Towards situational awareness from robotic group motion

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Abstract— **The control of multiple robots in the context of tele-exploration tasks is often attentionally taxing, resulting in a loss of situational awareness for operators. Unmanned aerial vehicle swarms require significantly more multitasking than controlling a plane, thus making it necessary to devise intuitive feedback sources and control methods for these robots. The purpose of this article is to examine a swarm's nonverbal behaviour as a possible way to increase situational awareness and reduce the operators cognitive load by soliciting intuitions about the swarm's behaviour. To progress on the definition of a database of nonverbal expressions for robot swarms, we first define categories of communicative intents based on spontaneous descriptions of common swarm behaviours. The obtained typology confirms that the first two levels (as defined by Endsley: elements of environment and comprehension of the situation) can be shared through swarms motion-based communication. We then investigate group motion parameters potentially connected to these communicative intents. Results are that synchronized movement and tendency to form figures help convey meaningful information to the operator. We then discuss how this can be applied to realistic scenarios for the intuitive command of remote robotic teams.**

I. INTRODUCTION

Mobile robots are becoming more prevalent in a variety of tele-exploration tasks such as surveillance of large areas, emergency response and military deployment. However, fully autonomous robotic systems are sensitive to unconstrained and dynamic environments, and human operator inputs are required in many critical scenarios. With scenarios that benefit from an increased number of deployed units, the operator's load also increases quickly and diverts his or her attention from gathering contextual information from the robots. In the end, most tele-operation tasks are about gathering knowledge on the deployment site, i.e. situational awareness (SA) for the mission. With larger robotic teams, the information to be processed by the operator may become overwhelming. For instance, an Unmanned Aerial Vehicles (UAV) swarm creates a large amount of data and requires significantly more multitasking than controlling a single UAV, because multiple vehicles must be supervised at once and the data collected by these UAVs – which may be of different types (visual, infrared, audio, etc.) and from different perspectives – must be aggregated by the operator. This can overwhelm operators and lead to loss of SA [1]. Since it was shown that adding multiple types of feedback modalities reduce cognitive workload [2] and improve operator SA, we aim at exploring one specific to swarms: group motion.

As we observed in a previous study [3], with robot swarms, the necessity to consider multiple individuals makes it necessary to develop intuitive channels of communication that rely on collective movements. We therefore examine a swarm's nonverbal behaviour as a possible communication way to help increase SA specifically in exploration scenarios.

This subscribes to the emergent interdisciplinary field of "machine behaviour" [4], which is concerned with the scientific study of intelligent machines, not only as engineering artifacts, but as a class of actors with particular behavioural patterns, able to influence human decisions at several levels. Because of the complex behavioural properties of the swarm, even if the individual algorithms covering the behaviour can be relatively simple, it can be difficult to formalize them analytically [5]. Therefore, we propose to combine design and engineering techniques with classical social sciences methods to study the behaviour of biological agents and their communication capabilities.

More specifically, this study aims to address two research questions:

1) Can the behaviour of the swarm provide sufficient predictive non-verbal communication power?
2) Can agents demonstrate specific behaviours (through their interaction with the world and other agents of the swarm) that are uniformly predictable by human observers?

We first cover the inspiration of our work from literature and then detail two user studies: 1. an exploratory set of eleven sessions for the typology of informative swarm motions, and 2. an online survey with 113 participants on the relationship between this typology and the perceived organization of the swarm. We then discuss results and potential applications.

II. MOTIVATION

A. Sharing situational awareness with robotic teams

Situational awareness is defined by Endsley as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [6]. Endsley's model defines three levels of SA including 1. the perception of the elements in the environment, 2. the comprehension of the current situation and 3. the projection of the future state . All of which are mandatory to conduct exploration

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missions, but might be more complex to acquire with artificial team members and remote deployments. Robotic units do not provide natural language modalities as with other human team members. Even in human-only teams, good situational awareness is more tedious to achieve in distributed teams, i.e. with team members not sharing the same working environment [7]. These hindrances become critical when the resources are limited (autonomy and reaction time available) and the consequences, costly.

