CoTeSys — Cognition for Technical Systems

Martin Buss[*], **Michael Beetz**[#], **Dirk Wollherr**[*]
[*] Institute of Automatic Control Engineering (LSR), Faculty of Electrical Engineering and Information Technology
[#] Intelligent Autonomous Systems, Department of Informatics
Technische Universität München
D-80290 München, Germany `www.cotesys.org`

Abstract. The CoTeSys cluster of excellence[a] investigates cognition for technical systems such as vehicles, robots, and factories. *Cognitive technical systems* (*CTS*) are information processing systems equipped with artificial sensors and actuators, integrated and embedded into physical systems, and acting in a physical world. They differ from other technical systems as they perform *cognitive control* and have *cognitive capabilities*. *Cognitive control* orchestrates reflexive and habitual behavior in accord with longterm intentions. *Cognitive capabilities* such as perception, reasoning, learning, and planning turn technical systems into systems that *"know what they are doing"*. The cognitive capabilities will result in systems of higher reliability, flexibility, adaptivity, and better performance. They will be easier to interact and cooperate with.

Keywords. *Cognition, Robotics, Vehicles, Automation.*

---

[a] CoTeSys is funded by the German Research Council DFG as a research cluster of excellence within the "excellence initiative" from 2006-2011, see also `www.dfg.de/en/research_funding/coordinated_programmes/excellence_initiative`. CoTeSys partner institutions are: Technische Universität München (TUM), Ludwig-Maximilians-Universität (LMU), Universität der Bundeswehr (UBM), Deutsches Zentrum für Luft- und Raumfahrt (DLR), and Max-Planck-Institute for Neurobiology (MPI), all in München.

I. Motivation and Basic Approach

People deal easily with everyday situations, uncertainties, and changes — abilities, which technical systems currently lack. Unlike artificial systems, humans develop and learn how to extract and incorporate new information from the environment. Animals have survived in our complex world by developing brains and adequate information processing strategies. Brains cannot compete with computers on tasks requiring raw computational power. However, they are extremely well-suited to deal with ill-structured problems that involve a high degree of unpredictability, uncertainty, and fuzziness.They can easily cope with an abundance of complex sensory stimuli that have to be transformed into appropriate sequences of motor actions[1].

Since brains of humans and non-human primates have successfully developed superior information processing mechanisms, CoTeSys studies and analyzes cognition in (not necessarily human) natural systems and transfers the respective insights into the design and implementation of cognitive control systems for technical systems.

To this end, cognitive scientists investigate the neurobiological and neurocognitive foundations of cognition in humans and animals and develop computational models of cognitive capabilities that explain their empirical findings. These computational models will then be studied by the CoTeSys engineers and computer scientists with respect to their applicability to artificial cognitive systems and empirically evaluated in the context of the CoTeSys demonstrators, including humanoid robots, autonomous vehicles, and cognitive factories.

CoTeSys structures interdisciplinary research on cognition in three closely intertwined research threads, which perform fundamental research and empirically study and implement cognitive models in the context of the demonstration testbeds, see Figure 1:

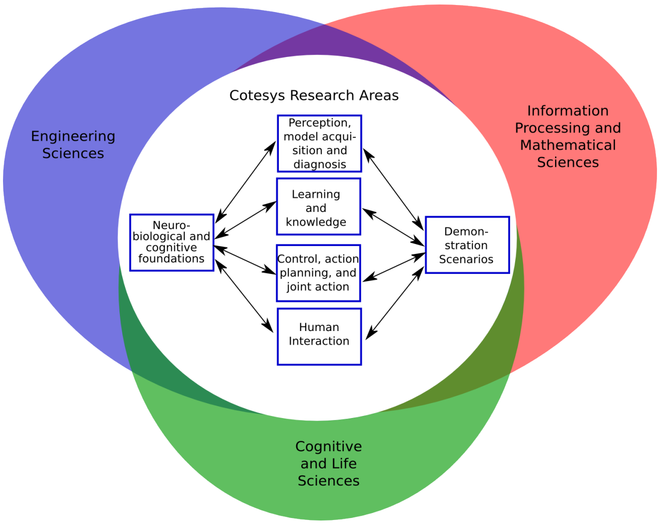


Fig.1: CoTeSys research strategy: Three research disciplines (cognitive and life sciences, information processing and mathematical sciences, and engineering sciences) work synergetically together to explore cognition for technical systems. Research is structured into three groups of research areas: cognitive foundations, cognitive mechanisms, and demonstration scenarios. Cognitive mechanisms to be realized include perception, reasoning and learning, action selection and planning, and joint human/robot action.

