The Definition of “Measurement” in the Light of Robotics

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Abstract

Robots becoming more versatile and intelligent, and their tasks being no longer limited to repetitive work in factories under the supervision of experts, the ways how they are acquiring information from the environment are necessarily changing. The intelligent robots of the future will base the control of their actions largely on something other than measurements in the traditional meaning of the word. Much like living organisms, they will instead rely mostly on perception and on “measurements” in a generalized sense that make no reference to standard units. This evolution in Robotics makes us rethink our understanding of the essence of the concept of “measurement.” It may eventually lead to a new generally accepted definition of the term “measurement” that will include not only perception, but also measurements that make no reference to standard units.

In support of these statements three robots that do essentially without traditional measurements will be introduced: a mobile robot with a calibration-free navigation system, a calibration-free object manipulator, and a humanoid personal robot that integrates a large number of skills and behaviors in one system entirely based on the concepts of perception and situation. Due to their independence of calibrations and numerical models they have shown in real-world experiments a remarkable degree of dependability and robustness against non-modeled changes of their own characteristics and modifications of their environment.

Keywords: Measurement Science, Robotics, perception, calibration-free systems

1 Introduction

In the sequel an impact of Robotics on Measurement Science will be discussed. It will be shown that Robotics is leading us to a new understanding of the foundations of Measurement Science and to a new meaning of the very concept of “measurement.”

Various definitions of the term “measurement” are offered in the literature:

- **DIN 1319:** The experimental procedure by which a specific value of a physical quantity is determined as a multiple of a unit or reference value.
- **IEEE 100:** The determination of the magnitude or amount of a quantity by comparison (direct or indirect) with the prototype standards of the system of units employed.
- **Internet:** Numerous similar definitions can be found.
- **Webster’s Dictionary** [Babcock 1976]: The act or process of measuring something. “To measure” is then, in turn, defined as
  (1) to ascertain the quantity, mass, extent, or degree of in terms of a standard unit or fixed amount, usually by means of an instrument or container marked off in the units;
  (2) to judge or estimate the extent, strength, worth, or character of (as a quality, action, or person); to appraise in comparison with something taken as a criterion.
- **[Kariya 1999]:** The word “measurement” covers a broad spectrum of connotations, including sensing, acquisition of signals carrying information, acquisition of knowledge by signal analysis, and utilization of knowledge.

Of these examples, the “official” definitions by DIN and IEEE, the ones to be found in the Internet, and also the first one given by Webster, clearly represent the traditional view of Measurement Science. In contrast to that traditional view, Webster’s second definition, and especially Kariya’s definition, reflect a much broader view. While Webster’s definition (published in 1976, when robots did not yet play a major role) refers to judgements made by humans in a nontechnical context, [Kariya 1999] is clearly concerned with “measurement” in a technical sense. Both definitions imply that measurements may also be performed without reference to standard units, and that even the processes, normally called perception, by which living organisms – and intelligent robots – continuously acquire information from their environments may be considered as measurements in a generalized sense.

Robots in research laboratories, and to some extent in commercial applications, are becoming more and more intelligent and rely increasingly on perception, rather than on measurements in the traditional sense, for forming an internal image of their environment and the situation they are in. It may be predicted that the growing academical and commercial importance of intelligent robots will eventually lead even the mainstream of Measurement Science to agree with the following statements:

- Perception should be considered a form of measurement, and Measurement Science should be understood to comprise the science of perception.
- Measurements do not necessarily have to refer to standard units and do not always require calibrations.

2 Trends in Robotics: Towards Intelligent Personal Robots

When robots are used in factories, a lack of robustness with respect to changes of the characteristics of the robot or its environment can to some extent be tolerated because the environment can be controlled, maintenance personnel is available, and the tasks are repetitive. Advances in technology are, however, beginning to enable robots to automate many tasks in non-manufacturing industries, such as agriculture, construction, health care, retailing and other services. These so-called “field and service robots” aim at the fast-growing service sector and promise to be key products for the next decades. They must operate in less controlled environments and perform a wider variety of tasks than industrial robots. Consequently, they also need a wider variety of sensory information on their environment.

From a technical point of view, service robots are intermediate steps towards a much higher goal: “personal robots”. They will in a few decades be as indispensable and ubiquitous as personal computers are today. They will operate in such varying and unstructured environments as, e.g., homes, shops, parks and streets without needing maintenance or programming. They will have to cooperate and coexist with humans who are not trained to cooperate with robots, and who are not necessarily interested in them.

