A set of robotic building elements

A set of building elements (900), comprising one or more building elements (101;701;901..907) with a housing (119) which is selected from a group of straight, bend, L-shaped, and T-shaped bodies with one or more end-portions (121); wherein the building elements are configured with at least one connector (103) configured as a plug integrated with or installed in at least some of the end-portions (121). The connectors (103) comprise: an abutment face (201) with a centre portion (202); a diagonally magnetized magnet arranged behind the abutment face (201); and a pair of a female engagement member (504) extending radially from the centre portion (202) and a male engagement member (503) extending from the centre portion (202); wherein a depth (D) of the female engagement member and a height (H) of the corresponding male engagement member is greater than a width (Wm) of the male engagement member or greater than a width (Wf) of the female engagement member. At least a first building element among the building elements (101;701) comprises at least a first one of the connectors (103); wherein the at least first one of the connectors (103) is rotatable mounted in a bearing (108) fixed to the first building element. A drive unit (114) is coupled to turn the first one of connectors (103) in response to a control signal and an energy storage unit (117) is coupled to supply operating power the drive unit. Preferably, the body members (119) are tubular or tubular with one or more branches.
A Combination of Machine Learning and Cerebellar-like Neural Networks for the Motor Control and Motor Learning of the Fable Modular Robot
We scaled up a bio-inspired control architecture for the motor control and motor learning of a real modular robot. In our approach, the Locally Weighted Projection Regression algorithm (LWPR) and a cerebellar microcircuit coexist, in the form of a Unit Learning Machine. The LWPR algorithm optimizes the input space and learns the internal model of a single robot module to command the robot to follow a desired trajectory with its end-effector. The cerebellar-like microcircuit refines the LWPR output delivering corrective commands. We contrasted distinct cerebellar-like circuits including analytical models and spiking models implemented on the SpiNNaker platform, showing promising performance and robustness results.

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A Combination of Machine Learning and Cerebellar Models for the Motor Control and Learning of a Modular Robot
We scaled up a bio-inspired control architecture for the motor control and motor learning of a real modular robot. In our approach, the Locally Weighted Projection Regression algorithm (LWPR) and a cerebellar microcircuit coexist, forming a Unit Learning Machine. The LWPR optimizes the input space and learns the internal model of a single robot module to command the robot to follow a desired trajectory with its end-effector. The cerebellar microcircuit refines the LWPR output delivering corrective commands. We contrasted distinct cerebellar circuits including analytical models and spiking models implemented on the SpiNNaker platform, showing promising performance and robustness results.

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Self-reconfiguration of Modular Underwater Robots using an Energy Heuristic
This paper investigates self-reconfiguration of a modular robotic system, which consists of a cluster of modular vehicles that can attach to each other by a connection mechanism. Thereby, they can form a desired morphology to meet task specific requirements. Reconfiguration can be needed due to limitations from dimensions of passable corridors for an underwater maintenance task, for supplemental instrumentation that is available on a particular robot, or as remedial action if one robot in a cluster suffers from malfunction. Being crucial for autonomous underwater vehicles, energy
consumed is employed as a heuristic. The paper shows how the Basic Theta* algorithm can be guided by an energy criterion to calculate a transition from start- to goal morphology. Individual robots are guided while minimizing the overall energy for propulsion and for balancing restoring forces and moments in morphologies. The properties of the proposed self-reconfiguration algorithm are evaluated through simulations and preliminary model tank experiments. The energy based heuristic for reconfiguration is compared to a traditional solution that minimizes the Euclidean distance.

**Collective Modular Underwater Robotic System for Long-Term Autonomous Operation**

This paper provides a brief overview of an underwater robotic system for autonomous inspection in confined offshore underwater structures. The system, which is currently in development, consist of heterogeneous modular robots able to physically dock and communicate with other robots, transport tools and robots, and recharge their batteries while underwater. These properties will provide the system, when fully developed, with unique capabilities such as ability to adapt robotic morphology and function to the current task and tolerate failures leading to long-term autonomous operations.

**Fable II: Design of a Modular Robot for Creative Learning**

Robotic systems have a high potential for creative learning if they are flexible, accessible and engaging for the user in the experimental process of building and programming robots. In this paper we describe the Fable modular robotic system for creative learning which we develop to enable and motivate anyone to build and program their own robots. The Fable system consists of self-contained modules equipped with sensors and actuators, which users can use to easily assemble a wide range of robots in a matter of seconds. The robots are userprogrammable on several levels of abstraction ranging from a simple visual programming language to powerful conventional ones. This paper provides an overview of the design of Fable for different user groups and an evaluation of critical issues when we attempt to integrate the system into an everyday teaching context.
Short-Range Sensor for Underwater Robot Navigation using Line-lasers and Vision

This paper investigates a minimalistic laser-based range sensor, used for underwater inspection by Autonomous Underwater Vehicles (AUV). This range detection system comprise two lasers projecting vertical lines, parallel to a camera’s viewing axis, into the environment. Using both lasers for distance estimation, the sensor offers three dimensional interpretation of the environment. This is obtained by triangulation of points extracted from the image using the Hough Transform. We evaluate the system in simulation and by physical proof-of-concept experiments on an OpenROV platform.
Fable: A Modular Robot for Students, Makers and Researchers
The vision of the Fable modular robotic system is to transform the development of robots from a process performed mainly by experts, to an easily accessible and motivating activity that enables a large range of users to assemble and animate their own robotic ideas. To achieve this vision, the Fable system consists of a range of modules equipped with sensors and actuators, which users can easily assemble into a wide range of robots within seconds. The robots are user-programmable on several levels of abstraction ranging from a simple visual programming language to powerful conventional ones. This paper provides a brief overview of the concept, design and state of development for the second version of the Fable modular robotic system.

