Symbiotic Robot Organisms: REPLICATOR and SYMBRION Projects

Special Session on EU-projects

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ABSTRACT

Cooperation and competition among stand - alone swarm agents can increase the collective fitness of the whole system. An interesting form of collective system is demonstrated by some bacteria and fungi, which can build symbiotic organisms. Symbiotic communities can enable new functional capabilities which allow all members to survive better in their environment. In this article we show an overview of two large European projects dealing with new collective robotic systems which utilize principles derived from natural symbiosis. The paper provides also an overview of typical hardware, software and methodological challenges arose along these projects, as well as some prototypes and on-going experiments available on this stage.

Keywords: *collective robotics, swarms, artificial evolution, reconfigurable systems*

1. INTRODUCTION

Nature shows several interesting examples for cooperation of individuals. Most prominent examples of cooperation are found in social insects [1], where specialized reproductive schemes (in most cases just a few out of thousands of colony members are able to reproduce) and the close relationships of colony members favoured the emergence of highly cooperative behaviours [2]. However, also non-eusocial forms of cooperative communities evolved, like the collective hunting in predatory mamals [3] (e.g., lions, whales, ...) or the trophallactic altruism in vampire bats. Such cooperative behaviours are mostly explained by reciprocal advantages due to the cooperative behaviours and/or by the close relationship among the community members. In contrast to that, cooperation sometimes arises also among individuals that are not just very distant in a gene pool, sometimes they do not even share the same gene pool: Cooperative behaviours between members of different species is called 'Symbiosis'. A non-exhaustive list of prominent examples are the pollination of plants by flying insects (or birds), the cooperation between ants and aphids. Also lichens, which are a close integration of fungi and algae and the cooperation between plant roods and fungi represent symbiotic interactions.

A common pattern in all these above-mentioned forms of cooperation is that single individuals perform behaviours, which - on the first sight - are more supportive for the collective of the group than for themselves. However, as these behaviours have emerged through natural selection, we can assume that these cooperative behaviours have their ultimate reasoning in a sometimes delayed and often non-obvious individual egoistic advantage.

Symbiotic forms of organization emerge new functional capabilities which allow aggregated organisms to achieve better fitness in the environment. When the need of aggregation is over, symbiotic organism can dis-aggregate and exists further as stand-alone agents, thus an adaptive and dynamical form of cooperation is often advantageous.

Lately, technical systems mimic natural collective systems in improving functionality of artificial swarm agents. Collective, networked or swarm robotics are scientific domains, dealing with a cooperation in robotics [4]. Current research in these domains is mostly concentrated on cooperation and competition among stand-alone robots to increase their common fitness [5]. However, robots can build a principally new kind of collective systems, when to allow them to aggregate into a multi-robot organism-like-forms. This "robot organism" can perform such activities that cannot be achieved by other kind of robotic systems and so to achieve better functional fitness.

To demonstrate this idea, we consider a collective energy foraging scenario for micro-robots Jasmine [6]. Swarm robots can autonomously find an energy source and recharge.

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The clever collective strategy can essentially improve the efficiency of energy foraging, but nevertheless a functional fitness of a swarm is limited. For instance, if the recharging station is separated from a working area by a small barrier, robots can never reach the energy source. However, if robots aggregate into more complex high-level organism which can pass the barrier, they will reach the docking station. In this way a cooperative organization of robotic system allows an essential increase of functional capabilities for the whole group. The large integrated project ”REPLICATOR” (www.replicatores.eu), funded by the European commission, within the work programme ”Cognitive systems, interaction and robotics”, deals with such issues as reconfigurability of sensors and actuators, adaptive control and learning strategies as well as working in real environments.

The cooperative (swarm-based or symbiotic) organization of the robotic system provides essential plasticity of used hardware and software platforms. The robot organism will be capable of continuously changing its own structure and functionality. Such an evolve-ability opens many questions about principles and aspects of long- and short-term artificial evolution and controllability of artificial evolutionary processes. The large integrated project ”SYMBRION” (www.symbrion.eu), funded by European commission, within the work programme ”Future and Emergent Technologies”, is focused on evolve-ability, dependability and artificial evolution for such robot organisms based on bio-inspired and computational paradigms. Both projects are open-science and open-source.

