Behavior-based Robotics, its scope and its prospects

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Abstract

The paper gives an introduction to behavior-based robotics and explains its prospects for industry. First, the roots of behavior-based robotics in the scientific fields of Artificial Life and behavior-oriented Artificial Intelligence are presented. Based on this, the important conceptual aspects of behavior-based robotics are explained. The concepts are further motivated and illustrated with experiments in an ecosystem-like setting, where mobile robots interact in autonomous re-charging and working tasks. In addition to basic research issues, more application oriented work and industrial prospects are presented.

1 Introduction

Behavior-based Robotics can be can be directly related to behavior-oriented Artificial Intelligence [15], a field which has its origins usually dated back in the late eighties. In that time, scientists started to argue against "classic" AI which is using symbolic representations and methods [6, 14]. Based on his experiences with (still) common approaches to robot control, Rodney Brooks for example propagated new research questions and methods. Instead of solving abstract, formalized problems, like e.g. playing chess, he argued for working with robots. In doing so, he propagated reactive mechanisms and that "the world is its best own model" in contrast to formal reasoning and abstract models [7]. Reactive control means roughly speaking, that there is a tight coupling between sensor values and motor activations and that there is no central control.

Another, though similar, root of behavior-oriented Robotics can be seen within the field of Artificial Life, or short Alife [10]. Also starting from the late eighties, scientist try to find out "basic properties" of life using computer based technology. In doing so, a part of the community is following the *animat* approach [19], i.e., they are using robotic devices which are inspired by animals (animat = animal + robot). As we will see throughout this paper, this viewpoint of inspiration from nature can be extremely useful for application oriented work as well.

Interestingly enough, behavior-oriented robotics tends to get robots more towards their original roots. Historically, the term "robot" was introduced in 1921 by the Czech writer Karel Capek in his satirical drama "R.U.R." (Rossum's Universal Robots). There, robots where human-like forced labors, which is by the way the literal translation of the Czech word "robota". Of course, being like humans is still way out for robots, but having some more natural properties is already a useful and feasible feature which is subject to behavior-oriented research.

In the rest of this paper, behavior-oriented robotics is presented in some detail and especially its industrial relevance and prospects are discussed. In section 2, the key aspects of behavior-based robotics are presented. Some of them are illustrated with concrete, application-oriented research work. Section 3 presents the VUB ecosystem, a basic research set-up where behavior-oriented robots engage in complex interactions in the search for "food" in form of electrical energy. The example of this set-up is used to motivated and explain some of the more long range issues and implications of this research. In section 4, one example of research with quite some application potential is presented in some detail. The so-called VisionCube is a special hardware devices, developed and implemented with behavior-oriented techniques and views in mind. It is a kind of extremely compact combination of a camera, a computer, and a controller. It can be used as control-hardware for autonomous mobile robots, for surveillance, and in many more areas. Section 5 concludes the paper.

2 Important aspects of behavior-based robotics

Standard robotics relies, pretty much like classic AI, on exact models as well as symbolic and centralistic control schemes. Behavior-based robotics on the other hand tries to achieve control through simultaneous operation of simple parallel processes, the so-called behaviors. So, behaviors stand in contrast to the classic notion of action where a single command activates effectors over a fixed time-period with clearly determined moments in time where the action starts and ends. Therefore, behaviors do not rely on complex models but on close, continuous couplings between sensor values and motor activations.

Sometimes, behavior-oriented AI is also denoted as bottom-up approach to AI. This means that, when following the route of Artificial Life, simple "creatures" and their "needs" are investigated first. Therefore, behavior-oriented AI still deals more with systems which are more related to "non-intelligent" animals like insects than with higher levels of cognition. This is also reflected in the related robotics activities.

After these general descriptions, we now have a look onto more concrete properties of behavior-oriented robots. In doing so, we will especially take application oriented aspects and industrial prospects into account. First, some properties are listed. Then, they are explained a little bit more detailed, each in its own subsection. In the following sections 3 and 4, they are then presented within two concrete examples. In doing so, their relation to each other is discussed and it is shown how they can be actually implemented.

