Towards Morphological Flexibility: Modular Robotics and Bio-inspired Control

Heiko Hamann, Jürgen Stradner, Thomas Schmickl

Artificial Life Laboratory of the Department of Zoology
Karl-Franzens University Graz, Universitätsplatz 2, A-8010 Graz, Austria,
{heiko.hamann, juergen.stradner, thomas.schmickl}@uni-graz.at

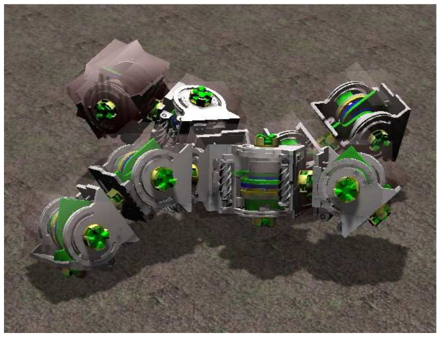
Abstract. As a contribution to the efforts towards robotic systems of higher flexibility we present our concept of morphologically dynamic robots. Within the projects SYMBRION and REPLICATOR, that focus on modular robotics, we have developed bio-inspired control techniques to achieve new concepts of dynamic, autonomous morphological structures. We propose three modes of coupling between robot modules: swarm, team, and organism mode. We demonstrate our concepts along with simple robot experiments.

1 Introduction

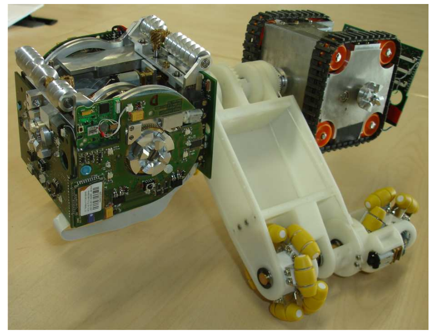
One of the future challenges of robotics research is to aspire to higher flexibility in robot systems. Higher flexibility in robot control is related to the challenge of autonomously determining intelligent actions in dynamic environments that might show unanticipated characteristics. Dynamic environments could also raise a demand of different quality: flexibility in morphology. For example, the robot might need to pass a narrow opening, a slippery surface might demand a lower gravity center, or the robot might need a longish body form to overcome a hole in the ground. Autonomous changes of a robot's body-form at runtime, possibly in rough terrain and as a reaction to unanticipated situations, constitute a big challenge for the methods of today's robotics.

1.1 Modular robotics

The research reported in this paper is allocated to the field of modular robotics. The idea is to have autonomous robotic modules with docking mechanisms that allow them to form physically connected 'super-robots'. Within the projects SYMBRION [9] and REPLICATOR [5] three types of such robot modules are developed (see Fig. 1(b)): backbone bot (strong main single-DOF actuator to move/rotate docked robots but also 2-DOF locomotion by a screw drive), scout bot (flexible locomotion), and active wheel (omnidirectional drive, ability to provide a lift for other robots). The robot modules possess actuators and sensors to dock/undock autonomously. This hardware is designed to allow for many morphological possibilities (cf. Fig. 1(a)) and is the necessary precondition to achieve autonomous morphological flexibility.



(a) simulation of backbone bots docked in a cross formation



(b) all 3 prototypes docked together, from left to right: backbone bot, active wheel, and scout bot

Fig. 1. Simulation and prototypes of the modular robots from the projects SYMBRION and REPLICATOR [9,5,4].

1.2 Switch of paradigms

According to our view a high degree of flexibility in robotics necessitates a switch of paradigms. Our hypothesis is that standard approaches of robot control hardly offer the potential for high flexibility and adaptivity. Instead we turn to systems that already obtain high degrees of flexibility, that is, we turn to biological systems for inspiration. Good examples of organisms, that show a special kind of morphological flexibility as an aggregate, are the slime molds *Dictyostelium discoideum* and *Dictyostelium mucoroides* [1]. These amoebas live as unicellular organisms but also have the ability to aggregate into a form of 'colony' during their life cycle. These colonies are aggregates of up to 10^5 amoebas that form the 'slug'-state of slime molds. This slug is not a true organism according to biology's definitions but the amoebas take different roles such as stalk cells, spore cells, and anterior cells [7]. The slugs themselves are formed in an aggregation phase regulated by a chemical substance. In this phase the amoebas generate a trail system with tree-structure by self-organization. We take the slime mold as our leading example for our efforts towards high flexibility in robotics.

