.e. what is the resulting state after applying the transformation of $T = \left[Q_c^{\|} \mid Q_c^{\perp}\right]$. In general, one has to analytically apply this similarity transformation (12) to derive the controllable states $\tilde{\boldsymbol{x}}_c$ based on the state $\tilde{\boldsymbol{x}}$. It is known that the similarity transformation T and the controllable states $\tilde{\boldsymbol{x}}_c$ in (12) depend on the neighborhood topology [16]. If now these controllable subspaces correspond to a single robot or a group (cell) of robots, then the human operator can locally control those robots independently. As the rate of convergence of the controllable system is different, the subsystems which are controllable by the human converge with different speeds as characterized in (13). Due to (14) the operator induces a breakup of the formation in the transient phase of the desired trajectories $\tilde{\boldsymbol{x}}_c(t)$ by his movement $x_{h,k}$. The divergence of the desired trajectories results in an internal force acting on the object [2]. To avoid this breakup (14) in the transient phase, only a single controllable state is required. Hence, we propose that the human leader should only control a single eigenmode, i.e. $\operatorname{rank}(Q_c) = 1$ and come up with the following proposition relating the controllability with the leader neighborhood N_h.

Proposition 1: The controlled consensus problem (9) has only one controllable eigenmode if and only if $\boldsymbol{b} = \mathbf{1}$.

Proof: The proof of sufficiency assumes that $\boldsymbol{b} = \mathbf{1}$. Since A is the principal submatrix of the Laplacian $-L$ (10), the row sum of A is -1. Hence, $A\boldsymbol{b} = -\mathbf{1}$. Iteratively, one can show that $A^k\boldsymbol{b} = (-1)^k\mathbf{1}$. Consequently, the controllability matrix $Q_c = \left[\mathbf{1}, -\mathbf{1}, \mathbf{1}, \ldots, (-1)^{N-1}\mathbf{1}\right]$ has $\operatorname{rank}(Q_c) = 1$. As the controllability matrix describes the controllable subspace, we know that the leader can only control the average of all followers. For the proof of necessity, to have a single controllable eigenmode, $\operatorname{rank} Q_c = 1$ and so all columns of the controllability matrix Q_c must be linearly dependent. Hence, there must exist an input vector $\boldsymbol{b}$ such that $\boldsymbol{b} = \alpha A\boldsymbol{b}$, where $\alpha \in \mathbb{R}$. By construction we always have $-A\mathbf{1} = \boldsymbol{b}$. Since A is always regular [13], $\alpha = -1$ and $\mathbf{b} = \mathbf{1}$. For $A^2\boldsymbol{b}, \ldots, A^{N-1}\boldsymbol{b}$ it can be shown iteratively. ■

Therefore, to have a single controllable mode, we need $\boldsymbol{b} = \mathbf{1}$. For $\boldsymbol{b} = \mathbf{1}$ the human leader is connected to all robots and so we have $N_h = \{1, \ldots, N\}$. Hence, all robotic followers in the formation need to know the state of the human leader. The controllable state is given by the average of the robotic states $\tilde{x}_c = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \tilde{x}_{i,k}$. The human input $\boldsymbol{x}_h$ has influence on the multi-robot formation via the cooperative term (3) resulting in the dynamical model (8) as shown in Fig. 2 Recalling the formulation of shared control the autonomous functionality is to always maintain the formation while the manual input of the human operator drives the aggregated robot state.

IV. Feedback to the human operator

We additionally provide a reality augmenting vibrotactile feedback to the human operator based on the multi-robot movement. By doing so we display the phase of the robot formation to the human operator when the multi-robot formation is in movement.

The human-robot interaction as depicted in Fig. 1 envisions a free-space motion where the haptic channel of the human operator is not overloaded. Thus we propose to supplement a haptic feedback here. In order to not restrict the workspace of the human by the haptic-feedback generating device as in the classical bilateral teleoperation, we employ wearable haptic technology here namely a vibrotactile cue. As the transfer of messages through a vibrotactile device is very limited [17], we only transfer a 1-dimensional scalar z as feedback to the human. The role of the feedback is to signalize when the robot formation is in the transient phase resulting from a human input $x_{h,k}$. The feedback to the human is defined as

$$z = \sum_{k=1}^{3} \left(\sum_{j \in N_h} \frac{x_{h,k} - x_{j,k}}{|x_{h,k} - x_{j,k}|} (|x_{h,k} - x_{j,k}| - d_{hj,k}) \right)^2 , \tag{15}$$

where the signals (3) are projected onto a single scalar z by using the sum of squares as feedback to the human.

