

# The Impact of Robotics on Measurement Science and Technology

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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. Much like living organisms, the intelligent robots of the future will rely more on qualitative perception and on “measurements” in a generalized sense that make no reference to standard units for controlling their actions, than on measurements in the traditional meaning of the word. This evolution in Robotics makes us rethink our understanding of the essence of the concept of “measurement.” It may eventually lead to a new definition of the term “measurement” that will include perception, and also measurements that make no reference to standard units.

**Keywords:** Measurement Science, Robotics, perception

## 1. Introduction

Measurement Science and Technology on the one hand and Robotics on the other hand, have had an impact on each other in many respects. For instance, robots are used in today’s factories to help produce and calibrate sophisticated measuring devices; on the other hand, robots often depend on similarly sophisticated measuring devices to perform their own tasks. Moreover, in some cases the development of sensors has been motivated by the needs of robots. Examples are laser and sonar range finders that help robots avoid collisions, and also special sensors for force and torque vectors and imaging sensors for forces and force distributions intended to give them a haptic sense.

In the sequel, however, a different aspect of the impact of Robotics on Measurement Science will be emphasized and 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” can be found 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.
- ▶ **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, and also the first one given by Webster, clearly represent the traditional view of Measurement Science and Technology. 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.

It may be predicted that the growing academical and commercial importance of robots that rely on perception, rather than on measurements in the traditional sense, for forming an internal image of their environment, 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 comprise the science of perception.
- ▶ Measurements do not necessarily have to refer to standard units and do not always require calibrations.

This impact of Robotics on Measurement Science is explained in detail in chapters 3 to 5, but first the present state of robotics and the direction of its development in the foreseeable future will be briefly discussed (chapter 2). Chapter 3 introduces some characteristics of the intelligent robots of the future and explains why they will lead us to include perception in our definition of the term “measurement.” Chapter 4 then illustrates the practical importance of machine perception by reporting results of real-world experiments with vision-based mobile robots showing that substituting traditional measurements by perception has, indeed, led to a more robust and flexible robot control. Calibration-free robots and measurements without reference to standard units are another field where Robotics is having an impact on Measurement Science; this is discussed in chapter 5. Finally, chapter 6 summarizes the main points and draws conclusions.

## 2. Trends in Robotics: From Industrial Robots to Intelligent Robots

Today's robots are mostly industrial robots. Such robots are of a great economic and technological importance. By 1996 approximately 860,000 robots had been installed worldwide. At that time 680,000 of them were still being used, for the most part in automobile and metal manufacturing [IFR 1997]. Typical applications include welding cars, spraying paint on appliances, assembling printed circuit boards, loading and unloading machines, and placing cartons on pallets. Experts estimate that by the year 2000 about 950.000 industrial robots will be employed worldwide.

Although industrial robots contribute very much to the prosperity of the industrialized countries, they do not have much impact on the fundamental concepts of Measurement Science and Technology. These robots rely heavily on measurements in the traditional sense. Having evolved from traditional machines equipped with automatic control, they typically depend on accurate numerical models of themselves and of the environment for planning and executing their actions. They must keep these models updated by a continuous stream of measurements. The success of the industrial robots populating today's factories shows this to be a sound concept – provided, the robots and their environment conform exactly to the internal numerical models. However, the robot, or an entire manufacturing system, usually comes to a halt when some unexpected or non-modeled condition occurs. An excessive change in temperature, brightness or other environmental characteristics, or an unexpected obstacle blocking the preplanned track of a mobile robot, could be sufficient for triggering such an event. It became obvious – sometimes in a painful way – that guaranteeing a sufficiently close match between the robots' internal models and the real world with all its uncertainty can be very cumbersome and expensive. At best it means frequent maintenance and adjustment of all equipment involved and extensive supervision and control of the environment.