1.3 Modes of coupling and bio-inspired methods of control

Morphological flexibility and degrees of cooperation can be categorized by three modes of coupling: swarm mode (physically separated, loosely coupled robots), team mode (physically separated robots interacting via radio, all-to-all communication), and organism mode (physically connected robots interacting via wires, e.g. communication bus). A group of robots can transition between these three modes autonomously by interacting loosely as a self-organizing swarm, by establishing sub-groups as teams with all-to-all communication, and by physically docking to each other forming robotic organisms. Robots in organism mode can reconfigure themselves between body forms without leaving the organism mode.

In addition, we try to achieve a high degree of flexibility concerning control methods by applying techniques that are inspired by signaling networks of unicellular organisms. In particular that is our Artificial Homeostatic Hormone System (AHHS) approach [2]. An AHHS is defined by a set of virtual hormones and a set of ordinary differential equations (ODE) that described their dynamics. The parameters of the ODE are defined by a sophisticated system of rules. Input from sensors triggers the secretion of hormones, hormones influence the dynamics of other hormones, and the current hormone concentrations determine the actuator control values. The underlying idea of the AHHS approach is to automatically synthesize robot controllers by methods from evolutionary computation. The high evolvability of AHHS controllers is caused by the inherent robustness to minor disturbances [3]. Furthermore, AHHS controllers are particularly adequate for modular robotics because hormones, that are diffusing throughout the robot organism, establish an implicit, low-level communication. In this paper, we summarize our approach on how to achieve a high degree of flexibility in both controlling and morphology.

2 Three modes of coupling

We discuss the concept of the three modes of coupling: swarm mode, team mode, and organism mode. Fig. 2 visualizes this idea schematically which is explained in the following. As a very simple example scenario we refer to a docking process between two modules (video online[1] and Figs. 3(a)&3(b)) which contains conceptionally all three modes (start in swarm mode, docking process as team mode, and organism mode after docking). Both robots are controlled by AHHS controllers. The robots are virtually subdivided into 2 compartments between which virtual hormones diffuse which introduces spatiality to AHHS allowing for an embodiment (see [2] for more details). Once the robots are docked, the hormones diffuse additionally between the robot modules as well.

Swarm mode: The swarm mode can be viewed as a natural initial state of a robot group that was placed randomly in an area and activated. The robots start to move randomly and encounter other robots by chance. In those situations they communicate loosely, for example, by infrared which might give an additional directional information. Global communication, for example, via radio is to be avoided because it does not scale arbitrarily. Examples of AHHS controllers without robot-robot communication are given in [8,6]. In our docking example, the swarm-mode phase is represented by the experiment's first third ($t < 1600$ in Fig. 3(b)) until the backbone robot triggers the docking process.

Team mode: In contrast to the limited use of communication between members in swarm mode, in team mode neighboring robots form sub-groups which exchange many (addressed) messages and share a lot of their information between

[1] `http://youtu.be/nYq47THMNLA`

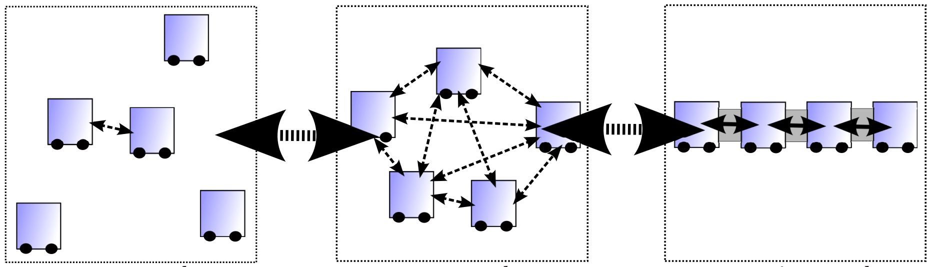
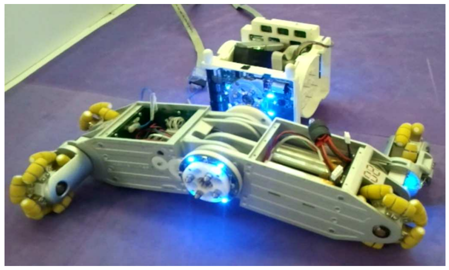