Both projects, consortia and the European commission are closely cooperating to achieve the targeted goals. It is expected that results of both projects create new technology for making artificial robotic organisms self-configured, self-healing, self-optimizing and self-protecting from a hardware and software point of view. This leads not only to extremely adaptive, evolve-able and scalable robotic systems, but also enables the robot organisms to reprogram themselves without human supervision, to develop their own cognitive structures and, finally, to allow new functionalities to emerge.

The rest of this paper is organized in the following way: In Section 2 we discuss a new paradigm of symbiotic systems. Section 3 gives an example of the energy foraging scenario. Sections 4 and 5 briefly mention the hardware and software challenges, where as Section 6 introduces several ideas towards evolve-ability of the robot organisms. Finally, in Section 7 we conclude this work.

2. NEW PARADIGM IN COLLECTIVE ROBOTIC SYSTEMS

Collective intelligence is often associated with macroscopic capabilities of coordination among robots, collective decision making, labor division and tasks allocation in the group [7]. The main idea behind this is that robots are achieving better performance when working collectively and so are capable of performing such activities which are not possible for individual robots. The background of collective intelligence is related to the capability of swarm agents to interact jointly in one medium. There are three different cases of such interactions:

1. In the first case agents communicate through a digital channel, capable for semantic messages exchange. Due to information exchange, agents build different types of common knowledge [8]. This common knowledge in fact underlie collective intelligence.

2. The second case appears when macroscopic capabilities are defined by environmental feedback. The system builds a closed macroscopic feedback-loop, which works in a collective way as a distributed control mechanisms. In this case there is no need of complex communication, agents interact only by kinetic means. This case if interaction is often denoted as a spatial reasoning, or spatial computing.

3. The third case of interactions we encounter in nature, when some bacteria and fungi (e.g. dictyostelium discoideum) can aggregate into a multi-cellular organism when this provides better chances of survival [9]. In this way, they interact not only through information exchange or spatial interactions, they build the closest physical, chemical and mechanical interconnections, through the agents still remain independent from each other.

The first two cases of interactions are objects of extensive research in many domains: robotics, multi-agents systems, bio-inspired and adaptive community and so on. However the practical research in the last case represents essential technological difficulties and therefore is not investigated enough. Despite the similarities between a robot swarm and multi-robot organism, such as a large number of robots, focus on collective/emergent behavior, a transition between them is a quite difficult step due to mechanical, electrical and, primarily, conceptual issues [10]. In the following sections we introduces corresponding challenges in more detail.

Now, we believe that research around the third case of interactions is concentrated on four important questions:

1. Reconfigurability, adaptability and learn-ability of the symbiotic systems. These issues include flexible and multi-functional sensors and actuators, distributed computation, scalability, modelling, control and other issues, which are closely related to the reconfigurable robotic research. The REPLICATOR project is focused on these points.

2. Evolve-ability of the symbiotic systems, which includes principles and aspects of long- and short-term artificial evolution and adaptivity as well as exploring and analogies to biological systems. The SYMBRION project is focused on these points.

3, 4 Embodiment of evolutionary systems for different environments and medias as well as investigation of information properties of such systems. These points are covered by other research initiatives and projects.

In this way, the next step in a further research within the collective robotic community can consist in investigation multi-robot organisms or, in other words, a transition from robot swarm to a multi-robot organisms. All further sections are devoted to demonstrate diverse aspects of such a transition.

3. EXAMPLE: ENERGY FORAGING SCENARIO

In this section we will demonstrate the advantages of symbiotic organization of autonomous robotic systems. We choose for this purpose an example of energy homeostasis, because it is applicable to both living and robotic organisms and so we can draw several analogies between them.

The distinctive property of any living organism is the energy homeostasis and, closely connected, foraging behavior and strategies [3]. The robots, equipped with on-board recharging electronics, can also possess its own energy homeostasis. In this way, when swarm robots get "hungry", they can collectively look for energy resources and execute different strategies in a cooperative energy foraging [11]. In critical cases robots can even decide to perform individual foraging, competing with other robots for resources.

The need of energy is a perfect example of natural fitness. If robots that are performing individual strategies find enough energy, they can survive in the environment. In turn, this means that these strategies were sufficient enough to balance these robots energetic budgets. Simultaneously, other energetically die if their behavioral strategy was poor. Based on such energy foraging, many of evolutionary approaches for different robotic species can be developed, compared and tested.