When robots are used in factories the above shortcomings can 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 a key product 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 toward a much higher goal: “personal robots” that will be in a few decades as indispensable and ubiquitous as personal computers are today. Personal robots must operate in such varying and unstructured environments as, e.g., homes, shops, parks and streets without needing maintenance or programming. They must 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 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 sharp contrast to traditional 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 concerned neither with the numerical values of flow and temperature in SI units, nor with the quantitative details of the characteristics of the faucet.
- ▶ 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 ideas 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 and motion planning 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 “situa-

tion” 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 are

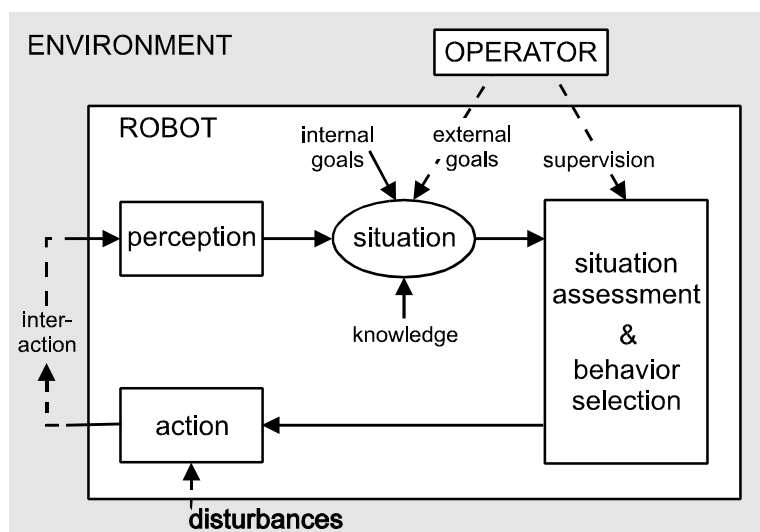
- ▶ perceivable objects in the environment of the robot and their suspected or recognized states;
- ▶ the state of the robot (the state of motion, the presently executed behavior, . . . );
- ▶ the goals of the robot, i.e., permanent goals (survival, obstacle avoidance) and transient goals emerging from 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” 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.



**Figure 1**

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

Typical questions 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 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 via a man-machine interface and to control behavior selection directly in exceptional situations, e.g., during supervised learning.

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.

## 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

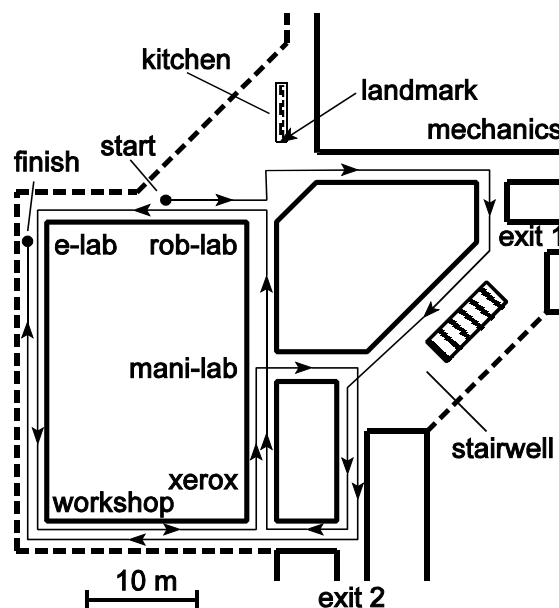


**Figure 2** The mobile robot *ATHENE II*

(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 the speed, orientation and position of the robot. Most experiments with these robots were performed in a laboratory building of our university (Figure 3).

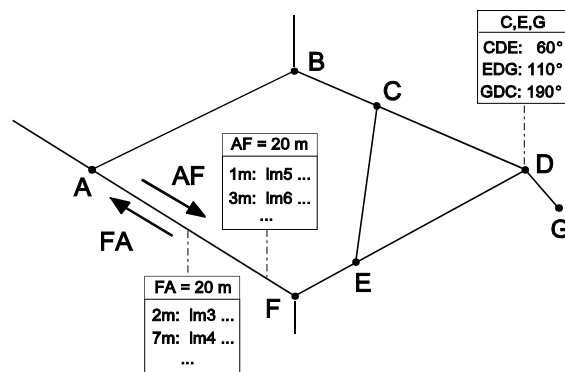
Our first attempt to realize autonomous navigation was entirely based on accurate models of the robot and the building, and it relied largely on traditional measurements. A global coordinate system was defined and, based on it, an accurate map of the relevant section of the building was produced. The coordinates of all corridors, walls, doors etc. were measured and encoded in the map. The idea was to define the desired trajectory of the robot in coordinates, too, and to use the dead reckoning navigator to let the robot follow the predetermined trajectory, much like the captain of a ship would navigate on the high seas. A dead reckoning navigator, as any integrating device, builds up errors of ever-increasing magnitude. To correct these errors the vision system was to be used for recognizing "landmarks," such as characteristic pillars, whose coordinates were also recorded in the map. Occasionally the robot would then determine its location relative to some of these landmarks, e.g., by triangulation, and reset the accumulated error of the dead reckoning navigator.