Fig. 2. Three modes of coupling: swarm mode (little communication via infrared, random robot-robot encounters), team mode (much communication via radio, coordinated motion), organism mode (permanent communication via bus, physical coupling).

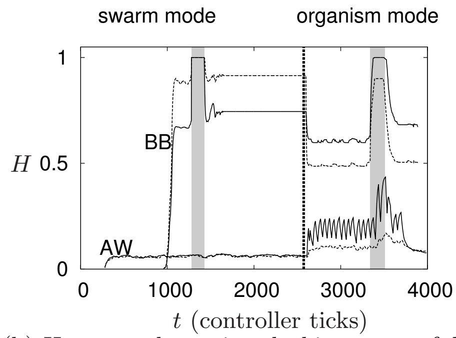
each other. They intensify their interactions, for example, by communication via radio. They might implement sophisticated team strategies, such as, task assignment or motion in formation. In our docking example, the team-mode phase is represented by the actual docking process ($1600 < t < 2573$).

Organism mode: The organism mode is of most interest in the above mentioned projects [9,5] because the hardware was mainly designed as modular robots. The robot modules form a robotic organism by coupling to each other physically. As shown in 3(a) the modules are able to dock autonomously. Once docked, an ethernet connection is establish and the robots are able to share their energy. The modules in such an organism have to agree on a common goal ideally without central control which could be both a single point of failure and a bottle neck (in terms of computation and communication).

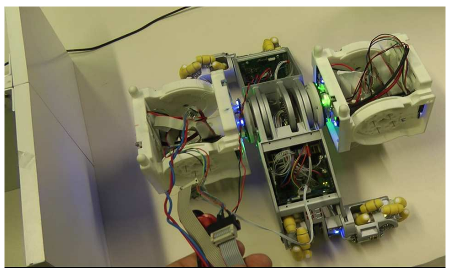
Fig. 3(b) gives the dynamics of 4 virtual hormone concentrations: one in each compartment of the backbone bot (BB), and one in each compartment of the active wheel (AW). The hormone concentrations are arbitrarily restricted to the interval $[0, 1]$ and certain hormone concentrations trigger actuations based on the defined rules of the AHHS. The gray areas give time intervals when sensor input at the back of the BB is activated as a show case by hand (actual sensor data used by the algorithm during docking not shown). The increase of the BB's hormones at $t = 1000$ are because of the activation of the robot and because of a 'base hormone production' that triggers an independent hormone production. Once the robots are docked ($t = 2573$) the hormone concentrations of the BB decrease rapidly because they immediately begin to diffuse into the AW (implemented via ethernet). The ragged curve of one of the hormone concentrations of the AW ($2600 < t < 3800$) is caused by the asynchronism between the microcontrollers of both modules. The hormone in the AW decays between incoming 'hormone messages' because AW achieves higher controller sampling rates. Furthermore, the sensor input triggered by hand at the BB's back is communicated via diffusing hormones to the AW (2nd gray area in Fig. 3(b)).



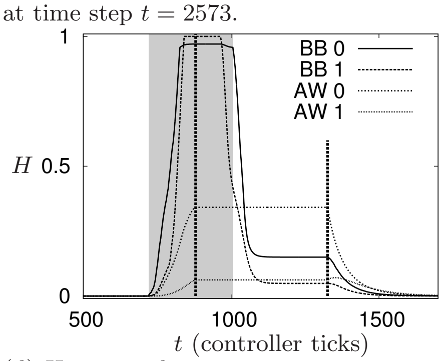
(a) Docking process, backbone bot (in the back) docks to active wheel (front)



(b) Hormone dynamics, docking successful at time step $t = 2573$.