A behavior-oriented robot is usually

- highly autonomous
- mechanical imprecise
- equipped with few computational resource
- improving through learning
- programmed with software re-use
- integrated in an environment

2.1 Autonomy

The word autonomy is derived from the Greek words "auto" (self) and "nomos" (law, rule). So, an autonomous system is a self-governed system. In a loose interpretation, autonomy can be seen as independence of a device from direct and continuous human supervision and maintenance. Often, autonomy for robots is set on a par with being mobile without the need of an umbilical cord; but this is a little bit too simplistic.

Autonomous robots face two major problems. First, they have to be capable to deal with unforeseen situations, i.e., they have to be adaptive. Second, they have to be capable of some resource management, especially in respect to energy.

Obviously, both capabilities can be extremely useful for diverse applications. One important area is space-robotics. As earth-based radio-communication is extremely time consuming, devices like the "Sojourner" have to be as independent as possible [13]. Therefore, the Sojourner got only occasionally a command from a human and drove most of the time autonomously on its mission on Mars.

But also down to earth, there are many areas where humans can not or should not have access and where in addition direct control of robots is impossible. One such area, which has a high commercial application potential, is sewage-systems. Especially in Europe, sewage systems tend to be in bad conditions, most parts of them are not accessible by humans, and their is an increasing pressure based on environmental concerns to enhance the situation. Existing approaches mainly rely on humans and wire-guided systems leading to high costs as well as limited range and flexibility. Therefore, autonomous robots like the prototype described in [9] are of importance in this area.

2.2 Mechanical imprecision

"Classical" robots are based on precise mechanics. This is necessary as these robots rely on exact models, e.g. to describe and compute their kinematics. Behavior-based robots are in contrast more like natural devices. Their control schemes rely more on mechanisms which are roughly speaking rules-of-thumb.

The need of mechanical precision of "classical" robots puts high demands on the parts, the assembling, and the maintenance of the robots. A behavior-oriented robot does not have these needs. Therefore, it can be produced much cheaper and with less weight as well. Often, off-the-shelf or even surplus mechanical and electromechanical components produced for the mass-market will do. In addition, the robot needs few or even no maintenance.

An example is Pemex, a de-mining robot developed at the EPFL in Lausanne. It is based on simple components, like e.g. bicycle wheels, and therefore it is rather cheap. This is very important as within this particular application area, there is a certain likelihood of the robot being destroyed. Therefore, it must be easily replaceable.

Another area where this feature plays an important role is the entertainment market. The SONY pet dog [8] for example consists of simple servos targeted for the toy-market.

2.3 Few computational resources

Partially as a consequence of the mechanical imprecision, behavior-oriented robots cannot rely on precise, complex models. Instead they have to be controlled with simple "rules-of-thumb". As a positive side-effect, their need for computational resources is small. Instead of intensive calculations of inverse kinematics, simple couplings between sensor-values and motor-activations are used. Therefore, less processing power is needed. Instead of detailed maps and/or world-models, simple beacons and general sensors are used to navigate the robot. Therefore, less memory is needed.

But how is it possible to save on the (electro)mechanical and on the computational side? Where is the trade-off?

To some extent the trade-off is simply hidden in the kind of tasks "classic" or behavior-oriented robots are best suited for. If very precise, repeated positioning is needed, "classic" robotics is the way to go. But everywhere else behavior-oriented robots become more and more competitive as they strongly benefit from the developments in respect to sensors, especially in the field of vision. More and more types of sensors are available at constantly dropping prices. Therefore, they can be used as basis for additional behaviors, increasing the robustness and usefulness of the robot. For example camera-chips, which start to be targeted for the toy-market, can be used for computational inexpensive visual servoing instead of kinematic control.

2.4 Improving through learning

As behavior-oriented robotics is related to AI, learning is a scientific issue for this field. But learning features for a behavior-oriented robot are also of interest apart from the quest of intelligence.

Learning, as the capability to change and improve his performance through experiences, can help the robot to cope with "surprises" due to his mechanical impression, unexpected situations in the environment, new tasks, and so on. In addition, learning can free the robot's designer and programmer from some of the "low-level" implementation, especially when it comes to finding "suited" parameter-settings.

It can be reasoned that learning capabilities are a necessary criterion for real autonomy. In the following section 3, we will have a more detailed look into this subject.