It will be a long way of research and development before personal robots with their intelligent communication abilities, learning capabilities, and nearly perfect safety and reliability can be realized. Nevertheless, it may be predicted that powerful sensor systems will be necessary to enable them to perceive their environments, to understand complex situations and to behave intelligently. Personal robots and other intelligent robots will interact with the world in a similar way as humans or animals do. The point is that, in contrast to traditional industrial robots, neither humans in their daily lives, nor animals, carry out any measurements, at least not in the traditional sense of the word (i.e., determining the magnitude of a quantity numerically). A few examples may serve to support this statement:

- Before sitting down on a chair we do not measure the height of the chair and the lengths of our legs; instead, we make a qualitative judgement whether the chair seems suitable for sitting on it, and maybe, whether it requires a specially adapted sitting-down behavior because it is either relatively low or relatively high.
- When washing our hands, we adjust the temperature and the flow of the water so that they are in a comfortable range, but we are neither concerned with the numerical values of flow and temperature in SI units, nor with the quantitative details of the characteristics of the faucets used for controlling them.
- Before driving a car we do not measure the transfer coefficient between the rotation of the steering wheel and the resulting steering angle of the front wheels; rather, when we start driving, we immediately develop a “feeling” for the influence of the steering wheel on the trajectory of the car.

What we humans do in these and many other situations, is called “perception.” We, and all animals, interact with the world very reliably and robustly on the basis of such qualitative perceptions. If robots, too, base their interactions with the world on perception, rather than on the measurement of individual environmental parameters they have the potential of achieving a similar degree of robustness and reliability as organisms. This will be pointed out in the sequel.

The concept of perception originated in Psychology. Now it is gaining importance in Robotics where, in the interest of flexibility and robustness, measurements in the traditional sense are partly being replaced by machine perception. This trend in Robotics has a strong impact on our understanding of the fundamentals of Measurement Science, making us even rethink the definition of the term “measurement.”

3 Intelligent Robots

Intensive research is directed toward the goal of realizing robots that will be as flexible, adaptable, and robust in their interaction with the world as living organisms. Although we are still far away from this goal, we are convinced that three key concepts will be crucial for the realization of such robots: behavior, situation assessment, and perception.

Behavior is the key to a powerful system architecture that enables a robot to interact with its environment in a sensible way, even if no certain and complete knowledge of the environment and the characteristics of the robot is available and, thus, the traditional approaches based on quantitative path planning and motion control are not feasible. A behavior-based robot solves this problem by having a repertoire of built-in behavior primitives and combining them dynamically as building blocks for constructing complex actions.

A key problem for any behavior-based robot is the ongoing selection of behaviors to be executed in each moment. Continuous *situation assessment* in real time is a strong basis for selecting dynamically in each moment the most appropriate behavior to be executed by a robot in its interactions with the ever-changing and largely unpredictable world.

Generally the term *“situation”* describes, among others, a “state,” a “combination of circumstances at a given moment” or “the sum of total internal and external stimuli that act upon an organism within a given time interval” [Babcock 1976]. In Robotics, we define the term “situation” in a more operational way as the set of all decisive factors that should ideally be considered by a robot in selecting its correct behavior at a given moment. These decisive factors include:

- Perceivable objects in the environment of the robot and their suspected or recognized states;
- The state of the robot (state of motion, state of actuators and sensors, presently executed behaviors, focus of attention of the perceptual system, . . .);
- The goals of the robot, i.e., permanent goals (survival, obstacle avoidance) and transient goals emerging from the actual mission description (the destination of the current trip, the corridors to be used, . . .);
- The static characteristics of the environment, even if they cannot be perceived by the robot’s sensors at the given moment;
- The repertoire of available behaviors, and knowledge of the robot’s abilities to change the present situation in a desired way by executing appropriate behaviors.

To react adequately to a given situation by selecting an appropriate behavior a robot must be aware of the situation, and it must predict the consequences of its decisions and actions on the situation. So, the ability to perceive and assess situations is a prerequisite for the ability to react to conditions and events in the environment. This, in turn, is a necessary part of the practical intelligence that service and personal robots will need to have.

Perception of objects in the robot’s environment, of their characteristics and of the relationships between them – rather than measurements in the traditional sense – is a suitable basis for situation assessment.

According to Webster's Dictionary [Babcock 1976] “perception” is defined as: reaction to sensory stimuli; direct or intuitive recognition; the integration of sensory impressions of events in the external world; awareness of the elements of the environment; a result of perceiving. “To perceive” means, according to the same source: to become aware of something through the senses; to become conscious of something; to create a mental image; to recognize or identify something, especially as a basis for, or as recognized by, action.

