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CoCoRo - The Self-aware Underwater Swarm

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***Abstract*—The EU-funded CoCoRo project studies heterogeneous swarms of AUVs used for the purposes of underwater monitoring and search. The CoCoRo underwater swarm system will combine bio-inspired motion principles with biologically-derived collective cognition mechanisms to provide a novel robotic system that is scalable, reliable and flexible with respect its behavioural potential. We will investigate and develop swarm-level emergent self-awareness, taking biological inspiration from fish, honeybees, the immune system and neurons. Low-level, local information processing will give rise to collective-level memory and cognition. CoCoRo will develop a novel bio-inspired operating system whose default behaviour will be to provide AUV shoaling functionality and the maintenance of swarm coherence. Collective discrimination of environmental properties will be processed on an individual- or on a collective-level given the cognitive capabilities of the AUVs. We will investigate collective self-recognition through experiments inspired by ethology and psychology, allowing for the quantification of collective cognition.**

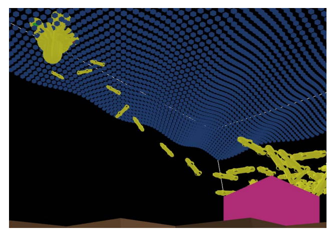
I. MOTIVATION, BACKGROUND AND INTRODUCTION

A. Why underwater?

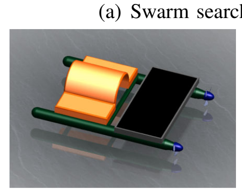
The ocean remains the most unexplored habitat on earth. It is home to an abundance of unknown organisms, undiscovered resources, and a magnitude of processes that are not well understood. In short, ocean exploration is one of the most prominent 'hot topics' in science today.

In CoCoRo, we propose a swarm-based robotic system that efficiently and autonomously searches areas of the ocean for specific, hard to find targets. Such targets could include black boxes of submerged planes, valuable resources or toxic waste dumps. The challenge lies in the difficulty of locating such targets from the water's surface; it requires extensive scouting of the sea bed. Toxic waste, for example leaking barrels on the sea bed, could produce a very weak and irregular toxin gradient that is very difficult for a single autonomous underwater vehicle (AUV, see Fig. 1(c)) to traverse and locate the source of. However, whereas a single AUV would need to employ a complex and time-consuming search pattern, a swarm of AUVs could act as a distributed sensor network (see Fig. 1(a)) and quickly comb through the area. A swarm could navigate such a weak and irregular toxin gradient, locate the source, and send its location to the base station (see Fig. 1(b)) which in turn could forward GPS coordinates to the cleanup team.

We believe that swarm systems require a 3-dimensional environment (underwater or airborne) to reveal their full



(a) Swarm searching the seabed



(b) Basestation

(c) AUV

Figure 1. Figure 1(a) depicts the CoCoRo system, comprising the base station on the water surface, a relay-swarm that communicates information to this base station and a ground-swarm that searches the sea bed for a specific target. Figure 1(b) shows the CoCoRo 'base station' design. Its on-board sensors and devices include GPS communication, sonar, compass, anemometer and inertial sensors. It is able to recharge the AUVs platform. Figure 1(c) shows the CoCoRo 'AUV' design. The platform is able to swim in 3D, achieve zero-power diving, and perform obstacle avoidance. The AUV can move at up to one body length per second. It possesses numerous on-board sensors such as distance, pressure, compass and inertial sensors.

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potential. This is due to the scaling issues that arise with increasing swarm size. On the one hand, swarm systems tend to increase their efficiency with increasing swarm size as the number of agent-to-agent interactions increases with swarm density (size). On the other hand, higher swarm densities lead to an increase of blocking (traffic jams) of the moving agents. In 3D environments the number of interactions between agents that can locally communicate is higher, as each agent may have more neighbours in its locale. Thus, collective computation can be more intense than in a 2D environment. Furthermore, traffic jamming is not as frequent in 3D, since there are more directions in which an agent can escape from a jammed position. Thus, we propose that swarm intelligence and swarm robotics can more readily exhibit collective cognition and collective intelligence in a 3D environment than in a 2D world (like epuck robots in a planar arena). The fact that motion in water is usually slow, and that buoyancy combined with thruster-driven propulsion offers interesting steering and motion capabilities, will allow this underwater swarm system to exhibit high levels of 'swarm intelligence'.

