Evolving Controllers for Programmable Robots to Influence Non-Programmable Lifeforms: A Casy Study

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Abstract. In this paper, a decentralized reaction-diffusion-based controller is evolved for a set of robots in an arena interacting with two simulated juvenile bees as non-programmable agents. The bees react to the stimuli that are emitted by the robots. The evolutionary process successfully finds controllers that produce proper patterns which guide the bees towards a number of given targets. The results show a preference of heat as the dominant stimulus causing movement of the bees.

Keywords: Evolutionary computation, decentralized control, robotics, reaction-diffusion based controllers, interactive agents

1 Introduction

In many cases in Evolutionary Robotics (ER) [1, 2], we deal with robots that move and make changes in their environment by manipulating passive objects. Some times, on the other hand, we aim to influence the behaviour of active agents that contain their own autonomous control mechanisms and interact with their environment independently. In this case, our robots need to act properly as a part of the agent's environment to maintain appropriate interaction with the agent. Animals are such autonomous agents. Groups of animals show complex patterns and behaviours arising from self-organization in the society based on local interactions [3]. Some animals have been studied [4] regarding the stimuli they generate and react to. The stimuli that are perceived by an animals can be initiated from the environment or generated by other animals. In the case of honey bees, such stimuli include heat, vibration, and light [5, 4].

In the context of an ongoing project [6, 7], we work towards guiding juvenile (still non-flying) bees to exhibit target behaviours. Young bees prepare brood cells for the honeybee queen, thus play an important role in the age demography and colony size dynamics of honeybees. They locate themselves and perform their colony work preferentially in the so called ”broodnest” region of the hive which shows a complex field of temperatures and other stimuli. Therefore, they are a central group of bees predicted to allow manipulating the development of the whole colony through a group of artificial (robotic) agents. This way, honeybees, important pollinators in ecology and agriculture which are currently affected by various threats, e.g. colony collapse disorder, can be monitored and probably also supported by such a novel bio-hybrid honeybee-robotic system.

In order to manipulate the behavior of the bees, a set of homogeneous autonomous stationary robots, called CASUs (Combined Actuator Sensor Units), are placed in an environment that is shared with bees. The robots can emit a number of stimuli that, based on knowledge from literature [5, 4] we believe bees react to them (e. g., heat, vibration, light). The different stimuli are of different physical nature and stimulate various reactions of the bees. Specific combinations of such stimuli emitted in certain spatiotemporal patterns can lead to specific behaviours of the bees. In this work we aim to evolve decentralized controllers for the CASUs to generate the appropriate stimuli patterns that will guide a group of bees to a desired movement. Feedbacks from the behaviour of the bees is used for evaluating the controllers during evolution.

In biological systems, pattern formation and symmetry breaking that leads to formation of various patterns, start from early phases in an organism's development. In embryos, e.g. fruit fly Drosophila melanogaster [8, 9], polarization of an organism is induced by some maternal cue in the form of morphogen gradients. This was also suggested by [10]. By using these gradients in the environment of the organism, some information is provided that is used for localization of the organism's units (cells) and participates in the process of development. The same concept has been used by many researchers in the field of artificial evolution and developmental systems by applying different representations (e.g., [11–13]). For example, by using Boolean logic circuits [11], gene regulatory networks ([14]), or neural networks [15, 16]. In this work, we used an instance of reaction-diffusion systems as the decentralized controllers for the robots.

Reaction-diffusion models are inspired by intracellular signalling in biological organisms. The models involve a process of local reaction between substances and diffusion of substances across the organism. Artificial Homeostatic Hormone System (AHHS) is an example of Reaction-diffusion models which is used to control the CASU robots. It has been originally introduced in [17] and successfully implemented for controlling locomotion in robots and generating complex patterns [18–21].

Here, we present the results of evolving AHHS controllers for simulated CASU robots that emit stimuli influencing the behaviour of simulated bees. The evolved solutions and the effectivity of the different stimuli in the evolved controllers are investigated demonstrating the preference of some stimuli over the others resulted from the evolutionary paradigm.