Playte, a tangible interface for engaging human-robot interaction
This paper describes a tangible interface, Playte, designed for children animating interactive robots. The system supports physical manipulation of behaviors represented by LEGO bricks and allows the user to record and train their own new behaviors. Our objective is to explore several modes of interaction, i.e. direct remote control, tangible programming, programming by demonstration, and programming by training, to learn the design principles for more accessible, engaging, and playful robots. We evaluate the system experimentally and report on key observations from play sessions. We conclude that Playte facilitates playful activities and is appropriate for the intended target group (age 6+). Further, we discuss lessons learned regarding pros and cons of the different supported interactions modes.

A distributed and morphology-independent strategy for adaptive locomotion in self-reconfigurable modular robots
In this paper, we present a distributed reinforcement learning strategy for morphology-independent lifelong gait learning for modular robots. All modules run identical controllers that locally and independently optimize their action selection based on the robot’s velocity as a global, shared reward signal. We evaluate the strategy experimentally mainly on simulated, but also on physical, modular robots. We find that the strategy: (i) for six of seven configurations (3–12 modules) converge in
96% of the trials to the best known action-based gaits within 15 min, on average, (ii) can be transferred to physical robots with a comparable performance, (iii) can be applied to learn simple gait control tables for both M-TRAN and ATRON robots, (iv) enables an 8-module robot to adapt to faults and changes in its morphology, and (v) can learn gaits for up to 60 module robots but a divergence effect becomes substantial from 20–30 modules. These experiments demonstrate the advantages of a distributed learning strategy for modular robots, such as simplicity in implementation, low resource requirements, morphology independence, reconfigurability, and fault tolerance.

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Self-reconfigurable modular robots, Locomotion, Online learning, Distributed control, Fault tolerance
Fable: Design of a Modular Robotic Playware Platform
We are developing the Fable modular robotic system as a playware platform that will enable non-expert users to develop robots ranging from advanced robotic toys to robotic solutions to problems encountered in their daily lives. This paper presents the mechanical design of Fable: a chain-based system composed of reconfigurable heterogeneous modules with a reliable and scalable connector. Furthermore, this paper describes tests where the connector design is tested with children, and presents examples of a moving snake and a quadruped robot, as well as an interactive upper humanoid torso.

Fable: Socially Interactive Modular Robot
Modular robots have a significant potential as user-reconfigurable robotic playware, but often lack sufficient sensing for social interaction. We address this issue with the Fable modular robotic system by exploring the use of smart sensor modules that has a better ability to sense the behavior of the user. In this paper we describe the development of a smart sensor module which includes a 3D depth camera, and a server-side software architecture featuring user tracking, posture detection and a near-real-time facial recognition. Further, we describe how the Fable system with the smart sensor module has been tested in educational and playful contexts and present experiments to document its functional performance.
Fault-tolerant gait learning and morphology optimization of a polymorphic walking robot

This paper presents experiments with a morphology-independent, life-long strategy for online learning of locomotion gaits. The experimental platform is a quadruped robot assembled from the LocoKit modular robotic construction kit. The learning strategy applies a stochastic optimization algorithm to optimize eight open parameters of a central pattern generator based gait implementation. We observe that the strategy converges in roughly ten minutes to gaits of similar or higher velocity than a manually designed gait and that the strategy readapts in the event of failed actuators. We also optimize offline the reachable space of a foot based on a reference design but finds that the reality gap hardens the successfully transference to the physical robot. To address this limitation, in future work we plan to study co-learning of morphological and control parameters directly on physical robots.

Playful Interaction with Voice Sensing Modular Robots

This paper describes a voice sensor, suitable for modular robotic systems, which estimates the energy and fundamental frequency, $F_0$, of the user’s voice. Through a number of example applications and tests with children, we observe how the voice sensor facilitates playful interaction between children and two different robot configurations. In future work, we will investigate if such a system can motivate children to improve voice control and explore how to extend the sensor to detect emotions in the user’s voice.
Sensor-coupled fractal gene regulatory networks for locomotion control of a modular snake robot

In this paper we study fractal gene regulatory network (FGRN) controllers based on sensory information. The FGRN controllers are evolved to control a snake robot consisting of seven simulated ATRON modules. Each module contains three tilt sensors which represent the direction of gravity in the coordination system of the module. The modules are controlled locally and there is no explicit communication between them. So, they can synchronize implicitly using their sensors, and coordination of their behavior takes place through the environment. In one of our experiments, all the three tilt sensors are available for the FGRNs and a simple controller is evolved. The controller is a linear mapping of one input sensor to the output. It is only based on one sensor input and ignores the other sensors as well as the regulatory part of the network. In another experiment, the controller's input uses one of the other sensors that carries less information. In this case, the evolved controller blends sensory information with the regulatory network capabilities to come up with a proper distributed controller. © 2013 Springer-Verlag.