However, if there are many robots foraging in the environment, several undesired effects can emerge: (1) the docking station can become a "bottleneck" resource that essentially decreases the swarm efficiency; (2) robots with a high-energy level can occupy the docking station and block low-energetic robots. These robots can energetically die (and so decrease the swarm efficiency); (3) many robots can create a "crowd" around a docking station and essentially hinder a docking approach. This can increase the total recharging time and makes worse the energetic balance of the whole swarm.

Robots, in pursuing their energetic homeostasis, have only two possible decisions to make: (1) to execute a current collective task or (2) to move for recharging. In balancing these two behaviours, a cooperative strategy may find the right timing and the right combination between these individual decisions of all robots. Lately, several strategies of energy foraging for a robot swarm up to 70 swarm agents are implemented, see Fig. 1. These cover different bio-inspired approaches [12], [13] and hand-coded strategies [14].

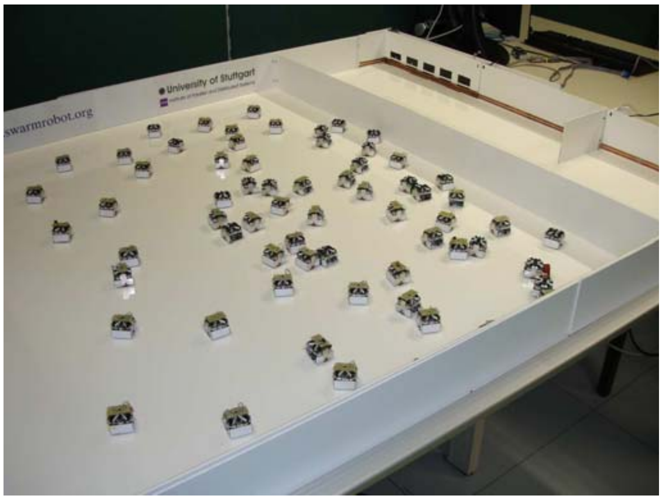
In one of these experiments, a few robots died close to the docking station and blocked the recharge area (we "simulated" this in the Fig. 1(b)). Robots that were in front of this barrier (away from the docking station) finally also died. This is the limit of functional fitness of swarm robots. There is no strategy, that allow swarm robots to overpass the barrier. Only when swarm robots would collectively emerge new functionality, like "pass the barrier", they would solve the "barrier problem".

Thus, an ideal solution for the "barrier problem" can be the aggregation of many single robots into one cooperative multi-robot organism. This way, they can reach the docking stations by "growing legs" and stepping over the barrier. In that case, the robots are helping each other in a cooperative manner, see Fig. 1(c).

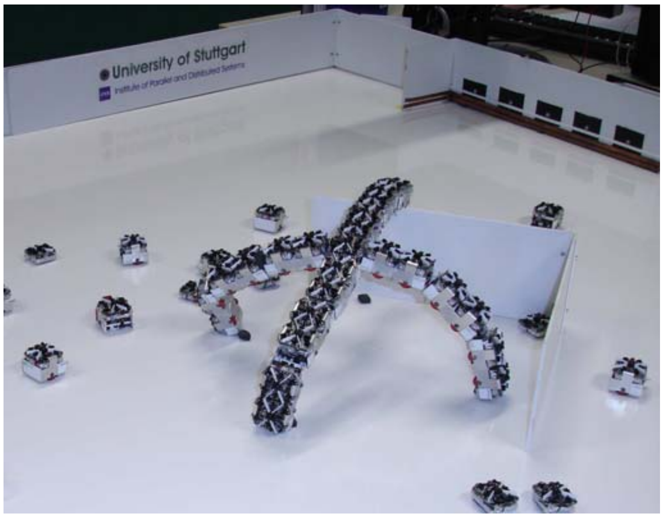
Obviously, such a robotic behaviour is extremely challenging from many viewpoints: Cooperative (symbiotic) robot systems have many similarities with known robotic research as e.g. mechanical self-assembling [15] or reconfigurable robotics [16]. However, the symbiotic form, show in Fig. 1, essentially differs from this robotic research, namely: (1) **Robots should be capable for autonomous aggregation and disaggregation;** (2) **Robots in the disaggregate state should possess individual locomotion**; (3) **There is no central control neither for disaggregated state (swarm) nor for the aggregate state (organism)**; (4) **Stand-alone robots should profit from the aggregation into organism**.

