Towards Natural Human-Swarm Teleoperation Using Hand Synergies

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***Abstract*— In this paper we present a novel approach for human-swarm teleoperation. This consists in exploiting the low dimensionality of the control inputs required to perform most grasping and manipulation tasks by humans, in order to intuitively and naturally control a swarm of robots. Moreover, the presented approach can be fully decentralized and, hence, entirely scalable. The teleoperation scheme is based on the definition of *swarm synergies* and leverages hand synergies to devise a natural mapping between the human hand of the user and a swarm of robots. The method has been validated in simulation and tested on actual robots on a swarm robotic research testbed.**

I. INTRODUCTION

The design of interfaces between a human operator and a swarm of robots is an open challenge in human-swarm interaction [1]. Several solutions have been proposed, that try to address this issue, see e.g. [2], [3], [4], [5], [6], [7]. In this paper, we consider the problem of manipulating objects with a swarm of robots controlled using only a human hand. The topic sits right in the intersection between swarm robotics and robotic manipulation. Indeed, the work done in robotic grasping has been the main source of inspiration that led to the novel human-swarm interface presented in this paper, specifically designed to target object manipulation using swarm of robots.

One of the most important results in the robotic grasping literature comes from neuroscience studies. Using principal component analysis (PCA), in [8] the authors show that the control of the posture of a human hand involves just a few *postural synergies*, that regulate the general shape of the hand. For this reason, a natural way of controlling a robotic swarm to manipulate objects consists in using synergies as inputs. With this in mind, in this paper we define synergies for swarms of robots entirely analogous to those discovered for human hands.

A. Motivations

Although a multi-robot system is able to fulfill missions that cannot be performed by individual robots separately, the external influence of a human input can provide the robotic system with higher-level cognitive functions. Indeed, endowing multi-robot systems with the intelligence of a human being has been foreseen as a key technique to enhance autonomous multi-robot systems [1]. Nevertheless, the control of robotic swarms by a human operator is a rather complicated task. That is mainly because, as mentioned in the Introduction, the interface with the human operator is still an open research problem.

Strategies to control multi-robot systems can be devised targeting the specific task that the human-swarm system has to accomplish. In this paper we focus on object grasping and manipulation, therefore a natural mapping between a human hand and a robotic swarm is sought. The work in [8] suggests that, out of the more than 20 degrees of freedom of a human hand, only two or three combinations can be used to shape the hand for basic grasps used in everyday life. [9] shows that the use of only one of these combination is indeed sufficient to control a robotic hand to perform a large number of grasping tasks. A similar approach can be employed to control a swarm of robots to perform grasping and manipulation tasks. If the goal were to control a robotic hand using a human hand, kinematic dissimilarities between the master (human hand) and slave (robotic hand) dictate the need of a natural and intuitive command mapping mechanism. In case the slave system is represented by a robotic swarm, the definition of a kinematic structure is required first. To this end, we propose to leverage formation control (a well-known technique in the swarm robotic literature) to define a kinematic structure, as will be explained in Section III. Once a kinematic structure has been defined, human hand synergies can be mapped to *swarm synergies* and used to control the swarm in a scalable, natural and intuitive way.

The main contributions of this paper are then the definition of a kinematic structure of a robotic swarm and its use in defining a scalable, natural and intuitive mapping between a human hand and a robotic swarm. We propose a *synergy-based formation control* for human-swarm teleoperation to accomplish grasping and manipulating tasks. To the authors' knowledge this is the first attempt to apply the concept of synergies to the teleoperation control of robotic swarms.

II. RELATED WORKS

The survey of human-swarm interaction (HSI) presented in [1] gives a broad overview on the contexts in which HSI systems are studied and presents most recent advances in HSI technology. Scalable human control strategies to deal with the large state spaces and the complex dynamics of multi-robot systems are recognized to be one of the most important requirements in the design of HSI systems.

In [3], the authors introduce the *flying hand*, i. e. a robotic hand consisting of a swarm of UAVs able to grasp a manipulate an object. The mapping between a human hand and the

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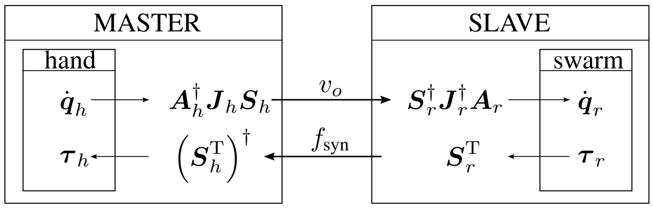

Fig. 1: The presented HSI framework.

flying hand is achieved as follows: desired motion of a virtual object being manipulated by the human hand is calculated and transfered to the swarm of UAVs. The work in [5] presents a task-oriented teleoperation where robotic system dynamically selects the most suitable robots and manages task transfers from one robot to another to achieve a smooth execution of teleoperated tasks. A solution to manipulation of a load in a plane is presented in [6], whereas [7] proposes a bilateral teleoperation scheme for cooperative aerial manipulation controlled by an haptic device.