B. Why swarms?

A 'swarm' is a system of loosely coupled units that interact and interfere with one another through (mostly) simple mechanisms. Although these interactions can be described by simple rules, the system as a whole is able to exhibit complex behaviours. A coherent group of AUVs may collectively process and coordinate their motion. The manifestation of complex group-level behaviours from relatively simple components is denoted by the term 'swarm intelligence' [1], [2], [3], and its physical manifestation in autonomous robots is referred to as 'swarm robotics' [4], [5].

The swarm approach has several advantages. Swarm robotic systems exploit the principles of self-organization in a similar manner to their natural counterparts, allowing collective decision making and group-level homoeostasis [6]. Swarm systems are highly scalable; adding members to the swarm does not impair the efficient functionality of the collective system. Such systems are often flexible, swarms are not easily trapped in local optima and they are able to exhibit many variants of collective behaviour. In addition, they tend to be robust: swarm systems can usually achieve their goals despite swarm members becoming lost. Most prominently, it is a characteristic of such systems that the collective is able to solve problems that individuals alone cannot.

C. Why self-awareness?

In real-world underwater environments, sensors of AUVs are subject to much more noise than those of land-bound robots, even under typical laboratory conditions. Imprecise sensor information, coupled with the inability to communicate over large distances restricts the capabilities of single AUVs. Our approach is to extend the capabilities of individual AUVs through use of swarms. However, being an autonomous member of a swarm requires special abilities from an AUV, namely, it has to be aware of its own state and the state of its swarm. It should, for example, know which swarm it belongs to (ground swarm vs. relay swarm), the size of its swarm, and the swarm's status (target status, energy status, etc.). By combining swarm-level information with their own statuses (e.g. depth, battery status, etc.), single AUVs should be capable of making decisions that best contribute to the swarm's performance. This nature of self-awareness exhibited by individual swarm members is a key aspect of the CoCoRo project which we envisage will help the swarm to meet the following challenges.

II. CHALLENGES, TASKS AND EXPERIMENTS

A. Which tasks does the swarm have to solve?

1) Deploy the swarm to the water: Due to their very small size the CoCoRo AUVs can be deployed by hand from a boat or from the shore. First the base station is deployed in the mission area, after which the AUVs must remain near the base station without losing contact with it.

2) Search for a target on the seabed: The CoCoRo AUVs should search the seabed for a specific target. Finding such a target will only be efficient if the AUVs work together.

3) Discriminate between multiple targets: If multiple targets are found by the same group of AUVs, the AUVs must have the capacity to discriminate between them.

4) Select the best of these targets: If several targets are detected, AUVs have to evaluate criteria that allow discrimination between targets of different quality. The swarm has to be able to select the target of highest quality.

5) Communicate search success to the water surface: After the swarm has located a target on the seabed the swarm must report the target's position and its quality to the base station.

B. What challenges do these tasks pose for the swarm?

1) Do not get lost in the ocean: AUVs can easily get lost in the vast ocean. To prevent this the base station will create a 'virtual fence' by emitting an acoustic signal from which AUVs can determine their distance from the base station. AUVs must determine when they are too far away and should return. The AUVs should additionally able to automatically return to the surface in case of malfunction or battery depletion.

2) Join multiple AUVs to one functional unit: A group of AUVs that is responsible for a given function within the swarm must distinguish itself as a sub-swarm. The coherence of this sub-swarm is based on local communication channels.

3) Utilize group-level interaction to increase performance: Within a swarm, different autonomous groups of AUVs (sub-swarms) must interact in a coordinated manner. These interactions on the group-level can be based on local and on global communication channels.

4) Cope with a noisy and heterogeneous environment: On all levels (swarm level, group level, individual level) the AUVs have to deal with problems such as sensor noise, changes in buoyancy due to external changes (e.g. water temperature or salinity), de-location of individuals by underwater currents, and interaction with marine flora and fauna (fields of seaweed, small fish schools near objects on the seabed). Such sensor noise can be compensated for by using the AUV swarm as a distributed sensor network.

5) Compensate for unavoidable losses of swarm members: If an AUV becomes lost due to unforeseeable events, the swarm must detect and compensate accordingly. The AUVs must have the capacity to continue their tasks on all levels, with only a small decrease in efficiency, due to the self-organised nature of the algorithms employed within the swarm.

