Replicator

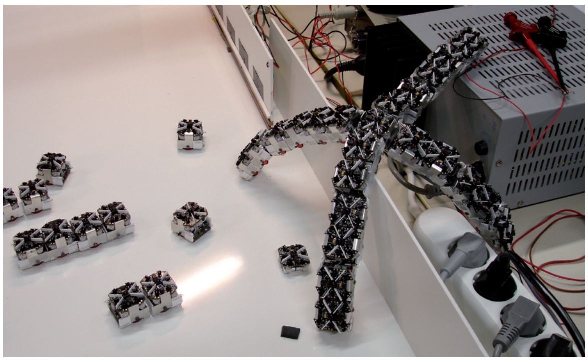
FP7 - 216620

Robotic Evolutionary Self-Programming and Self-Assembling Organisms

Emerging Self-organized Control

The Project

The Replicator project funded by the European Commission focuses on the development of an advanced robotic system, consisting of a super-large-scale swarm of small autonomous mobile micro-robots that are capable of self-assembling into large artificial organisms. These robotic organisms possess common energy and information buses as well as reliable legged, wheeled or climbing locomotion, based on modular sub-systems which can be autonomously reconfigured. Thanks to the heterogeneity of the elementary robots and their capability to share resources and communicate, the robotic organisms are able to achieve a large computational power, and rich close- and far-range sensing. The energy is autonomously harvested from external power sources.



A vision of a Replicator

Novel software development principles underlying robotic organisms, such as those for self-configuration, self-adjustment and self-learning, will be investigated. These principles will allow the organism adapting to the changes occurring at micro-robotic and multi-robot hardware structure and functional levels as well as at environmental morphodynamic levels. This enables the robotic organisms to emerge new functionalities, to develop their own cognitive and control structures and, finally, to work autonomously in uncertain situations without any human supervision.

The goal is the development of an organism that assembles itself from distributed micro-robots that are in interaction with the environment and themselves, meanwhile keeping in mind their systemic limitations, e.g. energy, and targets, e.g. searching victims, and environmental spatio-temporal constraints. The central features to be acquired by an organism are situational awareness, capability of self-assembly and distributed but coordinated control of engaging itself and its environment. The software frameworks at the disposal of such organisms describe how the software genotypes and phenotypes of the organism come about and evolve upon interaction with the environment and itself, and how they remain compliant with the underlying distributed hardware of the micro-robots.

Ultimately, these robotic organisms, which are extremely adaptive, robust, scalable and rich in sensing and actuating capabilities, will be used to build autonomous sensor networks, capable of self-spreading and self-maintaining in open-ended, even hazardous, environments. After an earthquake, for instance, a rescue worker or wheeled robot has major difficulties to enter a collapsed building and explore the rubble for victims. The organism on the contrary will be capable of disassembling and subsequently entering such inhospitable places. Furthermore, this organism will be capable of aggregating to crawl over obstacles of different sizes to reach victims. The organism will do so by adapting and evolving its functional shape to the observed environmental constraints and dynamics. It does so not only for controlling, but also for sensing itself as well as its environment.

Perception - Cognition - Action

The morphodynamics of an organism is subject to its own evolution and that of its environment. At operational timescales distributed situational-aware and goal-oriented self-management structures and schemes of a Replicator need to be active that are stable and robust under ``small-scale'' systemic and environmental transformations. Similarly, at ev-

