Learning from Nature
to Build Intelligent Autonomous Robots

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Abstract. Information processing within autonomous robots should follow a biomimetic approach. In contrast to traditional approaches that make intensive use of accurate measurements, numerical models and control theory, the proposed biomimetic approach favors the concepts of perception, situation, skill and behavior – concepts that are used to describe human and animal behavior as well. Sensing should primarily be based on those senses that have proved their effectiveness in nature, such as vision, tactile sensing and hearing. Furthermore, human-robot communication should mimic dialogues between humans. It should be situation-dependent, multimodal and primarily based on spoken natural language and gestures. Applying these biomimetic concepts to the design of our robots led to adaptable, dependable and human-friendly behavior, which was proved in several short- and long-term experiments.

Keywords. Bionics, robot system architecture, situation, skill, behavior

1. Introduction

Nature has created highly complex, efficient and dependable systems in the form of organisms since the very beginning of life on earth. Design and function of organisms have been optimized under evolutionary pressure over billions of years, a small step at a time. It is, therefore, an attractive idea to apply nature's solutions to today's engineering problems and, specifically, to the creation of robot intelligence.

A first step is to base a robot's sensor modalities, world modeling, control and communication with humans primarily on those principles that proved their effectiveness in nature. This biomimetic approach to the realization of robot intelligence differs from the traditional one in many respects. Table 1 gives an overview.

Table 1. Summary of biomimetic vs. traditional approaches to robot intelligence

Category	**Traditional Approach**	**Biomimetic Approach**
Sensor modalities	often only single modality often range sensors: laser range finder, sonar, radar, depth from stereo vision, motion, … seemingly suitable for constructing numerical models, e.g., 3-D surface reconstruction	multi-modal, combination of: • exteroceptors: vision, audition, touch, olfaction, gustation • proprioceptors: angle encoders, strain gauges, bodily acceleration sensors, kinesthetic sensors … • interoceptors: internal temperature measurements, battery gauging, … suitable for situation assessment
Modeling	global coordinates accurate geometrical maps detailed numerical models of the	local coordinates (if any) attributed topological maps qualitative models of relevant aspects of a vaguely

	robot and the external world complete knowledge of all robot and world parameters	known and ever-changing world largely qualitative internal model of the robot's situation
Robot control	accurate and complete calibration of sensors, actuators, kinematics etc. accurate measurements control theory	no or intrinsic calibration largely qualitative perception highly adaptive calibration-free control situation-dependent behavior selection and execution
Communication	exact trajectory teaching artificial, well-structured (usually written) command language commands and status reports based on coordinates	situation- and context-depending dialogues resembling inter-personal communication spoken natural language augmented by gestures and visual and haptic events commands and status reports based on current situation and perceivable objects

2. Human information processing

Especially if a robot, such as a personal robot, is supposed to work closely together with humans in human-populated environments, its information processing design might benefit from understanding the human one and from employing similar concepts.

An overall qualitative model of human performance was proposed by Rasmussen [1]. In his model he classified three typical levels of performance of skilled human operators: skill-, rule-, and knowledge-based performance (Figure 1).

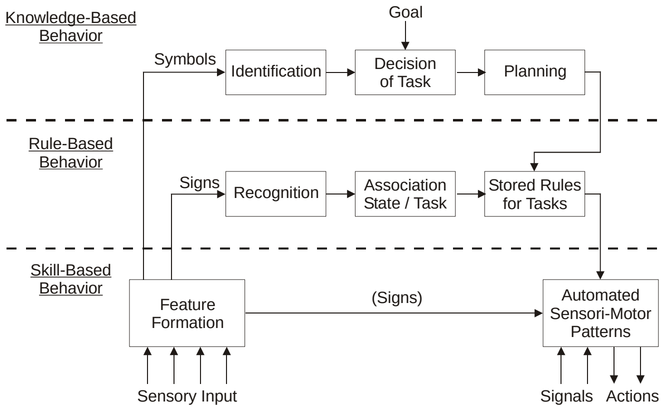

Fig. 1. Human information processing. Simplified model illustrating the three levels of performance of skilled human operators (Rasmussen [1]).

According to Rasmussen, a *skill-based behavior* represents „sensory-motor performance during acts or activities which [...] take place without conscious control as smooth, automated, and highly integrated patterns of behavior". Performance is mostly based on feedforward control which depends upon a very flexible and efficient dynamic internal world model. Handwriting and sports are examples of such well coordinated rapid movements.