C. How can experiments benchmark swarms in these tasks?

We have devised a generic experimental setup which will allow us to benchmark the CoCoRo system in the tasks aforementioned. The setup will consist of a water tank approximately 3 m deep and of at least 10 m^2 of surface. The bottom of the pool will be covered with seabed-like patterns for more realism. This way robots may use optical flow to estimate their displacement and roughly localize themselves. We will use specific objects for detection by the AUVs. These objects should be seen as a metaphor for toxic waste or flight data recorder that must be located in the ocean. At first these objects will actively emit signals detectable by AUVs. Thereafter, we will experiment with passive objects which may only be distinguished by their colour.

With this experimental setup, we will be able to use a CoCoRo system composed of one surface station and a swarm of AUVs. We plan to undertake experiments of incremental difficulty, because the tasks of the robots are related and interdependent. In the first of a series of experiments, we will drop a single target on the tank's bottom. The AUVs will shoal and explore the tank to locate the target, simultaneously maintaining a connected topology to avoid losing any AUV and maintaining a physical chain to stay in touch with the base station. Later experiments (see Fig. 2) build upon the first; we will introduce a target object together with distractor objects that resemble it. By processing information from multiple noisy measurements the system must discriminate between targets, and select the correct one. These experiments will provide quantitative results on the performance of the swarm in various tasks. Indicators and statistics of interest will include the ability of the system to maintain its operational state, the robustness to failure or loss of AUVs, as well as the speed and precision of the system.

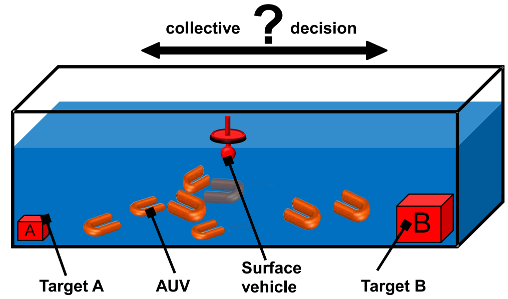

Figure 2. Collective discrimination between two environmental choices by a CoCoRo swarm system.

III. BEHAVIOURAL CONTROL AND ALGORITHMS CREATE AWARENESS

A. How can awareness be used on the individual level?

Todays AUVs are strongly limited in performance and abilities by the fact that they operate with pre-programmed tasks that specify platform parameters during an entire mission. Overcoming these limitations requires robotic systems that are able to autonomously make decisions and react to unforeseen and changing circumstances. This kind of situational awareness, make possible through a dense net of sensors, actuators and data processing units properly coordinated by control system algorithms, is the foundation for developing vehicles able to recognize themselves and make autonomous decisions. At the individual level this fusion of sensors, actuators and data processing will allow modules able to manage internal malfunctions and unpredictable events. The ability to self-determine the capacity to carry out long-term tasks, in terms of autonomy, failures, ability and environmental conditions, is of vital importance for achieving task objectives and for the safe operation of the system. We suggest that a conservative approach is fundamental for handling critical errors or abnormal events: in such situations an emergency ascent will guarantee the survival of the robot.

B. How can awareness be used on the group level?

One of CoCoRo's 'big vision' scenarios the search for toxic dumping grounds on the seabed. These are generally hard for single AUVs to locate, owing to their inefficiency in combing through suspected dumping areas. On the other hand, a swarm of AUVs can quickly and efficiently navigate and search through such areas. Our goal, however, is not simply to have swarms comb through the area logging the position and concentration of toxins. Instead, we will program our AUVs to use group-level awareness to *locate* the actual toxic source. This will be achieved by engineering

AUV interactions that generate an emergent taxis behaviour wherein the swarm as a whole follows the toxic gradient until the source is located. Such emergent taxis behaviours typically increase in efficiency with increasing swarm size. Preliminary simulations have shown such behaviour to be achievable even in absence of explicit inter-AUV communication.