2.5 Programmed with software re-use

As mentioned before, behaviors can somehow be compared to rules-of-thumb. They mainly rely more on the type of sensor(s) and motor(s) their based on than on the concrete robot they are controlling. Therefore, it is often very easy to port even low-level code from one robot to another. Parameter settings are usually not critical and work over a rather broad range. A good example are taxis-behaviors where a mobile robot drives towards a beacon. Based on a gradient from two sensors, the robot is turned towards the beacon while moving forward. In most cases, no actual calibration is needed as some "zigzagging" in the movement can be tolerated.

In addition, there is a strong research interest in getting more hierarchical and high-level structures into behavior-oriented programming, see e.g. [12]. In combination with the robustness of low-level functions, it can therefore be expected that in the near future it will be feasible to rely on general capabilities, like e.g. locomotion, as default building-blocks. Only task-related instructions have to be supplemented in a high-level manner.

2.6 Integrated in an environment

Last but not least, behavior-oriented robots are not seen as isolated devices, but as part of an environment. This has several consequences. First, the environmental cues can be or even have to be exploited for stable operation of the robot. For example beacons, as mentioned before, can substitute complex, detailed maps. Second, behavior-oriented robots are, much like animals, not seen as being "alone" in their environment. Instead, interactions between different robots as well as interactions between robots and humans are investigated and taken into account. Roughly speaking, behavior-oriented robotics includes a kind of social component.

This social component has several important practical implications. First, it allows for easy to handle and more accepted Human-Machine-Interfaces. In general, behavior-oriented robots do have a more "natural" appearance (subjectively seen), which is even exploited for entertainment [8]. Second, inter-robot-relations can be handled in a general way and do not rely on explicit programming. Robots can cooperate to achieve a common goal, they can learn through imitation, heterogeneity can be exploited, and so on. In addition, communication plays an important role. As today more and more devices get networking capabilities, this is an excellent opportunity to exploit the "social skills" of the robots for online scheduling and flexible task management.

3 A concrete set-up for basic research: the VUB ecosystem

The VUB ecosystem is a set-up where all the issues described above are investigated in an integrated manner, i.e., they are not tackled in an strictly reductionistic way, but in respect and relation to each other. In the ecosystem, robots operate autonomously over extended periods of time, while interacting with each other and doing some kind of working tasks. The main force which combines the single robots into the one concept of the ecosystem is the general need for energy. Without energy, the robots cannot keep operational.

The basic ecosystem [16, 11] (figure 1) is set up as follows. Simple mobile robots, the "moles"[1], are constantly roaming around in an arena surrounded by small walls. The arena also contains a charging-station where the robots can autonomously re-load their batteries and the so-called competitors. The

[1] This and following names for robot-types should not be taken too literal. They are used for convenience only and are not meant to imply direct relations to their natural counterparts.

