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Evolve-ability of the robot platform in the Symbrion project

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Abstract

In a swarm of robots the individual entities can profit from cooperation, emerge new behaviors and can increase the overall fitness. In a more advanced approach, robots work not only collectively, but can also aggregate into multi-robot organisms and can share energy, resources and functionality. This approach provides many advantages for robotic systems: the aggregated organism, considered as one robot, possesses an extended reliability, adaptivity and evolve-ability. In this paper we present the vision and the ongoing work in the large integrated European project "SYMBRION", dealing with self-assembling of swarm robots. We point out different challenges in the field of hardware and software as well as describe main principles of evolve-ability applied to the platform.

Keywords: *collective robotics, swarm robotic, artificial evolution, reconfigurable systems, pervasive computing*

1 Introduction

Cooperation among individual members of species can be observed in biological systems. This has evolved by natural selection over millions of years and helps species to survive [1]. There are different forms of cooperation, based on partner-like or egoistic principles [2], where individuals remain either independent of each other or form very close relationships. Cooperation in the case of close relationships can also take different forms; one of them is so-called symbiotic organization [4]. A prominent example is the *lysmata debelius* [8]. This shrimp is able to life in debris, but can also eat dead tissue and parasites from fish. Both the shrimp and the fish can benefit from this behavior.

The natural symbiosis represents the biological inspiration for the further development of robotic systems. The hope is that such a close relationship can provide robots several essential advantages which we observe in nature [6]. For example, a swarm of robots can emerge behavior and fulfill tasks that an individual can not. However, when there is a large obstacle (e.g. gap or wall), which robots cannot pass, the swarm will fail. The idea is that robots can aggregate into larger artificial organisms (close relationship) and so pass this obstacle [5]. In symbiotic robotics, each robot of the swarm is able to run as an individual or be aggregated in an organism. Being equipped with a docking mechanism, the robots can autonomously aggregate or disaggregate. Once the robots have been connected to each other, they are able to share resources such as computational power or energy over a common bus system.

Artificial organisms can continuously change their structure and functionality; this requires a high level of cooperation and organization. Additionally, aspects like self-configuration, self-healing, self-optimization and self-protecting are addressed. The ability of self-reconfiguration provides adaptation to different scenarios. The organism can also monitor itself and improve its own functionality through continuous optimization.

All these issues underlie the SYMBRION project (www.symbrion.eu), which focuses on symbiotic robot organisms. Based on bio-inspired approaches and computational paradigms, it focuses on better understanding artificial evolution and the control of such organisms. The robots should be able to re-program themselves and adapt to varying environments. The project started in February 2008 and is funded by the European Commission within the work program 'Future and Emergent Technologies'.

The SYMBRION project is closely linked with the REPLICATOR project (www.replicators.eu), also funded by the European commission within the work program 'Cognitive systems, interaction and robotics' and deals with

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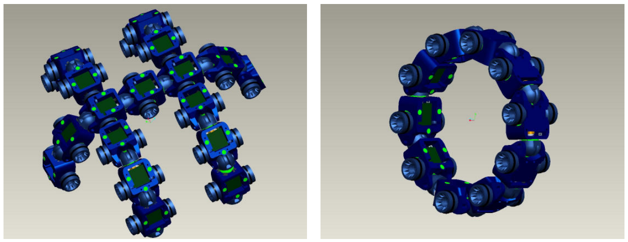
reconfigurability of sensors and actuators, adaptive control structures as well as with learning strategies for symbiotic robot systems. These two projects mutually affect each other and exchange knowledge in order to speed up development.

The rest of this paper is organized in the following way: In the section 2 we describe the underlying robot concept of adaptive multi-robot organisms. In section 3 we present the role of bio-inspired strategies like evolution and learning focused on evolve-ability. Section 4 shows ongoing work on implementation of evolve-ability in the platform. Finally, section 5 concludes this work.