The similarity in ideas of this definition and the modern definition for “measurement” as given by [Kariya 1999] is remarkable. It seems unlikely that a definition, such as Kariya’s, would have been proposed without the influence of robotics.

Typical questions for a robot to be answered by perception are:

- Which objects are present?
- What is the relationship between objects?
- Is it necessary to do something? What?

For a situation-oriented behavior-based robot such information is the equivalent of the measured data used by traditional machines based on control theory. This makes it reasonable to consider perception, at least when performed by machines, to be a kind of measurement, and this is exactly what Kariya’s definition implies.

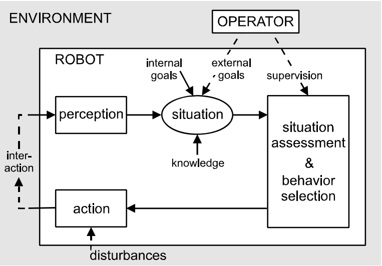

Figure 1

The roles of “perception” and “situation” as key concepts in the perception-action loop of a situation-oriented behavior-based robot.

Figure 1 illustrates these concepts. It shows, in a general form, the architecture of a situation-oriented behavior-based robot. The actions of the robot change the state of the environment, and some of these changes are, in turn, perceived by the robot. What the robot is perceiving, and what it knows, in combination with its goals, constitutes the actual situation from the robot’s point of view. After assessing the situation, an appropriate behavior is selected and executed, thus closing the loop. The role of a human operator is to define external goals for the robot via a man-machine interface and to control behavior selection directly in exceptional situations, e.g., during supervised learning.

Figure 2

One of the mobile robots used for developing navigation systems

Situation-oriented robot control has proven to be much more robust and flexible under real-world conditions than traditional model-based control, especially in less constrained environments not specifically prepared for the operation of robots. One reason is that the quantities necessary for updating the numerical models that are part of a traditional robot controller are often difficult to measure, e.g., the distance, mass and velocity of some external object posing a collision danger. Also, certain important decisions cannot be made from measurements alone; for instance, the hypothetical decision whether in a particular situation a collision of a mobile robot with a parked car should be caused to avoid a collision with a pedestrian.

Perception, rather than measurement in the traditional sense, is thus a prerequisite for, and a complement of, situation assessment and for intelligent, robust and flexible robot behavior.

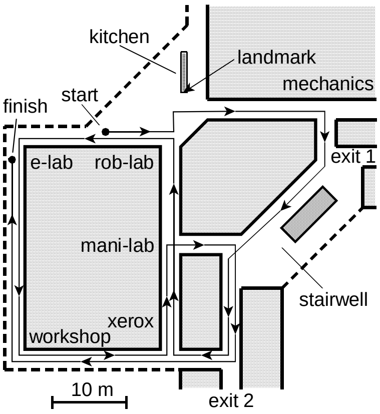

Figure 3

Ground plan of the laboratory used for navigation experiments. Dotted lines: window walls. Arrow lines show the course chosen for a specific experiment.

4 A Practical Example: Indoor-Navigation

4.1 From Measurements to Perception

ATHENE and *ATHENE II* (Figure 2) are mobile robots built for studying autonomous navigation in factory and laboratory buildings. Their main sensors are a vision system and shaft encoders (odometers) attached to two of the wheels of both robots. The signals generated by the shaft encoders are used by a dead reckoning navigator to compute continuously the speed, orientation and position of the robot. Most experiments with these robots were performed in a laboratory building of our university (Figure 3).

4.2 Designing the Navigation System

In our first attempt at robot navigation we tried to provide the robot with an accurate map and to have it navigate by dead reckoning on the basis of traditional measurements and a global coordinate system. The robot also carried a vision system, but its role was limited to updating the dead reckoning navigator occasionally by observing certain objects, such as pillars, used as landmarks. This approach failed, mainly because during sharp turns around corners the errors of the dead reckoning system built up so fast that the robot bumped into a wall before a suitable landmark for correcting the errors could be found.

Our second approach was behavior-based and somewhat perception-oriented. It used a topological map and no global coordinate system, and it was successful in allowing the robot to navigate in the corridors and factory-like environments . Now the vision system was the main sensor, and odometry was only used during brief intervals when no useful visual information was available, and as part of a specific method of motion stereo that does not require a camera calibration [Huber, Graefe 1991]. A disadvantage of the approach was, however, that artificial landmarks were needed at each intersection for triggering the robot’s corner-turning behavior.