This approach, based on an accurate map, on coordinates and on traditional measurements failed completely. The main reasons were (1) that generating an error-free map proved to be virtually impossible, in spite of spending considerable time and effort, and (2) that the measurement errors of the dead reckoning navigator could not be controlled. For instance, when the robot was supposed to execute a 90-degree turn, a random error of about 5 degrees often occurred. This caused the robot to hit a wall before the vision system had recognized landmarks that would have made an error correction possible. Although the cause of the measurement error is not quite clear, we assume that, due to the considerable width of each wheel, the effective lateral distance between the wheels fluctuated in a largely random way whenever the robot executed a sharp turn.



**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.



**Figure 4**

Section of a fictitious attributed topological map. Attribute lists (examples shown here in an abbreviated form) are attached to each node and each directed path.

In our second approach we implemented a behavior-based concept, where one elementary behavior was vision-guided wall-following and another one was turning corners by predetermined angles. As in the first approach, the corner turning was based exclusively on information from the wheel encoders. However, by the new approach the vision-guided wall-following behavior was now activated at the end of each corner-turning. It made the robot move in a direction parallel to the walls of the new corridor, regardless of any error of the corner-turning. No geometrically accurate map was needed; instead of it we used an attributed topological map (Figure 4). Such a map is similar to the subway maps issued by some cities, showing only a rough sketch of the geometry of the subway network, but the correct topology of the network, the correct order of stations and, as attributes, the names or numbers of the subway lines and sometimes the approximate travel times between two stations. Despite their lack of geometric accuracy these maps are perfectly suited for navigating a subway system. In fact, a subway traveler would not gain anything from a geometrically accurate map of the subway network.

The behavior-based approach, in combination with the attributed topological map, proved successful. When the robot follows a corridor, it cares neither about the exact length of the corridor that may be represented incorrectly in the map, nor about the accuracy of its odometers. While it approaches the end of the corridor, the robot recognizes visually an artificial landmark placed there and measures continuously its distance from the landmark by a motion stereo method. When the distance has dropped to a specific predetermined value, the robot knows that it has reached the corner and starts its corner-turning behavior. After completing the turn, the wall-following behavior is started again, and it corrects any errors that may have occurred during the corner-turning.

Although the behavior-based approach was successful, it did have two shortcomings related to each other: it needed specific artificial landmarks placed at a well-known location near each intersection and corner, and it depended on an accurate distance measurement for initiating its corner-turning behavior. A third approach was implemented to overcome these shortcomings.

The third approach was very similar to the second one, but it depends neither on artificial landmarks nor on accurate distance measurements for negotiating corners or intersections. When the robot knows from its (inaccurate) odometers and from its (inaccurate) attributed topological map that it is approaching a corner where it has to make a turn, it actively looks for the corridor

that should be branching off, and turns into it after seeing it. The renunciation of artificial landmarks has led to a significant increase in robustness and flexibility. It is an important step toward the development of robots able to navigate in arbitrary unstructured and possibly changing environments.

The map knowledge required by a situation-oriented behavior-based robot is of a semi-qualitative nature. An attributed topological map is well suited for encoding this kind of information. Generating such a map is easy for a human user because geometric accuracy is not required. This is a great practical advantage. Moreover, it has been shown that a behavior-based mobile robot can even acquire its map knowledge by machine learning [Wershofen 1996].

## 4.2 Discussion

The concept of situation-oriented behavior-based navigation as described in the previous section has evolved in three steps.

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 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. 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 carefully placed 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. Moreover, in the light of 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 achieved success, prove the power of the concept. Also, it was found that a robot designed according to the concepts of perception and situation assessment has the advantage of being a good basis for implementing a man-machine interface that allows humans to communicate with the robot in an easy and natural way [Graefe, Bischoff, 1997].