2 System Description

The idea of this work is to evolve decentralized controllers for a system consisting of two types of autonomous agents: one type of agents are unprogrammable but predictable (bees), and the other type are programmable and evolvable (robots). The system consists of a bounded arena with a number of CASU robots mounted on it, forming a grid and a number of juvenile bees moving in the arena. Juvenile bees are not able to fly. The robots emit several stimuli of different physical nature. Based on their physical properties, the stimuli emitted by a robot or by a user operator may diffuse in the arena and reach other robots. The bees may perceive the stimuli and change their behaviours accordingly. The CASU robots only perceive the light intensity. The robots are controlled by reaction-diffusion-based controllers containing virtual substances, called hormones. The dynamics of the virtual hormones are based on a number of rules and the diffusion rate of each hormone to the neighbouring robots (see section 3 for description of the applied controller). Figure 1 illustrates a conceptual example of the system consisting of two CASU robots and two bees.

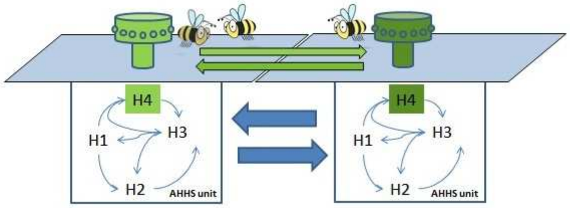

Fig. 1. The main concept of the experiment illustrated by an example consisting of two robots: The AHHS controller units with identical genomes run independently in different cells (robots). The units interact with each other via diffusion of hormones. There are four hormones represented in this example ($H1$ to $H4$). Some hormones ($H4$) are associated with production of some stimuli in the CASU robots. Stimuli can flow (diffuse) over the arena and reach the other CASU robot. Bees can sense the stimuli and react to them by standing still or moving to the neighbouring cell.

3 Short Summary of AHHS

An Artificial Homeostatic Hormone System (AHHS) [17, 22] is a reaction-diffusion-based system inspired by Turing process [23] that describes processes of natural growth and pattern formation. An AHHS is defined by a set of artificial hormones and a set of rules. The *hormones* are the state variables of the system. The *rules* define interactions between the hormones. Each rule defines the influence of a hormone on the concentration level of another hormone within an AHHS unit [1]. A diffusion process is defined as a means of communication between neighbouring units by transferring hormones from a unit to the neighbours in the direction of the gradient. The dynamics of the hormones are regulated by a set of associated parameters. These parameters include the rate of diffusion, the production rate, and the decay rate of each hormone. The sensory inputs

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[1] In this regard, AHHS is similar to Gene Regulatory Networks (GRNs).

influence the system by changing the hormone levels of an AHHS unit directly or via special rules. In the same way, particular hormones determine the output of each unit (for more details please see [17, 21]). An AHHS genome consists of all the parameters associated to different hormones and rules. The genomes are identical for all the AHHS units (e.g. robots) in a multi-unit organism and are adaptable to a given task by an evolutionary process.

In a formal representation, the dynamics of hormone concentration H at time t for hormone h is represented as follows:

$$\begin{aligned}\frac{\Delta H_h}{\Delta t} =& \alpha_h + D_h \nabla^2 H_h(t) - \mu_h H_h(t) \\ & + \sum_i \mathcal{L}_i(t),\end{aligned} \tag{1}$$

where α_h, D_h, and μ_h are base production rate, diffusion rate, and decay rate of hormone h, respectively. $\mathcal{L}_i(t)$ is the influence of a rule i,

A rule is defined as:

$$\mathcal{L}_i(t) = \theta(H_k(t))(H_k(t)\lambda_i + \kappa_i), \tag{2}$$

The output of the rule is applied to hormone concentration $H_h(t)$ and the input is $H_k(t)$ ($h = k$ is allowed). λ_i and κ_i are two parameters of the rule called dependent dose and fixed dose. These values are allowed to be negative. Trigger function θ determines whether or not the rule is executed:

$$\theta(x) = \begin{cases} 1 & \text{if } min_i < x < max_i \\ 0 & \text{else} \end{cases}, \tag{3}$$

where min_i and max_i are parameters of the rule (0.0 and 1.0 in this implementation).