2 From robot swarms to symbiotic organisms

Inspired by species which are living in symbiosis, we transfer this behavior to artificial robot swarms. One natural example is the fungus *dictyostelium discoideum* [3] which can either grow as a unicellular or aggregate to multicellular organism upon starvation. A similar behavior which can be easily transferred to artificial swarms is collective foraging. If the swarm becomes ”hungry” it can start to aggregate to a multi-cellular organism and collectively search for a docking station [7]. Figure 1 shows possible multi-robot organism configurations that allow accomplishment of tasks a robot alone cannot fulfill.



(a) (b)

Figure 1. *Examples of building 3D structures for an multi-robot organism.* ***(a)*** *Spider-like organism;* ***(b)*** *circular organism [12].*

The idea to provide robots equipped with equal sensors and actuators seems to be a big advantage however brings enormously redundancy to the organism. To avoid this overhead we use heterogeneous modules with different hardware configurations or even different kinds of modules. This approach simplifies the mechanical and electronic challenges and transfers the complexity to the software level.

The aggregated organism can be treated as a large, distributed network. In order to achieve evolve-ability on hardware and software level the robots have to be able to communicate over CAN-bus [11] or ZigBee and share their resources within the organism. A common wired bus system is used for both the CAN and the power exchange. A group of robots can deliver a high current to supply demands within the organism. The memory and processing power can also be handled as in common, distributed networks, merged together in order to get massive computing power for on-line computation tasks.

3 Adaptation through Evolution and learning

According to Nolfi and Floreano [10] evolution and learning are forms of biological adaptation that differ in space and time. While evolution affects a geographically distributed population, learning takes place within each individual. Furthermore, evolution can take several generations until adaptation, while learning allows an individual to adapt to changing environments during lifetime. In the SYMBRION project we want to observe both evolution and learning to forward the evolve-ability of the robot platform.

3.1 Evolution

In nature inheritable information of each individual is represented by genes building up a genome. Each generation passes the genome to its offspring. Through mutation, selection and exchange of genomes new traits can be produced and impact future generations.

In our project we adopt the idea of genomes. Each robot will have one or more genomes organized in an appropriate data-structure. As a first step, we will investigate how a genome for a robot have to be represented. Beside linear organized genomes, hierarchical and data-base based structures come into consideration. Additionally, we investigate, what information has to be coded into the genome, and how. In a previous experiment [9], the robot behavior is based on a Moore automaton. Atomic actions are represented by genes and the complete automaton builds the genome. For further development we like to add extra information to the genome. We discuss how to insert the control mechanisms as well as the way sensor data is interpreted. The genome with its complete information can than be evolved and reproduced continuously.

Moreover we investigate the impact of genome manipulation. Therefore we transfer biological principles to the robot platform. Besides variation (e.g. cross-over, mutation), we analyze selection operators (e.g. parent selection, survivor selection). As a result, new genes with new functionality can appear, which can increase the fitness of an individual or of the whole organism. By studying the genome structures and the evolutionary process we should be able to deduce general principles of evolution.

In order to exchange genomes, sexuality and reproduction play an important role. Thereby the type of exchanging genetic information can vary from simple cloning to sexual outcrossing. In addition to the reproduction rate, aspects such as mate choice, monogamy and polygamy have to be investigated. The experiences with various combinations of these aspects can help to speed up evolutionary processes.

Various numbers of generations reproduce and generate new offspring until the individuals satisfy the predefined requirements. Through selective rerproduction, the overall fitness can be increased and unsuitable solutions dismissed. To evaluate the current performance certain criteria can be taken into account. All criteria together can be combined into a fitness function. After calculating the fitness of each member the overall fitness of a swarm or an organism can be measured and the individual fitness can be compared to all others. As fitness criteria power units can be used. As soon as the power contingent is exhausted, a robot virtually dies.