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

According to the traditional definitions, a measurement always implies a quantitative comparison of the quantity to be measured with a standard unit, typically an SI unit. A carefully calibrated apparatus is then a prerequisite for any accurate measurement.

Industrial robots and other robots designed according to the traditional approach and based on quantitative models of themselves and of the world depend on measurements for continuously updating their models. The models are formulated from standard units, and the sensors used for updating the models must, of course, be carefully calibrated relative to the same units. For an industrial robot having only a few simple sensors this calibration is feasible, but costly. However, concerning the service robots and personal robots currently at the focus of Robotics research, the situation is different. Similar to organisms, they often have a large variety of sensors, some of them complicated and hard to calibrate, such as vision and sonar systems, haptic sensors, and combined force and torque sensors, to mention only a few examples. Calibrating all of them, and guaranteeing a continued condition of a good calibration for the entire robot is not practical. An “intelligent” robot depending on an exact calibration of all its sensors would, therefore, suffer from a severe lack of robustness if it were exposed to the real world.

Many researchers, including, e.g., [Hollinghurst, Cipolla 1994], [Hosoda, Asada 1994] [Jägersand, Nelson 1995] and [Yoshimi, Allen 1994], to mention only a few, have in recent years 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 how measurements without calibrations may be realized, and how robots may benefit from renouncing calibrations. Undoubtedly, this will eventually also influence the “official” definitions of the term “measurement.” The ideas of calibration-free measurement and calibration-free robots may be illustrated by the following two examples, a method using an uncalibrated video camera for measuring distances and a completely uncalibrated articulated arm robot for object manipulation.

### 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 measurements need not refer to standard units; robot-internal arbitrary units whose relationships to SI units are unknown are sufficient.

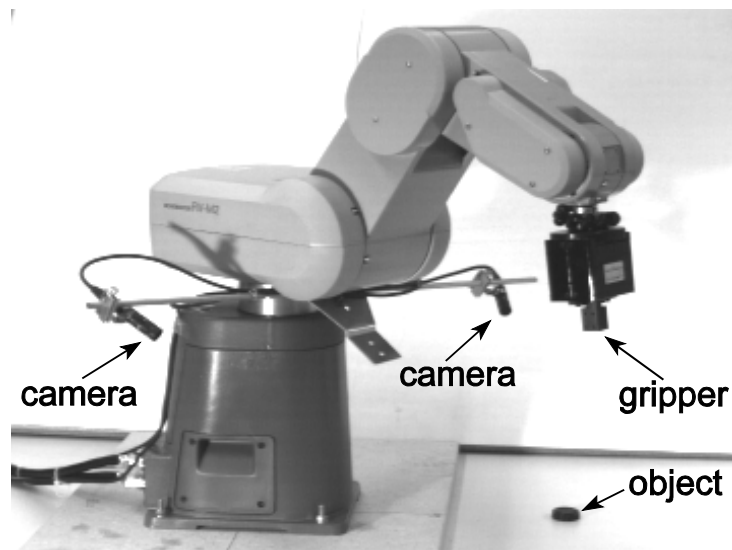
A motion stereo method for this purpose was introduced by [Graefe 1990]. It is based on the fact that, when a forward-looking camera approaches an object, the image of the object expands. While the rate of expansion is proportional to the approach speed, it is a nonlinear function of the distance between 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 robot navigation. Object manipulation by vision-guided 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 an arbitrary camera-centered coordinate system 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.



**Figure 5**

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

Grasping experiments performed with an uncalibrated manipulator arm (Figure 5) 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 misadjustments 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. Moreover, the approach is a good basis for studying machine learning [Graefe et al. 1997].

## 5.4 Discussion

In summarizing these results it may be stated that renouncing 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. 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.

Other advanced robots whose sensing still is closer to traditional measurement than to perception also tend to avoid the notoriously cumbersome and costly calibration of their sensing subsystems. Therefore, they use increasingly sensing techniques that neither make reference to standard units nor require any calibration.

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 (originally developed in Psychology) 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 in his invitation to this workshop.

## Acknowledgment

Some ideas presented in this paper and the form of the presentation are partly a result of discussions with Rainer Bischoff.

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