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Trendafilov, Dari Borisov; Almansoori, Ahmed; Bredeche, Nicolas; Carletti, Timoteo; Tuci, Elio

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# Empowerment-based prediction of swarm performance in collective perception

Dari Trendafilov<sup>1,2</sup>, Ahmed Almansoori<sup>1</sup>, Nicolas Bredeche<sup>2</sup>, Timoteo Carletti<sup>1</sup>, and Elio Tuci<sup>1</sup>

<sup>1</sup> Namur Institute for Complex Systems, University of Namur, Belgium

<sup>2</sup> Sorbonne Université, CNRS, Institut des Systèmes Intelligents et de Robotique, ISIR, F-75005 Paris, France

{dari-borisov.trendafilov, ahmed.almansoori, timoteo.carletti, elio.tuci}@unamur.be

nicolas.bredeche@sorbonne-universite.fr

**Abstract.** We apply a recently introduced information-theoretic complexity measure for predicting swarm performance in the Collective Perception scenario. Our approach builds on the principle of Empowerment, which offers a task-independent, universal and generic utility. We evaluated the empowerment measure with respect to the performance of one recent state-of-the-art neural network decision-making controller. The results reveal significant strong correlation between the levels of empowerment and both the accuracy and completion time achieved by a simulated swarm operating in nine distinctive environmental patterns and five swarm communication ranges, used previously to assess swarm performance. These findings suggest the potential of empowerment to analytically predict swarm performance and support the design of more efficient decision-making strategies.

**Keywords:** Swarm robotics · Collective decision-making · Information theory · Empowerment.

## 1 Introduction

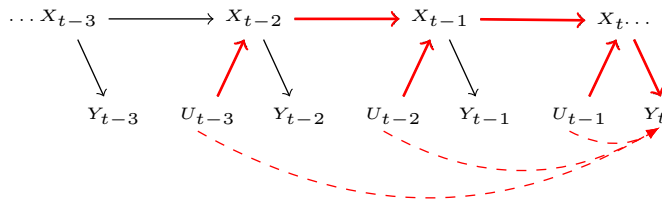
Swarm robotics studies multi-robot systems in which each robot has its own controller, perception is local and communication is based on spatial proximity [5]. The group-level response emerges from a self-organisation process [4], based on the interaction between the robots and their physical environment. However, the autonomous nature of this process poses a challenge for designers, since it is notoriously difficult to infer which set of individual actions could lead to the emergence of a desired collective response. Traditional design methods lack the ability to tackle problems and swarms of increasing complexity in uncertain and unpredictable environments. To enable large swarm-like robot collectives, generic measures of behavioural diversity could be highly beneficial. They could facilitate establishing the theoretical bounds on the complexities of individual robots, swarm and environment, and assessing their interactions and trade-offs.

In this study, we apply a recently introduced information-theoretic complexity measure – based on empowerment [6] – for predicting swarm performance in the Collective Perception scenario [8]. Intuitively, empowerment quantifies the amount of control an agent has over its environment by assessing the potential future states an agent can influence and perceive through its actions. We evaluate the empowerment measure with respect to the performance of one state-of-the-art neuro-controller developed recently with evolutionary algorithms [9].