At the next level – *rule-based behavior* – human performance is goal-oriented, but structured through stored rules (procedures). These rules may have been obtained through instructions, derived from experience or deduced by conscious problem-solving or planning. Rules are typically defined as „if ... then ... else" clauses, and operators would experience them as stereotype acts. Rasmussen makes a distinction between skill- and rule-based behavior by the level of training and attention a person requires to perform a certain task. Whereas skill-based performance does not necessitate a person's conscious attention, rule-based performance is generally based on explicit know-how.

At the highest conceptual level human performance is goal-controlled and *knowledge-based*. It requires a mental model of the system or task enabling the person to develop and predict different plans to reach a certain goal.

Rasmussen's model is well suited to describe a typical service task, such as serving a drink, in terms of the required knowledge, rules, skills, symbols, signs and signals. It is interesting to see that both a human and a robotic servant could apply the same model to decompose the given task into a set of elementary action patterns. Supposed that the servant would know how to serve a drink, he would probably apply the following *rules*:

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grasp bottle, grasp glass, fill glass from bottle,
approach table, place glass onto table
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Each rule would in turn be composed of elementary *sensorimotor skills*, e.g.:

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grasp bottle := locate object bottle, open hand,
move hand towards object, close hand around object
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Each sensorimotor skill would require *signals* (i.e., continuous sensory input) or a *sign* (to start some automated sensorimotor skill). The completion of a rule or sensorimotor skill is indicated by a *sign* representing a specific system state. The rule „grasp bottle" could thus be terminated by the sign „hand closed around the object", the termination sign of the rule „approach table" could be, e.g., „docking position reached".

Knowledge-based operations are necessary when a set of rules does not yet exist to describe a specific task or when an unfamiliar situation occurs. For example, imagine that the servant experiences unexpected difficulties because the bottle is not open. To handle this exception it is required to devise a plan and probably a set of rules allowing the removal of the cork (or any other stopper) before being able to fill the glass. On this knowledge-based level, sensory inputs are interpreted as symbols that are related to concepts and functional properties, i.e., problem solving requires knowledge about the process („when the stopper has been removed, the filling can begin").

3. Robot Information Processing

So far, basically three paradigms for organizing robot information processing have emerged: *hierarchical* (sequential), *reactive* (parallel), and *hybrid.* As a combination of hierarchical and reactive, the hybrid approach is meant to combine the best of both worlds. It allows the implementation of both purely reactive behaviors (= reflexive behaviors) and more cognitively challenging (computationally more expensive) functions to a varying degree. Although quite a number of hybrid architectures have been developed (see [2] for an overview) it is still an open research question how to organize and coordinate the reactive and deliberative parts of the system. As part of our solution to this question, we introduced a situation-oriented skill-based system architecture [3] that – according to our biomimetic approach – favors perception over measurement, and situation-based calibration-free control over accurate modeling and classical control theory. This architecture is based itself on the concepts of situation, perception, behavior and skill, which are briefly explained in the sequel and illustrated in Figure 2.

According to the classical approach, robot control is model-based and depends on a continuous stream of accurately measured data. Numerical models of the kinematics and dynamics of the robot and of the external objects that the robot should interact with, as well as quantitative sensor models, are the basis for controlling the robot's motions. The main advantage of model-based control is that it lends itself to the application of classical control theory and, thus, may be considered a straight-forward approach. The weak point of the approach is that it breaks down when there is no accurate quantitative agreement between reality and the models, which is all too often the case.

Organisms, on the other hand, have the ability to continuously cope with, and to survive in, the complex, dynamic and unpredictable real world. They are robust and adapt easily to changes of their own conditions and of the environment. They never need any calibration, and they normally do not know the values of any parameters related to the characteristics of their „sensors" or „actuators". Obviously, they do not suffer from the shortcomings of model-based control which leads us to the assumption that they use something other than measurements and numerical models for controlling their behaviors. Perhaps their behavior control is based on a *qualitative and holistic assessment of situations* and the *selection of actions* to execute from an existing repertoire on that basis.