3.1 Stimuli

Every CASU robot acts as a source of three different types of stimuli, say types A, B, C. Stimuli types are different in terms of their physical properties and the reaction of the bees to them (see Table 1). A stimulus of type A is attractive (e.g. heat and chemicals) and a stimulus of type B is repulsive (e.g. light and magnetic field). A bee tends to move away towards a neighbouring cell if the intensity of stimulus type A is higher or the intensity of stimulus type B is lower in the neighbouring cell. A stimulus type C is stopper (e.g. vibration), meaning that if the level of the stimulus is above a threshold value, the bee stops in the cell ignoring the attractive or repulsive stimuli.

The behaviour of a bee positioning in a cell, say *newcell*, is formulated by the following equation:

$$\begin{aligned} attr_i &= (A_i - A_{curr}) + (B_{curr} - B_i) \\ newcell &= \begin{cases} \arg\max_i attr_i, \text{ if } attr_i > 0 \text{ and } C_i < th \\ curr \text{ otherwise} \end{cases} \end{aligned} \tag{4}$$

where *curr* is the current cell and A_i, B_i, and C_i are respectively the intensities of stimuli type A, B, and C in cell i.

In this experiment we use an abstract simulation of heat, light, and vibration as examples of stimuli of types A, B, C respectively. The intensity of the stimuli and the increase amount of the stimuli in each time-step are both limited between 0 and 1.

In the simulation, every time-step assumes to correspond to 1 second in reality. The threshold value for the reaction of the bees to the vibration is set to 0.05 and other parameters are represented in Table 1. The effects of stimuli on the bees are assumed to be linear for simplification of the simulation.

Table 1. Characteristics of stimuli

Stimulus	**TypeA/Heat**	**TypeB/Light**	**TypeC/Vibration**
Effect	attractive	repulsive	stopper
Diffusion rate	0.2	0	0.01
Decay rate	0.1	1	0.9
Instantly reachable	no	yes	no
Directional/Blockable by bees	no	yes	no

4 Experiment

In the following experiments, a 2-dimensional grid arena of size 5×5 is simulated. Every cell of the grid contains a CASU robot that is controlled by an AHHS unit. The AHHS units can communicate with the units in their von Neumann neighbourhood via diffusion of virtual hormones. The AHHS genomes are identical in all the units and evolve by using the Wolfpack-inspired Evolutionary Algorithm (WEA) [24]. The evolutionary algorithm is chosen due to its capability of maintaining diversity in the population along with its simplicity of implementation.

Each CASU can emit three different types of stimuli. The bees are simulated based on their natural reactions to the stimuli. The goal is to guide the bees to reach a number of given target positions in the arena.

A virtual hormone of every AHHS unit is associated to each of the stimuli-emitters of the CASUs. The concentration level of the associated hormone in every time-step is used to determine the additional amount of intensity of the stimulus. AHHS genomes with 8 hormones and 15 rules are evolved to adapt the decentralized controller for the desired behaviour of the bees.

The reproduction operator of the evolutionary algorithm is mutation (no crossover). Proportional selection (based on fitness) operating on the upper half of the population is used to generate offspring. The population size is 30. The experiment is repeated for 25 independent evolutionary runs.

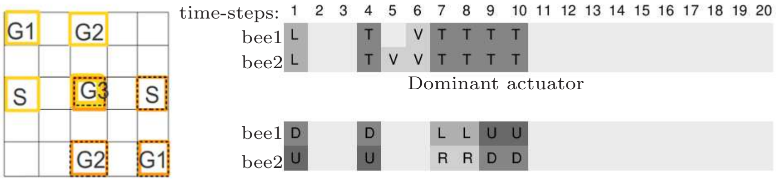
4.1 Task

At the beginning, two simulated bees are placed in (0,2) and (4,2) positions. The simulation runs for 20 time-steps. In the first time-step, the light is turned on manually with maximum intensity in the top-right corner of the arena in order to break the symmetry of the arena. The manually added light is removed after the first time-step.

The task of the controllers is to lead the bees to reach a number of targets (Figure 2a) in 10 time-steps and stay there until the end of the simulation. The fitness function is calculated based on the number of targets reached by the bees and the distance to the next target as follows:

$$\begin{aligned} Fitness &= N_{reahed} + 1 - R \\ R &= \frac{distancToTarget}{W + H} \end{aligned} \tag{5}$$

where N_{reahed} is the number of targets that are already reached, and R is the relative distance to the next target. W and H are respectively the width and the height of the arena (equal to 5).