In this paper, we introduce a partially decentralized controller for swarm grasping, manipulation and transportation. The introduction of swarm synergies in robotic swarm teleoperation has the following benefits: (i) it allows to reduce the dimensionality of the control input that is sent to the robots and (ii) it allows to define a scalable, natural and intuitive way of controlling the robotic swarm, by projecting the human hand synergies onto the multi-robot input space.

III. SYSTEM MODELING

In this section we present in detail the teleoperation framework used to control a robotic swarm by means of a human hand. The tools from the grasping and the multi-robot control literature are briefly introduced and modified to be applied to the proposed framework. Fig. 1 depicts the general teleoperation framework in which the presented work would fit and reports the notation that will be used throughout this section. In this paper we focus only on the top branch that connects master (human hand) and slave (robotic swarm) devices.

Let $\boldsymbol{q}_h \in \mathbb{R}^{n_q}$ be the vector of generalized coordinates used to characterize the human hand configuration, n_q being the number of actuated joints. The reduced dimension representation of the hand configuration in terms of synergies is denoted by $\dot{\boldsymbol{z}}_h \in \mathbb{R}^{n_z}$, where n_z is the dimension of the synergy space. The relation between the derivative of the two vectors is encoded by the $\boldsymbol{S} \in \mathbb{R}^{n_q \times n_z}$ matrix as follows [10]:

$$\dot{\boldsymbol{q}}_h = \boldsymbol{S}_h \dot{\boldsymbol{z}}_h .$$

Two more matrices are required to analyze general grasping problems: the grasp matrix $\boldsymbol{G}_h \in \mathbb{R}^{6 \times n_c}$ and the hand Jacobian $\boldsymbol{J} \in \mathbb{R}^{n_c \times n_q}$, where n_c denotes the dimension of the contact space and depends upon the adopted contact model between hand fingers and manipulated object (see [11] for further details). These matrices allow to establish the following relations:

$$\dot{\boldsymbol{p}}_o = \boldsymbol{G}_h^{\mathrm{T}} \boldsymbol{u} \tag{1}$$

$$\dot{\boldsymbol{p}}_h = \boldsymbol{J}_h \dot{\boldsymbol{q}}_h , \tag{2}$$

where $\boldsymbol{u} = [\dot{\boldsymbol{o}}_h^{\mathrm{T}}, \boldsymbol{\omega}_h^{\mathrm{T}}]^{\mathrm{T}}$ denotes the object twist, $\boldsymbol{p}^o$ and $\boldsymbol{p}^h$ denote the vectors of contact points on the object and on the hand, respectively. As in [11] we consider the human hand in contact with a virtual object used to describe the hand action in the object domain. Choosing as virtual object the minimum sphere inscribable in the hand fingertips $\boldsymbol{p}_h$ and considering the effect that the object motion has on those points we can write:

$$\dot{\boldsymbol{p}}_h = \boldsymbol{A}_h \begin{bmatrix} \dot{\boldsymbol{o}}_h \\ \boldsymbol{\omega}_h \\ \dot{\boldsymbol{r}}_h \end{bmatrix} , \tag{3}$$

where $\boldsymbol{A}_h \in \mathbb{R}^{n_c \times 7}$ is defined as

$$\boldsymbol{A}_h = \begin{bmatrix} \boldsymbol{I} & -[p_{1h} - o_h]_\times & p_{1h} - o_h \\ \cdots & \cdots & \cdots \\ \boldsymbol{I} & -[p_{ih} - o_h]_\times & p_{ih} - o_h \\ \cdots & \cdots & \cdots \end{bmatrix} , \tag{4}$$

and $[\cdot]_\times$ denotes the skew-symmetric matrix associated with its three-dimensional vector argument. The first six columns of $\boldsymbol{A}_h$ corresponds to the transpose of grasp matrix $\boldsymbol{G}_h$. At this point, combining the above equations we can write:

$$\begin{bmatrix} \dot{\boldsymbol{o}}_h \\ \boldsymbol{\omega}_h \\ \dot{\boldsymbol{r}}_h \end{bmatrix} = \boldsymbol{A}_h^{\dagger_r} \dot{\boldsymbol{p}}_h = \boldsymbol{A}_h^{\dagger_r} \boldsymbol{J}_h \boldsymbol{S} \dot{\boldsymbol{z}}_h , \tag{5}$$

where $\boldsymbol{A}_h^{\dagger_r}$ represents the right pseudoiverse of $\boldsymbol{A}_h$.