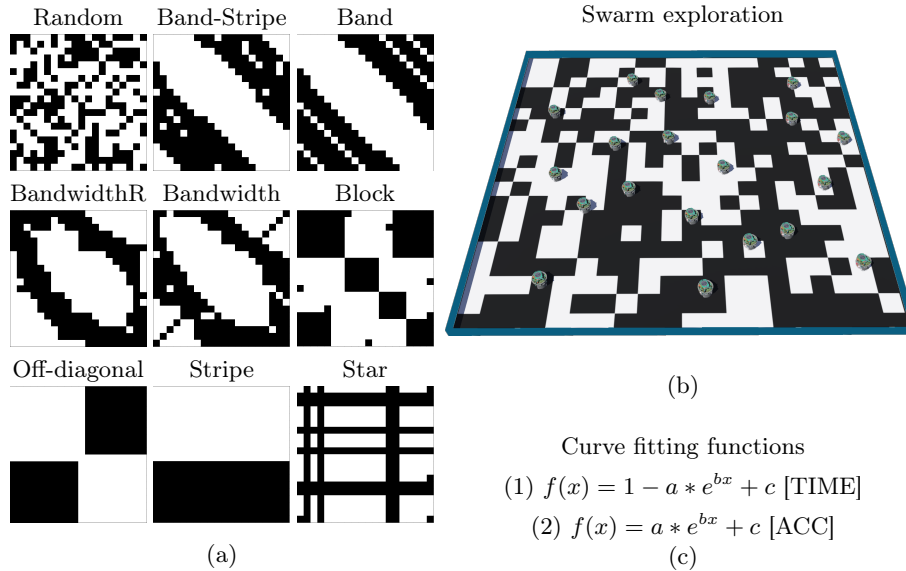
## 2 Method

In [8] we proposed a novel generic measure for the characterization of task difficulty in collective perception, based both on the environmental complexity and the robot’s embodiment. With the aim to provide a more rigorous theoretical treatment for evaluating task complexity, we explored the potential of empowerment [7] to capture and predict the effect of different topological structures of the basic features and the agent morphology on the task difficulty. We developed an empowerment model of the Collective Perception paradigm, which represents the perception–action loop of an embodied agent and its environment as a communication channel, where, when an agent performs an action, it injects information into the environment, and subsequently reacquires part of this information from the environment via its sensors (see Fig. 1). For stochastic dynamic systems in which transitions arise as the result of making a decision, empowerment measures the information an agent can inject into its environment and later perceive by its sensors. Our study revealed that the empowerment trends resonate well with task difficulty levels measured empirically by swarm performance.

In another study [9], we have developed a neuro-controller for individual opinion formation, operating in a randomly distributed environment (of 55%–45% ratio) with swarm communication range of 30cm (see Fig. 2b). The performance of this neuro-controller was evaluated with a simulated swarm of 20 e-puck2 robots in various operating conditions, defined by 45 distinct environments, de-



**Fig. 1.** Perception–action loop as a causal Bayesian network. Empowerment is defined as the Shannon channel capacity from the sequence of actions  $U_t, U_{t+1}, \dots, U_{t+n-1}$  to the resulting observation  $Y_{t+n}$  through the environment  $X_{t+1}, X_{t+2}, \dots, X_{t+n}$  after an arbitrary number of ( $n$ ) time-steps:  $C(U_t, \dots, U_{t+n-1} \rightarrow Y_{t+n}) = \sup_{p(\mathbf{u})} I(U_t, \dots, U_{t+n-1}; Y_{t+n}), \mathbf{u} = (u_t, \dots, u_{t+n-1})$ .



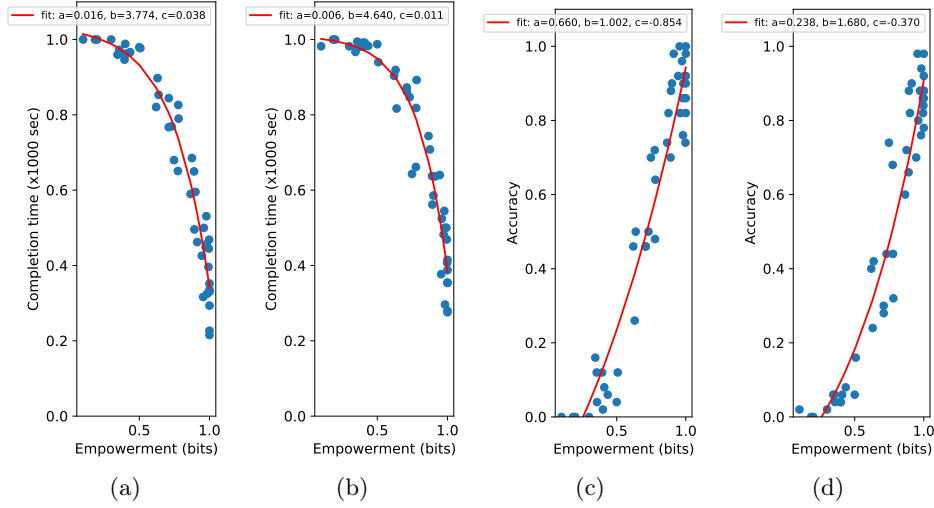
**Fig. 2.** (a) Benchmark patterns used in our study, proposed by [2] and employed to assess swarm performance in collective perception [1]. Feature distribution ratio between black and white tiles is 55% – 45% for all patterns. (b) Swarm of 20 e-pucks exploring the arena colored with the Random pattern. (c) Functions used for least squares curve fit to the data presented in Fig. 3 – (1) consensus time, and (2) swarm accuracy.

