Self-organisation and self-optimisation

Research in Germany on future technical systems…

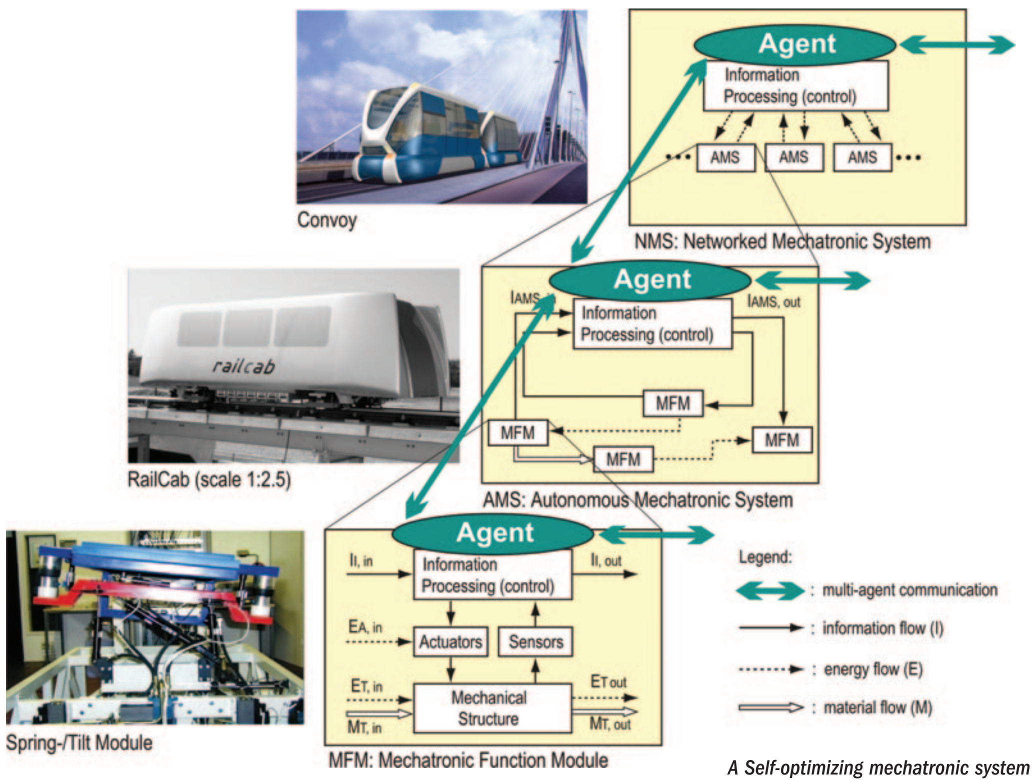
The Heinz Nixdorf Institute is a research centre within the University of Paderborn. It was founded in 1987, initiated and supported by Heinz Nixdorf, one of Germany's leading computer pioneers. He wanted to create a symbiosis of computer science and engineering in order to provide critical impetus for new products and services. This includes interactions with the social environment. Our research is aligned with the programme 'Dynamics, Mobility, Integration: En-route to the technical systems of tomorrow'. In training and education, the Heinz Nixdorf Institute is involved in many study programmes at the University of Paderborn. The most important goal in education and training is to communicate competencies that are critical in tomorrow's economy. At present, 10 professors and 200 researchers are working at the Heinz Nixdorf Institute. Approximately 30 young researchers per year receive a doctorate in our institute.

Vision of the institute

Our research focuses on a symbiosis of computer science and engineering and aims to provide decisive impetus for new products and services for the global markets of tomorrow. Our activities will create new workplaces and sustain prosperities. The problems we have to solve are complex. There are numerous influences that must be considered from areas such as natural sciences, technology, economics, ecology, and the social environment. We are adopting an interdisciplinary approach because we see that this offers the best possibility to find solutions for complex problems.

The technical systems of tomorrow will be able to adapt to changing operating and environment conditions independently and also have some cognitive abilities. They will consist of components with an inherent partial intelligence. These components will be connected to large, mostly mobile systems, which are highly complex and dynamic. Such systems will not be controlled globally. Therefore local strategies must be developed for good performance of the entire system. The design, control and the realisation of such technical systems require new approaches and ask for interdisciplinary research at the edge between computer science and engineering.

In the following we report about some of our projects concerning self-organisation and self-optimisation in machine engineering, robotic co-operation, and peer-to-peer based parallel computing. For more information about the Heinz Nixdorf Institute, see www.hni.uni-paderborn.de/en/.