The swarm-based approaches, which is underlying the ag-

(a)



(b)



(c)

Figure 1: (a) Docking of a few robots for recharging. Shown is the two-line approach: the first line - recharging robots, the second line - robots waiting for recharging; (b) The "barrier problem" - robots are separated form docking stations by a barrier; (c) A possible solution to the "barrier problem": swarm robots form a symbiotic multi-robot organism and collective pass the barrier.

gregation processes, differs primarily from aggregated systems which are studied in the field of "reconfigurable robotics". In the following we consider on-going work with aggregated (symbiotic) robot organisms.

4. HARDWARE CHALLENGES

The main feature of a modular robot consists in being composed of several potentially independent modules, with limited complexity and capabilities, which are able to connect to each other in different configurations, in order to form a robot with greater capabilities. The global knowledge and the functionalities of the assembled robot generate by sharing of information and of resources between modules and by the fundamental capability of self-reconfiguration, in order to meet the demands of different tasks or different working environments. As a consequence, the overall functionalities and capabilities of a robotic modular organism are deeply related to the hardware structure and functions of its basic composing modules.

At the current stage of development of the projects (both projects started in 2008), the development of the hardware represents one of the hardest issues. In general, the concept of hardware design is as follows:

1. Independence for separate robots, this includes capabilities for communication, computation and sensing as a stand-alone robot, as well as individual locomotion and energy management.

2. Large computational power of the organism, required for performing on-line and on-board evolutionary approaches.

3. Heterogeneity of individual robots, which allows their later specialization within the organism.

4. Rich sensing and communication capabilities of the organism. The more robots are joined in the organism, the more functional diversity the organism can demonstrate.

5. Possible higher independency from human in term of energy, support and maintenance.

The consortia considered many state-of-the-art reconfigurable solutions, such as superBot [17], M-Tran [18], PolyBot [19], molecube [20], HYDRA/ATRON [21] and others, even visited some of these labs for exchange of experience. Currently, we follow three different developmental lines, which will be later fused into one or two first prototypes.

4.1 Mechanical Challenges

The mechanical design of a robot, which is working together with other robots inside a swarm, differs in several points from the design of a robot being a part of an organism. In the first case, criteria like small size, simple kinematics, simple casing, high mobility and low price define the design of the robot. On the other hand, a robot inside of a self-reconfigurable organism needs docking elements, high-power motors to produce enough torque, depending on the design of the organism one or more independent degrees of freedom and a casing with high stiffness to handle reaction between robots. Within the REPLICATOR and SYMBRION projects, one of the challenges will be to combine the characteristics of both kinds of robots into one.

In the beginning, there seems to be a few major problems that need to be solved. First of all the robot must have a docking element capable of handling the stress of several robots docked to it while applying all their forces (e.g. gravity, reaction, inertia force). Additionally, the docking element needs to assure the automatic coupling of several electric contacts needed for information exchange and power distribution between the robots inside an organism. Beside technical requirements the docking element should support the self aggregation of the robots. No matter how the position of two robots to each other is, the docking procedure should work. Therefore the docking element needs to balance misalignment and displacement to a certain degree. To increase the amount of possible structures for the organism and to simplify docking for the robots, all docking elements will be unisex and there will be at least four docking elements on each robot. Another problem is the mobility of the robot requested by the swarm based requirements. In order to guarantee local communication between robots, a reasonable velocity (i.e. a contacting rate) is needed. The kind of suitable locomotion is under evaluation.

The general approach in the state of art of modular robotics is the development of "cube-like" robotic modules with internal motors, batteries and control. The docking ports are usually placed on the sides and both locomotion and lifting abilities are provided mechanically separating the module in two blocks, able to bend reciprocally. This bending allows the lifting of attached modules, but often represents the only locomotion strategy for the robot, that can be quite slow and complex to control in accuracy and resolution of movement. Hence, as a new feature in modular robotics, we are currently considering to introduce higher locomotion capabilities, for instance integrating wheels in the modules, giving more independency to each module. The aim is to fabricate modules that are firstly conceived as independent robots rather than "just" modules to be assembled in a robotic organism. The increase in independency for what concerns locomotion allows in this way single modules, now robotic units, to move and explore the environment, rapidly acquiring information about the environment. Subsequently, they can rapidly reach their neighbours and, as a last process, engage assembly. Furthermore, wheeled modules could be used by the robotic organism as "wheeled feet" in order to have a faster global locomotion. As advanced feature, the wheels themselves could be an actuation mechanism (i.e., a rotational degree of freedom), considering to integrate into the wheels the docking mechanism. A wheeled-locomotion approach is characterized by a very high-energy efficiency on smooth surfaces, but it could show limitation on sandy or pebbly surfaces and even in facing small obstacles (like electrical cables, grass, etc.). The first concept in order to solve this issue consists in moving from a basic mini-rover configuration with four wheels to a caterpillar-based robotic unit, able to provide locomotion even on challenging surfaces and environments.