Experiments, Fractals, Genes, Sensors, Controllers
Adaptive Strategy for Online Gait Learning Evaluated on the Polymorphic Robotic LocoKit

This paper presents experiments with a morphology-independent, life-long strategy for online learning of locomotion gaits, performed on a quadruped robot constructed from the LocoKit modular robot. The learning strategy applies a stochastic optimization algorithm to optimize eight open parameters of a central pattern generator based gait implementation. We observe that the strategy converges in roughly ten minutes to gaits of similar or higher velocity than a manually designed gait and that the strategy readapts in the event of failed actuators. In future work we plan to study co-learning of morphological and control parameters directly on the physical robot.

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The Assemble and Animate Control Framework for Modular Reconfigurable Robots

This paper describes the “Assemble and Animate” (ASE) control framework. The objective of ASE is to provide a flexible and extendable control framework, which facilitates rapid development and deployment of modular reconfigurable robots. ASE includes a simple event-driven application framework, a library of common control and adaptation strategies, and a module abstraction layer which allows ASE to be cross-compiled for a number of different modular robotic platforms and easily ported to new platforms. In this paper we describe the design of ASE and present example applications utilizing ASE for planetary contingency, adaptive locomotion, self-reconfiguration, and tangible behavior-based programming.

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Towards Python-based Domain-specific Languages for Self-reconfigurable Modular Robotics Research

This paper explores the role of operating system and high-level languages in the development of software and domain-specific languages (DSLs) for self-reconfigurable robotics. We review some of the current trends in selfreconfigurable robotics and describe the development of a software system for ATRON II which utilizes Linux and Python to significantly improve software abstraction and portability while providing some basic features which could prove useful when using Python, either stand-alone or via a DSL, on a selfreconfigurable robot system. These features include transparent socket
A Distributed Strategy for Gait Adaptation in Modular Robots

In this paper we study online gait optimization for modular robots. The learning strategy we apply is distributed, independent on robot morphology, and easy to implement. First we demonstrate how the strategy allows an ATRON robot to adapt to faults and changes in its morphology and we study the strategy’s scalability. Second we extend the strategy to learn the parameters of gait-tables for ATRON and M-TRAN robots. We conclude that the presented strategy is effective for online learning of gaits for most types of modular robots and that learning can effectively be distributed by having independent processes learning in parallel.
Anatomy-based organization of morphology and control in self-reconfigurable modular robots

In this paper, we address the challenge of realizing full-body behaviors in scalable modular robots. We present an experimental study of a biologically inspired approach to organize the morphology and control of modular robots. The approach introduces a nested hierarchy that decomposes the complexity of assembling and commanding a functional robot made of numerous simple modules. The purpose is to support versatility, scalability, and provide design abstraction. The robots we describe incorporate anatomy-inspired parts such as muscles, bones, and joints, and these parts in turn are assembled from modules. Each of those parts encapsulates one or more functions, e.g., a muscle can contract. Control of the robot can then be cast as a problem of controlling its anatomical parts rather than each discrete module. To validate this approach, we perform experiments with micron-scale spherical catom modules in simulation. The robots we simulate are increasingly complex and include snake, crawler, quadruped, cilia surface, arm-joint-muscle, and grasping robots. We conclude that this is a promising approach for future microscopic many-modules systems, but also that it is not applicable to relatively weak and slow homogeneous systems such as the centimeter-scale ATRON.

Keyword: Distributed control, Design abstraction, Modular self-reconfigurable robots, Scalability, Hierarchical morphology and control, Versatility
In this paper we study distributed online learning of locomotion gaits for modular robots. The learning is based on a stochastic approximation method, SPSA, which optimizes the parameters of coupled oscillators used to generate periodic actuation patterns. The strategy is implemented in a distributed fashion, based on a globally shared reward signal, but otherwise utilizing local communication only. In a physics-based simulation of modular Roombots robots we experiment with online learning of gaits and study the effects of: module failures, different robot morphologies, and rough terrains. The experiments demonstrate fast online learning, typically 5-30 min. for convergence to high performing gaits (≈ 30 cm/sec), despite high numbers of open parameters (45-54). We conclude that the proposed approach is efficient, effective and a promising candidate for online learning on many other robotic platforms.
Fractal Gene Regulatory Networks for Robust Locomotion Control of Modular Robots

Designing controllers for modular robots is difficult due to the distributed and dynamic nature of the robots. In this paper, fractal gene regulatory networks are evolved to control modular robots in a distributed way. Experiments with different morphologies of modular robot are performed and the results show good performance compared to previous results achieved using learning methods. Furthermore, some experiments are performed to investigate evolvability of the achieved solutions in the case of module failure and it is shown that the system is capable of come up with new effective solutions.