With a more operational aim we define a robot's (internal) situation as *the set of all decisive factors* that should ideally be considered by a robot in selecting the correct action at a given moment. These decisive factors include:

- the goals of the robot, i.e., *permanent goals*, usually internal goals of the robot, such as survival, and satisfaction of desires, intentions and plans; and *transient goals* emerging from the actual mission;
- the *state of the robot* (state of motion, state of actuators and sensors, presently executed behaviors, focus of attention of the perceptual system,...);
- the *state of the robot's environment*, i.e., perceivable objects in the environment and their suspected or recognized states; and static characteristics of the environment, even if they currently cannot be perceived by the robot's sensors;
- the *repertoire of available skills and knowledge* of the robot's abilities to change the present situation in a desired way by executing appropriate skills.

Main basis for the recognition of situations are *perceptions* that integrate sensory impressions of events in the external world. Perceptions help the robot to become aware of something through its senses. Generally speaking, perception plays a similar role in the biomimetic approach as measurement does in the traditional one.

In the proposed system architecture situations provide the framework for structuring a set of possible robot *skills*. A *skill* is a goal-directed, well organized ability that is inbuilt, *can be* acquired and improved through learning, and is performed with economy of effort (derived from psychological literature [4]). Whereas a skill describes functional underpinnings of a robot and is implemented as a specific software module, a *behavior* is an observable activity. Skills may thus be the basis for behaviors. It should be noted that a robot may show a certain behavior not only based on the execution of skills, but also based on purely reactive responses to external or internal stimulations, e.g., reflexes. Figure 2 (left) illustrates our definition of the term „situation" by embedding it in the perception-action cycle of a situation-oriented skill-based robot. As defined above, the robot's image of the situation emerges at any given moment by combining internal and external goals, knowledge and percepts.

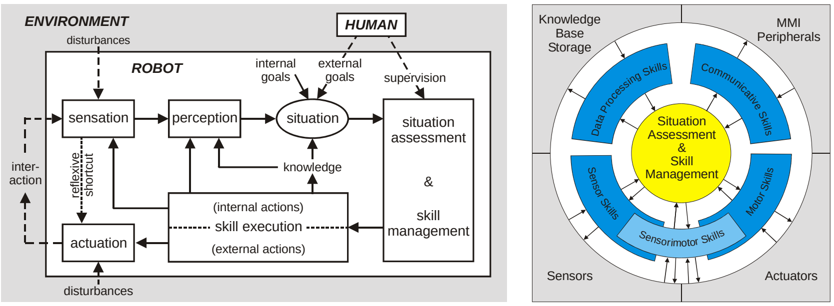

Fig. 2. Biomimetic robot information processing. Left: Perception-action cycle of a situation-oriented skill-based robot in interaction with its environment (and a human) based on the key concepts of perception, situation, and skill. Right: System architecture of a personal robotic assistant based on those key concepts.

4. Implementation

Due to space limitations the actual implementation of the described fundamental concepts can only be sketched. Figure 2 (right) shows the essence of the situation-oriented skill-based robot architecture as we have implemented it. The situation module (situation assessment & skill management) acts as the deliberator of the whole system. It is interfaced via skills in a bidirectional way with all hardware components – sensors, actuators, knowledge base storage and MMI peripherals (man-machine and machine-machine interface peripherals). Skills have direct access to the hardware components and, thus, let the robot sense, think (plan) and act. They obtain certain information, e.g., sensor readings, generate specific outputs, e.g., arm movements or speech, or plan a route based on map knowledge. Skills report to the situation module via events and messages on a cyclic or interruptive basis to enable a continuous and timely situation update and error handling. Whereas some skills require real-time connections to and from the situation module, e.g., sensor skills, non-real-time performance is sometimes allowed, e.g., for data base maintenance and route planning.

The situation module fuses data and information from all system components to make situation assessment and skill management possible. As such, it provides **cognitive skills**, i.e., it is responsible to plan an appropriate skill sequence to reach a given goal. By activating and deactivating the inbuilt skills, the situation-dependent concatenation of skills is realized that leads to complex and elaborate robot behavior.

Motor skills control simple movements of the robot's actuators. They can be arbitrarily combined to yield a basis for more complex control commands. Encapsulating the access to groups of cooperating actuators leads to a simple interface structure, and allows an easy generation of pre-programmed motion patterns. **Sensor skills** encapsulate the access to one or more sensors and provide the situation module with proprio-, extero- and interoceptive data. **Sensorimotor skills** combine both sensor and motor skills to yield sensor-guided robot motions. **Data processing skills** organize and access the system's knowledge bases. They return specific information upon request and modify existing, or add newly gained, knowledge to the data bases. Various types of knowledge bases are being used, including an attributed topological map for storing the static characteristics of the environment, an object data base, a subject data base and a list of missions to accomplish. Communication takes place via various different channels (acoustic, optical, tactile) and requires a variety of **communicative skills** to preprocess input from humans and to generate a valuable feedback for them according to the current situation and the given application scenario. They depend on various sensor skills to receive the required information, e.g., hearing skills for understanding speech, vision skills, and even tactile skills, to allow situated dialogues with references to visible and tangible objects and subjects in the world.

