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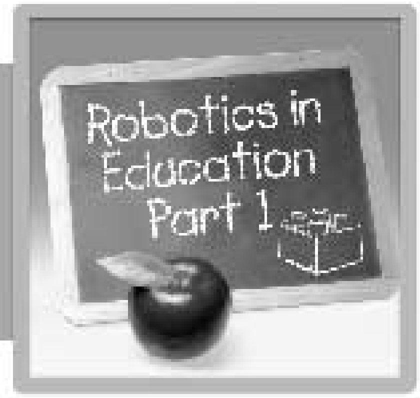
Teaching System Integration in Engineering Curricula at Universities via Popular and Effective Robot-Design Competitions



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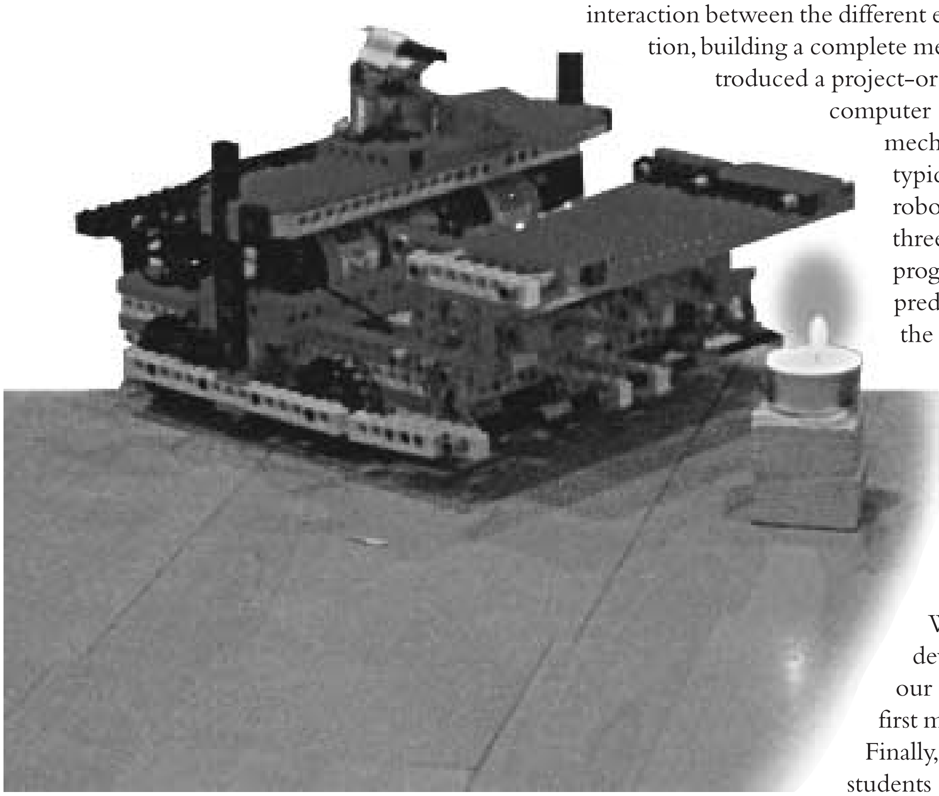
Vision-Guided Mobile Robots for Design Competitions

By ALBERT-JAN BAERVELDT, TOMMY SALOMONSSON and BJÖRN ÅSTRAND

Most modern engineering products make use of some kind of "intelligence." This intelligence, often implemented on a microprocessor, is essentially what makes a product a mechatronic product. Today's engineers need at least a basic knowledge of mechatronic design techniques and elements, such as sensors, actuators, mechanics, electronics, real-time software, and computer hardware. However, to be able to truly understand the interaction between the different elements and, thus, to obtain a synergistic integration, building a complete mechatronic system is a necessity. Therefore, we introduced a project-oriented course in our master's degree program for computer systems engineering with a specialization in mechatronics where the students design and build a typical mechatronic product in the form of a mobile robot. The basic idea is that each group of two or three students is given a mobile robot kit to build and program a mobile robot with software to perform a predefined task. The task is the same for all groups. At the end of the course, the robots developed compete with each other in their performance of the assigned task.

After three years of running the course, the addition of a color vision system to our robot kits resulted in major improvements. In this article, we first present the robot kit we use and discuss the experiences we gained in, and shortcomings of, our robot competitions. We then present the low-cost color vision system, developed especially for our course. We also discuss our experiences in the 1998 competition, where we first made use of the system, and the 2001 competition. Finally, we present the results of a questionnaire given to students who have completed the course.