Another aspect of work in CoCoRo will be the exploitation of group-level awareness to initialise and mediate self-repair. Our work will take inspiration from immunology in developing algorithms capable of error detection at both the individual-AUV and multiple-AUV group levels, and deploy appropriate recovery mechanisms. Such recovery mechanisms allow the swarm to re-organise and maintain operation despite the occurrence of faults. Our work is premised on Cohen's view of the immune system as a cognitive system [7], and capacity of the immune system to mediate self-recovery. Specifically, we focus on the murine autoimmune disease experimental autoimmune encephalomyelitis (EAE), a model for multiple sclerosis in humans. Many mice induced into EAE spontaneously recover from autoimmunity [8] through the actions of a regulatory network of cells that recognise, monitor and respond to the actions of autoimmune T cells. By adopting algorithmic principles from the manner in which these mice are able to recover from autoimmunity, CoCoRo AUVs will monitor one another, detect behaviours of individual swarm members which are detrimental to the overall performance of the swarm, and react accordingly. Such corrective responses may be limited to individual AUVs, or may spread across several robots to constitute a collective response. To illustrate, the failure of an individual robot in a chain-like group which relays information between two locations may be perceived by several other individuals that recognise a loss in quality of the group's performance. Each of them may generate an appropriate response, and may propagate it to their neighbours. As a collective, certain robots alter their behaviour to restore the swarm's quality of service.

C. Generating and harnessing awareness at the swarm level

At the swarm level, self-awareness allows the swarm as a whole to monitor and regulate its own collective activity. Mechanisms for creating (self-)awareness may be distributed over several groups, depending on the capacity of agents to perform computation, communication, or more generally, to maintain the required level of interactions.

In CoCoRo we will use following approaches for creating awareness at the swarm level. One method is 'self-adapting Artificial Neural Networks' (ANNs) which are modulated by global or local information spread throughout the self-organised AUV swarm. These modulations can be interpreted as 'moods' or 'emotions'. The messages that are spread throughout the swarm can be quite simple compared to the communication required to coordinate a group of agents conventionally. In CoCoRo, a single, or group of, AUV(s) can modulate behaviours of other AUVs by spreading messages via local or global information channels. The modulation of these individual behaviours will lead to a change of behaviour of the whole swarm due to the self-organised nature of the AUV "super-organism". The advantage of this approach is the re-use of neural structures necessary for all modes of operation, modulating only those parts of the ANN relevant to the given task. Such systems allow the interweaving of nodes that are modulated with those that are not. In this manner, awareness concerning the current situation of the swarm is coded in the distribution of behaviour-modulating messages within the swarm. Due to unequal distributions of information (e.g., due to usage of local communication channels) swarm members behave differently in different parts of the swarm, resulting in a division of labour. Examples of such modulatable ANNs are found in [9]. We refer readers to [10] for an overview of artificial emotions in swarms, and [11], [12] for an overview of modelling emotions and neuro-modulation.

Another closely related approach concerns nonlinear oscillators coupled by means of an electrostatic field [13]. This approach is efficient in small underwater vehicles, owing to the low computational resource requirements needed to generate multiple collective phenomena [14], e.g., in collective decision making [15]. Water is a shared communication medium, and thus this approach can naturally constitutes a globally coupled system (e.g. mean field) [16]. Self-awareness in such systems can be achieved through well-known dynamical systems such as travelling waves in spatially excitable media (e.g., FitzHugh-Nagumo systems [17]), the introduction of delayed feedbacks [18], or on other methods that reflect the global status locally. Such dynamical processes represent collective models that can handle distributed sensor data and perform reasoning about common activities [19].

Although single swarm members may not have access to information at the global-level (i.e. information about the group's activity), the swarm itself can process such information in a decentralized manner in order to regulate and adjust its common activities. Consider, for instance, a task of collective discrimination: the system is confronted with two or more objects and has to identify and select a target object. Single AUVs have limited sensory capabilities, thus they are not able to monitor the activity of the group in its entirety.

One problem that is alleviated through swarm-level self-awareness is that of detecting task completion. The swarm must determine whether it has completed its task in order to either transmit its findings to the base station, or simply switch to a new task. This metacognitive information may be obtained by implementing a mechanism of quorum sensing wherein individual AUVs gather information and collectively agree on whether their objective has been attained.

A second challenge arises through the swarm's detection of multiple similar objects. Here discrimination is more difficult, and the swarm is more likely to make errors. In the worst case the swarm must randomly select between alternatives because they cannot be distinguished. If the swarm recognises the difficulty of the task, it can report its uncertainty rather than making mistaken assertions. For instance, if the opinion of the AUVs continually oscillates between several alternatives without stabilizing, the swarm may trigger a specific response indicating uncertainty, which would in turn improve the correctness of its decisions.