A Self-optimizing mechatronic system as multi-agent system

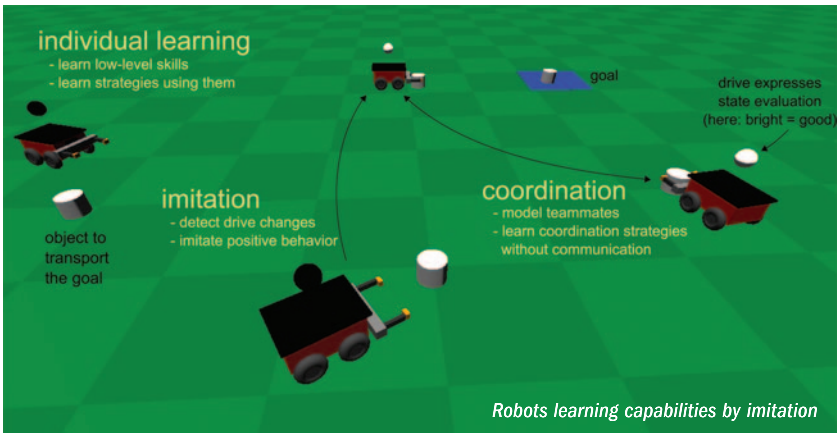
Self-optimisation in mechanical engineering

Mechatronics – the combination of mechanics, electronics, and computer science – indicates the trend towards intelligent technical artifacts. It also opens completely new potentials of self-adaptation to varying environmental conditions. In our Collaborative Research Centre (CRC) 614 "Self-Optimising Concepts and Structures in mechanical Engineering", funded by the German Science Foundation (DFG) for 12 years, these potentials are investigated especially concerning self-optimisation. CRC 614 concentrates on the methods to design the intelligent mechatronic systems of tomorrow. These artifacts will be characterised by inherent partial intelligence, a partial intelligence that allows such systems to optimise their behaviour dynamically to the ever changing environment.

More specifically we define self-optimisation as the endogenous modification of a system's objectives due to changing environmental influences. Resulting from these modified objectives, the system's behaviour is adapted autonomously by modifying respective parameters and even the system's structure. This means that self-optimisation reaches significantly beyond traditional control and adaptation strategies. Self-optimisation enables operational systems empowered with inherent intelligence to react autonomously and in a flexible manner to changing operational conditions.

From the mechanical engineering point of view, CRC 614 deals with the mechanical artifacts of tomorrow, artifacts that are built from system elements with inherent partial intelligence. From the point of view of information processing, such artifacts are distributed systems of communicating and co-operating agents.

The CRC's vision is a new school of engineering intelligent mechatronic systems. This school is constituted by a collection of process models, design methods, tools, and best practices.



Robots learning capabilities by imitation

The entire project is organised into four areas:

Project area A: Foundations and potentials of self-optimisation

Here basic research of the paradigm of self-optimisation is carried out from an engineering point of view. Two basic approaches are considered: numerical techniques based on a priori defined mathematical models of the system behaviour, and alternatively learning and planning techniques based on a black box description of system behaviour where this behaviour is obtained by collecting experience from experiments.

Project area B: Design methods and tools

In this area, methods and tools are developed that allow designing innovative systems following the paradigm of self-optimisation. UML-based design and verification techniques for self-optimising multi-agent systems are forming the software engineering platform of CRC 614. Novel extensions of UML (Mechatronic UML) and innovative verification techniques enable designing highly dependable systems. As in self-optimising systems essential decisions are deferred to the operational phase, virtual prototyping together with well-planned experiments to be carried out are mandatory. An appropriate environment is developed within this project area. All such activities have to be embedded into a seamless design methodology, a methodology that considers self-optimisation as a first class citizen.

Project area C: Implementation methods

In this project area the paradigm of self-optimisation is transferred to implementations by means of hardware, system software and control software. Reconfigurable hardware provides a platform that is ideally suited for self-optimising systems. A seamless design process is being developed to support such a platform. To enable lean support by system software, the real-time operating system (RTOS) used should follow the paradigm of self-optimisation as well. Innovative concepts based on system virtualisation and profile variation are developed. RTOS services offered include online verification in case of reconfiguration. Finally, as self-optimised controllers reach beyond classical adaptive controllers, the adequate control theory has to be developed. For this purpose, extended model-based control theory is combined with behaviour-based planning.

Project area D: Self-optimising products and systems

Here prototypes of new components and systems are developed to enable evaluating the novel concepts and to provide a substantial impact on product innovation. Self-optimising functional units like electric drives, energy storage, or actuators as well as entire systems for integrated energy management, system dynamics, or reliability management are investigated. An innovative rail-based transport system on demand (RailCab by University of Paderborn) is used as a benchmark for demonstrating the potentials of self-optimisation.