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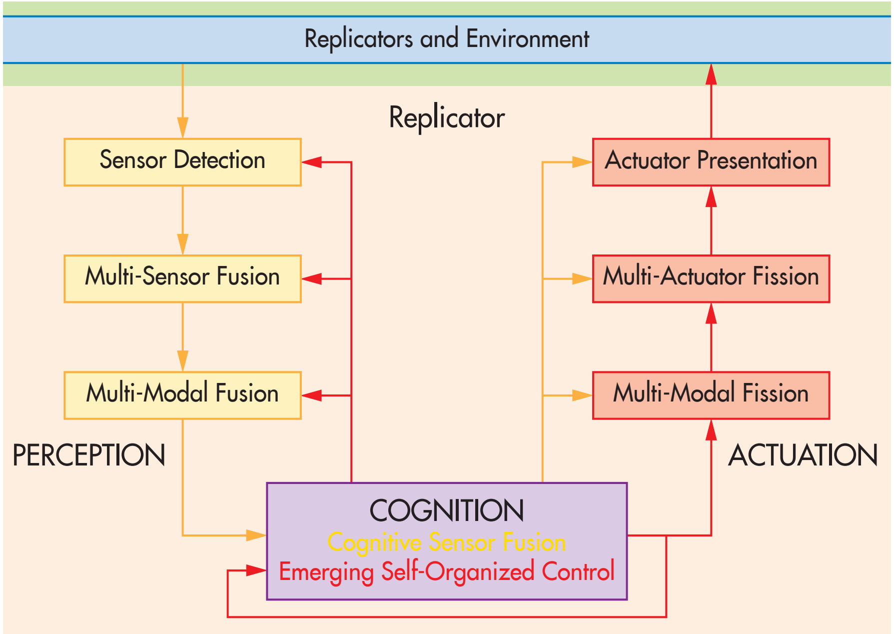
olutionary time-scales self-adaptation structures and schemes need be active that are fit and sustainable enough under ``large-scale'' systemic and environmental transformations. The emerging self-organization of the self-management and self-adaptation should meet specific performance criteria keeping in mind the systemic and environmental capabilities and limitations. For example, a robotic rescue team should be capable of acquiring self-organization abilities to transform from a swarm of micro-robots or organisms to a large-scale organism that is capable of penetrating through and crawling over debris to reach a victim. This control of its morphodynamics by such a collective of organsisms manifests itself as a set of distributed heterogeneous multi-robotic modules at critical scales. At operational time-scales such control modules allow for instance contextualizing attention and anticipation needed by cognitive multi-sensor fusion, decision making and multi-actuator splitting modules. At evolutionary time-scales such control modules allow adapting those management modules.



Replicators and environment

In this context enabling the emergence of self-organized control, including self-management and self-adaptation of the self-assembly and the self-evolution of an organism, is one of the main challenges in swarming multi-robotics. Emergence refers to how integrative levels of complex morphodynamics arise out of a multiplicity of relatively simple but spatio-temporally inhomogeneous interactions or co-evolution:

- Weak emergence: A system forms new structures and displays new behaviours as a result of elementary local (inter)actions of system modules. This does not mean that system or module structure and dynamics have dramatically changed; the shapes and behaviours have simply not been observed before and cannot be associated to an equivalence class represented by critical indices of module or system structure and dynamics, respectively.
- Strong emergence: A system forms new structures and displays new behaviours that are entrained by the context and the (non-) local interactions amongst sub-modules and their environments across spatio-temporal scales and dynamic regimes. This type of emergence involves the (co-) evolution of both system and environment: the equivalence class of critical indices definitely evolves.

Allowing the emergence of self-organized control is of paramount importance in order to let multi-robotic systems individually or collectively master in a flexible way arising dynamic and evolutionary complexity issues. These problems concern the degradation of stability, robustness, sustainability and fitness of the goal-oriented and situational aware control modules for self-management and self-adaptation.

The emerging self-organized control approach should allow such an organism both contextualizing and adapting it and other modules at critical operational and evolutionary scales. Such issues have till now not yet been addressed in geometric control or planning within robotics. Only in the seminal work of Haken on synergetics, the first ingredients to arrive at the self-formation and the self-organization of control structures and schemes are touched upon. Although Haken provides many insights on weak emergence, his approach may also be very valuable in dealing with strong emergence and therewith co-evolution of systemic and environmental morphodynamics.

In order to enable both types of emergence hybridization of sub-modules of robotic organisms and their environment through interfaces and interaction mechanisms is indispensable. Furthermore, distributed self-organized control modules of Replicators need besides such hybridization mentioned above also their own typical modular interfaces and mechanisms to be put in place. For how to accomplish this the reader is kindly referred to the leaflets on the hardware and software architecture and the cognitive sensor fusion of a Replicator organism.