The interpretation of this signal z is as follows. Since (8) is a dynamical system, an immediate change of the human input $x_{h,k}$ always results in a transient phase of the robot followers $\boldsymbol{x}$. This transient phase is not caused by a delay, but by the propagation of $\boldsymbol{x}_h$ through (1) and (3). The time until the robots have reached its steady-state and have re-established the human-robot formation, i.e. $\forall i : |x_{i,k} - x_{h,k}| = d_{ih,k}$, is called convergence time. As long as the robots are in the transition phase, i.e. $\exists i : |x_{i,k} - x_{h,k}| \neq d_{ih,k}$,, the desired formation is not established. So the signal is $z \neq 0$ and there is feedback to the human depending on how far the robots are apart from the desired formation distance to the leader. If the desired formation is reached, $\forall i : |x_{i,k} - x_{h,k}| = d_{ih,k}$, then $z = 0$ in (15) and no signal is transferred to the human. This is intuitive as it decreases the closer the robots are to their desired formation. The human operator as a leader benefits from knowing when the robot team reaches its steady-state.

As a single scalar z has to be transmitted by the vibrotactile feedback to the human, we decide to alter the frequency f_{vib} of the vibrotactile stimuli. Highest sensitivity of the stimuli for the human is achieved at frequencies up to 300 Hz [17]. Hence, we choose the transmitted frequencies to be $0 \ldots 300$Hz, where 0 Hz means that the robots are in steady-state, $z = 0$, and 300 Hz corresponds to a maximal value z_{max} of z which is heuristically determined. A linear mapping between the feedback signal z and the vibrotactile frequency is given as

$$f_{\text{vib}} = \begin{cases} \alpha z & \text{if } \alpha z \leq 300Hz \\ 300Hz & \text{else} \end{cases} \tag{16}$$

where $\alpha > 0$ is a scalar of appropriate unit. A feedback to the human via a haptic channel is given by (15) and (16) as depicted in Fig. 2.

V. Experiments

The goal of the experimental evaluation is to show that the internal forces resulting in a cooperative manipulation task is subject to the neighbors N_h. Furthermore, the subjective experience of the human operator commanding a team of robots is assessed in a preliminary user-study.

A. Experimental setup

In this section, behaviours of manipulators in different human robots formations are investigated. The differences between two formation scenarios are analysed with respect to the motion of the manipulators and the internal force of the manipulated object.

The experimental setup consists of three KUKA LWR 4, see Fig. 3. A Cartesian impedance control scheme (6) is employed to ensure compliance of the end-effectors. Since we only consider translational movements for the manipulators, the rotational impedance parameters are in gravity compensation. A workspace extension for all robotic manipulators by a mobile platform can be accomplished according to a potential function approach presented in [2]. In our experiments the object is an exercise ball with a diameter of 0.65 m and a weight of 1.159 kg. All Cartesian positions are captured by a passive-marker QualiSys motion capture system at a frequency of 200 Hz. During the experiment, the human participant holds a marker-equipped handle in order to command the robot formation. For giving feedback (15) to the human the wearable vibrotactile wristband is developed at PERCRO lab to wirelessly deliver haptic stimuli at the user's wrist(16). The parameters for the tasks are chosen equally for each manipulator in all dimensions for (6) as $M = 10I_3$, $D = 120I_3$, $K = 160I_3$ and for (3) as $\delta_{ij} = 1, \forall i, j$. In order to evaluate different combinations of robotic neighbors and the importance of providing feedback to the human, three different scenarios are tested:

(a) No feedback to the human, $z = 0$, and the human neighbors as $N_h = \{2, 3\}$
   (1) without manipulated object.
   (2) with manipulated object.
(b) No feedback to the human, $z = 0$, and the human neighbors as $N_h = \{1, 2, 3\}$
   (1) without manipulated object.
   (2) with manipulated object.
(c) Feedback to the human provided by (15) & (16) and the human neighbors as $N_h = \{1, 2, 3\}$

B. Experimental design

1) Design & Procedure: Three robots are controlled to establish a formation. The participants are told to put on the wearable wristband and to grasp the handle with their right hand. They are instructed to manipulate the object by moving the handle. The manipulation phase lasts for approximately 60 seconds. For the first 30 seconds no feedback is given to the participants (b1). After 30 seconds they are provided with feedback (c).