When comparing Rasmussen's model of human information processing (cf. Fig. 1) with our model of robot information processing (cf. Fig. 2) the three blocks „feature formation", „recognition" and „identification" are realized by sensor skills, and „automated sensor-motor patterns" are mostly realized by motor and sensorimotor skills. The cognitive skills provided by the situation module correspond to the three blocks „decision of task", „planning" and „association state/task". Part of „planning" and „stored rules for task" are realized by data processing skills. As communicative skills involve the entire information processing system they cannot be assigned to an individual block of Figure 1.

All tasks and threads of the robot's software system run asynchronously, but can nevertheless be synchronized via messages or events. Overall control is realized as a finite state automaton that is capable of responding to prioritized interrupts and messages. A finite state automaton has been preferred over other possibilities because of its simplicity. Motor skills are mostly implemented at the microcontroller level within the actuator modules. The other skills are implemented on a network of digital signal processors that is physically embedded in a PC.

5. Real-world experiments

Over the years four of our robots have been equipped with different variants of the described system architecture and brought into short- and long-term field trials: two autonomous vehicles (*ATHENE I* and *II*), a stationary manipulator and a humanoid robot (*HERMES*). All robots were endowed from the start with certain basic skills, and were able to incrementally extend their knowledge and skills through learning.

Calibration-free navigation. Two different vision-guided mobile robots were used as experimental platforms for learning to navigate a network of corridors by concatenating simple vision- and odometry-based sensorimotor skills: *HERMES*, a humanoid personal robotic assistant, and the older *ATHENE II*, a transportation robot with tricycle wheel configuration. *HERMES* has a unique wheel configuration with two independently driven and steered wheels mounted at the front and the back, and two caster wheels arranged at the centers of the left and right sides of a quadratic undercarriage allowing many different drive modes (differential, car-like, fork-lift, omnidirectional) [5]. While *ATHENE II* is equipped with a monochrome video camera mounted on a 1-DOF platform steerable around its vertical axis, *HERMES*' main sensors are two monochrome video cameras mounted on independent pan/tilt drive units, in addition to a pan/tilt unit that controls the common „head" platform. Various standard lenses (from wide angle to tele) and a Suematsu lens were used during the experiments.

It should be explicitly noted that it would have been difficult and time-consuming to measure all relevant kinematic parameters of such versatile robots with any degree of accuracy and to design model-based controllers for all possible modes of operation. Our calibration-free approach makes it unnecessary.

For testing our calibration-free navigation concept we have equipped both robots with reliable, robust and sufficiently fast dynamic vision systems [5]. They yield the required data, such as the position of a guideline that is typically detected at the intersections of the floor with the walls despite adverse conditions, such as specular reflections and difficult illumination conditions, in general, at video field rate (i.e., 50 Hz).

In the beginning of the actual driving experiments *HERMES* and *ATHENE II* were placed somewhere in a corridor. Their exact orientation and position were unknown, but a section of the guideline had to be in the field of view. Corridor navigation was possible and worked fine in a tilt angle range from 0° (horizontal) to about 50° (looking downward). Negative tilt angles (i.e., looking upward) were not tested, but could have worked as long as the guideline was visible. Based on their navigation skills map building and delivery missions were successfully performed (Fig. 3. left).

Calibration-free manipulation. Manipulation experiments were first carried out with the vision-guided stationary manipulator [6] (Fig. 3, middle). The cameras are attached to the robot on metal rods at the first link so that they rotate around the axis of joint 1 together with the arm. They are mounted in a rather unstable way to make the impossibility of any calibration or precise adjustment obvious, and to allow easy random modifications of the camera arrangement. Objects of various shapes could be grasped, although no knowledge regarding the optical or kinematic parameters of the robot was used. Even arbitrary unknown rotations and shifts of the cameras were tolerated while the robot was operating, which demonstrated the robot’s extreme adaptability. Furthermore, it was shown that such an extreme adaptability does not necessarily have to degrade pick and place cycle times if appropriate learning schemes are used.