To withstand and overcome the above-mentioned systemic and environmental operational and evolutionary pressures the robotic organisms will be able to acquire and to diversify in a natural way a set of distributed modules for self-management and self-adaptation.

On the one hand, across operational scales emerging self-organization by such organisms will yield ``bootstrapping'' stable and robust modular self-management structures and schemes upon positive and negative feedback amongst Replicators and environment with respect to their structures and schemes performance:

- Positive feedback amongst the micro-robots results in the formation of stable modular self-management structures of a Replicator.
- Negative feedback between Replicator and environment results in robust (low-cost and flexible) situational-

aware and goal-oriented self-management schemes of a Replicator provided by those structures.

The human operator will not directly control the system any more after defining general mechanisms and setting policies and rules for the self-management, in particular the automatic configuration of modules; automatic discovery, and correction of faults; automatic monitoring and control of resources to the management requirements; proactive identification and protection from arbitrary attacks or incidents. Positive and negative feedback can help the organism in an operational mode to structurally couple and functionally fine-tune its own dynamics to the emergence of its own systemic and environmental rhythms, patterns and waves. This ensures a certain level of stability of the systemic morphodynamics at operational scales.

On the other hand, across evolutionary scales emerging self-organization by such organisms will yield ``learning'' of fit and sustainable modular self-adaptation structures and schemes upon coarse graining and renormalization of evolving hybridized networks of robotic organisms and environments:

- Coarse graining results in the formation of fit modular self-adaptation structures of a Replicator.
- Renormalization results in the organization of sustainable modular self-adaptation schemes of a Replicator provided by those structures.

Analogous positive and negative feedback, coarse graining and renormalization help a robotic organism entrain its environment at evolutionary scales, and vice versa.

One type of problem that the robotic organisms in the project have at least to be capable of dealing with is the decrease in monitoring and control performance due to an increase in uncertainties and incompleteness of the observed and actuated own systemic and environmental physical fields. Such perturbative changes, for instance variation of surface roughness due to rainy conditions, may significantly influence the performance of Replicators climbing hills. Of course, this class of changes may also concern developmental systemic aspects of Replicators, such as changes in reaction times caused by ageing.

Another as important but more evolutionary type of problem the project's robotic organisms have to deal with is a non-perturbative change in the morphodynamics of both the organsims and the environment. This class of changes causes organsisms and environment to entrain each other across spatio-temporal and dynamic scales. The relevant physical morphodynamics that they can observe and display dramatically alters. For instance, if a robotic organsim acquires the capability to resurrect from the plane and to partially form a bridge, then such physical obstacles like rivers can be readily surpassed.

The question arises which emerging self-organized modular requirements to impose such that a robotic organism in interaction and co-evolution with itself and its environment lets emerge a certain level of stable, fit and sustainable self-managing and –adaptation modules.

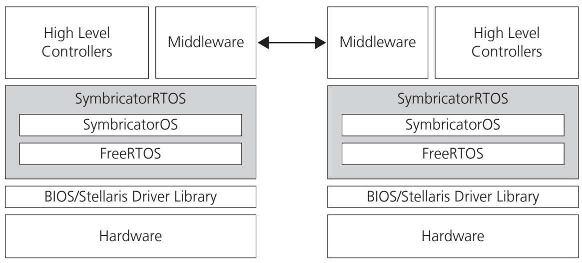
First Step

In robot structure formation research combining co-evolution, weak emergence and decentralization has not been satisfactorily addressed yet:

- Co-evolution – strong emergence- results in an extension and fast exploration of the configuration space for the fittest robot structures, and enables scalability in terms of the types and the number of robots. Besides that co-evolution of CAD/CAM models leads to an acceleration of structure formation, the human is taken out of the loop.
- Weak emergence results in macroscopic robot structures stemming from various hierarchies of microscopic structures. On a temporal dimension these structures may take the form of rhythms of coupled oscillators. On a spatial dimension such structures may occur as physically attached elements.
- Decentralization of control of the formation of the robot structure prevents a single point-of-failure in case the supervising entity breaks down.