Keyword: Robot Control, Evolutionary Computation, Modular Robots, Fractal Gene Regulatory Networks
Elements of a development ecosystem for modular robot applications

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Exploit Morphology to Simplify Docking of Self-reconfigurable Robots
In this paper we demonstrate how to dock two self-reconfigurable robots and as a result merge them into one large robot. The novel feature of our approach is that the configuration we choose for our robots allows the robots to handle misalignment errors and dock simply by pushing against each other. In 90 experiments with the ATRON self-reconfigurable robot we demonstrate that two three-module robots can dock in 16 seconds without using sensors and are successful in between 93% and 40% of the attempts depending on approach angle and offset. While this is a modest step towards fast and reliable docking, we conclude that choosing appropriate configurations for docking is a significant tool for speeding up docking.

Morphology Independent Learning in Modular Robots
Hand-coding locomotion controllers for modular robots is difficult due to their polymorphic nature. Instead, we propose to use a simple and distributed reinforcement learning strategy. ATRON modules with identical controllers can be assembled in any configuration. To optimize the robot’s locomotion speed its modules independently and in parallel adjust their behavior based on a single global reward signal. In simulation, we study the learning strategy’s performance on different robot configurations. On the physical platform, we perform learning experiments with ATRON robots learning to move as fast as possible. We conclude that the learning strategy is effective and may be a practical approach to design gaits.
Reusable Electronics and Adaptable Communication as Implemented in the Odin Modular Robot

This paper describes the electronics and communication system of Odin, a novel heterogeneous modular robot made of links and joints. The electronics is divided into two printed circuit boards: a General board with reusable components and a Specific board with non-reusable components. While the General board is common to the design of every type of module, such as power, actuator, sensor and structure, the Specific board is unique to each type of module. The communication system, one of the most important reusable components of Odin, is based on local buses that can be extended by bridging electrical signals. The implementations of actuator and power links show that splitting the electronics into General and Specific boards allows rapid development of different types of modules, and an analysis of performance indicates that the communication system is simple, fast and flexible. As the electronic design reuses approx. 50% of components between two different types of modules, we find it convenient for heterogeneous modular robots where production costs demand a small set of parts. In addition, as the features of the communication system are desirable in modular robots, we think it is suitable for such systems as well as useful for future research into flexible network topologies.

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A functional language for programming self-reconfigurable robots

A self-reconfigurable robot is a robotic device that can change its own shape. Self-reconfigurable robots are commonly built from multiple identical modules that can manipulate each other to change the shape of the robot. The robot can also perform tasks such as locomotion without changing shape. Programming a modular, self-reconfigurable robot is however a complicated task: the robot is essentially a real-time, distributed embedded system, where control and communication paths often are tightly coupled to the current physical configuration of the robot. To facilitate the task of programming modular, self-reconfigurable robots, we are currently developing a functional, domain-specific language that allows the programmer to use pattern matching and higher-order functions to program closely coordinated groups of modules. In more detail, higher-order functions are used to specify behaviors that are applied to groups of modules and a distributed pattern matching mechanism is used to select specific behaviors from these functions depending on the state of the individual modules. We have implemented our language for a virtual machine running on the ATRON self-reconfigurable robot.
Anatomy-Based Organization of Modular Robots

This paper presents a novel biologically-inspired hierarchical approach to organizing and controlling modular robots. The purpose of our approach is to decompose the complexity of assembling and commanding a functional robot made of numerous simple modules (thousands to millions) by introducing a hierarchy of structure and control. The robots we describe incorporate anatomically-inspired parts such as muscles, bones and joints, and these parts in turn are assembled from modules. Each of those parts encapsulates one or more functions, e.g. a muscle can contract. Control of the robot can then be cast as a problem of controlling its anatomical parts rather than each discrete module. We show simulation results from experiments using gradient-based primitives to control parts of increasingly complex robots, including snake, crawler, cilia-surface, armjoint- muscle and grasping robots. We conclude that this approach is promising for future many-modules systems, but is currently impractical on most existing platforms.

Keyword: Intelligent robots, Robot control, Mobile robots, Control hierarchy, Grasping robots, Gradient-based primitives, Structure hierarchy, Anatomy-based organization, Anatomically-inspired parts, Modular robots, Functional robot

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A unified simulator for Self-Reconfigurable Robots

Generic simulation platforms such as player/stage are an essential tool in mobile robotics, but until now no similar platforms have been available for the field of self-reconfigurable robots. We here present a generic simulation platform for modular, self-reconfigurable robots: the unified simulator for self-reconfigurable robots (USSR). USSR is based on a physics engine, allowing simulation of both self-reconfiguration and dynamic interaction with the environment. The simulator is implemented as a framework that provides numerous components that can be combined to form new or existing modular robots, allowing easy experimentation: USSR currently includes support for the ATRON, Odin, and M-TRAN modular robots.

