Towards Hierarchical Hybrid Architectures for Human-Swarm Interaction

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Abstract

This contribution summarizes an integrated view on human-swarm interaction which investigates how human cognition should be joined with the distributed intelligence of robot swarms. From our perspective, a capable human-swarm hybrid that is embedded in the world can be formalized as nested agent interaction matrices that are hierarchically organized.

Human-Swarm Interaction

A joint human-swarm loop (JHSL) is a hybrid agent where humans are joined with a robot swarm via interfaces to solve particular tasks in the world (Hasbach and Bennewitz, 2021). While swarm engineering is the discipline that focuses on the design of robot swarms (Dorigo et al., 2021), human-swarm interaction (HSI) investigates how the cognitive decision making capabilities of humans can be merged with the distributed intelligence of robot swarms (Hasbach and Bennewitz, 2021; Kolling et al., 2016).

In general, a JHSL is made of at least three interdependent facets; humans, swarm robots, and interfaces. Recently, we have proposed a view on HSI that aims at integrating these different facets, or views, of the JHSL (Hasbach and Bennewitz, 2021). From this integrated perspective, humans, robot swarm and interfaces are considered to be the building blocks for designing an intelligent hybrid agent that is situated in the world. We therefore proposed that HSI could also be interpreted as (hybrid) human-swarm *intelligence*. Fig. 1 shows a simplified summary of the human-swarm intelligence design space.

In this contribution, we summarize an aspect of our previous work by elaborating on how a JHSL can be formalized as nested interaction matrices that are hierarchically organized and what this means for the design of HSI.

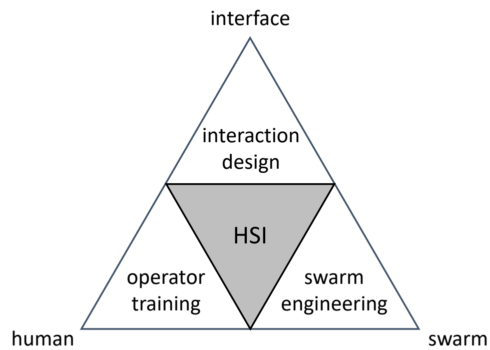

Figure 1: The triad of human-swarm intelligence summarizes its main facets and design dimensions: human (operator training), swarm (swarm engineering), and interface (interaction design, e.g., user experience). Adapted from Rockbach and Bennewitz (2021).

Hierarchical Hybrid Architecture

Intelligent Hybrid Agents

A JHSL $L = \{H, S, C, I\}$ can be described as a set of humans H, swarm robots S, components $C \subseteq \{H, S\}$, and local interaction matrices I. A component c_i is a group of locally interconnected human and swarm agents that must interact to achieve subgoals as a collective. The agents may participate in multiple components simultaneously. The set of local interaction matrices I defines the information architecture of the JHSL, i.e., the (possible) local interactions inside and between agent components C (Hasbach and Bennewitz, 2021; Heylighen, 2001; Simon, 1982). For example, a subswarm engaged in a collective decision making task (Hamann, 2018) in a local area can be considered a component c_i that is determined by the locally dense agent interaction matrix i_i that in turn is a subset of the overall agent interaction possibilities I.

In general, an intelligent JHSL L must deal with the dynamics in the world E by implementing sensory-action rules that enhance the probability of reaching a desired target state $e_{goal} \in E$ (Russell and Norvig, 2016; Wooldridge, 2009). Therefore, the interaction possibilities I between humans and the robot swarm should not be the design goal itself but rather the means in order to maximize the capabilities of the JHSL that gets the tasks done in particular situations (Hollnagel and Woods, 2005). More specifically, the complexity of the interaction dynamics should be kept as minimal as possible while the capability of the JHSL to reach goal states should be as maximal as possible (Hasbach and Bennewitz, 2021). This design principle is vividly demonstrated by the sparsely connected interaction matrix of the human nervous system (Genç et al., 2018).

In sum, three layers of nested interaction networks are defined in our framework:

1. Layer 1: The sensor-decide-action loops *in* each participating agent that determines the behaviour of a single human or robot agent.

2. Layer 2: The sensor-decide-action loops *combined* by the participating agents *in* each component that determines the behaviour of a functional subgroup of interacting human and robot agents.