A differential drive is easy to implement and to control. However, not every movement is possible. The docking of two robots in the orientation of their wheel axis is only possible with a non trivial motion sequence. A non-holonomic drive is capable of positioning the robot everywhere and in any orientation to another robot, but is difficult to implement in design as well as in control. With at least two degrees of freedom a movement by crawling is also possible. Unfortunately, this is done by use of the main actuators which consume a lot of power. The optimal solution depends therefore on the scenario for the robots. At the moment, a crawling like locomotion is likely for the replicator robot while a mixture between non-holonomic and differential drive is more suitable for the SYMBRION robot.

These are only two challenges out of many which need to be solved within the REPLICATOR and SYMBRION projects, but in the end we will know much more about suitable design of self aggregating robots.

4.2 Electronic Challenges

The electronic design is a huge challenge due to strong restrictions of the size of the robot and the complexity of the hardware design. Each stand-alone robot is equipped with two processors, one main microcontroller (MCU) and one shadow microprocessor (CPU, see Fig. 2). The breakdown in microcontroller and microprocessor was deliberately intended to separate computational tasks within the single cell.

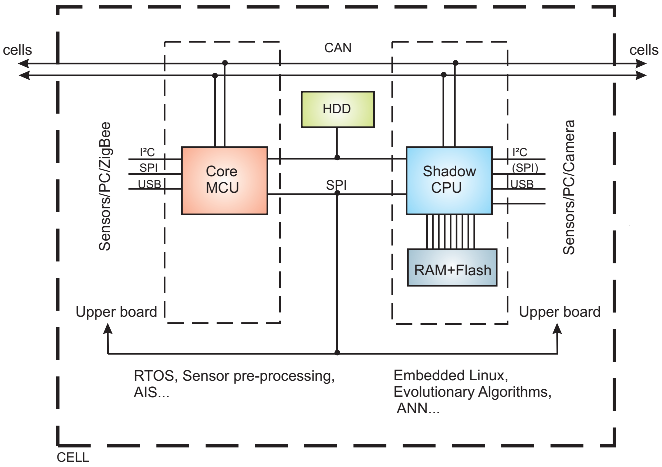


Figure 2: Functional electronic design of modules.

The core microcontroller performs basic functionality (e.g. sensor pre-processing, running artificial immune system) and keeps the robot alive. The shadow microprocessor is mainly responsible for bio-inspired approaches like the genetic algorithms, sensor fusion, ANNs etc. and is more powerful in comparison to the core processor. Due to higher computational power results in higher energy consumption, the shadow processor is able to run at different power-down modes when computational power isn't needed.

One of the biggest challenges during the electronic design is the development of the shadow processor module in a tiny size as well as finding solutions for shared resources like memory, power and communication capabilities.

5. SOFTWARE CHALLENGES

Beside the hardware challenges, the project is faced with many software requirements. Because robots can either run independently, as a swarm, as an organism, or even as a swarm of organisms, the interaction has to be managed in an organized and efficient way.

The different layers of software development are shown in Fig. 3. On the bottom layer there are two different processors, which are able to communicate with each other and have to be coordinated at the robot level. To cope with the additional difficulties a swarm or an organism causes, a middleware-like system is necessary. On top of this abstraction layer high-level control mechanisms and distributed applications can be integrated.

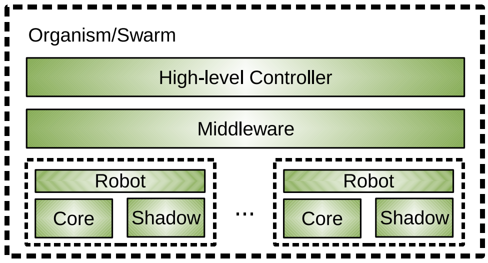


Figure 3: Different layers for software development.