For a remote robotic deployment, the operator(s) SA is continuously fed by the field units to fulfill the mission, but also to manage the remote robots. This task quickly becomes mentally challenging for the operator. As Cummings and Mitchell [8] demonstrated in a targeting mission, four UAVs is the largest number an operator can actively control at once without losing SA to the point of mission degradation. The solution to manage larger robotic groups is two-fold: autonomy (e.g. self-decision-making) and intuitive SA sharing. Indeed, high autonomy by itself can reduce significantly the operator workload related to the commands, but can still undermine the achievement of SA for the mission. Hsieh et al. [9], for instance, deployed more than 15 ground and air robots to evaluate how the operator situational awareness can be optimized. Their solution was to transfer the raw data from the robots sensors, only when queried, directly to the operator for analysis. While this gives all flexibility to the operator to parse and interpret the low-level information, it also needs a large information management system and can delay the interpretation of the field situation.

On the other hand, Amelink et al. [10] allowed operators to select their preferred level of abstraction when performing a basic navigation and surveillance mission. Operators uniformly preferred higher levels of abstraction, unless a unit required special attention (UAV failure). Similar findings were extracted from experiments involving a single UAV, where Augmented Reality was leveraged to communicate high-level intents (goals of the robot to the operator [11], [12].

In the end, with more processing power and intelligence available on modern robotic platforms, sharing only high-level information could be preferable to decrease the operator load and focus the attention on the most relevant information for mission SA. The key is to find the proper communication way to intuitively convey this information to the operator. In the case of a tele-exploration task, a clue was given by the work of Memar and Esfahani [13]: SA is more related to the operator aptitude to track multiple objects at the same time rather than the system's effectiveness at visual search. Therefore using the motion of the group to convey information could be a more intuitive approach for the operators.

B. *Using collective movement to communicate*

It is part of the design of socially interactive robots to make use of nonverbal expressions to provide feedback about their internal state and to allow a fluid and intuitive human interaction [14], [15], [16], [17]. Social robots may use deictic gestures to point towards a direction [18], gaze cues to create a shared attentional space and coordinate collaborative tasks [19], and emblematic gestures to communicate intentions and affective states [20]. Such a vocabulary of nonverbal expressions is contingent on the artificial reproduction of a gestural and postural repertoire. The recent emergence of non-humanoid robots such as drones has motivated the exploration of other signaling channels bases and motion patterns [21], [22], [23]. However, in the case of robot swarms, the absence of a definite physicality, and the ability to reconfigure at will, prevent the use of common nonverbal expressions used in the context of social interactions. An observer facing a swarm of robots has to rely on other kinds of intuitions to decode possible feedback about the swarm's ongoing operations. He or she has to consider the emergent properties resulting from multiple individual behaviours, for instance the tendency for the individuals to remain close to each other, or to match velocities. Specific intuitions, belonging to the domain of perception of ensemble (e.g. average velocity, average direction), or to the domain of Gestalt properties (e.g. common fate), govern the perception of the swarm as a coherent entity. As such, informing the user of the swarms current state and its mission status would depend on the capability to harness those intuitions and to use the expressive potential of collective movements to convey communicative intents. Determining the parameters of a swarms behaviour specifically correlated to expressive figures remains an uncharted field of investigation. Recently, researchers have started examining how swarm behaviours are associated with emotional states [24]. Our own experimental investigation has demonstrated how the expressiveness of a swarm is connected with the variation of parameters of spatial and temporal synchronicity [3].