The third approach, based on situation assessment and largely on perception, proved to be much more robust and flexible. At the core of this approach is the idea that the robot should use its sensors to *perceive* its environment and maintain an internal image of its dynamically changing *situation* [Bischoff et al. 1996].

The behavior that is most suitable for the situation in that moment is then selected and executed. Due to this approach, the navigation task now appeared simple: No artificial landmarks were needed, the map was easy to generate, and a few behaviors and classes of situations were sufficient. This simplicity, and the demonstrated reliability and robustness of the navigation system prove the power of the concept.

A comparison among the three different approaches shows clearly that the robustness of the robot has increased in proportion to the degree to which measurements (in the traditional sense), quantitative models and coordinate-based control were substituted by perception and situation-oriented behavior-based control. Traditionally, computer-controlled machines have used measurements to obtain the necessary information from the outside world. Now experience with advanced robots has shown that such complex systems can greatly benefit from substituting perception for measurements (in the traditional sense of the word). The thus demonstrated practical usefulness of perception for complex technical systems is a good reason for considering perception, at least when done by machines, as included in the concept of "measurement."

5 Measurements without Reference to Standard Units

5.1 Standard Units and Calibration

Many researchers, including, e.g., [Hollinghurst, Cipolla 1994], [Hosoda, Asada 1994] [Jägersand, Nelson 1995] and [Yoshimi, Allen 1994], to mention only a few of the pioneers, have addressed the problem of controlling robots without having to calibrate their sensors. The goal of that work is the calibration-free robot, or at least a robot needing only an approximate, easy-to-perform calibration. This is another respect, besides the inclusion of machine perception, where Robotics is leading us to a different understanding of the concept of "measurement." Kariya's definition of the term is an example. It does not make any reference to standard units and, thus, implicitly admits the possibility of measurements without standard units.

In the sequel it will be shown that measurements without calibrations may actually be realized, and how robots may benefit from doing without calibrations. The ideas of calibration-free measurement and calibration-free robots may be illustrated by the examples sketched in the following sctions: a method using an uncalibrated video camera for measuring distances, a completely uncalibrated articulated arm robot for object manipulation, and a navigation system for mobile robots that, due to their optics or kinematics, would be difficult to calibrate.

5.2 Distance Measurement by Motion Stereo with an Uncalibrated Video Camera

A mobile robot must consider in its maneuvers the presence of other objects, including objects in front of it, such as obstacles to avoid or workstations to approach. To avoid an obstacle, or to dock gently at a workstation, the robot must know its distance from the object or the time remaining (on the assumption of constant velocity) until contact with the object. The robot will not normally communicate the results of its time or distance measurements to the outside world; it will use them only internally for controlling its own motions. Therefore, the corresponding measurements need not refer to standard units; robot-internal arbitrary units whose relationships to SI units are unknown are sufficient.

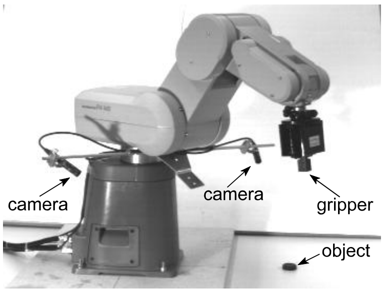

Figure 4

The manipulator arm used for grasping experiments. Two cameras attached to the arm are the only sensors used. The entire system is completely uncalibrated.

A motion stereo method for such applications was introduced by [Graefe 1990]. It is based on the fact that, when a forward-looking camera approaches an object, the image of the object expands. While the rate of expansion is proportional to the approach speed, it is a nonlinear function of the distance between the camera and the object. Measuring the rate of expansion in the image yields the distance and the time-to-contact (for details cf. [Graefe 1990]). The method was implemented and tested on the mobile robot *ATHENE* [Huber, Graefe 1991] and on a road vehicle [Huber, Graefe 1993]. In both cases the precision of the measured distance was better than 1%, although an uncalibrated camera, whose optical parameters were completely unknown, was used. Psychological evidence suggests, by the way, that human car drivers subconsciously use a similar method for estimating distances when they approach obstacles [Lee 1976].

5.3 Calibration-Free Object Manipulation

The idea of motion control without calibration is not limited to mobile robots. Object manipulation by vision-guided robot arms is another application. According to the concept of object and behavior-oriented stereo vision [Graefe 1995] objects may be manipulated by a completely uncalibrated manipulator arm controlled by a vision system using a pair of completely uncalibrated cameras. The key point of the concept is that the robot learns to correlate arbitrary motion commands that it sends to its motors on one hand, with the resulting changes in the images produced by the two cameras on the other hand. On this basis it computes a sequence of control commands that bring *the images* closer and closer to their desired final state. When finally both images suggest that the world seems to be in its desired state, the world really is in that state, characterized, for instance, by the gripper touching an object to be grasped. In other words, for the robot the goal of image interpretation is not a quantitative model of the 3-D world, but numerical parameters for control commands that will bring about a desired situation in the images and, thus, in the world.