5.1 Robot OS

On the robot level it is necessary to adopt mechanisms to coordinate data and data flow in a suitable way, and at the same time it is essential to predict and organize the behaviour of the multitasking system. It is also critical for the project to deal with the event driven architecture of the robot especially in respect to the real-time sensor system. For this reason a Real-Time Operating System (RTOS) builds the base of the software structure. The software architecture of the robot is modular and provides basic functionalities such as creation and termination of tasks and threads, inter-task communication, inter-processor communication, external event management, and memory allocation. Additionally the robot runtime system has to provide the middleware system with appropriate interfaces.

5.2 Middleware

Once the robots are aggregated into a more advanced multi-cellular organism it is essential to have an efficient controlling and coordinating mechanism. Therefore a middleware layer is introduced which defines unified interfaces and communication services according to the individual robot capabilities. The distributed middleware controls synchronization processes between nodes, configures and handle the communication bus (CAN) and manages distributed memory and energy resources. Furthermore it has to provide the robots with an abstraction layer between the operational system functions and the high-level controller domain.

5.3 High-level control concepts

Our projects will evaluate and test a variety of different control-concepts for the single robots as well as for the aggregated high-level robotic organism. Example can be given by artificial immune and artificial neuronal networks, different learning mechanisms as well as classical model-based controllers. In the following we describe one of these controllers - a bio-inspired controller concept which we call "Hormone-Driven Robot Controller" (HDRC). A data-structure that will hold configuration information for the robot, especially for the used software controllers of the robotic node, is called "Genome" in our constortia's terminology. This Genome will contain also a set of rules that link the degradation and the secretion of hormones to the local levels of other hormones. The secretion of hormones can be triggered by other hormones or by receptors that get activated by receiving environmental stimuli. Hormones can alter the sensitivity of receptors, trigger activities, modulate certain controllers or even activate/deactivate whole (sub-)controllers. This way we expect that a variety of systems can easily evolve:

1. **Homeostatic systems:** These hormone systems can

allow the organism to regulate a variety of internal properties around a homeostatic set point. For example, an robot "hungry" for light but located in the dark, can increase its motion level, thus will increase its chance to find a light spot.

2. Adaptive behaviours: Hormones can reflect a change of state of the environment, thus they can modulate controllers to respond to these environmental changes.

3. Target-oriented behaviours: Hormones with very fast dynamics (short-term acting hormones) can be even used to steer robots autonomously towards certain targets or to actively avoid areas or objects. This can be used in the previously mentioned foraging-for-energy scenarios.

3. Signal propagation and timing: As hormones are passed also among the robotic nodes in an aggregated organism, hormones can be used for signal propagation along the body of this organism. In nature, such systems show frequently the ability to perform rather well working timing tasks (see for example the synchronization of fireflies in [2]). We can expect to evolve such signal-propagation mechanisms also in our aggregated robotic organisms, possibly synchronizing the movement patterns of legs or other body parts.

To allow the HDRC to evolve the above-mentioned tasks and to evolve the needed functionality to perform such tasks, we have to implement a separate hormone controller. This controller is created from the evolved information in the Genome and frequently simulates hormone secretions (additions), degradations and diffusion within each robotic node. Using the available communication capabilities of the robots, the hormones are exchanged also between the robotic nodes, thus allowing a diffusion of virtual hormones within the whole higher-level organism.

Fig. 4 shows two distinct ways how the HDRC can be used in two different swarm states:

State 1: Fig. 4a shows that each robot is contains several virtual compartments, which associated with different real robot "body parts". In the case depicted here, each robot contains 2 lateral, one frontal and one terminal compartment. In the center, there is a fifth (central) compartment located. Sensors can trigger excretion of hormones into their corresponding local compartment and actuators can be modulated/affected only by hormone concentrations which are present in their corresponding compartment. Hormones are diffused to neighboring compartments and to to the central compartment. In the depicted case, a light sensor senses an obstacle to the left of the robot. It triggers the secretion (addition) of a hormone into this segment, which enhances the speed of the associated left motor. By diffusion, the same hormone reaches also the right compartment, where it can decrease the rotation speed of the right motor: The robot turns to the right. A central luminance sensor (central compartment) can trigger the secretion of another hormone, which generally increases motor speed on both sides: The robot drives (forages) faster in brighter illuminated areas.

State 2: Fig. 4b shows a totally different usage of the HDRC: One robot started to call other robots for aggregation. It secrets a specific "head-marking" hormone. This hormone is secreted only in the first robot that starts the aggregation. Due to the diffusion process and the increasing chain length, the concentration of this hormone decreases, as the robotic organism gets larger. By using this gradient as a source of information for the "tail robots", the organism can be limited to certain sizes and there is always a gradient inside of the organism that points towards the "head". This gradient information can also be important for coordinating body movements.