Keyword: Physics engine, Unified simulator, Dynamic interaction, mobile robots, Control system analysis computing, Modular robot, Self-reconfigurable robot

Flexible, fpga-based electronics for modular robots

In this paper we introduce electronics for the ATRON self-reconfigurable robot based on field programmable gate arrays (FPGAs). The immediate advantage of using FPGAs is that some of the module’s electronics can be moved into the FPGA, thereby the number of components can be reduced. In the case of the ATRON the number of components is reduced by 20%. Another advantage is that handling of low-level hardware, which is interrupt heavy, can be moved out of the main processor (also implemented on the FPGA) as we will exemplify with a simple FPGA-based communication system. Finally, we can reprogram the FPGA and therefore integrate task-specific electronics without physically changing the electronics or we can reconfigure the electronics for specific tasks. The disadvantages of an FPGA-based design include the cost of FPGAs, the extra layer of complexity in programming, and a limited increase in power consumption compared to micro-controllers. However, overall FPGAs make the electronics of modular robots more flexible and therefore may make them more suitable for real applications.
Spatial Computing with Labels

A reconfigurable robot is a robot that can change shape. Programming reconfigurable robots is complicated by the need to adapt the behavior of each of the individual module to the overall physical shape of the robot. In this position paper, we investigate a simple approach to allow the programmer to abstract over the concrete shape of a robot using the notion of a label as a simple means of addressing various parts of the structure of a robot. Labels provide the programming language designer with a means of stratifying two main components of a spatial programming language for modular robots, namely specifying the physical structure of a robot and specifying its behavior. Based on previous experience with the ATRON robot, we find that labels are a useful concept for programming modular robots.

Keyword: Spatial computing, Robotics, Spatial programming language, Programming languages, Programming language designer, Modular robots, ATRON robot, Software engineering, Robot programming, Reconfigurable robot

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Organisations: University of Southern Denmark
Authors: Stoy, K. (Ekstern), Schultz, U. P. (Ekstern), Christensen, D. J. (Intern)
Publication date: 2008
Towards interactive programming of modular robots

Programming modular robots is typically a difficult and time-consuming task. In this position paper we describe our vision for a programming platform supporting interactive and incremental development of autonomous controllers for the ATRON and Odin modular robots. Currently, the platform consists of execution environments for the respective robots, a simulator, and a user-interface that allows for straightforward remote control using simple gait control tables. We envision interactive programming of distributed controllers being done by incrementally transitioning from simple remote control of a specific robot configuration to autonomous control of a whole class of similar robot configurations. This incremental transition relies on three key elements: (1) using symbolic names to globally identify what components (modules, specific sensors, actuators, etc.) to control, (2) describing behaviors using a distributed scripting language, and (3) dynamically updating code in the running system. We conclude that in this way we may possibly ease the task of programming modular robots by combining the highly interactive development style of the on-line approach with the expressiveness and ease of use of a scripting language.

A domain-specific language for programming self-reconfigurable robots

A self-reconfigurable robot is a robotic device that can change its own shape. Self-reconfigurable robots are commonly built from multiple identical modules that can manipulate each other to change the shape of the robot. The robot can also perform tasks such as locomotion without changing shape. Programming a modular, self-reconfigurable robot is however a complicated task: the robot is essentially a real-time, distributed embedded system, where control and communication paths often are tightly coupled to the current physical configuration of the robot. To facilitate the task of programming modular, self-reconfigurable robots, we have developed a declarative, role-based language that allows the programmer to define roles and behavior independently of the concrete physical structure of the robot. Roles are compiled to mobile code fragments that distribute themselves over the physical structure of the robot using a dedicated virtual machine implemented on the ATRON self-reconfigurable robot.

A new meta-module for controlling large sheets of ATRON modules

In this paper we present a 2D meta-module for the ATRON robot, which simplifies the motion constraints significantly. The motion capabilities of the new meta-module is similar to that of previous sliding cube style modules with the addition of one extra action, which is shown to improve the motion capabilities of the modules greatly. In general our work shows that if
A self-reconfigurable communication network for modular robots

We present a novel hybrid communication system for modular robots, based on inter-module buses that can connect on-demand to form arbitrary network topologies. In addition to describing the implementation of this hybrid communication system, we analyse transfer rates and reliability, validating the results using a Spice 1 simulation and a proof-of-concept experiment performed on a hardware prototype. Thus, we find the system is fast, since it has a potential to provide a maximum transfer rate of 9.9Mbps divided by the maximum bus length measured in meters, with buses as large as 256 modules. The system is also found to be small in size, power saving and reliable. These features, in combination with its flexibility, make hybrid communication suitable for modular robots.