On the slave side, a relation between object motion and swarm synergies has to be derived. Starting from the desired object motion, we can define the matrix $\boldsymbol{A}_r$ as the matrix that relates the object velocities to the velocities of points of contact between the robotic swarm and the real object that has to be grasped and/or manipulated, i. e.:

$$\dot{\boldsymbol{p}}_r = \boldsymbol{A}_r \begin{bmatrix} \dot{\boldsymbol{o}}_h \\ \boldsymbol{\omega}_h \\ \dot{\boldsymbol{r}}_h \end{bmatrix} \tag{6}$$

This matrix is defined as follows:

$$\boldsymbol{A}_r = \begin{bmatrix} \boldsymbol{I} & -\boldsymbol{R}_{\frac{\pi}{2}} & p_{1r} - o_r \\ \cdots & \cdots & \cdots \\ \boldsymbol{I} & -\boldsymbol{R}_{\frac{\pi}{2}} & p_{ir} - o_r \\ \cdots & \cdots & \cdots \end{bmatrix} \in \mathbb{R}^{n_c^s \times 5} , \tag{7}$$

where n_c^s depends on the number of contact points and the contact model adopted at the slave, $\boldsymbol{R}_{\frac{\pi}{2}}$ is the 2×2-matrix that rotates vectors of $\frac{\pi}{2}$ in the plane, and o_r is the point to which o_h is mapped.

Now, in order to define swarm Jacobian and swarm synergies, let us proceed as follows. Let $\mathcal{G} = (V, E)$ be the graph consisting of a set of nodes V and a set of edges $E \in V \times V$. $\mathcal{G}$ defines the topology of the multi-robot system that is the slave of the teleoperation system considered here. To define synergies, generalized coordinates are required. To this end, let us consider the formation error defined for each robot i [12] as:

$$\mathcal{E}_i = \sum_{j \in \mathcal{N}_i} \omega_{ij} \left(\|\boldsymbol{x}_j - \boldsymbol{x}_i\|^2 - d_{jk}^2 \right)^2, \tag{8}$$

where $\mathcal{N}_i$ is the set of neighboring robots of robot i, $\boldsymbol{x}$ is the robot pose, d_{jk} are the distances that one would desire to maintain in a formation, and ω_{ij} are formation gains. Therefore, the values of d_{jk} lend themselves to be used as generalized coordinates of a virtual kinematic structure of the robotic swarm. This way we can, first of all, define a swarm Jacobian $\boldsymbol{J}_r$. Moreover, by recording data of the motion of the robots and perform the PCA to extract the most important linear combinations of actuated virtual joints, thus getting the matrix $\boldsymbol{S}_r$.

We have now all the required transformation matrices to get from the human hand synergies velocities $\dot{\boldsymbol{z}}_h$ to the robotic swarm synergies velocities $\dot{\boldsymbol{z}}_r$. This evaluates to the following expression:

$$\dot{\boldsymbol{z}}_r = \boldsymbol{S}_r^{\dagger_l} \boldsymbol{J}_r^{\dagger_l} \boldsymbol{A}_r \boldsymbol{K}_c \boldsymbol{A}_h^{\dagger_r} \boldsymbol{J}_h \boldsymbol{S}_h \dot{\boldsymbol{z}}_h \tag{9}$$

where $\boldsymbol{K}_c$ is a gain matrix.

The human hand synergies that are evaluated real time, as explained before, are turned into synergies of the robotic swarm and communicated to the robots individually. Then, each robot minimizes its cost defined in (8) in a completely decentralized fashion. For this reason, we say that the algorithm is partially decentralized. Exploiting communication between agents, the master would potentially be required to communicate only with one of the robots of the swarm.

IV. EXPERIMENTS AND RESULTS

With the goal of grasping and manipulating objects in a plane using a swarm of planar robots, a human operator has been asked to shape his hand as to grasp and rotate a spherical object around an axis fixed in space. The generalized coordinates of the human hand $\boldsymbol{q}_h$ (4 coordinates for each finger) have been recorded using a Leap Motion device[1]. Using these data, the synergy matrix $\boldsymbol{S}_h$ has been computed using standard PCA.

A. Simulated experiments

Simulations have been carried out in MATLAB using the Syngrasp MATLAB toolbox [13] (to simulate the master hand) and the Robotarium simulator[2] (to simulate the robotic swarm slave). Snapshots in Figures 2a and 2b show the first two synergy-actuated motions using the paradigmatic hand model provided by the Syngrasp MATLAB toolbox. The joint velocities $\dot{\boldsymbol{q}}_h$ are read in real time from the Leap Motion device and their low dimensional representation in terms of synergy is computed as $\dot{\boldsymbol{z}}_h = \boldsymbol{S}^{\dagger_l} \dot{\boldsymbol{q}}_h$, where $\boldsymbol{S}^{\dagger_l}$ denotes the left inverse matrix of $\boldsymbol{S}$[3]. The corresponding slave side motion, computed according to (9) can be seen at the bottom of Figures 2a and 2b.