1. Systemic Neuroscience, Cognitive Science, and Neurocognitive Psychology — Develop computational models of cognitive control, perception, and motor action based on experimental studies at the behavioral and brain level.

2. Information processing technology — Investigate and develop algorithms and software systems to realize cogni-

---

[1] References are too numerous to be included in this paper; a follow-up survey paper will include references and related projects in detail.

tive capabilities. Particularly relevant are modern methods from Control and Information Theory, Artificial Intelligence including learning, perception, and symbolic reasoning.

3. Engineering technologies — The areas of mechatronics, sensing technology, sensor fusion, smart sensor networks, control rules, controllability, stability, model/knowledge representation, and reasoning are important to implement robust cognitive abilities in technical systems with guaranteed performance constraints.

In recent years, these disciplines studying cognitive systems have crossfertilized each other in various ways.[2] Researchers studying human sensorimotor control have found convincing empirical evidence for the use of Bayes estimation and cost function enabled control mechanisms in natural movement control. Bayesian networks and the associated reasoning and learning mechanisms have inspired research in cognitive psychology in particular the formation of causal theory with young children. Functional MRI images of rat brains have shown neural activation patterns of place cells similar to multimodal probability distributions in robot localization using Bayesian filters.

The conclusions that CoTeSys draws from these examples are that (1) successful computational mechanisms in artificial cognitive systems tend to have counterparts with similar functionality in natural cognitive systems; and (2) new consolidated findings about the structure and functional organization of perception and motion control in natural cognitive systems show us much better ways of organizing and specifying computational tasks in artificial cognitive systems.

However, cognition for technical systems is not the mere rational reconstruction of natural cognitive systems. Natural cognitive systems are impressively well adapted to the computational infrastructure and the perception and action capabilities of the systems they control. Technical cognitive systems have computational means, perception and action capabilities with very different characteristics.

Learning and motor control for reaching and grasping provide a good case in point.While motor control in natural systems takes up to 100ms to receive motion feedback, high end industrial manipulators execute feedback loops at 1000Hz with a delay of 0.5ms. In contrast to robot arms, control signals for muscles are noisy and muscles take substantial amounts of time to produce the required force. On the other hand, antagonistic muscle groups support the achievement of equilibrium states. Thus, where in natural systems predictive models of motion are required because of the large delay of feedback signals, robot arms can perform the same kind of motions better by using fast feedback loops without resorting to prediction. Given these differences, we cannot expect that generally all information processing mechanisms optimized for the perceptual apparatus, the brain, and the limbs of humans or non-human primates will apply, without modification, to the control of *CTSs*.

II. The Cognitive Perception/Action Loop

CoTeSys investigates the cognition in technical systems in terms of the cognition-based perception-action closed loop. Figure 2(left) depicts the system architecture of a cognitive system with multi-sensor perception of the environment, cognition (learning, knowledge, action planning), and action in the environment by actuators. All research within CoTeSys is dedicated to real-time performance of this control loop, in the real world. On the higher cognitive level, the crucial components comprise environment models, learning and knowledge management, all in real-time and tightly connected to physical action. The mid- and long-term research goals in CoTeSys are to significantly increase the functional sophistication for robust and rich performance of the perception-action loop.