General information
State: Published
Organisations: University of Southern Denmark
Authors: Garcia, R. F. M. (Ekstern), Stoy, K. (Ekstern), Christensen, D. J. (Intern), Lyder, A. (Ekstern)
Publication date: 2007

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ATRON robots: Versatility from self-reconfigurable modules

Traditional fixed morphology robots are limited to purely functional adaptation and thereby to a limited range of applications. In contrast modular self-reconfigurable robots can dynamically and autonomously change both their function and morphology to meet new demands of changing tasks. Therefore, self-reconfigurable robots have the potential to become highly versatile. This paper documents and discusses the application versatility of self-reconfigurable robots in general and of the ATRON system in particular. We present a range of different self-reconfigurable robots assembled from the ATRON base module. The robot’s ability includes locomotion (snake, car, and walker), manipulation of objects (serial manipulator, conveyer belt) and autonomous change of functionality and shape (locomotion configurations, many-module shape-change). We also demonstrate the structure of simple anatomical building blocks (bones, muscles, etc.) which we envision can be assembled into more complex robots of future miniaturized modules.

Keyword: Modular, Robot, Locomotion, Legged locomotion, Manipulation, Manipulators
Experiments on fault-tolerant self-reconfiguration and emergent self-repair

This paper presents a series of experiments on fault tolerant self-reconfiguration of the ATRON robotic system. For self-reconfiguration we use a previously described distributed control strategy based on meta-modules that emerge, move and stop. We perform experiments on three different types of failures: 1) Action failure: On the physical platform we demonstrate how roll-back of actions are used to achieve tolerance to collision with obstacles and other meta-modules. 2) Module failure: In simulation we show, for a 500 module robot, how different degrees of catastrophic module failure affect the robot’s ability to shape-change to support an insecure roof. 3) Robot failure: In simulation we demonstrate how robot faults such as a broken robot bone can be emergent self-repaired by exploiting the redundancy of selfreconfigurable modules. We conclude that the use of emergent, distributed control, action roll-back, module redundancy, and self-reconfiguration can be used to achieve fault tolerant, self-repairing robots.

Keyword: Distributed control, Emergent phenomena, Self-adjusting systems, Redundancy, Fault tolerance, Robots
Hierarchical robots
This paper introduces the concept of hierarchical robots, which is a type of modular robots assembled from a hierarchy of modules, and a preliminary realization of this concept: the Odin robot. Odin currently consists of ten modules of two different classes, one class of modules provide structure and the other actuation. We describe the mechanical design of these modules and their electrical design with specific focus on their hybrid communication system whose topology can be changed on-line. We demonstrate the features of this communication system in a simple experiment and also demonstrate how the assembled Odin robot can produce locomotion. While it is too early to make a conclusion regarding the usefulness of hierarchical robots in general, we think that our work indicates that we may be able to simplify the manufactured modules at the bottom of the hierarchy while increasing the functionality of the assembled hierarchical robot.

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Conference: IROS Workshop on Self-Reconfigurable Modular Robot, San Diego, CA, USA, 01/01/2007
Source: orbit
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

Locomotion of Miniature Caten Chains: Scale Effects on Gait and Velocity
Scaling down the module size of a selfreconfigurable robot will have a profound effect on the module's characteristics, e.g. strength to mass ratio. In this paper we explore how the characteristics of chains of modules, specifically locomotion velocity and best gait type, might change with the scale of those modules. The simulated experiments we report on here examine module sizes from (11μm to 698μm radius) and chain lengths from 3 to 30 modules. All gaits tested were based on central pattern generators optimized using a genetic algorithm and hill climbing. Our results show that scaling affects both the preferred type of gait as well as a chain’s overall performance (average velocity). In summary, there is a tradeoff where larger scales face the challenge of overcoming gravity, while smaller sizes face the challenge of staying in contact with the ground and the friction it provides. We show that in between these two extremes lies a “best” module size for given environmental, physical, and engineering constraints.
Keyword: Microrobots, Mobile robots, Interconnected systems, Self-adjusting systems, Motion control

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Authors: Christensen, D. J. (Intern), Campbell, J. (Ekstern)
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Scopus rating (2015): SJR 1.074 SNIP 1.332 CiteScore 1.59
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BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.658 SNIP 1.406 CiteScore 1.64
ISI indexed (2013): ISI indexed no
Neighbor detection and crosstalk elimination in self-reconfigurable robots

This paper addresses two issues concerning communication between neighbor modules in self-reconfigurable robots. The first issue is automatic neighbor detection that is due to modules self-reconfiguring, whereby the local communication network topology dynamically changes. The second issue is crosstalk between non-neighbor modules, where data packages send through an infrared communication channel are received by a non-neighbor module because of reflections. In this paper, we proposed algorithmic solutions to automatic neighbor detection and crosstalk elimination. The algorithms are simple, distributed, self-organizing and robust. For validation, they are implemented and evaluated on the physical ATRON system. In conclusion, the algorithms are efficient and effective and we argue that these algorithmic contributions may be applicable on other systems as well.

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State: Published
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Authors: Christensen, D. J. (Intern), Brandt, D. (Ekstern), Schultz, U. P. (Ekstern), Stoy, K. (Ekstern)
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Roles and self-reconfigurable robots

A self-reconfigurable robot is a robotic device that can change its own shape. Self-reconfigurable robots are commonly built from multiple identical modules that can manipulate each other to change the shape of the robot. The robot can also perform tasks such as locomotion without changing shape. Programming a modular, self-reconfigurable robot is however a complicated task: the robot is essentially a real-time, distributed embedded system, where control and communication...
paths often are tightly coupled to the current physical configuration of the robot. To facilitate the task of programming modular, self-reconfigurable robots, we have developed a declarative, role-based language that allows the programmer to associate roles and behavior to structural elements in a modular robot. Based on the role declarations, a dedicated middleware for high-level distributed communication is generated, significantly simplifying the task of programming self-reconfigurable robots. Our language fully supports programming the ATRON self-reconfigurable robot, and has been used to implement several controllers running both on the physical modules and in simulation.