No measurements in the traditional sense, no world coordinates and no calibrations are involved. Instead, a direct transition from image coordinates in arbitrary camera-centered coordinate systems to motion control commands is realized. The control commands may be computed by means of a specific type of Jacobian matrix developed for this application, the Sensor Control Jacobian [Graefe, Maryniak 1998]. It relates only robot-internal quantities, like image coordinates and motor control words, to each other. No calibration constants relating the internal quantities to any external ones are used.

Grasping experiments performed with an uncalibrated manipulator arm (Figure 4) have shown that this approach performs well and robustly in the real world [Vollmann, Nguyen 1996]. A robot based on this approach has been shown to tolerate, for instance, large arbitrary mis-adjustments of the cameras without any degradation of its performance. This robustness is in sharp contrast to the dependence on a careful calibration that is normally characteristic for stereo vision systems.

5.4 Calibration-Free Navigation

Calibration-free approaches may also be used to realize navigation systems for mobile robots. A strikingly simple implementation of that concept was presented by [Graefe, Bischoff 2004]. It enables a mobile robot to follow, e.g., a wall of a corridor in a building, or a lane marker on a road by using its vision system, even if no numerical model of the camera, the kinematics of the robot or anything else is available. On the robot *ATHENE II* it was tested successfully, even when the normal lens of the camera was replaced by a strongly distorting lens that combines a high resolution in the center of the image with a low resolution in its outer parts and consequently a wide field of view. On the humanoid robot *HERMES* (Figure 5) it worked dependently despite the robot's non-modeled omnidirectional undercarriage and the varying and practically unknown viewing directions of its cameras. It may be concluded that robot navigation systems of remarkable robustness and dependability may be realized that do not require any calibration and use no measurements in the traditional sense.

5.5 Discussion of Calibration-Free Approaches

In summarizing these results it may be stated that doing without calibrations in the design of robots and their sensing systems has a great potential for gaining robustness and flexibility. Moreover, considering the high costs of calibrations and maintenance of robots, it also has significant economic advantages. As in the case of perception, the demonstrated success of calibration-free approaches in Robotics will cause the study of measurements without calibrations and without standard units to become an integral part of Measurement Science.

6 A Humanoid Robot

HERMES, a humanoid robot with 22 degrees of freedom and an omnidirectional undercarriage (Figure 5) [Bischoff, Graefe 2004], is a fairly complex multi-functional machine. It combines all the discussed concepts (and more) in one system. Due to its calibration-free navigation and manipulation systems it can navigate in known and unknown environments, and it can manipulate a variety of objects in a variety of environments without having quantitative models of either one of them and without performing any measurements in the traditional sense. It has demonstrated its robustness and dependability in a long-term experiment when it performed in a museum for half a year for several hours a day. It may, thus, serve as a proof that replacing traditional measurements by calibration-free sensing and perception is, indeed, a useful approach to the construction of even rather complex systems.

Figure 5
Versatile personal robot assistant *HERMES*; size: 1.85 m x 0.7 m x 0.7 m; mass: 250 kg.

7 Summary and Conclusions

Two related developments in modern Robotics have been discussed: qualitative perception and calibration-free measurements. They have not only a great potential for contributing to the much needed robustness and flexibility of future robots, but also a significant impact on Measurement Science.

In contrast to the traditional control approach implemented in most of today's industrial robots and emphasizing numerical models and traditional measurements, the control of future intelligent robots will be based on perception, situation assessment and behavior. Control strategies based on these concepts have been realized on several research robots and have proved their utility in real-world experiments. Moreover, robots designed according to the new approach need very few calibrations, if any, which greatly simplifies their initial deployment and later maintenance in practical applications.

Both of these developments in Robotics are having a significant impact on Measurement Science. Before the advent of robots the concepts of "perception" and of "measurement" were unrelated to each other. One belonged to Psychology, and the other one to Physics and Engineering. Also, measurement without calibration would have been considered a contradiction in itself according to the traditional definition of the term "measurement." Now Robotics, undoubtedly an engineering science, is adopting, for good reasons, the concepts of perception and even of measurements without calibration. The importance and success of these developments in Robotics are leading us to reconsider the standard definition of "measurement" and generally adopt a new one, similar to the one proposed by Kariya..

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