IV. FOUNDATIONS OF AWARENESS: HARDWARE, ELECTRONICS AND OPERATING SYSTEM

A. What hardware constraints exist?

The design of the AUV platform must reflect the requirements of true autonomy and operation in an underwater environment. Where platform size is concerned, a small robot would be the ideal solution for improving system dynamics (less inertia) and performing tasks in extreme environments. However, size is strictly constrained by the volume required for batteries, electronics and mechanical systems. A compromise must be struck between size, technological constraints and autonomy. The latter plays a fundamental role in underwater robots and depends on many factors such as shape, hardware, processing and sensing requirements. Hardware and software complexity partially dictates power requirements, which in turn significantly influences the efficiency of the system. For this reason it is vital to identify ad-hoc solutions to developing hardware systems with high efficiency and to avoid sensing and processing redundancies.

Wireless communication will provide data exchange necessary for supporting swarm control and self-awareness. Fro this point of view there are several aspects to consider in the design of the AUV platform, including bandwidth, communication range, power, and communication protocol. It is also important to consider that wireless communication in underwater environments is not efficient, thus new kinds of communication are to be considered. Finally, the embedded CPU and operating system needs to be defined as a compromise between boards, size, computational burden and power consumption. This choice is fundamental to ensuring the feasibility of required computations (data processing) and for ensuring AUV's autonomy.

B. Hardware design maximizes awareness on all three levels

High-level behavioural algorithms need information about AUVs to plan and actuate control strategies. These data have to be shared between modules and for this purpose wireless communication plays a fundamental role. Since high quantities of data have to be exchanged, maintaining the minimum bandwidth necessary for communication requires the implementation of an efficient communication protocol. A swarm of small AUVs distributed over a large area can perform certain tasks more accurately and in less time than one larger vehicle. Onboard sensors across a swarm provide a global vision of the environment, which can inform swarm control strategies. Sensors for interacting with the environment must be defined based on each task the swarm, and in as such each robot, has to accomplish. For instance, in flocking it is essential to sense the intensity and the direction of water currents in order to plan the trajectory of the entire swarm and avoid collisions. Onboard sensors (e.g. battery energy check, inertial and distance sensors) are dedicated to support the behavioural algorithms of single AUVs, giving them the capability to plan their work autonomously.

C. Sensors & communication support high-level behaviours

Local sensing allows distance measurements, colour detection, detection of the spatial position of a signal, robot-object and object-object discrimination, and recognition of object shapes. It also includes other sensing systems such as 3D accelerometer, compass, pressure sensor, humidity/temperature sensors, energy sensors. Distance measurement can be based on absorption properties of water (for example 1dB/m for optic, 40 dB/m for RF100MHz and 100dB/m for electric field), which depends on frequency/wave-length, salt concentration, pressure and several other parameters.

When the distance measurement system is calibrated in the test conditions, attenuation of the signal provides information about the distance between sender and receiver. Due to a lower absorption, an optical system is the most suitable for this purpose. Maximal distance can be calculated based on the fact that an analog blue light LED at 40-60mW and 10 degree opening angle can be sensed by a photodiode (with amplifier) at the distance of 1.2-1.4m. Provided the surface reflects 80% of a signal, the sensing range (based on reflection) is about 0.4-0.5m. Thus, active distance measurement, where an object is equipped with an emitting LED, is more preferable since this allows a larger sensing radius R_s. Sensing range can be improved by emitting more light energy, however this does not always effectively increase the sensing radius. For instance the approach discussed in [20] leads only to 2.1m direct sensing for 400mW cyan LED.

Another method of distance measurement is based on the flying time between sending a signal and receiving its reflection: active acoustics. The relatively low speed of sound of roughly 1500 m/s (this requires measurement of time in μs scales, which can be easily implemented, for instance by phase-detection approach) makes hydro-acoustic waves well suitable for this purpose. The hydro-acoustic approach is well researched, however it requires computationally-intensive noise-cancellation and reconstruction techniques, especially in case of hydro-acoustic arrays [21].