Evolution of Shape-Changing and Self-Repairing Control for the ATRON Self-Reconfigurable Robot

The ATRON self-reconfigurable robot consists of simple interconnected modules. Modules move relative to other modules and as a result change the shape of the robot. The ATRON modules are difficult to control because of complex motion constraints on the modules. Motion constraints are reduced by using meta-modules composed of three modules. A meta-module may emerge from unstructured groups of modules if three modules are connected in the right configuration. The meta-module then moves on a surface of modules and stop at another position. To attract moving meta-modules and thereby to specify the shape-changing task of the robot we use attraction-points. In this work we evolve a distributed artificial neural network controller for the modules. The controller is identical on every module and controls when a meta-module emerges, how it move and when it stops. In simulation we demonstrate how this control strategy allows the ATRON robot to shape-change to support an unstable roof, build a bridge across a gap and to self-repair a broken bone. We conclude that the control strategy is able to shape-change and self-repair the ATRON robot independent on whether it consists of dozens, hundreds or thousands of modules.

Keyword: Distributed control, Interconnected systems, Self-repairing control, Complex motion constraints, Robots, Self-adjusting systems, Meta-modules, Distributed artificial neural network control, Interconnected modules, Neurocontrollers, ATRON self-reconfigurable robot, Motion control, Shape-changing control
Selecting a Meta-Module to Shape-Change the ATRON Self-Reconfigurable Robot

The ATRON self-reconfigurable robot consists of simple one degree of freedom ATRON modules. The motion capabilities of an individual module are therefore quite limited. To compensate for this, meta-modules composed of more than one module are used to shape-change the system. Meta-modules emerge from the environment created by other modules, move on the surface of other modules and stop at a new position. The flow of meta-modules, from one place to another on the structure of modules, realizes the desired self-reconfiguration. In this paper we compare six different meta-module types composed of ATRON modules. Variations of meta-module morphology and meta-actions are investigated for its ability to shape-change the robot. We conclude that two of the investigated meta-module types are able to shape-change the robot to an acceptable extent.

Keyword: Centralised control, Path planning, Robots, Motion control, Decentralised control

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Authors: Christensen, D. J. (Intern), Strøy, K. (Ekstern)
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ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.441 SNIP 1.123 CiteScore 0.93
ISI indexed (2011): ISI indexed no
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Scopus rating (2009): SJR 0.5 SNIP 1.084
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.471 SNIP 0.996
Scopus rating (2007): SJR 0.47 SNIP 1.11
Scopus rating (2006): SJR 0.467 SNIP 1.029
Scopus rating (2005): SJR 0.46 SNIP 1.325
Scopus rating (2004): SJR 0.533 SNIP 1.333
Scopus rating (2003): SJR 1.442 SNIP 1.42
Scopus rating (2002): SJR 1.169 SNIP 1.308
Sensor networks and self-reconfigurable robots
A self-reconfigurable robot is a robotic device that can change its own shape. Self-reconfigurable robots are commonly built from multiple identical modules that can manipulate each other to change the shape of the robot. The robot can also perform tasks such as locomotion without changing shape. We observe that the challenges in programming self-reconfigurable robots are similar to the challenges in programming sensor networks: a large number of low-end embedded systems connected using ad-hoc networking need to gather information using sensors and to communicate information to other systems in the network. However, there are significant differences as well, notably a self-reconfigurable robot must typically function autonomously and the network topology will evolve continuously as the robot changes its shape. Software for self-reconfigurable robots, beyond controlling shape-change and locomotion, remains largely unexplored, but we believe experiences from sensor networks to be applicable within this domain. Moreover, we present an initial design of a middleware for self-reconfigurable robots and relate it to similar solutions for sensor networks.

Towards artificial ATRON animals: Scalable anatomy for self-reconfigurable robots

HYDRA: From cellular biology to shape-changing artefacts
The HYDRA work provides insight into the exploitation of holistic behavioural and morphological adaptation in the design of new artefacts. The potential of the new design principle has been exemplified through the construction of robotic systems that can change morphology. Two prototype building block systems has been developed, HYDRON for a uid scenario, and ATRON for a terrestrial scenario. In the HYDRON case, the individual module can perform 3D motion and is able to arrange in clusters of specic formation without the necessity of physical connections. In the ATRON case, the modules are individually simpler, attach through physical connections, and perform 3D motions by collective actions. Control mechanisms identied from cellular biology has been successfully transferred to the physical building blocks.
Metamodule control for the ATRON self-reconfigurable robotic system

This paper presents an approach for distributed control for the individual modules in the ATRON self-reconfigurable robotic system. The ATRON is a lattice-type module, which has a single degree of freedom. The system is reconfigured using metamodules, which are simple, consisting of only three modules. But they have far higher capabilities than a single module, because they can crawl relatively freely on the surface of other modules. We let the metamodules emerge from the structure and migrate from one place to another, before they die and become structure again. Then, by controlling the ow of metamodules, we can change the shape of the structure. We introduce three different algorithms for migration of metamodules on the structure, and show that by using these, we can make the structure change its shape significantly in a controllable manner.