III. STUDY 1: A TYPOLOGY OF COMMUNICATIVE INTENTS

The first study is an attempt to establish a typology of communicative intents conveyed by the collective movements of a robot swarm. This is a follow-up to our previous studies [3] that examined the level of perceived organization and the state attributed to some collective patterns of movement. Collective behaviours of a robot swarm may convey messages for a user to get information about the swarms state and current operations. As we need to map the expressive potential of a robot swarm, we started investigating the possible communicative intents a swarm may transmit through group motion. This study examines participants descriptions of motion sequences to extract a list of communicative categories.

A. *Swarm motion design for spontaneous verbalization*

Our investigation started with the design of five video clips representing robotic units conducting an exploration mission until they start communicating with the operator through their motion. Those clips depicted five small table-top robots (Zooids [25]) moving over a white background (Fig. 1). The motion sequences were designed using Buzz, a programming

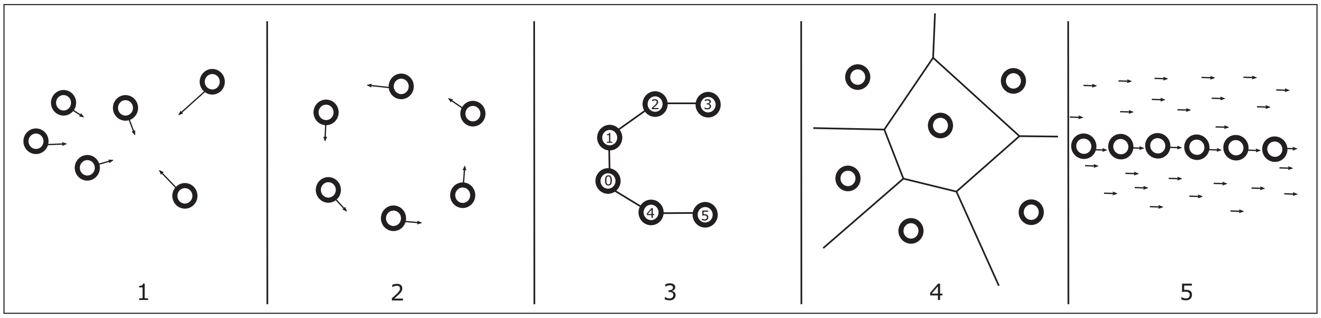

Fig. 1. Common swarm behaviours implemented for this study: 1. aggregation, 2. cyclic pursuit, 3. graph formation, 4. uniform deployment, and 5. aligned flocking.

language and virtual machine created by our research group to facilitate the developers work when dealing with decentralized algorithms [26]. The main peculiarity of Buzz is that it merges bottom-up behaviour development (i.e. assigning tasks to specific robots) with a top-down strategy definition for the whole swarm. We used the five decentralized control algorithms detailed in our previous work [27]: 1. aggregation, 2. cyclic pursuit, 3. graph formation, 4. uniform deployment, and 5. aligned flocking. These control algorithms, representing common swarm behaviours, constitute a template from which obtaining information about the way observers intuitively interpret collective movement and extract meaningful patterns from it. The rationale for the creation of the video clips was to represent a sudden change in the swarms organization, possibly indicating that the swarm is attempting to convey a message. For this purpose, each clip started with a 10s sequence of random movements. After this duration, the robots organize themselves into one of the five motion patterns shown in Fig. 1. All sequences are available online (`http://initrobots.etsmtl.ca/sazooid`).

B. Methods

Ten participants (6 males and 4 females, aged between 14 and 44) were presented with videos of the five sequences executed by five small table-top robots (Zooids). The order of presentation of the five sequences was randomized. Participants were instructed to imagine that the sequences represented five drones sent to explore an unknown environment. Their task was to describe what message the drones were trying to convey by their movements. To keep their description the most succinct possible, they were told to imagine having to transmit this message to another person (an operator) that would have to make a decision to control the drones.