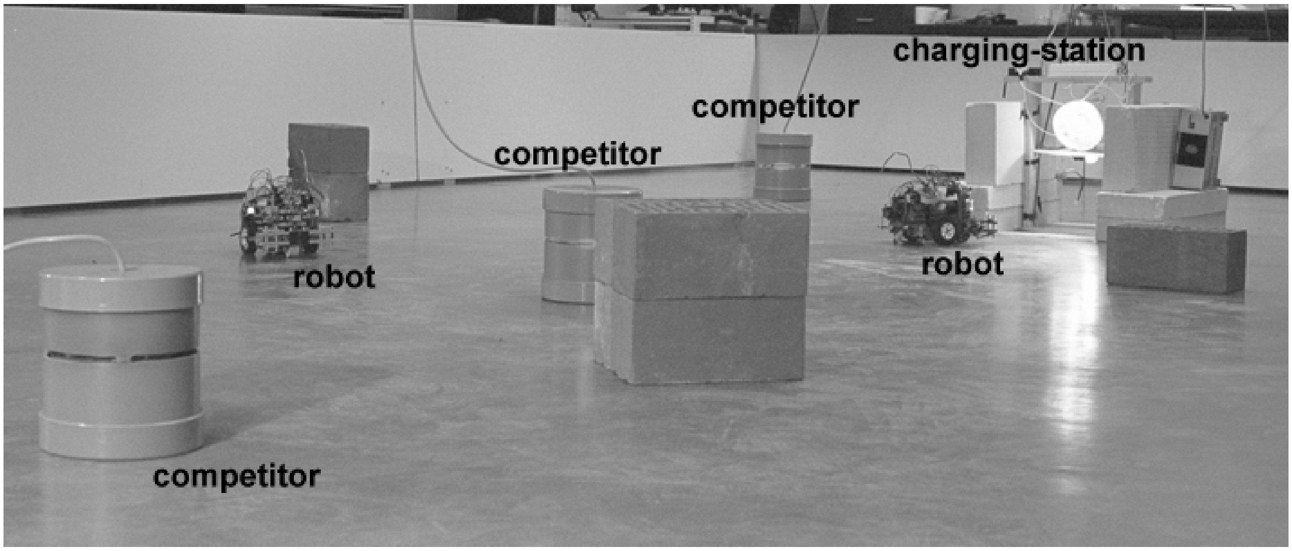

Figure 1: A part of the basic ecosystem with charging station, two robot "moles", three competitors, and several bricks as obstacles.

competitors are small boxes housing lamps emitting a modulated light. These lamps are connected to the same global energy-source as the charging-station. If the robots "knock" several times against a competitor, the lamps inside the competitor dim, and the robot has an additional amount of energy at disposal from the charging-station. After a while, the competitor recovers, i.e., the lamps inside return to their default brightness. The competitors establish a kind of working task for the robots which is "paid" with energy.

The robots are highly autonomous. They are also very mechanically imprecise; most of them are actually build using toy-construction-sets like e.g. LEGO. All computation is done on-board using a simple micro-controller based board (more about the control-hardware in the next section). The behaviors with which they are controlled are fairly simple. The robots are capable of touch-based obstacle-avoidance through bumpers based on switches. When a touch is sensed, the robot backs up a bit and turns slightly away. Furthermore, active IR sensors are used for touch-less obstacle-avoidance. The robot emits modulated IR and depending on the amount and direction of reflected IR received, some positive or negative values are added on each drive-motor, resulting in a slight turn. In addition, the robots do phototaxis towards the charging-station which is equipped with a bright white light and the competitors which emit a modulated light.

All behavior run in parallel and their effect on the motors is simply added up. There is no global control or arbitration mechanism. This leads to so-called emergent phenomena, which are kind of side-effects from the superposition of different behaviors and their interactions with the robots environment. For example the "fighting" of competitors is not explicitly programmed into the robots. Instead, it emerges out of the phototaxis towards the modulated light and the touch-based obstacle-avoidance. Due to the phototaxis, the robots are kind of attracted by the competitors. Consequently, they drive towards them, they bump into them, the touch-based obstacle-avoidance causes them to retract, they are attracted again, and so on. As a result, a robot bumps several times into a competitor until the competitor dims and the attraction is gone. Note, that the number of bumps is not explicitly programmed and that there is an automatic adaptation to the "strength" of the competitors.

In some experiments the robots learn the basic behaviors [2]. The learning process is guided by rather general mechanisms as the crucial feedback is based on energy consumption. I doing so, some longterm monitoring is used which can, roughly speaking, be compared to "hunger" and there is some shortterm monitoring which can be compared to "pain". An important feature of this research is that this learning process can create completely new behaviors as well as finetune existing ones for better performance.

Other ongoing research in the ecosystem includes the introduction of new robot "species" and work on cooperation [3]. The so-called "mouse" (figure 2) is a kind of enhancement of the "moles" by supplying vision-capabilities [1]. Vision tends to play a more and more important role within robotics in general as it can be used for kind of universal sensors and there is a fast developing mass-market for related hardware.

The "mouse" can perceive the charging-station and competitors more accurately and from longer distances. Though this is an advantage, one should not forget that the camera and the related computational

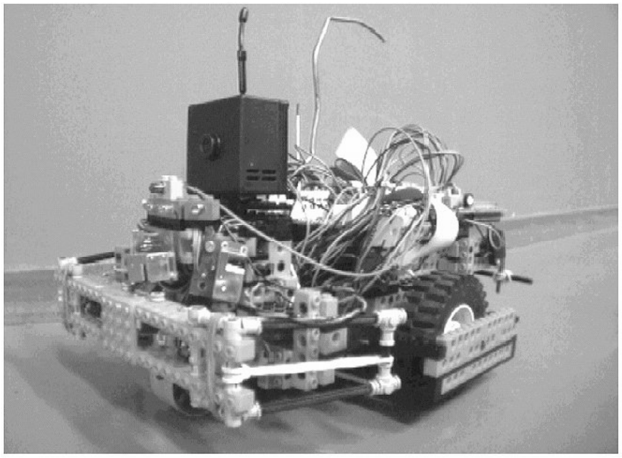

Figure 2: The robot "mouse" with its camera at the front.

hardware has to be powered with energy. So, there is a direct, measurable trade-off between better perception helping to find "food" in form of electrical energy, and the energy needed to power these capabilities.