Projects:

Human Brain Project

The Neurorobotics Platform (NRP) developed in the Human Brain Project (HBP) is an Internet-accessible simulation system that allows the simulation of robots controlled by spiking neural networks. It targets researchers of multiple fields. Prospected users include but are not limited to neuroscientists wanting to validate brain models in the context of closed action-perception loops as well as robotics researchers wanting to develop new neuro-inspired controllers.

Department of Electrical Engineering

Automation and Control

Centre for Playware

Copenhagen Center for Health Technology

Period: 01/04/2016 → 01/04/2018

Number of participants: 4

Acronym: HBP

Project participant:

Tolu, Silvia (Intern)
Lund, Henrik Hautop (Intern)
Baira Ojeda, Ismael (Intern)
Christensen, David Johan (Intern)

Project

**Reconfigurable Modular Robotic System for Aquatic Environment**
Department of Electrical Engineering
Automation and Control
Centre for Playware
National Institute of Aquatic Resources
Section for Oceans and Arctic
Department of Mechanical Engineering
Engineering Design and Product Development
Fluid Mechanics, Coastal and Maritime Engineering

Period: 01/02/2016 → 31/01/2018
Number of participants: 6
Acronym: REMORA
Project participant:
Christensen, David Johan (Intern)
Mariani, Patrizio (Intern)
Visser, Andre (Intern)
Özkil, Ali Gürcan (Intern)
Nielsen, Ulrik Dam (Intern)

Project Manager, academic:
Galeazzi, Roberto (Intern)

**Fault-tolerance and reconfiguration for collaborating heterogeneous underwater robots**
Department of Electrical Engineering

Period: 15/08/2014 → 14/02/2018
Number of participants: 3
Phd Student:
Nielsen, Mikkel Cornelius (Intern)

Supervisor:
Christensen, David Johan (Intern)
Main Supervisor:
Blanke, Mogens (Intern)

**Financing sources**
Source: Internal funding (public)
Name of research programme: Stipendie fra udlandet
Project: PhD

**Modular Robotics for Underwater Environments**
Department of Electrical Engineering

Period: 15/12/2013 → 14/03/2017
Number of participants: 6
Phd Student:
Furno, Lidia (Intern)

Supervisor:
Christensen, David Johan (Intern)
Main Supervisor:
Blanke, Mogens (Intern)
Examiner:
Niemann, Hans Henrik (Intern)
Ludvigsen, Martin (Ekstern)
Schultz, Ulrik Pagh (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Interactive Modular Playware and Play Dynamics
Department of Electrical Engineering
Period: 01/12/2012 → 15/03/2015
Number of participants: 3
Phd Student:
Fogh, Rune (Intern)
Supervisor:
Christensen, David Johan (Intern)
Main Supervisor:
Lund, Henrik Hautop (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Modular Robotic Playware
Department of Electrical Engineering
Period: 01/12/2012 → 07/09/2016
Number of participants: 6
Phd Student:
Pacheco, Moises (Intern)
Supervisor:
Christensen, David Johan (Intern)
Main Supervisor:
Lund, Henrik Hautop (Intern)
Examiner:
Andersen, Nils Axel (Intern)
Støy, Kasper (Ekstern)
Werfel, Justin (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Playware for Welfare Technology
Department of Electrical Engineering
Period: 01/12/2012 → 30/09/2016
Number of participants: 5
Phd Student:
Jessen, Jari Due (Intern)
Main Supervisor:
Lund, Henrik Hautop (Intern)
Examiner:
Christensen, David Johan (Intern)
Kjær, Per (Ekstern)
Marti, Patrizia (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.

Relations
Publications:
Evaluation and understanding of Playware Technology – trials with playful balance training.
Project: PhD

Sensorbaseret realtidsstyring af robotter
Department of Electrical Engineering
Period: 01/12/2012 → 15/06/2016
Number of participants: 6
Phd Student:
Andersen, Thomas Timm (Intern)
Supervisor:
Andersen, Nils Axel (Intern)
Main Supervisor:
Ravn, Ole (Intern)
Examiner:
Christensen, David Johan (Intern)
Nielsen, Kurt (Ekstern)
Robertsson, Anders Robert Karol (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Playful Human-Robot Interaction based on Adaptive Modular Playware
Department of Electrical Engineering
Period: 01/02/2011 → 31/01/2013
Number of participants: 3
Phd Student:
Moghadam, Mikael (Intern)
Supervisor:
Christensen, David Johan (Intern)
Main Supervisor:
Lund, Henrik Hautop (Intern)

Financing sources
Source: Internal funding (public)
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