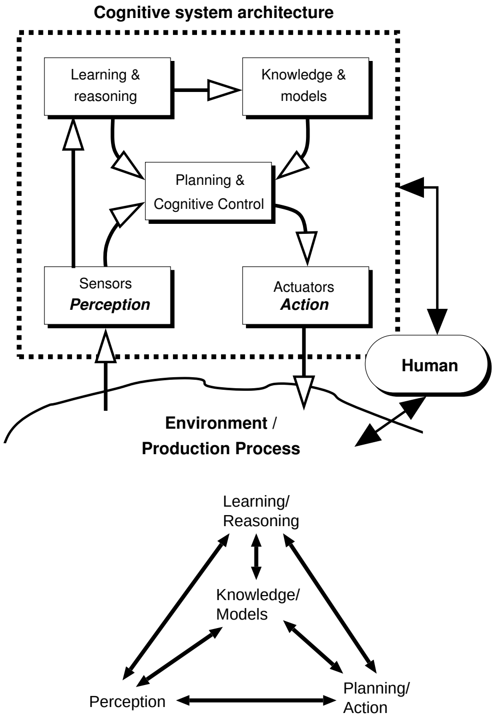


Fig. 2: The cognitive system architecture: The perception-action closed loop (left) and the interplay of the cognitive capabilities (right).

The mapping of the technical system operation onto the perception-action cycle depicted in Figure 2(left) might suggest that we functionally decompose cognition into modules where one module performs motor action, another one reasoning, and so on. In order to achieve the needed synergies, the coupling of the different cognitive capabilities must be much more intense and interconnected as depicted in Figure 2(right). For example, the system can *learn to plan* and *plan to learn*. It can *learn* to plan more reliably and efficiently and also *plan* in order to acquire informative experiences to

---

[2] Indeed, Mitchell has pointed out in a recent presidential address at the National Conference on Artificial Intelligence the next revolution is expected to be caused by the synergetic cooperation of the computing and the cognitive sciences.

learn from. Or, perception is integrated into action to perform tasks that require hand-eye coordination. Futher, perception often requires action to obtain information that cannot be gathered passively. This CoTeSys view on the tight coupling of the individual cognitive capabilities is important because it implies the requirement of close cooperation between CoTeSys's different research areas.

CoTeSys investigates the perception-action loop within a highly interdisciplinary research endeavor starting with discipline-specific views of the loop components in order to obtain a common understanding of key concepts, such as *perception*, *(motor) action*, *knowledge and models*, *learning*, *reasoning*, and *planning*.

Perception is the acquisition of information about the environment and the body of an actor. In cognitive science models, part of the information received by the receptors is processed at higher levels in order to produce task-relevant information. This is done by recognizing, classifying, and locating objects, observing relevant events, recognizing the essence of scenes and intentional activities, retrieving context information, and recognizing and assessing situations. In control theory, perception strongly correlates with the concept of observation — the identification of system states that are needed to generate the right control signals. Artificial intelligence, a subfield of computer science, is primarily concerned with perception and action; perception is often framed as a probabilistic estimation problem and the estimated states are often transformed into symbolic representations that enable the systems to communicate and reason about what they perceive.

(Motor) Action is the process of generating behavior to change the world and to achieve some objectives of the acting entity. To produce action, primate brains use a quasi-hierarchy ranging from elementary motor elements at lower cortical levels to complex "action" sequences and plans at higher levels. Natural cognitive systems use internal forward models to predict the consequences of motor signals to account for delays in the computation process and filtering out uninformative incoming sensory information. This cognitive science view can be contrasted to control theory, where behavior is specified in terms of control rules. Control rules for feedback control are derived from accurate mathematical dynamical system models. The design of control rules aims at control systems that are controllable, stable, and robust and can thereby provably satisfy given performance requirements. Action theories in artificial intelligence typically abstract from many dynamical aspects of actions and behavior in order to handle more complex tasks. Powerful computational models have been developed to rationally select the best actions (based on decision theory criteria), to learn skills and action selection strategies from experience, and to perform action aware control.