3.2 Learning

An important trait of intelligence is the ability to learn. In contrast to evolution, learning process takes place during lifetime and enable faster adaptation to not predictable changes in the environment at the time of birth. Evolutionary processes can take several generations until an adaptation to new environmental conditions can be successfully. The learning process is limited to a single individual [10] and can take place on different levels of complexity. On a low level, two robots can learn how to dock to each other. Based on that, a group of robots can learn how to build up an organism. When the robots are capable of a few different structures, they have to learn, which kind of structure is suited best to a certain situation. To cope with these different levels and especially the complexity, we will investigate different learning strategies like online, offline learning as well as reinforcement learning. A central point of learning will be the definition of rewards and how to evaluate them. Additionally, we have to investigate how to trade off the costs for learning and the benefit from learned behavior.

Another aspect is the modularization of behaviors. After learning some elementary behaviors, a robot does not have to process actively the same actions again. For example, a human does not have to think about the coordination of the legs, when he decides to walk. The involved parts of the leg are combined to a higher level action and the intention to move forward includes automatically every single position of the appropriate body elements. By combining more and more atomic and complex behaviors to new patterns, a robot can get more and more advanced and can free ressources to learn higher-level behaviors.

From time to time established modules have to be adapted to changing conditions. For instance, a spider-like organism loses a robot element in a leg, the locomotion has to be recalculated and changed to the new configuration. The aim in our project is to analyze the circumstances for modularization and to enable the robots to decide autonomously which patterns can succeed or have to be rebuilt.

Based on learning and modularization a robot can start to anticipate environmental conditions. In a next step the anticipation mechanisms can predict the environmental response to a single action. Furthermore, several patterns can be combined and future behavior can be predicted. Finally, it will be interesting to address the inverse problem of actions. A robot or organism can plan to achieve certain targets or behaviors.

Unfortunately, learned knowledge is not necessarily fixed into the genetic code and is lost after the death of an individual. Therefore we will observe different strategies of passing knowledge from experienced robots to less experienced ones. Better performing robots can teach others and increase the overall fitness of a swarm or an organism.

4 Adaptation in multi-robot platforms

In the 'SYMBRION' project there are different levels of adaptation. During the development of the robot platform the manifold possibilities of adaptation has to be taken into account. The future system should not only be able to adapt on software level, but also be able to evolve on mechanical and electronic levels.

4.1 Principle of evolve-ability embedded into mechanical platform

One of the most critical aspects of designing adaptive systems represents the hardware platform. The platform (mechanical system and electronics) being once developed is difficult to change anymore during its life-cycle. The idea behind the hardware-related evolve-ability is to build small modules which can build large organisms. This idea is a central point of cellular as well as reconfigurable robotics. New aspects in these works can be introduced by involving concepts of swarm robotics. Heterogeneous swarm robots build robot organisms in a symbiotic way by assisting each other, sharing functionality and specializing within these organisms. There is no evolve-ability on the level of separate modules, however the organism can change its own morphology and hence the functionality.

To investigate topological aspects of evolve-ability on the level of organisms, we build simplified polymer models of real modules to explore inexpensively and quick morphological properties of different macroscopic structures.

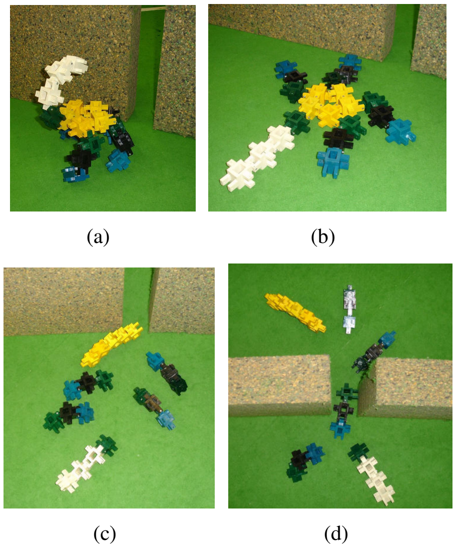

(a) (b)
(c) (d)

Figure 2. *Possible gate-trough scenario with topological models of PUZZBOT.* ***(a)*** *Aggregated unsymmetrical scorpion;* ***(b)*** *Planar (on-surface) organism;* ***(c)*** *Organism disaggregated on mesoscopic modules;* ***(d)*** *Passing the gate in mesoscopic modules.*

