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***Abstract*—**

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 author shows 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 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. [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.

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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

Let $\boldsymbol{q}_h \in \mathbb{R}^{n_q}$ be the vector of generalized coordinates for describing the human hand configuration, where n_q denotes the number of actuated joints. The reduced dimension representation of hand configuration is represented by the vector $\dot{\boldsymbol{z}}_h \in \mathbb{R}^{n_z}$, where n_z denotes the dimension of the synergy space. The relation between the derivative of the two spaces is encoded by the $\boldsymbol{S} \in \mathbb{R}^{n_q \times n_z}$ matrix according to

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

Two other matrices are of interest when analyzing a grasp: 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 (see [10] for further details). These matrices allows 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 $\boldsymbol{u} = [\dot{\boldsymbol{o}}_h^{\mathrm{T}}, \boldsymbol{\omega}_h^{\mathrm{T}}]^{\mathrm{T}}$ denote 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 [10] 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

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

and 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

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

where $\boldsymbol{A}_h^\dagger$ denotes the right pseudoiverse of $\boldsymbol{A}_h$. The same applies for the slave side...

$$\dot{\boldsymbol{z}}_r = \boldsymbol{S}_r^\dagger \boldsymbol{J}_r^\dagger \boldsymbol{A}_r \boldsymbol{K}_c \boldsymbol{A}_h^\dagger \boldsymbol{J}_h \boldsymbol{S}_h \dot{\boldsymbol{z}}_h \tag{6}$$

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

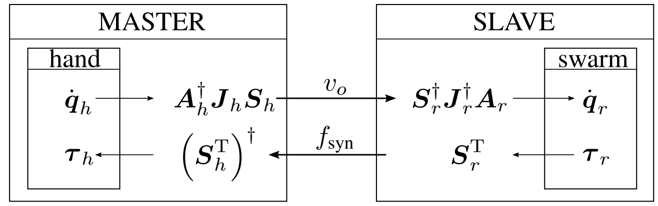

Fig. 1: HSI framework

IV. EXPERIMENTS AND RESULTS

A human operator has been asked to shape his hand as he was grasping and manipulating by rotation a spherical object. Generalized coordinates of the human hand $\boldsymbol{q}_h$ (4 coordinates for each finger) have been recorded using Leap Motion device. The synergy matrix $\boldsymbol{S}$ has been computed using PCA. Snapshots in Fig.?? show the first two synergy-actuated motion using the paradigmatic hand model included in Syngrasp MATLAB toolbox [11].

A. Simulation

The simulated experimental tests test have been realized by reading in real time $\dot{\boldsymbol{q}}_h$ from the Leap Motion device and computing its reduced space representation as $\dot{\boldsymbol{z}}_h = \boldsymbol{S}^\dagger \dot{\boldsymbol{q}}_h$[1]. The corresponding slave side motion, computed according to (6) can be seen in Fig.??

B. Real scenario

Real experiments have been performed using the Robotarium, an open, remote-access multi-robot testbed [12]. These are motivated by the difficulties of having a realistic simulation of contacts with the object at the slave side.

V. CONSLUSIONS

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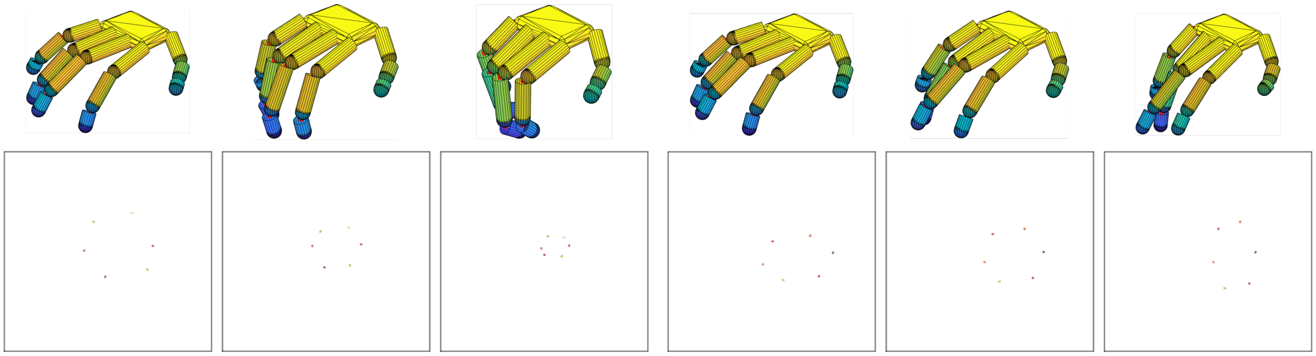
[1]Note that $\boldsymbol{S}^\dagger$ denote the $\boldsymbol{S}$ left inverse matrix. This means that plugging $\dot{\boldsymbol{z}}_h$ into (6) is equivalent to project $\dot{\boldsymbol{q}}_h$ onto the column space of $\boldsymbol{S}$. check this



(a) (b)

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