Knowledge (Models) in cognitive science is conceived to consist of both declarative and procedural knowledge. Declarative knowledge is recognizing and understanding factual information known about objects, ideas, and events in the environment. It also contains the inter-relationsships between objects, events, and entities in the environment. Procedural knowledge is information regarding how to execute a sequence of operations. In cognitive science various models have been proposed as part of computational models of motor control and learning to explain behavior of human and primate behavior in empirical studies. Most prominent are the forward and backward models of actions for the prediction of the actions' effects and sensory consequences and for the optimization of skills. Graphical models have been proposed to explain the acquisition of causal knowledge with younger children. In control systems, various mathematical models, such as differential equations or automata that capture the evolution of dynamical systems, are used. Research in artificial intelligence has produced powerful representations for joint probability distributions and symbolic knowledge representation mechanisms. It has developed the mechanisms to endow *CTSs* with encyclopedic and common sense knowledge.

Learning is the process of acquiring information, and, respectively, the reorganization of information that results in new knowledge. The learned knowledge can relate to skills, attitudes, and values and can be acquired through study, experience, or being taught, the cognitive science view. Learning causes a change of behavior that is persistent, measurable, and specified. It is a process that depends on experience and leads to long-term changes in behavior. In control theory, adaptive control investigates control algorithms in which one or more of the parameters varies in real time, to allow the controller to remain effective in varying process conditions. Another key learning mechanism is the identification of parameters in mathematical models. In artificial intelligence, a large variety of information processing methods for learning have been developed. These mechanisms include classification learners, such as decision tree learners or support vector machines, function approximators, such as artificial neural networks, sequence learning algorithms, and reinforcement learners that determine optimal action selection strategies for uncertain situations. The learning algorithms are complemented by more general approaches such as data mining and integrated learning systems (see DARPA Initiative – grand challenges).

Reasoning is a cognitive process by which an individual or system may infer a conclusion from an assortment of evidence, or from statements of principles. In the cognitive sciences reasoning processes are typically studied in the context of complex problem solving tasks, such as solving student problems, using protocol analysis methods ("think aloud"). In the engineering sciences specific reasoning mechanisms for prediction tasks, such as Bayesian filtering, are employed and studied. Other reasoning tasks are solved in the system design phase by the system engineers, where control rules are proven to be stable. The resulting systems have no need for execution time reasoning, because of their guaranteed behavior envelope. Artificial intelligence has developed a variety of reasoning mechanisms, including causal, temporal, spatial, and teleological reasoning, which enables *CTSs* to solve dynamically changing, interfering, and more complex tasks.

Planning is a process of generating (possibly partial) representations of future behavior, prior to the use of such plans, to constrain or control current behavior. It comprises reasoning about the future in order to generate, revise, or optimize the intended course of action. In the artificial intelligence view plans are considered to be control programs that can be executed, be reasoned about, and be manipulated.

III. The Integrated System Approach to *CTSs*

The demonstrators are of key importance for the CoTeSys cluster. Demonstrators and demonstration scenarios are designed to challenge fundamental as well as applied research in the individual areas. They define the milestones for the integration of cognition into technical systems.

The CoTeSys researchers integrate the developed computational mechanisms into complete control systems and embed them within the demonstrators. The research areas specify the kinds of experiments they intend to perform in the context of the demonstrators. They also specify metrics to evaluate the progress. Thus, the demonstrators become cross area research drivers that enforce researchers to collaborate and produce software components that successfully function in integrated cognitive systems. The demonstrators also transfer basic research efforts into applied ones and thereby promote cooperation with the industry.

The focus on demonstrators and integrated system research is also important as a research paradigm. The cognitive capabilities of *CTSs* enable them to *reason* about the use of their information processing mechanisms: they can check results, debug them, and apply better suited mechanisms if default methods fail. Therefore, their information processing mechanisms do not need to be hard coded completely. They should still be correct and complete but through dynamic adaptation rather than static coding. This is important because in all but the simplest cases completeness and correctness come at the cost of those problems becoming unsolvable — computationally intractable at best. For example, computing a scene description from a given camera image is an ill-structured problem, checking the validity of statements in a given logical theory is undecidable, computing a plan for achieving a set of goals is intractable for all but the most trivial action representations.