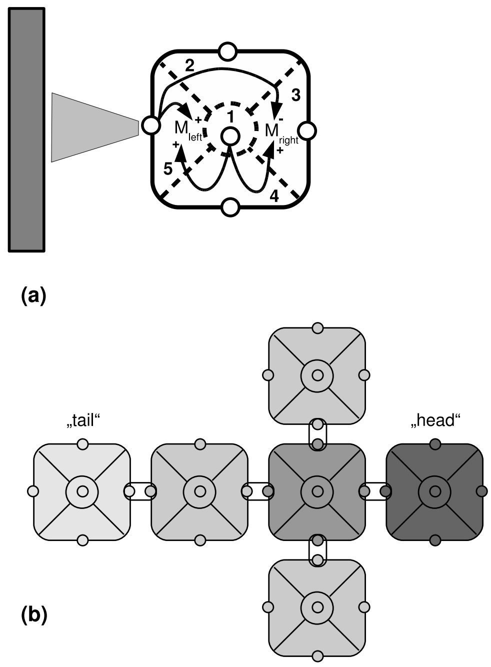


Figure 4: (a) Schematic drawing of a hormone-driven robot controller (HDRC) performing an obstacle-avoidance behaviour. Receptors can trigger hormone secretions. these hormones can differ through several virtual body compartments inside of a single robot. Hormones can switch on or off actuators, modulate actuator function or interfere with other hormones; (b) Several robotic nodes are coupled together to a higher-level organism. Simulated hormones are floating through the "body", forming hormone gradients. In the picture, a dedicated "head"-hormone is shown. These hormone gradients can support the formation of aggregated organisms out from the "fuzzy" swarm state, which is formed by many free-driving or free-walking robots.

5.4 Simulation Framework

To test, compare and verify different robot designs, different organism configuration and the controllers in a quick and cheap way, a simulation environment needs to be implemented. The simulation should offer an easy and fast way to create a test environment and to design some basic robot architectures to test the availabilities the robot might have. Later the simulation can be used to test different organism configurations and to verify the different controllers. Furthermore, the simulation can be applied in long term scenarios to explore biologic mechanisms like evolutionary and genetic algorithms, collective and symbiotic behaviour and neuronal networks.

In the REPLICATOR and SYMBRION projects we will use Delta-3D for the simulation framework, see Fig. 5. It offers lots of interfaces and has already successfully been used in other simulations. The aim is to simulate the physics of the single robots, as well as that one of a whole organism.

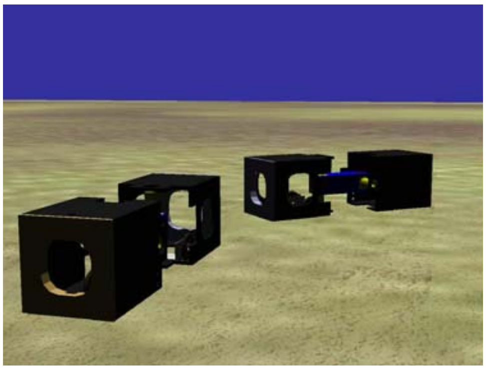


Figure 5: Screenshot of the Simulation Environment Using Delta 3D.

3D-models from CAD-programs can easily be loaded into the environment and without any effort a robot model can be created in the simulation. Different robot configurations like form, size and the position and orientation of the joints of the robot can be easily created and tested within the environment. Additionally the simulation needs to integrate the controller into the environment without modifying it with the aim that the robot will behave in the simulation nearly the same as in the real environment. Therefore a hardware abstraction layer (HAL) needs to be strictly specified, which will offer the same functionality for the actual robot and the simulated one. A robot controller will only use the functionality of the HAL, so that a robot, developed in a simulation environment, will run on a real robot and vice versa.

As the requirements to the simulation will grow with the complexity of the controller, running the simulation on just one computer or even just on a single core won't be sufficient enough. Therefore a distributed simulation will be mandatory. For this purpose Delta-3D offers an interface to the High Level Architecture (HLA), a general purpose architecture for distributed computing. Using this architecture the simulation can be executed on several computers having different platforms located within a local area network or connected through the internet as well.