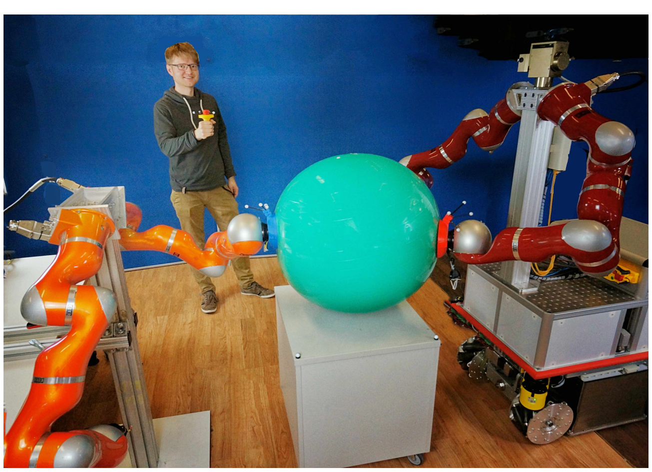

Fig. 3. Human operator controls a group of robots which cooperatively manipulate an object

2) Participants: A total of 12 participants volunteered to take part in this study where they became the human leader in the multi-robot formation. All participants were right handed. The average age of the participants was 27.7 years at the time of testing, and 3 of them were female. 9 of them have previously worked with robots.

C. Results and discussion of user study

We use a visual analogue scale to assess the subjective experience of the human in terms of the safety, ease, likeness of guiding the robotic team. Furthermore, by swapping the feedback in conditions (b1) and (c) the preference of having the vibrotactile feedback to assist the guidance is evaluated. In (c) the human received vibrotactile feedback based on (15) and (16). In (b1) no feedback was transmitted. The data are normalised between $0 - 10$ where 10 being the positive experience, and averaged across the participant. The results indicated that the participants experienced the guidance of the robotic team very safe with a mean score of 9.373 ± 0.590. Furthermore, a high score of ease (M = 9.003 ± 0.878) and likeness (M = 9.136 ± 1.121) in controlling the team are reported. The preference of using the vibrotactile feedback is reported slightly lower to the other subjective measures, scoring 7.567 ± 2.05. The analyses indicates that the user-centric guidance of robotic team is successfully implemented and vibrotactile feedback design based on the cooperative term (15) and (16) is preferred by the participants. Further investigation will elucidate wether the lower subjective appreciation of the vibrotactile feedback is due to the transmitted signal (15) or due to the mapping onto the vibrotactile outputs (16).

D. Results and discussion of conditions (a) and (b)

For the sake of readability, we only consider one dimension, $k = 1$. To compare conditions (a) and (b) a human input trajectory is recorded for reproducibility of the experiment. The recorded trajectory is replayed four times to cope with conditions (a1), (a2), (b1), and (b2).

The conditions (a) and (b) differ in N_h which result in different controllable subspaces. Fig. 6 depicts graphs of scenarios (a) and (b), respectively. By evaluating (12) for condition (a) we calculate one uncontrollable subspace $\tilde{x}_{\bar{c}} = \frac{1}{\sqrt{2}}(\tilde{x}_{2,1} - \tilde{x}_{3,1})$. Hence, the human can independently control two states $\tilde{x}_{c,1}$ and $\tilde{x}_{c,2}$ with different eigenvalues: $\lambda_1^{A_c} = -3.41$ and $\lambda_2^{A_c} = -0.59$. Due to (14) the desired trajectories of $\tilde{x}_{c,1}(t)$ and $\tilde{x}_{c,2}(t)$ diverge. For condition (a1) the controllable subspaces results as $\tilde{x}_{1,1}$ and as the average of $\frac{1}{\sqrt{2}}(\tilde{x}_{2,1} + \tilde{x}_{3,1})$. Since there are two independently controllable subspaces for condition (a), there is a deviation of the trajectory $p_{1,3}$ compared to trajectories $p_{2,1}$ and $p_{3,1}$ as shown in Fig. 4. As the human has no influence on the $\tilde{x}_{2,1} - \tilde{x}_{3,1}$, both actual trajectories $p_{2,1}$ and $p_{3,1}$ are equal.

For (b1) the locally controllable subspace is the aggregated state $\tilde{x}_c = \frac{1}{\sqrt{3}}(\tilde{x}_{1,1} + \tilde{x}_{2,1} + \tilde{x}_{3,1})$. Hence, the operator only guides one controllable eigenmode of the robot team which