We will explain the interaction between demonstrator research and the other research areas using the cognitive factory as an example. The same kinds of interactions between demonstration scenarios and the other research areas will be realized by the cognitive vehicle and the cognitive humanoid robot demonstration scenarios.

The Cognitive Factory – as an Example for the Interaction between the Demonstrators and the other Research Areas.

The steadily increasing demand for mass customization, decreasing product life cycles, and global competition require production systems with an unprecedented level of flexibility, reliability, and efficiency. The equipment of production systems with cognitive capabilities is essential to satisfy these requirements, which must be addressed to strengthen the high-end production in developed economies.

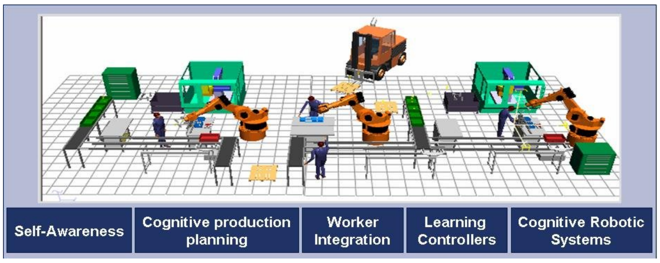


Fig.3: Production chain in the cognitive factory; ©Prof. Zäh, iwb, TUM.

CoTeSys will investigate a real world production scenario as its primary demonstration target for cognitive technologies in factory automation. An example production chain includes an industrial robot, autonomously cooperating robots, fixtures, and conveyors to handle and process these parts. In addition, it contains an assembly station where human workers and robotic manipulators jointly perform complex and dynamically changing tasks of assembling the parts.

The demonstrator challenges the cognitive capabilities of technical systems in important ways. The production chain includes a sheet metal driving machine. Driving – by incrementally forming metal sheets through hammering – is a process that can produce high quality, complex parts with arbitrary 3D shapes. With the required flexibility this production step can up to now only be performed by human experts. Using machine learning and planning methods, the industrial robot will learn to perform this complex task reliably, flexibly, and accurately for varying material properties and target shapes. An adaptive action model of the deformation steps allows the robot to optimize and refine its operation with experience. The robot will even be capable of planning of complex deformation processes including adequate sequences of deformation steps and the best step parameterization. The cognitive capabilities of the robot enable it to economically produce one-of-a-kind automobile body parts in handcraft quality.

Another cognitive aspect of this demonstrator is that it uses sensor networks in order to be aware of the operations in individual machines, robots, and transportation mechanisms. Using sophisticated data processing capabilities, integrated data mining and learning mechanisms, the machines learn to predict the quality of the outcome based on properties of the work piece and their parameterization. They form action models specific to the situation and use them to optimize production chain processing.

Another station in the cognitive factory mounts parts into the car body. The weight of the parts and the complexity of the step requires joint human robot action. Heavy parts and tools will be handled by industrial robots and mobile platforms will provide parts on the fly, such that human workers will be relieved from repetitive and strenuous operations and can focus on tasks that require high-level reasoning. The robot learns informative predictive models of the workers' actions by observing them. The predictive models are then used for synchronizing the joint actions. To adapt to their co-workers, cognitive mechanisms will enable the machines to explain their behavior, for example why they have performed two production steps in a certain order. The machines are equipped with plan management mechanisms that allow them to automatically transform abstract advice into modifications of their own control programs.

IV. Research Areas

Research on neurobiological and neurocognitive foundations of cognition — Basic research investigates the neurobiological and neurocognitive foundations of cognition in technical systems by empirically studying cognitive capabilities of humans and animals at the behavioral and brain level. Researchers will investigate, in human subjects, the *cognitive control* of multi-sensory perception-action couplings in dynamic, rapidly changing environments following an integrative approach by combining behavioral and cognitive-neuroscience methodologies.

The research task is to establish experimentally how these control functions are performed in the brain, in order to provide (1) neurocognitive "models" of how these functions may be implemented in technical systems and (2) guidelines for the effective design of man-machine interfaces considering human factors. One of the key results for the research areas studying cognitive mechanisms will be a comprehensive model of cognitive control combining mathematical and neural-network models with models of symbolic, production systems-type information processing. In contrast to existing models that are limited to static, uni-modal (visual) environments and simple motor actions the CoTeSys model will cover cognitive control in dynamic, rapidly changing environments with multi-modal event spaces.