Optical systems with integrated optics allow focusing of light and as such increase sensitivity. There are several works which describe application of cameras in underwater navigation [22], however these also point out the complexity of image processing tasks [23]. For the development of a small platform, the optic distance measurement system is preferable due to its simpler electronics and unsophisticated signal processing. To provide directional sensing, the platform can be equipped with multi-channel systems. Application of an active acoustic approach can be investigated when a long range of sensing distances is required.

Local directional communication can be established by analog and modulated light; omni-directional by electric field and low-frequency RF (frequency or emitting power affect the communication radius R_c). The communication distance and bandwidth are co-dependent values, increasing one of them decreases the other one. The best tested transfer rate for a local optical communication is 119 kbps with IrDA QAM modulation. Acoustic and ultra-low-frequency RF can provide global omni-directional communication (max. range of hundreds of meters). Sonic waves travel very well under water and the energy and build-space required for generating and receiving them is relatively low. This approach is used in acoustic modems [24]. The drawbacks of this approach are that multiple reflections can cause distortions in the signal. Therefore, acoustic signals can be used as a global communication system for very short analog signals.

RF systems represent a trade-off between the frequency (i.e. communication distances) and the size of integrated antennas (i.e. the size of platform). Due to water connectivity, the attenuation of radio waves depends on the used frequency, which in turn dictates the size of antenna. High frequencies ($>$ 100 MHz) only need a small antenna (0.1 m) while their range is restricted to 2.5 m. Lower frequencies (100 kHz) have a long range (100 m), but need a large antenna (100 m). Communication ranges of standard 900 Mhz (GPS) and 2.4 GHz (ZigBee) are only of 10 cm and 2.5 cm correspondingly. For such systems, the control circuits are more complex than those for optic or acoustic approaches. Since bandwidth for low-frequency RF is not sufficient for application of standard protocols (e.g. ZigBee), global RF communication has still some open problems. Depending on requirements for global communication, both, acoustic and low-frequency RF S&C can be implemented (acoustic one is more favourable due to less complex hardware).

D. Operating system supports awareness of the system

The self-aware properties of swarms that CoCoRo seeks to investigate all emerge from the perceptions and behaviours of individual members of the swarm. Successful operation of these algorithms requires that individual swarm members can perceive and compute in real-time. CoCoRo will investigate the role of light-weight artificial immune system algorithms, which have a proven track record in anomaly detection problems, in fault detection in individual swarm members. For example, these algorithms can be used to predict and manage processor schedule overruns [25]. We will also embed a default behaviour in the operating system: all robots that are running the operating system will boot up into a state such that their default behaviour is to school.

V. CONCLUSIONS

In this article we argue for cognition and self-awareness as a crucial functional prerequisite for a swarm of underwater vehicles. Cognition is necessary on all levels (individual, group & swarm) since our swarms must act autonomously, operate in a harsh environment and do so despite only limited access to sensor data. The key issue is to design AUVs in such a way that collective cognition-generating mechanisms can work efficiently, and that individually collected data is best exploited by the system. We have discussed in detail the constraints on AUV design as well as limitations and possible workarounds in underwater communication and sensing. Without a certain level of cognitive capacity, a collective system of AUVs will not coordinate their actions and 'understand' the environment. Self-awareness, self-monitoring and self-control are important in preventing the malfunction of the robotic system in harsh underwater environments. We have opted for swarm systems in addressing CoCoRo's 'big vision' scenarios, as these systems are usually robust, scalable, flexible and capable of operating with limited actuation and sensing capabilities. However, the swarm approach dictates that individual AUVs are small and cheap to manufacture, which in turn limits sensor and actuation potential. In the end, a compromise must be found between size and costs one the one hand, and equipment and capabilities on the other. Self-awareness and cognition cannot be easily measured, yet the fields of of ethology and psychology have developed a set of experimental setups that can measure cognitive functionality in living organisms whilst treating brains as black boxes. We will adopt similar approaches in measuring the collective capabilities of our robotic systems. This might surprise the engineering community, but it is well motivated by the fact that we heavily exploit biological-inspiration and self-organization to generate collective cognition in our system. Hence, cognition and self-awareness arise as emergent phenomena, which we can quantify despite treating AVUs as black boxes. By investigating distributed cognition systems in robotic swarms, we will not only solve a a challenging set of engineering problems, but will make important contributions to cognitive science also.

VI. ACKNOWLEDGMENTS

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