rived from the combination of nine distributions of the perceptual cues (see Fig. 2a) and five communication ranges (i.e., 10, 20, 30, 40, and 50 cm).

### 3 Results

Based on the empowerment model of the Collective Perception paradigm and following the procedure of [8], we computed the average empowerment levels for all 45 test environments studied in [9] and related these levels to the swarm performance measured empirically and averaged over 50 simulation trials per condition, where the trial duration was limited to 1000s. Due to the evolutionary bias in our neural network controller, leading to a variable performance gap between the black- and the white-dominant environments, we performed our analysis separately for both types of environments. We conducted tests for correlation between empowerment and these standard performance indicators and found significant strong correlation in all cases.

Additionally, we have applied a least squares curve fit to our data using the scipy library, based on the functions shown in Fig. 2c, and data reflecting – (1) consensus time, and (2) swarm accuracy, as a function of empowerment level. The corresponding curves and their characteristics (see Fig. 3) reveal similar fits for black- and white-dominant environments with minor deviations in the



**Fig. 3.** Empowerment vs. consensus time – (a) black-dominant, (b) white-dominant environment. Empowerment vs. swarm decision accuracy – (c) black-dominant, (d) white-dominant environment. Empowerment was computed with the Blahut-Arimoto algorithm [3] and swarm performance was measured and averaged over 50 simulation trials per each of the 45 experimental conditions (nine environments and five communication ranges). The correlation between empowerment and both performance indicators is significant in all (a-d), according Pearson, Spearman and Kendall tests. The curve fit is based on the functions shown in Fig. 2c – (1) for (a)  $a=.02, b=3.8, c=.04$  and (b)  $a=.006, b=4.6, c=.01$ ; and (2) for (c)  $a=.66, b=1, c=-.85$  and (d)  $a=.2, b=1.7, c=-.37$ .

parameters. This highlights the generalization capabilities of our measure, which identifies the similarity in the overall trends of black- and white-dominant performance, even though the actual levels of these indicators vary across conditions. These results suggest the relevance of the proposed measure for characterizing task difficulty and predicting swarm performance in collective perception.

Empowerment vs.	Pearson $\rho : p$	Spearman $\rho : p$	Kendall $\rho : p$
<b>Time (black-dominant)</b>	-0.91 : 2e-18	-0.95 : 3e-24	-0.82 : 3e-15
<b>Time (white-dominant)</b>	-0.89 : 3e-16	-0.96 : 5e-25	-0.83 : 1e-15
<b>Accuracy (black-dominant)</b>	0.96 : 7e-25	0.9 : 3e-17	0.75 : 9e-13
<b>Accuracy (white-dominant)</b>	0.95 : 1e-22	0.92 : 4e-19	0.78 : 1e-13

**Table 1.** Empowerment vs. consensus time/swarm decision accuracy correlation.

## 4 Conclusion

This paper demonstrates a proof-of-concept example for the application of the information-theoretic measure of empowerment as a predictor for swarm performance in the Collective Perception task. The results reveal a significant strong correlation between this measure and standard swarm performance indicators (i.e., completion time and swarm decision accuracy) recorded in simulated experiments with 20 robots in a range of conditions while varying both the environmental feature distribution and the swarm communication range. This suggests the potential of the approach in providing an analytical tool for making predictions and providing theoretical bounds, based solely on properties of the agents and the environment and independently from the task, which allows to apply the same model to further scenarios, e.g., site selection or shortest path problem.

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