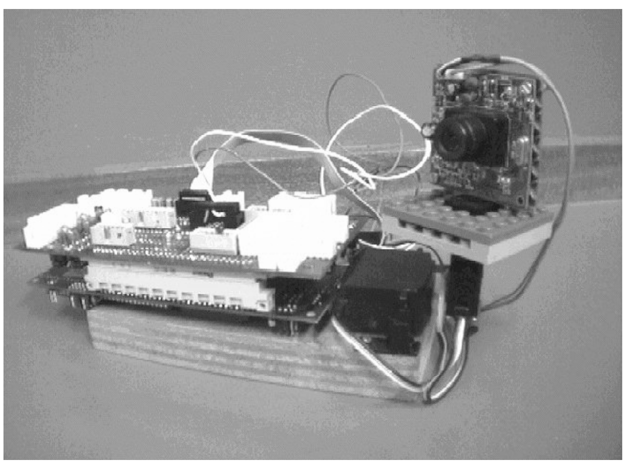

Figure 3: The "head", a robot forced to cooperate.

Another new inhabitant of the ecosystem is the so-called "head" (figure 3). It consists of a camera on a pan-tilt-unit and has quite some vision capabilities. As it is not mobile, the "head" cannot access the charging-station and it is forced to cooperate. The "head" can track mobile robots and it can perceive so-called pitfalls which are kind of inverse charging station where the batteries of the mobile robots are partially dis-charged. When a mobile robot approaches a pitfall, which he cannot distinguish from the charging station, the "head" can warn the mobile robot. The mobile robot in exchange can share the benefit of the saved energy with the head.

4 From basic research towards applications: the VisionCube

So far in this paper, mainly the consequences of behavior-based robotics for mechanical and electromechanical components, programming, and environment are discussed. Here, we have a short look on the implications for the control hardware.

In the VUB AI-lab, we have quite some tradition of developing special hardware for robot control. Based on previous work [17, 18], the RoboCube [4] and the VisionCube [5] are the most recent approaches. They both reflect the main ideas of behavior-oriented control. They are small and compact with low power-consumption facilitating to be used in mobile and stand-alone devices. They both are layed out to deal with various sensors and motors as well as radio-communication. The VisionCube, on which we focus here, is in addition equipped with high-resolution color vision.

The main idea of VisionCube is to have a compact, i.e., slightly larger than a cigarette-pack, device which combines the basic features of a camera, a computer, and a controller. This means the VisionCube has downloadable functionality to read an image from a C-MOS image chip, to process it onboard, to trigger and/or control external devices, and to transmit data if necessary. It is intended as inexpensive and extremely compact alternative to the camera-framegrabber-PC approach in applications with low to medium processing needs. In addition to "normal" robotic applications, VisionCube can for example be used for surveillance. It can be programmed to trigger an alarm and a recording-function based on a change in difference images, which indicates an intrusion in the observed area.

VisionCube's hardware and its Kernel are especially layed out to support behaviors. Different visual or other software modules are executed round robin in simulated parallel at a speed suited for real time control (40 Hertz cycle-frequency).

5 Conclusion

The paper gives a short introduction to behavior-based robotics. It relates this field to its origins in ALife and behavior-oriented AI, and it motivates and explains the main features. Namely, autonomy, mechanical imprecision, low computational needs, improvement through learning, programming with software re-use, and integration in an environment are presented and explained as interesting features of behavior-based robots.

In doing so, examples from basic as well as application oriented research are used to illustrate these features and to give references for additional reading. Two examples are discussed in a little bit more detail.

The VUB ecosystem is presented as a basic research set-up, where all of these features are present and investigated in relation to each other. The ecosystem features different types of robots, roaming around in the search for energy and engaging in kind of working tasks. The second more detailed example is the VisionCube, a special control hardware inspired by behavior-oriented concepts. The VisionCube is an extremely compact device which combines a camera, a computer, and a controller at the size of a cigarette-pack.

5.1 Acknowledgments

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