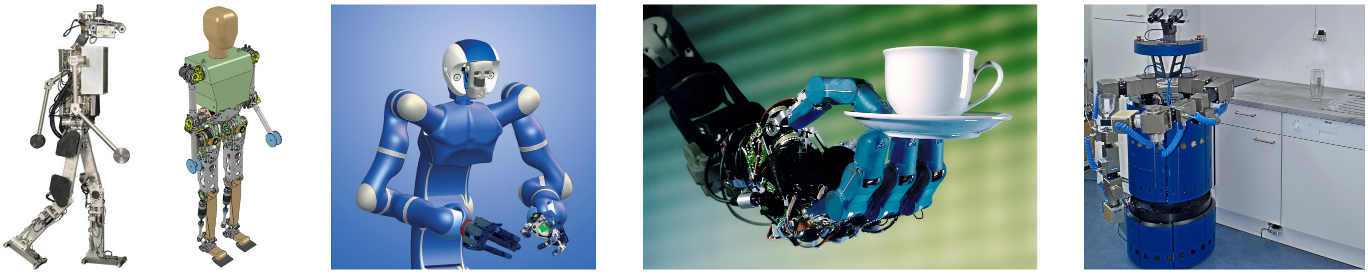
Research on perceptual mechanisms designs, implements, and empirically analyzes perceptual mechanisms for cognition in technical systems. It integrates, embeds, and specializes the mechanisms for their application in the demonstration scenarios. The challenge for the area is to develop fast, robust and versatile perception systems that allow the CoTeSys demonstrators to operate in unconstrained real-world environments; to endow cognitive technical systems with perception systems that acquire, maintain, and deliver task-relevant information through multiple sensory modes rather than vast sensor data streams. Besides lower level perceptual tasks, the CoTeSys perception modules will be capable of recognizing, classifying, and locating a large number of objects, of conceiving and assessing situations, contexts and intentions, and interpreting intentional activities based on perceptual information. Perceptual mechanisms at this performance level must themselves be cognitive. They have to filter out irrelevant data, focus attention based on an understanding of the context and the tasks they are to execute. The perceptual capabilities investigated are not limited to the core perceptual capabilities. They also include post-processing reasoning such as the acquisition of environment models and diagnostic reasoning mechanisms that enable *CTSs* to automatically adapt to new environments and to debug and repair themselves.

Research on Knowledge and Learning — The ultimate goal of the CoTeSys cluster is the realization of technical systems that *know what they are doing*, which can *assess how well they are doing*, and *improve themselves based on this knowledge*. To this end, research on knowledge and learning will design and develop a computational model for knowledge processing and learning especially designed to be implemented on computing platforms which are embedded into sensor-equipped technical systems acting in physical environments. This model — implemented as a knowledge processing and learning infrastructure — will enable technical systems to learn new skills and activities from potentially very little experience, in order to optimize and adapt their operations, to explain their activities and accept advice in joint human-robot action, to learn meta-knowledge of their own capabilities and behavior, and to respond to new situations in a robust way.

The research topics that define the CoTeSys approach to knowledge and learning in *CTS* include the following: Firstly, the development of a probabilistic framework as a means for combining first-order representations with probability. This framework provides a common foundation for integrating perception, learning, reasoning, and action while accommodating uncertainty. Secondly, a model of "Action Meta-Knowledge" is developed, which considers actions as information processing units that automatically learn and maintain various models of themselves, along with the behavior they generate. These models are used for behavior tuning, skill learning, failure recovery, self-explanation, and diagnosis. Thirdly, a comprehensive repertoire of sequence learning methods partly based on theories of optimal learning algorithms. Finally, an embedded integrated learning architecture employing multiple and diverse learning mechanisms capable of generalizing from very little experience.