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Robot Design Competitions

Motivation

The idea of a robot competition is not new; they have been held for several years at, for example, Massachusetts Institute of Technology (MIT) in Boston and Eidgenössische Technische Hochschule (ETH) in Zurich. Having a robot competition in an academic curriculum is highly beneficial, as it gives students open-ended problem spaces, teaches them to work in groups (of two or three persons), and stimulates creativity. It is our experience that students see the design of a mobile robot focused on competition as very stimulating and personally meaningful, especially when they take a project from conception through to implementation and testing. The pedagogical aspects of a robot design competition are discussed more thoroughly by Martin [1] in his Ph.D. thesis.

Robot Kit

The robot kit we use was developed at MIT. Low cost was the major reason for our choice, as every group should have its own robot (ten robots in our case). The MIT kit costs about US$600. The mobile robot kit consists of an onboard computer, several sensors, motors, batteries, and LEGO building parts. The motor package consists of four dc motors and one servo motor. The sensor package consists of several contact switches, photodiodes, photoresistors, light-emitting diodes, and infrared senders and receivers. The LEGO building parts, such as gears, wheels, rotational joints, chains, plates, and beams, are provided to build the mechanical components of the robot. The computer board is built around a 68HC11 microcontroller and is equipped with 32-kB RAM together with the necessary input/output (I/O) components to be able to drive the motors and read the sensor values, including H bridges and analog-to-digital (A/D) converters. The computer board can be programmed with a real-time operating system called Interactive C, which is based on the C programming language. The kit is shown in Figure 1.

As we found the sensor package rather limiting, we added a distance sensor able to measure between 10-80 cm and an accelerometer to be able to measure tilt. As a distance sensor, we employed a GP2D12 sensor from Sharp, which is based on triangulation available at low cost and small size (about US$25). This sensor has proven to be appropriate and, because of its small field of view, very suitable for locating objects such as golf balls.

Example Competition: Robot Golf Open

An example of a robot competition is the 1996 robot contest called Robot Golf Open. The contest arena was a rectangular square of 2×2 m, surrounded by a 15-cm high wall. The green was located in the middle of the arena and was a 7-cm high disk with a diameter of about 40 cm. The hole was in the green, as can be seen in Figure 2. Seven golf balls were randomly placed on the arena. It was the task of the robot to locate the balls, pick them up, and put them in some way into the hole, which gave two points for each ball. One point was given if the ball was only placed on the green. It is emphasized here that the robots performed the task autonomously, i.e., it made decisions as to how to control itself according to the software running on the onboard computer based on sensory information. Two robots "played golf" against each other for a period of 2 min.

The robot used the distance sensor to search for balls. The green could be found with a phototransistor, as a light was placed at the green. Contact switches informed the robot when it established contact with the green or collided with the surrounding wall or with the other robot. It was exciting to watch the competition, as all robots were able to place at least one ball on the green and often managed three or four.

Experiences and Shortcomings

The first course at Halmstad University was started in 1995, and we have now held seven competitions. For a short description of each competition, see [2]. Our experience in the course is that it is very attractive to students, and the competition day has become a known event, drawing about 250 spectators. The fact that the students are able to demonstrate their robots to so many people and the fact that the daily newspapers and local

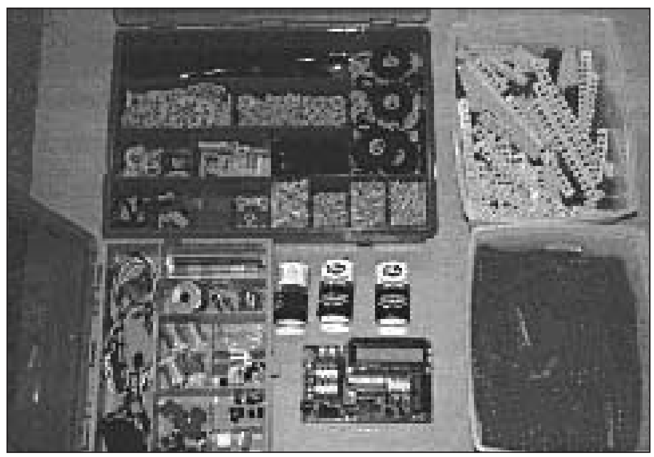

Figure 1. *The robot kit, developed at MIT, is distributed to each student group.*