If robot structure formation is established upon multi-local attachment of groups of micro-robots using combinations of above principles, highly powerful and parallel reconfiguration tactics and strategies can become available to robotic organisms.

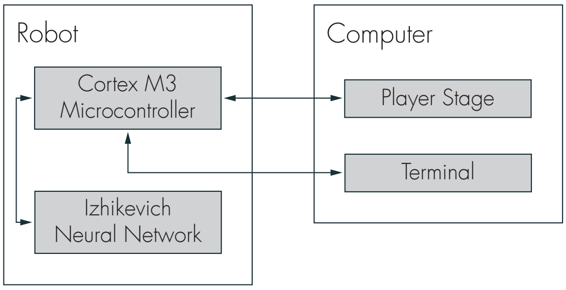
In order to enable a robotic organsims to engender such structure formation modules the project has build a software architecture for emerging self-organized control similar to that for cognitive sensor fusion. In order to ensure full flexibility at the software level but also continuous compliance at the hardware level, a generic hooking system via the Symbricator RTOS has been created. This hooking system enables different modules to interact with each other by defining a NeuralNetworkTask and making use of Address Event Representations (AERs).



Software architecture

Such a NeuralNetworkTask can compose above robot structure formation tasks. All these tasks know how to talk about reconfigurations and systemic and environmental goals in terms of AERs. They are intrinsically linked as each has a bearing on the others in normal operation of the organism.

The neural network on the Cortex M3 processor - the micro-controller used for lower level data processing tasks on the Replicator robots – will enable the robot to interpret the input from its infrared sensors in such a way that it doesn't collide for example with the walls in the simulated environment. Nonlinear recurrent spiking neural networks, such as a Izhikevich neural network, are used to learn at different operational and evolutionary scales to represent the stochastic properties of the multi-sensory input patterns given the systemic and environmental morphodynamics.

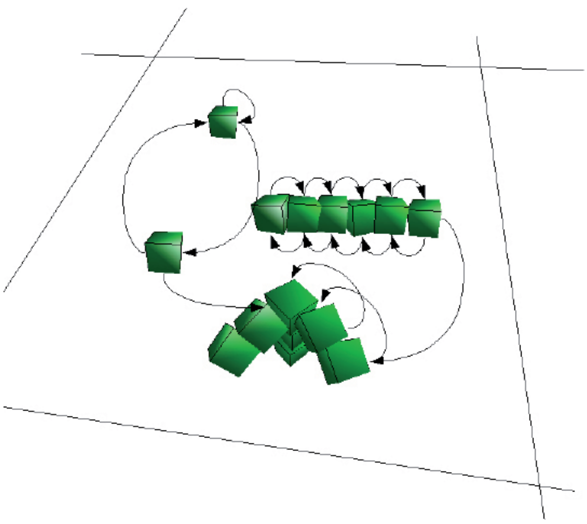


Robot - computer interaction

The simulation environment in player/stage will allow modeling physics: the systemic and environmental gauging and renormalization can be grounded.

In this context robotic structure formation starts with a phase of self-synthesis. This phase begins with a scattering of physically separate individual robot cells that may scour their environment for interesting features or particular sources of information or energy. For some reason, for example the discovery of such a source or the encountering of an obstacle, robot cells may begin to aggregate together and conjoin. The configuration stage can be triggered by the actions of a specific robot or a group of robots experiencing similar situations or it may be triggered by explicit communication by a single robot. The system through which this is achieved will be adaptable and robust to many kinds of stimulus with various possible outcomes also available.

The slime mold exhibits a similar life cycle as that envisaged for a project's robotic organism: single micro-robots live separately whilst looking for energy; when energy becomes scarce, single micro-robots start looking for others to join with and to send messages to other to do the same. The result of this process is that the separate micro-robots aggregate and join to produce a larger multi-robot organism that can monitor and engage the environment at the expense of much less energy. This may be advantageous in case rubble has to be removed in order to reach a an earthquake victim.



Robot aggregation

Background Information

Web: http://www.replicators.eu
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