With its two arms with 6 DOF and a two-finger gripper each and a bendable body, *HERMES* possesses an even more complex manipulation system which – besides grasping - allowed us to carry out human-robot interaction experiments. The biggest advantage of our skill-based approach is that it enormously reduces complexity in designing intelligent robot behaviors, such as taking/handing over objects from/to people, placing them onto other objects and gesturing in communicative acts.

Communication and interaction. *HERMES* has been presented successfully at trade fairs, in television studios and a museum and at various demonstrations in our institute environment. The robot is able to deliver simple services within initially unknown environments for users that may be initially unknown, too. Services handled by the robot include, but are not limited to, transportation tasks, entertainment, and gathering and providing information about people and their living or working environment (Fig. 3, right). For example, many types of dialogues exist to *cooperatively* teach the robot new knowledge and to build a common reference frame for subsequent execution of service tasks. It is possible for the robot – besides learning an attributed topological map of the environment - to learn persons’ names, to learn how locations and objects are denominated by a specific person, where objects of personal and general interest are located, and how to grasp specific objects. This requires several databases and links between them in order to retrieve the required information [7].

One of the most promising results of our experiments is that the biomimetic approach seems to pay off. First, despite the complexity of the overall system the nature-inspired system architecture allows the integration of newly developed skills very easily making the system scalable. Second, although we experienced drifting of system parameters in the long-term experiments due to temperature changes or simply wear of parts or aging, the robots’ performances were not affected by such drifts because our algorithms only rely on qualitatively (not quantitatively) correct information and adapt to parameter changes automatically. We found that the implemented skills worked very well not only around our laboratory, but also in other settings, despite the rather different appearance of objects of interest (e.g., corridors, docking stations). Third, according to the museum staff who ran our longest field trial for a period of more than 6 months (2001/10- 2002/04) in the Heinz Nixdorf MuseumsForum (HNF) in Paderborn, Germany, *HERMES* was one of the few robots at the show that could regularly be demonstrated in action, and among them it was considered the most intelligent and most dependable one. This statement is supported by the fact that the museum staff never called for advice once the initial setup was done.

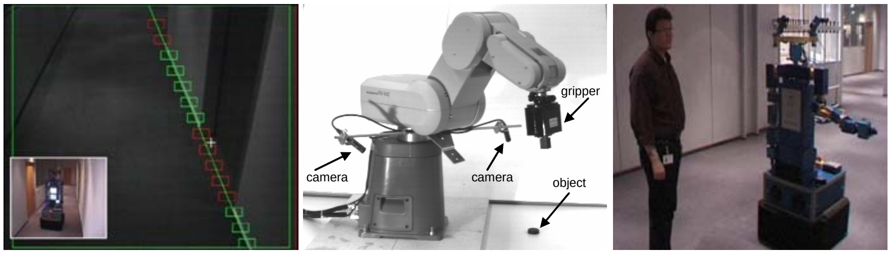

Fig. 3. Experiments and Results. Left: Image taken by the *HERMES*' vision system during corridor navigation (tracking a guideline, indicating two forms of interruptions (door and junction). Middle: Setup of stationary robot arm used for grasping (Mitsubishi Movemaster RV-M2, 5 DOF, two-finger gripper and a stereo vision system). Right: *HERMES* describing the way to a location of interest by means of voice and gestures.

6. Summary and conclusions

A biomimetic approach to the realization of robot intelligence by studying Mother nature's best ideas and then imitating her designs and processes to solve robotic problems has been proposed. A robot information processing architecture was derived by studying Rasmussen's model of human information processing. It has been implemented on various robots and has proved to endow robots with intelligent situation-oriented behavior. The ability to sense in a human-like way by means of vision, touch and hearing – the most powerful sensor modalities known – is enabling our robots to perceive their environments, to understand complex situations and to behave intelligently.

While today's robots are mostly strong with respect to a single functionality, e.g., navigation *or* manipulation, our results illustrate that many functionalities can be integrated within one single robot through a nature-inspired unifying situation-oriented skill-based system architecture. Furthermore, testing a robot in various environmental settings, both short- and long-term, with people having different needs and different intellectual, cultural and social backgrounds, is enormously beneficial for learning the lessons that will eventually enable us to build dependable personal robotic assistants.

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