Research on action selection and planning — addresses the action production aspects of cognition in technical systems. These aspects include the realization of motion and manipulation skills, the context-specific selection of the appropriate actions, the commitment to courses of activity based on foresight, and specific action capabilities enabling competent joint human-robot action.

To generate high performance and safe, action planning and control for locomotion, manipulation and full body motion is integrated. The planning and control system should be capable of working with minimal, non-technical, and qualitative descriptions of tasks. High performance and safe operation



©Prof. Ulbrich, TUM ©Prof. Hirzinger, DLR ©Prof. Beetz, TUM

Fig.4: Demonstrator platforms used in the planned scenarios for cognitive humanoid robots. At the left are two humanoid robots (Johnnie and Lola) to be used for walking and full body motion research. Next is the upper body Justin is used for investigating highly dexterous manipulation capabilities. Its hand serving a coffee set is shown next to the right. On the right is a mobile robot with industrial strength arms that serves as the initial platform for the AwareKitchen scenario.

will enable close cooperation with humans. Another focus is to enable cognitive robots to accomplish complex tasks in changing and partly unknown environments; to manage several tasks simultaneously, to resolve conflicts between interfering tasks, and to act appropriately in unexpected and novel situations. They even have to reconsider their course of action in the light of new information. Hence, the long term vision is to develop action control methods and a *design methodology* to be embedded into self-organizing cognitive architectures.

Research on human factors studies cognitive vehicles, robots, and factories from a human factors and cognitive psychological point of view. Particular emphasis is placed on the interpretation of the environment and the communication with humans enabling human-machine collaboration in unstructured environments. The state-of-the-art in all aspects of human-machine communication will be advanced in order to equip cognitive systems with highly sophisticated communication capabilities. To achieve these goals neurobiology and technology are to inspire each other and thereby develop the following aspects of cognitive technical systems: *advanced input/output technology*, such as speech, gesture, motion, and gaze recognition is created to construct intuitive *user interfaces and dialogue techniques*, as well as sophisticated methods to evaluate the multi-modal interaction of humans and systems. The highest and most complex level involves *emotion, action, and intention recognition*, with which cognitive systems become more human-like. To pursue these goals novel computational *user models* of cognitive architectures and appropriate experimental evaluation methods are investigated.

V. Demonstrators and Scenarios

The CoTeSys demonstrators provide the other areas with demonstration platforms and challenges in the form of demonstration scenarios. The research results from the other research areas will be integrated, specialized, embodied, and validated in three scenarios:

1. Cognitive mobile vehicles: aerial vehicles for exploration and mapping, terrestrial offroad vehicles, and collaborative rescue missions for autonomous aerial-terrestrical vehicle teams.

2. Cognitive humanoid robots: the two-legged humanoid robots Johnnie and Lola are equipped with lightweight arms and multi-fingered hands from DLR. They constitute the main platforms and their control systems are extended to perform full body motion. The demonstration scenarios will feature complex everyday activity, complex full body motion, and sophisticated manipulation of objects.

3. Cognitive factory: a production line for individualized manufacturing of car bodies is considered. Cognitive aspects include skill acquisition, process planning, self-adaptation, and self-modelling. The production line includes autonomous mobile robots with manipulators in order to achieve the necessary flexibility of machine usage.

©Prof. Wünsche, UBM ©Prof. Hirzinger, DLR

Fig.5: Two autonomous vehicles serving as demonstrators in the CoTeSys cluster: *The UBM vehicle MuCAR-3* and *The DLR blimp*

The AwareKitchen with a cognitive robotic assistant. One of the demonstration scenarios for the humanoid robot demonstrators is the AwareKitchen with robotic assistant, where the sensor-equipped kitchen is to observe the actions of the people in the kitchen, to provide assistance for the activities, and to monitor the safety of the people. For details about this scenario and results the reader is referred to the companion paper [1].

REFERENCES

[1] M. Beetz, “The AwareKitchen for Cognitive Robotics,” in *Proc. 4th COE Workshop on Human Adaptive Mechatronics (HAM)*, (Tokyo, Japan), 2007.