(c) Collision avoidance, robotic organism (right) and wall (left)



(d) Hormone dynamics, sensor input vanishes at $t = 1006$, turning ends at $t = 1326$.

Fig. 3. Two example scenarios, upper row: docking process between a backbone bot (BB) and an active wheel (AW), lower row: collision avoidance of an organism consisting of 2 BBs and an AW. The hormone dynamics (right column) is given for two robot modules each, 2 compartments per module, gray areas indicate sensor input.

In a second example we show a collision avoidance behavior of an organism controller by an AHHS controller (see Figs. 3c,d, video online[2]). The two BBs are lifted up by the active wheel which is moving forward towards the wall to the left in Fig. 3(c). For this example, the sensors of the AW are turned off and only the BB to the front is able to sense the wall. The front BB's hormones and those of the AW are shown in Fig. 3(d). The gray area indicates the time interval during which the front BB perceives the wall by its proximity sensors. A particular rule of its AHHS controller triggers a hormone production based on this sensor input and the hormone concentration increases rapidly. This hormone diffuses (communicated via ethernet) to the AW which, in turn, triggers the turning behavior at $t = 880$. At $t = 1006$ the input to the BB's proximity sensors vanishes as the wall is out of view and subsequently the hormones drop in the BB. They are conserved in the AW because it is programmed to pause all hormone updates and to continue turning for $\Delta t = 320$ time steps.

[2] `http://youtu.be/_Cx8-viiask`

3 Conclusion

In the projects SYMBRION [9] and REPLICATOR [5] we aim for a robot system of high flexibility. On the one hand, modular robots provide the possibility of dynamic morphologies but, on the other hand, it also comes with the challenge of designing control methodologies which cope with this variability. The idea of this work is to control all modes (swarm, team, organism) and dynamic morphologies with our bio-inspired control approach of hormone systems.
Currently we extend our former research of offline evolutionary computation [2] to online, onboard evolution of AHHS controllers at runtime on the robots. The underlying reasoning is that the robotic system should be able to adapt to unanticipated situations. This ability for flexible reactions not only to needs of morphological change but also to needs of behavioral changes is a promising approach for autonomous robotic systems and might help in developing robotic systems that survive in dynamic environments.

Acknowledgments

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References

1. Camazine, S., Deneubourg, J.L., Franks, N.R., Sneyd, J., Theraulaz, G., Bonabeau, E.: Self-Organizing Biological Systems. Princeton Univ. Press (2001)
2. Hamann, H., Schmickl, T., Crailsheim, K.: A hormone-based controller for evaluation-minimal evolution in decentrally controlled systems. Artificial Life 18(2) (2012), (in press)
3. Hamann, H., Stradner, J., Schmickl, T., Crailsheim, K.: Artificial hormone reaction networks: Towards higher evolvability in evolutionary multi-modular robotics. In: Fellermann, H., Dörr, M., Hanczyc, M.M., Laursen, L.L., Maurer, S., Merkle, D., Monnard, P.A., Støy, K., Rasmussen, S. (eds.) Proc. of the ALife XII Conference. pp. 773–780. MIT Press (2010)
4. Levi, P., Kernbach, S. (eds.): Symbiotic Multi-Robot Organisms: Reliability, Adaptability, Evolution. Springer-Verlag (February 2010)
5. REPLICATOR: Project website (2012), http://www.replicators.eu
6. Schmickl, T., Hamann, H., Crailsheim, K.: Modelling a hormone-inspired controller for individual- and multi-modular robotic systems. Mathematical and Computer Modelling of Dynamical Systems 17(3), 221–242 (2011)
7. Siegert, F., Weijer, C.J.: Three-dimensional scroll waves organize dictyostelium slugs. PNAS 89(14), 6433–6437 (July 1992)
8. Stradner, J., Hamann, H., Schmickl, T., Crailsheim, K.: Analysis and implementation of an artificial homeostatic hormone system: A first case study in robotic hardware. In: The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'09). pp. 595–600. IEEE Press (2009)
9. SYMBRION: Project website (2012), http://www.symbrion.eu