In the given work we focus on one possible scenario, where mechanical evolve-ability can be demonstrated. This simple scenario represent a motion from A to B through a narrow gate, see Figure 2(a). The size of this gate is chosen to be smaller than the size of the organism. As an organism the unsymmetrical scorpion is chosen (see more in www.symbrion.eu). There are several ways to pass this gate, for instance to change the morphological form of the organism, e.g. from the scorpion-like to the snake-like. One of these ways is to disaggregate to mesoscopic modules which still possess a capability for common locomotion, see figure 2(b)-(d). In Figure 3 we demonstrate a possible mesoscopic aggregation of modules and show the principle of movement. The minimal number of DoF in these modules is two. The first DoF is in the front of the robot and used for pushing the robot forwards. The second DoF is behind and is used as a bearing point for motion. It seems that only vertical DoF are enough for this kind of common locomotion.

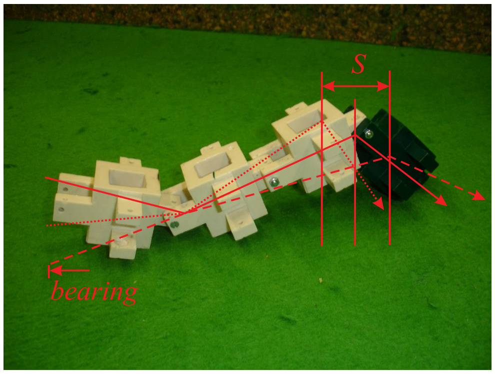


Figure 3. *Mesoscopic aggregation of modules with common locomotion.*

4.2 Evolve-ability needs special electronic design

According to the mechanical design presented in the previous section organisms consist of many small robots which are able to aggregate. In order to allow evolve-ability as well for electronic design, we are following the strategy of small modules (PCBs) wired to a common electronic system.

In the last view years the rapid development in the area of embedded system opens new ways for electronic design especially in the field of micro robotics. Components are getting smaller, cheaper, include a lot of peripherals and due to ultra low voltage technology consume less power. For these reasons we are able to develop high-tech modules which can still remain small and suitable for our robots. The maximum available size for the PCBs is bounded to 40x40mm. Depending on the role of swarm members, robots have one or many PCBs implemented. Two different main PCBs are at the moment in developing, both equipped with powerfull microprocessors (Figure 4). All vital tasks are running on the *core* PCB equipped with Cortex M3 microcontroller from the ARM family (www.arm.com). It is responsible for tasks like sensor pre-processing, locomotion control, artificial immune system (AIS) and for simple individual tasks. A real-time operating system (RTOS) is running on it and ensures real-time ability for each robot and for the whole organism.

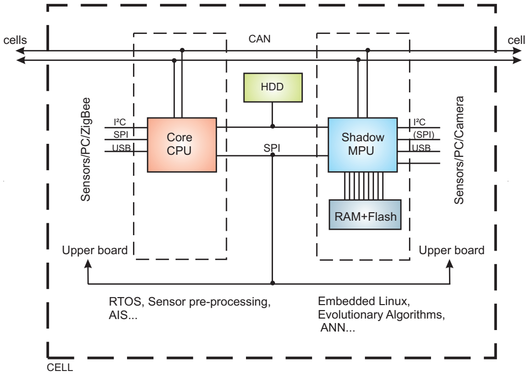


Figure 4. *Schematic diagram for electronic design for one single robot.*

On the *shadow* PCB, the XScale microprocessor, usually used in modern PDA devices is assembled and provides high computation power, enough memory and a lot of useful peripherals. The so-called ”system on chip” allows direct interfaces to camera, laser scanner, sensors and actuators. This CPU runs with embedded linux and with the operation frequency up to 600 MHz it is able to cover tasks like strategy calculation and selection, adaption, artificial neuronal networks (ANN) or trajectory planning. In order to reduce power consumption the ability of changing the running frequency is available (wireless speedstepping) and even if there is no need for tasks mentioned above, the processor can be driven in sleep mode and do not consume energy.