6. TOWARDS EVOLVE-ABILITY OF THE ROBOT ORGANISM

Within the projects, the creation of evolvable or otherwise adaptive software and hardware is the main focus. However, from the conceptual point of view, achievement of evolve-ability for the robot organism is planned in two complementary ways, which we call bio-inspired (or bio-mimicking) and engendering-based approaches.

6.1 Bio-inspired/bio-mimicking approach

Any bio-inspired approach is based on analogies to living organisms and is carried out by the biological partners in our consortia. Our bio-inspired control algorithms use neither any global point of information nor any form of complex knowledge. Our algorithms are stable to a wide range of environmental conditions and are extremely robust. Therefore, the bio-inspired strategies in projects are going to draw advantage from the well-known robustness/simplicity as well as from the plasticity/adaptability derived from natural systems. Our goal is to create stable, robust and adaptable robotic organisms. Here we will investigate a variety of concepts, such as:

1. Genome: All robotic organisms will carry one or several Genomes. A Genome is a collection of genes, which carry information about controller structure and controller dynamics. A gene can be a simple part of a blueprint, which "depicts" a part of the final controller. But a gene can also work as a rule, which is used to "construct" parts of the final controller. In the latter case, there can be interferences between different genes, thus competition or cooperation can arise also on the genetic level. A self-organized process can be established which will be able to create a flexible, but robust controller structure.

2. Controller: We will investigate several controller types, ranging from rules-based controllers, to Evolvable Artificial Neural Networks (EANN), to hormone-based controllers and to even hand-coded controllers that execute hand-optimized (modular) parts of the whole organism's behavioural repertoire.

3. Sexuality/Reproduction: We plan to enhance and to speed-up the dynamics of artificial evolution by implementing virtual-reproduction of robots. A separate process will allow to remove controllers from the least fit robots and to re-initialize them with mixtures (interbreeds) of the controllers of more fit robots. We will also investigate the advantages of sexual reproduction in such scenarios.

4. Embryology: To allow well-ordered controllers to emerge from the information stored in the Genome, we will mimic embryological processes, driven by a virtual hormone system.

6.2 Engineering-based approach

The engineering-based approach is complementary to the bio-inspired one and focuses in such issues as learning, distributed decision making, navigation and so on. Generally, consortium focuses on three following approaches (these approaches are closely connected so that finally it will be a kind of hybrid framework):

1. On-line learning. On-line learning is based on the behavior level and uses automatically generated feedback. The feedback comes from internal, external and virtual sensors. Some direct feedback can be sensed through vision-based subsystem, by using FRID-based identification or localization technologies, by using smart laser scanner, sound, light, humidity, temperature, internal energy sensor and other sensors. It is intended to use middleware and sensor-fusion approach to generate complex non-direct feedbacks through virtual sensors. Since off-line mechanisms can hardly be applied to real robots, the challenge of the proposed approach is to perform non-supervised learning without any off-line mechanisms (or at least with a minimum of them). This can be achieved by combining evolving computation with rewards/feedback/fitness calculated on-line. Therefore the whole approach can be named "on-line learning".

2. Evolutionary computation. High computational power of the system allows running on-line and on-board such well-known approaches as genetic programming (GP) (e.g. [22]), Genetic Algorithms (GA) (e.g. [23]). To avoid the problems posed by a huge search space, we intend to integrate limitations, originating from hardware platform. Another set of problems we are aware of are the fitness functions required for these algorithms. These fitness functions are very difficult to calculate based only on local sensor data. Moreover these functions are evaluated extremely delayed because the organism mostly assess their fitness after accomplishing the task.

3. Approaches from the domain of Distributed Artificial Intelligence (DAI). On-line learning as well as GA/GP include diverse aspects of DAI such as a distributed knowledge management, semantic information processing, navigation and actuation in the environment, planning, sensor fusion and others. Development and implementation of these approaches is an important step towards evolve-ability of the robot organisms.

7. CONCLUSION

In this short paper we made on overview of two large European projects, dealing with a new paradigm in collective systems, where the swarm robots get capable of self-assembling into a single symbiotic multi-robot organism. We introduced an energy foraging scenario for both robot species and demonstrated that a transition between collective and symbiotic robot forms represents a very hard problem. It involves not only hardware and software issues, but also very basic questions being also open not only in biological but also in engineering sense. We demonstrated the main hardware and software challenges and the road-map how to achieve the evolve-ability of the robot organisms.

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