3. Layer 3: The sensor-decide-action loops *combined* by the components that determines the behaviour of the *overall* JHSL.

Thus, layer 1 is nested in layer 2 which in turn is nested in layer 3. Note also that the layers refer to modelled abstractions of the JHSL, rather than to actual physical differences.

Hierarchical Hybrid Architecture

Consider a JHSL that is part of a search-and-rescue scenario (Hasbach and Bennewitz, 2021; Murphy, 2014). The main purpose of such a hybrid disaster response team is to locate, evacuate and treat a maximum number of victims while minimizing the risk for the own participating agents.

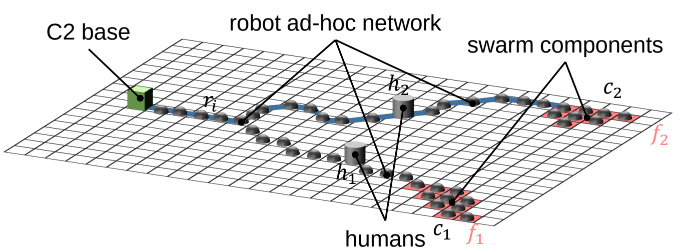

Figure 2: Example of a JHSL situated in a world with a search-and-rescue scenario. The C2 base is coupled with relevant task features of the environment, such as the health state of victims, via the robot ad-hoc network where humans and robots form local components that act in the environment. A possible path between C2 and the task feature f_2 via the JHSL components is shown in blue.

Fig. 2 shows an example of a search-and-rescue JHSL in a simplified $\mathbb{N}^2$ environment. A socio-technical command and control (C2) base is placed at a save location in the west with the role of coordinating different assets (Bluhm et al., 2021). Similar to the control architecture of the nervous system (Albus, 1981; Hasbach and Bennewitz, 2021; Hohwy, 2013), C2 constitutes a higher-order structure that has a broad view of the situation but also needs time to decide. On the other hand, the two deployed search-and-rescue operators that can be seen in the centre have a more narrow-detailed view of the situation while they can act directly, and therefore faster, in the environment. The robot swarm subsets in turn are located directly at relevant but hostile parts of the environment F, $F \subseteq E$, in the east and have once again a narrower view with shorter reaction times. The robots participating in c_1 and c_2 form two dense interaction submatrices that render them a component, or a team, nested inside the larger hybrid interaction matrix.

To conclude, the swarm S can take the role of interfacing higher-order human agents with relevant task features in order to extend the human sensory-motor range (Hasbach and Bennewitz, 2021; Rockbach and Bennewitz, 2021; Sheridan, 1992). This hierarchical hybrid architecture of the JHSL is shown in Fig. 3.

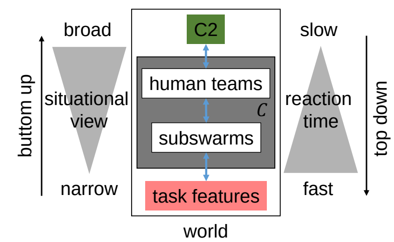

Figure 3: Model of layer 3 that shows the hierarchical hybrid architecture for HSI with narrow-fast loops at the front-end to relevant task features and slow-broad loops at the back-end of the organizational hierarchy.

As adaptation is considered the underlying principle of decision making in complex worlds (Ashby, 1960; Hasbach and Witte, 2021; Hollnagel and Woods, 2005), the JHSL must be able to dynamically adjust its interaction matrices to different situations. For example, imagine the situation where a search-and-rescue team locates possible victims that it cannot treat by its own capacity. How should the hybrid interaction matrix of layer 2 and layer 3 adapt? If available, the local team could call for other assets in the area that may either allocate by themselves or are guided by the C2 element. When these allocated assets join the first-responder team, they will start working together (Coucke et al., 2020; Salas et al., 2008), i.e., form a new enhanced component[1] in terms of a locally denser interaction matrix compared to the rest of the system.

Importantly, it should be remembered that the organizational structure of the JHSL (Fig. 2) should be adapted to the current situation. The design of HSI must take such considerations of hybrid intelligence into account.

[1] The enhancement of a subsystem by joining other agents is a simplification, see Hamann and Reina (2021).

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