In case of heterogeneous modules many possible configurations for applying of these two main boards are possible. For example almost all modules in a swarm can be equipped with the *core* board. On several special modules (e.g. modules with camera/laser scanner) responsible for tasks which needs higher computational power and memory the *shadow* board can be attached. Both modules can be mixed within the organism to achieve advanced behavior. The communication between different main boards within the robot or within the organisms is possible by the docking mechanism which allows wired connection of the CAN bus. Additionally, a common power bus can deliver required energy demands for the system load or for recharging of batteries in parts of the organism.

Additionally, small PCBs have to be intergrated into the robot and can be exchanged depending on the role of the heterogeneous modules in a swarm and in an organism. For example a small PCB can be intergrated in a wheel and the controller on it can provide all necessary computation for the locomotion. The modularity reached by using small electronic modules opens new opportunities for mechanical design and for adaptation.

To achieve a very strong density of the components on mini PCBs, multi-layer design is inalienable. These is one of the biggest challenges for electronic design and can be only achieved by using very professional PCB layout software.

4.3 Adaptive Software Framework

The development of the software framework is very challenging. The robots can be treated as stand-alone units, as a swarm, an organism or even as a swarm of organisms. For each ’state of aggregation’ the requirements are different. The future software framework has to be extendable and modular. The support of different controll mechanisms is fundamental and controllers have to be exchangeable during runtime. Furthermore a common genome structure and interfaces for learning have to be implemented. The role of the software framework is to abstract functions from lower levels to a higher level. The different layers of the future software structure are shown in Figure 5.

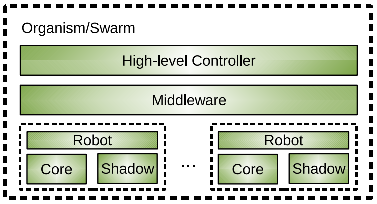


Figure 5. *Software structure for multi-robot organisms.*

The robot runtime system has to band the *core* and the *shadow* processor together. Both processors have to be coordinated in order to share workload and different tasks. Because a robot will run in a real environment, an event driven architecture has to handle incoming stimuli and internal states in a suitable manner. A real-time operating system takes care of the basic functions of the processors. Different tasks and threads can run in parallel on a robot and hence have to be scheduled fairly and in a proper way. Due to small capacities an efficient memory management has to take care of allocation and administration of memory. Additionally, the robot runtime system provides basic communication channels like ZigBee or CAN and controls power consumption. Fundamental for cooperation in a swarm or aggregation to an organism will be the interfaces to the middleware system, which will cope with the additionally requirements.

The middleware system supports aggregated organisms with necessary functionality on organism level. It synchronizes processes and reliable communication between the robots through unified interfaces and manages distributed memory and energy exchange. Thereby the middleware system abstracts complex functions for high-level controllers and allows a fast and efficient way to develop different controllers.

4.4 High-level Controller

Because of the complexity for locomotion and cooperation suitable controller concepts are very important. A controller runs on a robot and has internal or external stimuli as input. This input can change different internal states and trigger an output like motion or other actuators. Figure 6 shows the general concept for a controller. The input from external and internal sensors are fed into the controller. Likewise, they can flow into a sensor fusion module. This module can proceed measured data and fuse them. Additionally, the robots is able to exchange sensor values and the sensor fusion module includes them into the fusion procedure. The raw and the fused sensor data are given to the

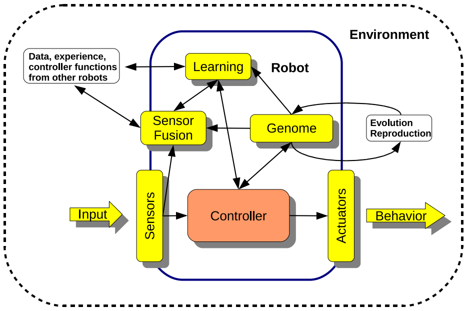


Figure 6. *Controller concept for the future platform.*

controller for processing and mapping the internal states to some actuator output. It is possible, to take the sensor values and pass it to the learning engine. This engine can process current values and deduce or improve controller functions by applying the bio-inspired learning approaches. The new functions can then be integrated into the controller or replace obsolete functions. Furthermore, the learning engine can receive experiences and functions from other robots, validate them and add them to the own function pool.