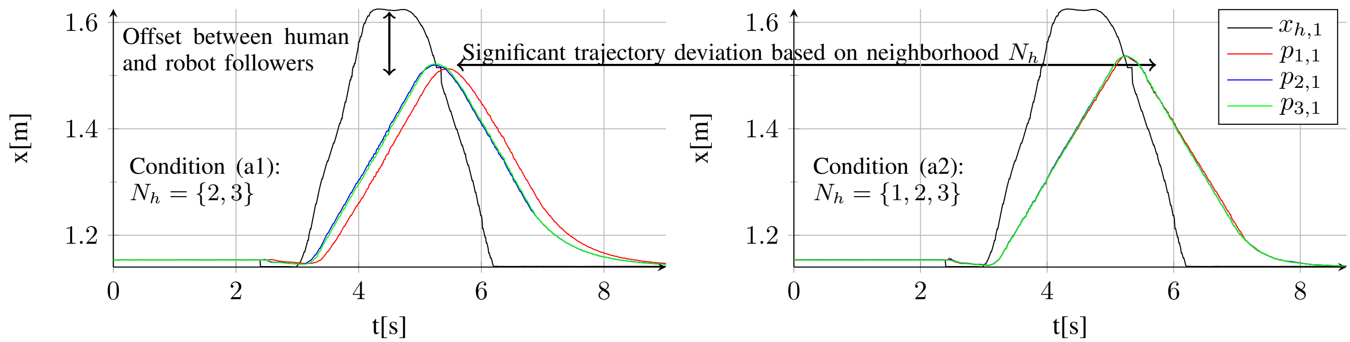

Fig. 4. Three physically uncoupled robots, i.e. without object, are controlled by the identical human input $x_{h,1}$ under different neighborhoods N_h. Different neighborhood topologies result in different controllable subspaces. Hence, the robot positions $p_{i,1}$ in one direction diverge due to different neighborhood $N_h = \{2, 3\}$ (left) and $N_h = \{1, 2, 3\}$ (right).

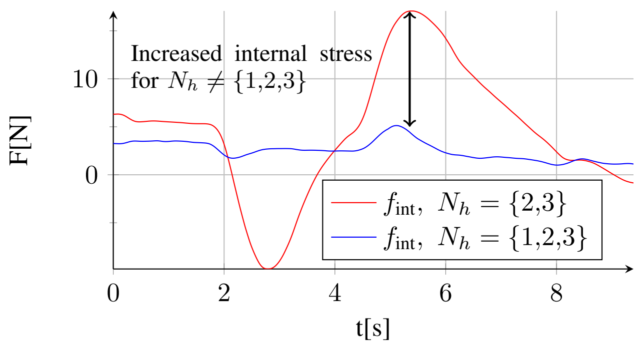

Fig. 5. Internal force between manipulator 1 and 3 in direction $k = 3$ resulting from different scenario conditions (a2) and (b2)

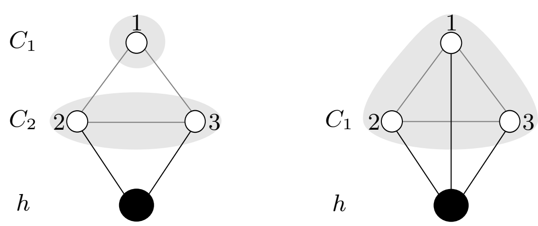

Fig. 6. Formations resulting from the scenario conditions (a) and (b). Human leader is denoted as •. Left: For $N_h = \{2, 3\}$ the human controls the cells C_1 and C_2 independently. Right: For $N_h = \{1, 2, 3\}$ the human controls the aggregated state of all robots within C_1.

moves the states $\tilde{x}_{1,1}$, $\tilde{x}_{2,1}$, $\tilde{x}_{3,1}$ simultaneously. Due to that the robot trajectories $p_{1,1}$, $p_{2,1}$, and $p_{3,1}$ are equal in Fig. 4. Hence, there is no breakup of the formation due to (14).

Since the deviation of the trajectory of $\tilde{x}_{1,1}$ is not in compliance with the object geometry an increased internal force on the object results for (a2), see Fig. 5. For $N_h = \{1, 2, 3\}$ in (b2) moving the aggregated robot state results in a reduction of internal forces acting on the object as shown in Fig. 5. It is demonstrated that the scenario (b) results in manipulator motions without considerable deviations and the internal force exerted on the object is reduced.

VI. Conclusions

In this paper we propose a control law and a feedback strategy for a robot team controlled by a single human in a cooperative manipulation task under formation-based paradigms. By analyzing the controllability of such a human-robot formation we deduce that a one-to-all connection is beneficial for the manipulation task. The effectiveness and quality of the virtual formation for cooperative manipulation is successfully demonstrated in experiments and a user study.

Acknowledgments

The work is partly supported by the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement no. 601165 of the project "WEARHAP - Wearable Haptics for Humans and Robots". The author would like to thank PERCRO, Scuola Superiore Sant'Anna , Pisa - Italy `a.frisoli@sssup.it` for providing the vibrotactile wristband.

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