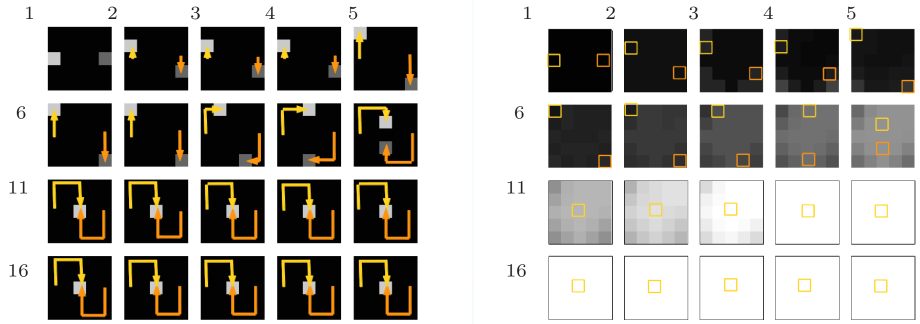


a) Arena configuration b) Sequence of dominant (effective) stimuli and behaviours

Fig. 2. a) The arena, starting points and target positions of the bees. Yellow (solid) and orange (dashed) squares indicate the targets for two different bees. The bees start at their S positions and they have to reach G1, G2, and G3 in maximum 10 time-steps and stay in G3 until the end of the experiment (until 20th time-step). b) Sequence of dominant stimuli (top two rows), and actions of the bees (bottom two rows). L, T, and V respectively indicate light, heat, and vibration as dominant stimuli for the particular bee in the particular time-step. D, U, L, R, indicate a movement to toward the bottom, top, left, and right respectively. The empty squares (very light gray coloured) indicate no movement of the bee in that time-step.

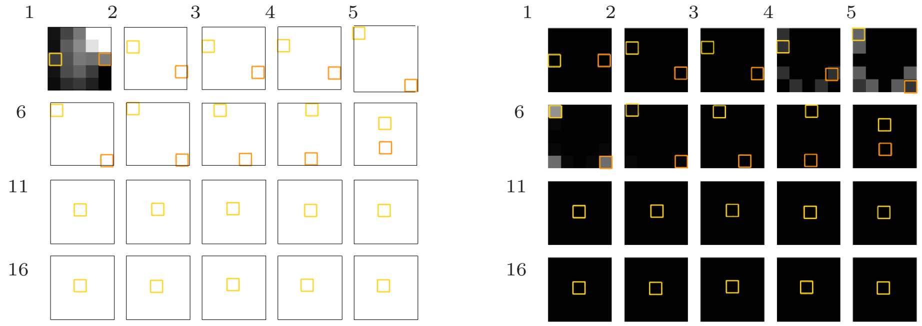
4.2 Results

Figure 4 represents the fitness trajectory over the number of evaluations. As it is represented in the figure, maximum fitness is reached for the median of the evolved solutions of all runs after 30,000 evaluations while the maximum fitness was reached by some runs already after 5,000 evaluations.



(a) Bee positions

(b) Heat intensity



(c) Light intensity

(d) Vibration intensity

Fig. 3. The position of the bees (a), and the intensities of the stimuli (b-d) are represented for every time-step (numbers indicate time-steps).

In order to have a better understanding of the solutions we looked at the stimuli emitted by the evolved controllers. Figure 5a considers only the steps where bees are moving. Recall that movement is caused by light and/or heat stimuli. Figure 5a represents the proportion of the movements of the bees where heat is the dominant stimulus. As the figure shows, heat is the most dominant stimulus that is responsible for moving the bees from their places. It is the case in most of the runs. In one of the runs the movement is caused only by light. There is no run where heat is the stimulus for triggering movement for the whole duration of the run. It is because at the beginning, when heat is uniformly low over the arena, light is manually emitted for a short time. The low proportion for the heat in the early steps of evolution is due to the dominance of the vibration stimulus in the early evaluations that prevents the movement of the bees. The number of the movements during the early evaluations is very low and its usually only limited to one movement that is initiated by the manual light. The number of steps where both light and heat agree on one direction for moving a bee are negligible during the whole evolution (data not shown).