[1] www.leapmotion.com

[2] www.robotarium.org

[3] This means that plugging $\dot{\boldsymbol{z}}_h$ back into (9) yields a projection onto the column space of $\boldsymbol{S}$.

B. Real experiments

Real experiments have been performed on the Robotarium, a remotely accessible swarm robotics test bed [14]. As the simulated experiments already confirmed the successful application of the proposed teleoperation framework, real experiments have been motivated by the difficulties of having a realistic simulation of contacts between the robots and the object to grasp or manipulate. Figures 3a and 3b show the application of the first two synergies that have been extracted from the collected data and that can be used to grasp and rotate an object in a plane. The robustness of the system, introduced by the presence of the human operator, has guaranteed a successful application of the proposed teleoperation strategy to actual robots as well.

V. CONSLUSIONS AND FUTURE WORK

In this paper we proposed a novel, intuitive and natural way of controlling swarms of robots using the capabilities provided by the human hand. This has been achieved by controlling the multi-robot system using hand synergies. These are obtained by extracting the principal components of the joint motions in a human hand. Then, by defining a proper kinematic structure of the swarm, they are mapped onto the synergy space of the robotic system. Thus, a natural and intuitive way of controlling a robotic swarm is achieved. The proposed teleoperation framework has been tested both in a simulated environment and on a team of actual differential drive robots on the Robotarium.

Future work to improve the method presented in this paper will consist in designing an haptic device (such as an exoskeleton) capable of transferring the sensed forces back to the human operator. This will allow the operator to exploit both visual and force feedback in order to further improve the performances of the teleoperation system.

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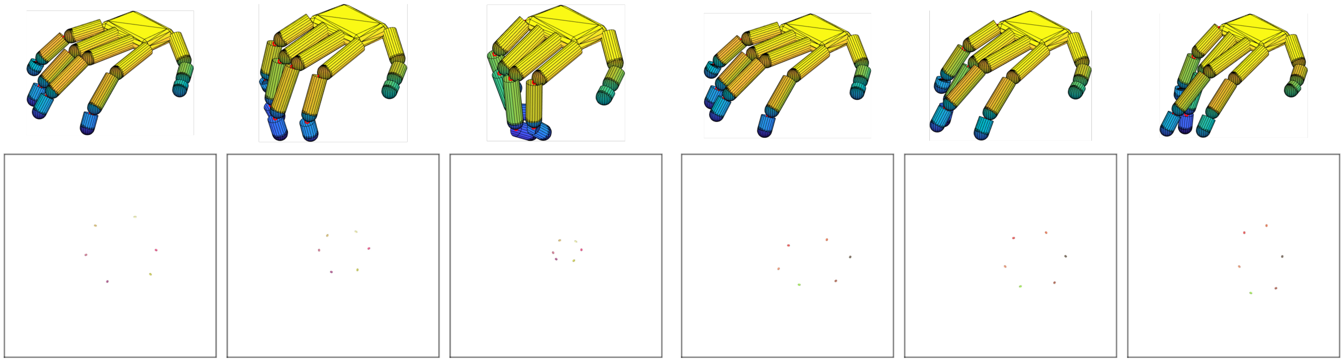
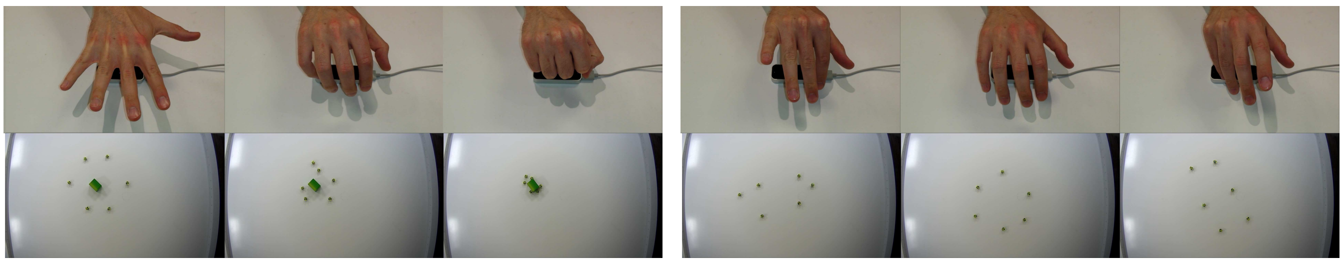


(a) First synergy. (b) Second synergy.

Fig. 2: Snapshots of the simulated environment used to test the proposed teleoperation framework.



(a) First synergy. (b) Second synergy.

Fig. 3: Snapshots of the video recorded on the Robotarium, a remotely accessible swarm robotics testbed, on which the proposed teleoperation framework has been validated.

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