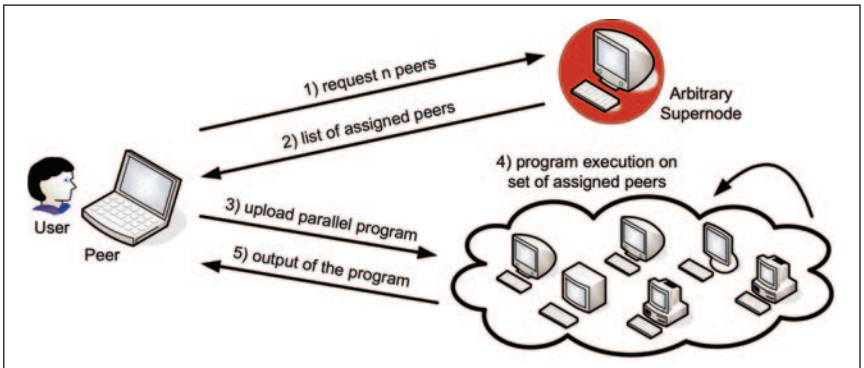
In total eight researchers of Heinz Nixdorf Institute are among the leaders of subprojects of this CRC: Professor Dangelmaier, Professor Gausemeier (General Chair), Dr Kleinjohann, Dr Porrmann, Professor Rammig (Deputy Chair), Professor Rückert, Professor Schäfer (Deputy Chair), and Professor Trächtler. For more information about the CRC 614 see www.hni.uni-paderborn.de/en/priority-projects/sfb-614/.

Self-organising robotic co-operation

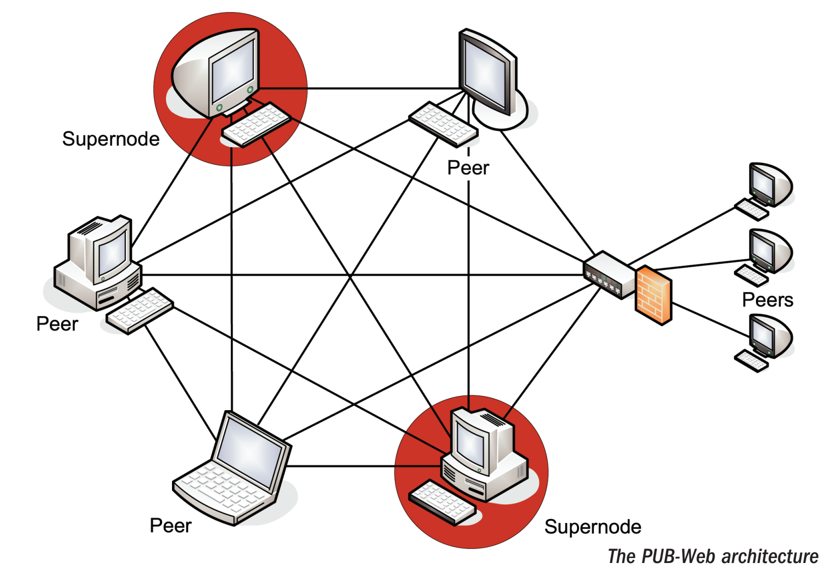
Our research on self-organising robotic co-operation is inspired and supported by the priority research programme 'Organic Computing' of the German Science Foundation (DFG) (see www.organic-computing.de/spp) and by the European project 'FRONTS' (Foundations of Adaptive Networked Societies of Tiny Artefacts) (see http://fronts.cti.gr/index.php/home) within the FET Proactive Initiative: Pervasive Adaptation in the 7th framework programme. Organic Computing has emerged recently as a challenging vision for future information processing systems. Organic Computing is based on the insight that we will soon be surrounded by large collections of autonomous systems, which are equipped with sensors and actuators, aware of their environment, communicate freely, and organise themselves in order to perform the actions and services that seem to be required. An 'Organic Computing System' is a technical system, which adapts dynamically to the current conditions of its environment. It will be self-organising, self-configuring, self-optimising, self-healing, self-protecting, self-explaining, and context aware. The priority research programme 'Organic Computing' of the German Science Foundation (DFG) addresses fundamental challenges in the design of Organic Computing systems; its objective is a deeper understanding of emergent global behaviour in self-organising systems and the design of specific concepts and tools to support the construction of Organic Computing systems for technical applications. The Heinz Nixdorf Institute participates with two projects.