For a bee to stay in a cell, either vibration is more than the threshold value or there is no preferable cell in the immediate neighbour in terms of light and heat stimuli. Figure 5b represents the proportion of standing steps where vibration is dominant (over the no-preference status). The figure does not show a high median for the proportion of vibration stimulus in the evolved solutions.

Figure 2b shows the behaviour of the bees against an example evolved controller for the robots. The dominant stimuli and the action that the bee takes is represented over the 20 steps of the experiment. The figure shows that the bees do not move in many steps due to no preference for the neighbouring cells. The status of the arena over the 20 steps, and the intensity of each stimuli are represented in Figure 3. As it is represented in the figure, heat starts to emit in the corners at the beginning and the emission goes towards the centre of the arena. after some time the whole arena gets a uniform heat. Light is only effective at the first step which is emitted due to the manual turn on. Vibration is generated around the corners of the arena and for a short time is the effective stimulus keeping the bees at their places.

5 Conclusion

A reaction-diffusion based controller called AHHS (Artificial Homeostatic Hormone System) is evolved as a decentralized controller for a simulated system consisting of controllable agents and non-controllable agents. The controllable agents are stationary-robots that their controllers are under evolution. The robots emit three different stimuli which cause reactions in the non-controllable agents. The non-controllable agents are bees that, based on the relevant literature [5, 4] are sensitive to a number of stimuli including light, heat, and vibration, which are emitted by the robots in the experiment investigated in this work. Due to the interaction between the robots and the bees, the bees are successfully guided to locate themselves in a number of pre-defined targets. The influence and the

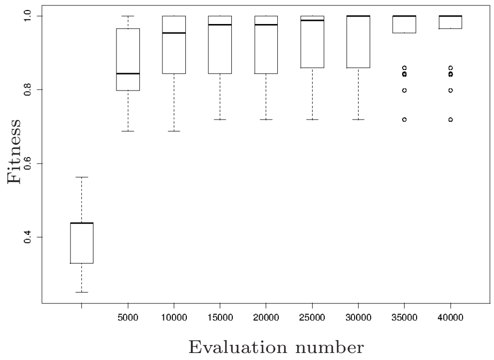


Fig. 4. Fitness progression for 25 runs. The fitness values are scaled between 0 and 1. Box-plots indicate median and quartiles, whiskers indicate the most extreme data points which are no more than 1.5 times the length of the box away from the box, circles indicate outliers.

dominance of the different stimuli are then investigated and it is shown that evolution prefers to use heat over light for causing movements.

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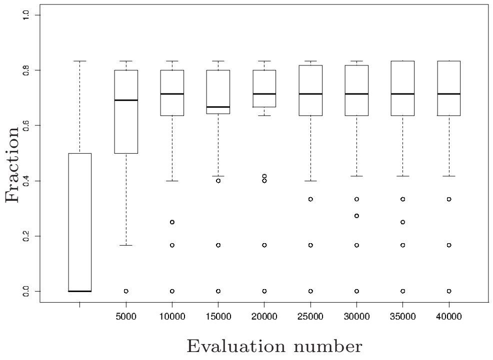
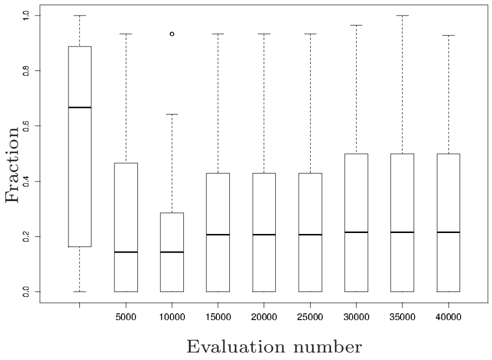


(a) Fraction of movements with dominance of heat



(b) Fraction of standing steps with dominance of vibration

Fig. 5. Proportion of dominant stimulus in movement (a) and standing still steps (b). Each data point represents the proportion acheievd by the fittest controller over time. Data is pulled from 25 independent repetitions of the experiment. Box-plots indicate median and quartiles, whiskers indicate the most extreme data points which are no more than 1.5 times the length of the box away from the box, circles indicate outliers.

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