From the 55 descriptions obtained (5 sequences $\times$ 11 participants), we extracted verb phrases (i.e. syntactic units composed of at least one verb and its dependents: objects, complements and other modifiers). Examples of verb phrases (VP) we collected include "(the robots) try to say that something needs to be investigated at this place", "(the robots) ask for some help", "(the robots) are exploring this position to determine where the danger is coming from". Due to the intrinsic vagueness of some descriptions and some redundancies, we sometimes included more than one VP into what formed a logically connected proposition.

C. Results

We extracted a list of 197 VPs (aggregation: 44; cyclic pursuit: 34; shape formation: 37; uniform deployment: 47; linear flocking: 35). These VPs were then grouped by similarity by two judges. The two initial classifications were respectively composed of 17 and 19 categories. A comparison between the two classifications led to a smaller set of categories. In defining the final categories, we were led by the research of broad classes of communicative intents that could fit realistic messages transmitted during the course of the drones' mission. After having excluded 77 VPs that were too difficult to understand or that merely described the configuration adopted by the swarm, we determined the following distribution of VPs:

- 26.7% of the VPs corresponded to the description of an action performed by the swarm ("they are dancing", "they are trying to find a way to escape", "they caught something");
- 18.3% of the VPs described the swarm as exploring a position or a zone ("they try to identify something", "they are exploring an unknown territory");
- 15.8% of the VPs indicated a communication between the robots of the swarms ("they are trying to agree on something","they are concentrated on one another more than on the environment");
- 15% of the VPs described an action of pointing towards a location ("they try to indicate something they have found", "they try to direct the attention towards this point");
- Finally, 10%, 7.5% and 5.8% of the VPs concerned respectively a communication on the state of the mission ("they found something hostile"), an indication on the current state of the swarm ("they are alert"), and a request sent by the swarm ("they need some help").

From this distribution, we propose the following set of seven communicative intents conveyed by a robot swarm:

- **Current state of the swarm**: messages related to the operational status of the swarm (breakdown, autonomy status, etc.) and affective states manifested through the collective movement (being in a state of confusion, fear, joy, etc.);

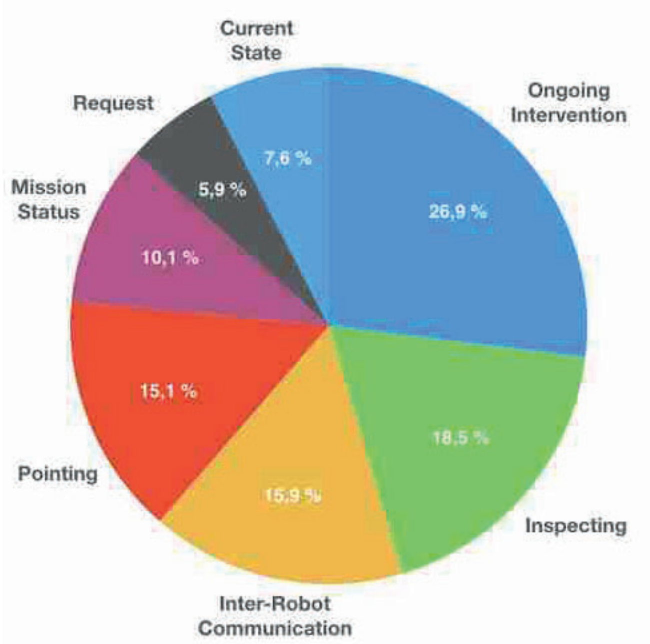

Fig. 2. Distribution of the categories of communicative intents.

- **Request**: messages conveying the need for help, a request for intervention, or more resources needed at a particular position;
- **Pointing**: deictic messages referring to a point of interest, a direction, a particular object;
- **Inspecting**: messages indicating the ongoing investigation of a position or zone on the field;
- **Ongoing intervention on the field**: messages indicating the organization of the swarm for the purpose of taking action on the field;
- **Inter-Robot Communication**: messages indicating the fact that the robots are currently transmitting information to one another;
- **Mission Status**: messages relative to the current state of the ongoing mission.