The role of the genome in the controller concept is to map the controllers behavior into inheritable information. Additionally, the sensors fusion module and the learning engine can be coded into the genetic sequence. The genome itself can then be exchanged by evolutionary approaches and passed to the offspring. The continuous reproduction can guarantee an ongoing adaptation process for individual robots as well as for the swarm or an organism.

In our project we want to observe different concepts for controllers. One of the controller concepts we want to observe is the classical model-based one. The determination of the optimal behavior and the parameters for the individual agents can be found by experiments or simulation. For a better performance probabilistic modelling approaches will be added.

Another controller concept we want to investigate is a hormone-driven controller concept. The degradation and secretion of hormones can be organized by a rule set based in the genome. Hormones can be triggered by other hormones or by receptors activated by environmental stimuli.

Because biological organisms are often controlled by neuronal systems, we also want to observe artificial neuronal networks (ANN). The multi-robot platform can aggregate and connect to each other and behave like a neuronal network and mimic the complex neuronal structures from nature.

5 Conclusion

In this paper we presented the ongoing work and the visions of the SYMBRION project. A symbiotic robot organisms aggregated from stand-alone robots raise many challenges in the field of hardware, electronic and software design. We pointed out bio-inspired concepts to handle complexity of cooperation and organization. To ensure evolve-ability of the future platform we have to address the mechanical chassis as well as the electronic design. Both enable the possibility for transition from swarms to organisms and require high level controllers for sophisticated behavior. Finally, we touched the future procedure to achieve the evolve-ability of the platform.

References

[1] D.J. Futuyma, *Evolutionary Biology*, Sinauer Associates, Inc, Sunderland Massachusetts, 1986.

[2] G. Weiss, *Multiagent systems. A modern approach to distributed artificial intelligence*, MIT Press, 1999.

[3] H. Haken, *Synergetics: An introduction*, third edition, Springer Verlag, New York, 1983.

[4] A.E. Douglas, *Symbiotic Interactions*, Oxford University Press, England, 1994.

[5] S. Kornienko, O. Kornienko, A. Nagarathinam, and P. Levi, *From real robot swarm to evolutionary multi-robot organism*, In Proc. of the CEC2007, Singapore, 2007.

[6] S. Camazine, J-L. Deneubourg, N.R. Franks, J. Sneyd, G. Theraulaz and E. Bonabeau, *Self-Organization in Biological Systems*, Princeton University Press, Princeton, NJ, USA, 2003.

[7] S. Kornienko and O. Kornienko, *Collective energy homeostasis in a large-scale micro-robotic swarms*, Robotics and Autonomous Systems (under resubmitting).

[8] R. T. Bauer, *Remarkable Shrimps - Adaptations and natural History of the Carideans*, University of Oklahoma Press, April 2004.

[9] L. König, K. Jebens, S. Kernbach and P. Levi, *Stability of on-line and on-board evolving of adaptive collective behavior*, EUROS08, 2008

[10] S. Nolfi and D. Floreano, *Evolutionary Robotics - The Biology, Intelligence, and Technology of Self-Organization Machines*, Bradford Book, MIT Press, London, England, 2000.

[11] E. Meister, *Development of CAN-based Computational Cells for Multi-Robot Organisms*, Diploma Thesis, University of Stuttgart, Germany, 2007.

[12] M. Rothermel, *Mechanical design and assembly of a swarm robot with docking capability for building multi robot organisms*, Study Thesis, University of Stuttgart, Germany, 2007.