In the project 'A Modular Approach for Evolving Societies of Learning Autonomous Systems', headed by Professor Rammig and Dr Kleinjohann, we develop a modular approach for realising self-organising and self-optimising autonomous systems that show emergent behaviour in societies of such systems. Current approaches already deal with the question how individual systems cope with failures and provide first solutions for individual self-adaptation. However it is unclear how a system's individual self-adaptation influences the behaviour and performance of the entire system society. We investigate how a system can learn to use its capabilities in changing environments while at the same time paying attention to the overall group behaviour. We follow a modular approach where a system is able to learn a model of itself and its environment including its group members; it can be used to predict which adaptation alternatives are most promising in a certain situation. For behaviour assessment we follow decentralised evaluation functions based on socio-biological paradigms like emotions and drives that do not only consider the system's own behaviour and improvement of its own state but also take into account its group's behaviour and goals. To support fast adaptation of a system's behaviour we combine individual exploration with imitation of successful behaviours of team mates. Furthermore we investigate how group behaviour emerges from such imitation and how such emergent behaviour can be characterised, for instance in terms of group clustering or performance. The developed modular approach that supports these features will be evaluated in simulation and by our Paderkicker robots.

In the project 'Smart Teams: Local Distributed Strategies for Self-Organising Robotic Exploration Teams', headed by Professor Friedhelm Meyer auf der Heide and Professor Christian Schindelhauer (Freiburg, a former member of the Heinz Nixdorf Institute) we aim at laying the algorithmic foundations for a scenario where an exploration team of robots – we call it a smart team – has to organise itself in order to fulfil tasks like exploring an unknown terrain and executing work in this terrain. Examples for such a task are rescue expeditions in dangerous areas or expeditions in the oceans or on planets. The work of such a smart team has to be guided by strategies for exploration, for finding important objects, and for assigning to such an object a subgroup of robots that jointly have the capabilities necessary to process the object. The challenge is that all these tasks have to be executed by local, distributed strategies that act on the mobile network of the moving robots, and have to result in a robust, effective self-organisation of the team. None of these robots ever will have more than very restricted, local knowledge about the global state of the system. Their



Running a parallel program with PUB-Web



The PUB-Web architecture

decisions are solely based on their own observations and findings, from which a globally good behaviour of the whole team has to emerge. We analyse the quality of our strategies both theoretically, e.g. by means of competitive analysis, and experimentally based on our simulation platform.

Peer-to-peer based parallel computing

Computationally intense calculations – for example, crash test simulations or the weather forecast – are usually conducted on huge, expensive parallel machines, which are often solely acquired for this purpose. But since, in many companies and institutes, there are hundreds or even thousands of computers that are only utilised at a very low extent, it is obvious to exploit this immense available computing power for such complex calculations (and, thus, avoid acquiring a pricey parallel machine).

But these computers in a company network are not available at all times – due to a system hang or because an employee temporarily heavily utilises the computer for his own work and, thus, has no resources left over. Thus, management software for using this computer cluster as a parallel machine is required, which flexibly adapts to changing parameters and is fault-tolerant against single failing components. The importance of these aspects even grows when extending the scenario of parallel computation from a local computer network to the internet.

When integrating computers from many different partners into a global internet-based parallel machine, a self-organising middleware without centralised structures eases both setup and maintenance of the system. As well, it significantly increases availability and stability of the system since there no longer is a bottleneck or a single point of failure at a centralised server. Instead, administrative tasks are handled by a dynamic subset of the peers, the so-called supernodes.

Our Paderborn University BSP-based Web Computing (PUB-Web, see http://pubweb.cs.uni-paderborn.de/) library supports these features: as a peer-to-peer system, it dynamically adapts to the changing environment of a computer network. Periodically creating automated backup copies of the process states, PUB-Web guards against failures of single computing nodes, and, employing intelligent load balancing algorithms, the continually fluctuating available computation power is fairly shared among all parallel processes.

Anybody who participates in the PUB-Web network with at least one computer is enabled to run his own parallel programs: first, he has to connect to an arbitrary supernode and announce his computing request. A multi-level, distributed load balancer fairly schedules his program, and at the time it is assigned, the user's peer is returned a list of peers to run the program. After code uploading, this subset of peers executes the program in a self-organised way and finally sends the results back to the user's peer. In case of heavy availability fluctuations or in case of faulty nodes, peers may be added to or removed from the subset during runtime by the load balancer.

In order to prove the power of PUB-Web under real conditions, we have built a test environment, which consists of more than 100 networked computers spread all over Europe, in the scope of the project AEOLUS (Algorithmic Principles for Building Efficient Overlay Computers, see http://aeolus.ceid.upatras.gr/), supported by the European Union within the 6th framework programme. Professor Meyer auf der Heide and Professor Monien from the Heinz Nixdorf Institute are involved in this project.

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