The distribution of the communicative intents extracted from this study is illustrated in Fig. 2.

IV. STUDY 2: RELATIONSHIP BETWEEN COMMUNICATIVE INTENTS AND PERCEIVED ORGANIZATION

From the previous study, we obtained a list of categories of communicative intent that forms a vocabulary of non-verbal expression for robot swarms. To understand how the categories of communicative intent are related to the identification of collective patterns of movement, we conducted a second study investigating the relationship between parameters of perceived organization and the categories previously described. This study was based on the motion sequences designed for the first study, that served as a basis for the evaluation of the following parameters of perceived organization, introduced in [3] :

- a parameter of **aggregation**, corresponding to the impression for an observer that the robots forming the swarm tend to stay together rather than scattering;
- a parameter of **synchronization**, or the impression that the robots are aligning their movements;
- a parameter of **leadership** addressing the impression that the robots are following or chasing a member of the swarm;
- a parameter of **figure** formation corresponding to the identification of figures from the configurations formed by the swarm (e.g. a square or a circle); and
- a parameter of **reactivity** that assesses whether robots composing the swarm tend to react to each other.

A. Methods

This study was conducted online using the video clips designed for the first study. The participants were recruited through direct email invitations and with promotion of the study over social networks. We reached out to 112 participants, 22% men, 77% women and 1% other. The age of participants was well distributed: 23% below 29, 32% between 30 and 39, 28% between 40 and 49 and 17% were above 50. The participants did not receive financial compensation for this study, and the protocol was approved by both universities' ethical committees (University Paris 8 and Polytechnique Montreal). Before the online questionnaire started, all participants had to accept the consent form for this study. The order of the sequence has a known influence on the result for each video and so we asked the participants to select one of three possible orders based on their age group (less than 25, between 25 and 35 and above 35). To assess the values of communicative intents and perceived organization, participants completed a survey comprising two different scales (Table I). For each item of the different scales, we used a seven-point Likert scale with response ranging from 0 (strongly disagree) to 6 (strongly agree).

B. Results

As shown in Table I some communicative intents are specifically related to parameters of perceived organization. We used Kendall's τb correlation test to assess the contribution of each parameters in our dataset.

The first result is that all categories of communicative intent (except Current State of the Swarm) are positively correlated to the formation of salient figures. This result suggests that the possibility to identify iconic formations may help the recognition of a communicative behaviour. This seems to be the case especially for *Pointing*, *Request*, *Inspecting*, and *Mission Status*, which show the strongest levels of correlation with this parameter.

The identification of communicative intents tends also to be dependent on the perception of the robots as synchronizing their movements, as illustrated by a positive correlation between this parameter and all but two (*Inspecting* and *Mission Status*) categories of communicative intent. This may suggest that a sufficient level of perceived synchronization is necessary for observers to identify an attempt of the swarm

TABLE I

TWO SCALES TO ASSESS THE VALUES OF COMMUNICATIVE INTENTS AND PERCEIVED ORGANIZATION

1	on a scale from 0 to 6, indicate to which extent you agree with the following statements: • the robots communicate between each other; • the robots signal their current state; • the robots signal their mission status; • the robots take action on their environment; • the robots inspect their environment; • the robots point to something in their environment; • the robots send a request;
2	on a scale from 0 to 6, indicate to which extent you agree with the following statements: • the robots tend to stay in groups; • the robots tend to synchronize their movements; • the robots tend to follow one of theirs; • the robots tend to react to the movements of the other robots; • the robots tend to form figures;

TABLE II

CORRELATION SCORES FOR THE SEVEN CATEGORIES OF COMMUNICATIVE INTENTS (τB)

	State of the Swarm	Request	Pointing	Inspecting	Ongoing Intervention	Inter-Robot Communication	Mission Status
tend to stay in group	0.075	0.063	0.039	-0.010	**0.094**	0.238	0.011
tend to synchronize	**0.092**	**0.115**	**0.170**	-0.019	**0.104**	**0.197**	0.062
tend to follow one of theirs	0.045	0.036	0.02	0.059	0.058	**0.174**	0.008
tend to form figures	-0.001	**0.100**	**0.105**	**0.087**	**0.082**	**0.068**	**0.105**
tend to react to each other	0.053	0.012	0.045	**0.119**	**0.105**	**0.276**	0.070

to communicate. *Pointing*, *Ongoing Intervention*, and *Inter-Robot Communication* are the most strongly associated to this parameter. The fact that *Inspecting* is not significantly correlated to the tendency to synchronize possibly means that participants sometimes perceived the action of inspecting as a collection of individual actions, each robot of the swarm having its own independent procedure of inspection.

The tendency to perceive the robots as reacting to each other seems also to be an important parameter for the identification of communicative intents. In this case the categories most strongly associated with this parameter were: *Inspecting*, *Ongoing Intervention*, and *Inter-Robot Communication*. On the other hand, the tendency to perceive the robots following one of their own is significantly correlated to *Inter-Robot Communication*. The identification of this category may indeed depend on the detection of chasing relationships among the robots' movements.

V. DISCUSSION & CONCLUSION

In these two studies we explored forms of non-verbal communication suitable for UAV swarms. With the goal of using collective behaviours as a communication channel to convey messages about the swarms status, we established a typology of communicative intents related to group motion parameters. The first study was based on the extraction of broad categories of communicative intent from spontaneous descriptions of common swarm behaviours. We found that a majority of the descriptions used by participants refers to a form of direct relationship between the swarm and the field it overlooks, in the form of direct intervention, inspection of a zone, or the action of pointing towards a location. We found also that a fair amount of the descriptions point to communication between the robots. Using the terminology elaborated by Endsley [6] to describe levels of situational awareness (SA), we found that most messages identified by participants concern the first two levels. The swarm's behaviour contributes to the comprehension by the users of some relevant elements in the environment (first level). The swarm is seen as trying to attract the attention towards a particular location (*Pointing*), or the zone it is trying to cover (*Inspecting*). Other communicative categories we extracted can be associated to the second level of SA: comprehension of the current situation. At this level the swarm's behaviour may provide cues regarding the significance of the elements of the situation with respect to its mission or some constraints the swarm is currently facing. The swarm is thus perceived as giving indication on its current operational state (*Current State*), on its need for support (*Request*), or conveys a sense of the action it is trying to accomplish (*Ongoing Intervention*), or reporting on the current state of its operations (*Mission Status*).

This first vocabulary of communicative intents is associated with certain group motion parameters. We found in Study 2 that most categories of communicative intent are associated with a combination of parameters of forming figures and synchronization, as well as to the perceived tendency for the robots to react to each other. Elaborating on these simple parameters, and the way they are temporally organized inside sequences of movements, we could imagine that more expressive figures could be designed to convey specific messages related to a mission. For instance, during search and rescue mission, a swarm could convey the immediate necessity of an intervention using a combination of synchronized movements over a portion of the covered area and the formation of a symbol indicating the nature of the resources needed at this location.

Our extracted typology of information from swarm motion identified by non-expert users will be used to design reactions of field robots so they are able to convey information to their operator. We observed in previous studies [1] that even trained operators (e.g. astronauts) are challenged by the interpretation of swarm behaviour when looking down at a simple mission planner in an exploration task. A classic approach would add an overlay of information on the operator screen to increase his or her understanding of their behaviour and situational awareness of the mission, but it would result in an increase of cognitive load as well. The typology of information from swarm motion makes it possible to communicate with the operator without this overlay and situational awareness might even be possible without a screen-based mission planner: when line-of-sight is possible, the operator has direct access to this communication channel. We are also currently exploring the use of proxy table-top robots as a visualization of the deployed robots.

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