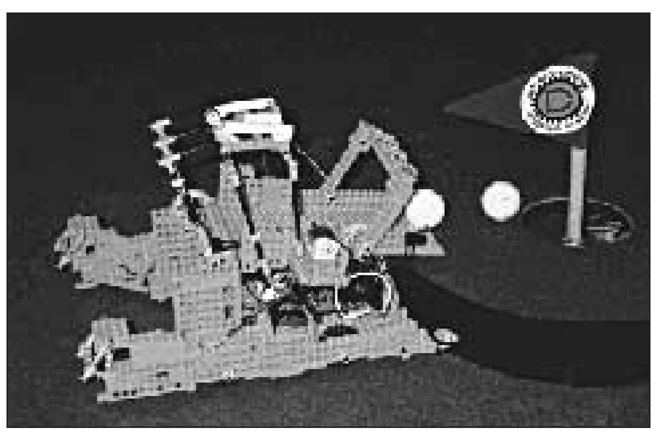

Figure 2. *One of the robots delivering the golf balls at the green, trying to reach the hole.*

radio and TV report on the competition strengthens students' self-confidence and motivation in the course.

The students learn to integrate the different components of a mechatronic system and apply and integrate their previous knowledge. They also experience the limitations of the sensors. What works in theory does not always work in real life. Using LEGO blocks also appears to be very successful as it is easy to build and rebuild the mechanical parts of the system. The drawback we experienced with the MIT robot kit is that the sensors are quite limited in their performance of intelligent processing. As the course is part of a master's program in computer systems engineering, an increase in the complexity of the intelligent processing algorithms is desirable. Thus, we soon added more advanced sensors, such as the earlier mentioned distance sensor. Nevertheless, the perception capabilities of the robot were still quite limited, thus, there was a limit to the complexity of the possible tasks.

Low-Cost Color Vision System

Motivation

It would be appropriate to have a computer vision system that can significantly enhance the perception capabilities. Especially in the case that a color camera could be employed, many different objects could be distinguished and located while using straightforward image-processing algorithms. This would allow the design of very challenging robot competitions, which require a fair amount of intelligent processing. Unfortunately, computer vision systems are generally relatively expensive, do not easily fit on a robot of about 30 × 17 cm, and require a great deal of computer power. However, because of the recent popularity of multimedia and the Internet, the prices of small color cameras that integrate the necessary A/D conversion have now reached an acceptable level for our purposes. Connectix, for example, offered a color camera in 1998 that has a parallel interface and is approximately the size of a ping-pong ball for about US$250.

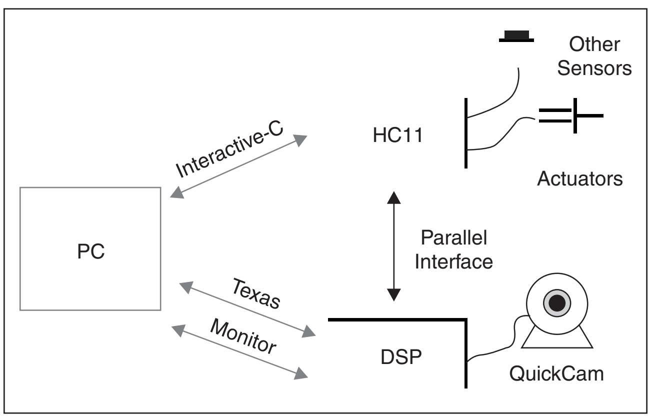

Figure 3. *System overview with all major communication links. The parts and links in grey are used only during development.*

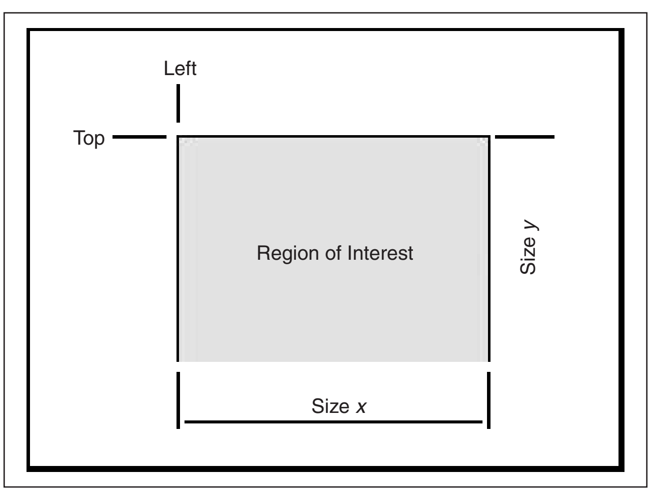

Figure 4. *A region of interest can be chosen freely.*

Overview

The vision sensor in our system is a color camera from Connectix called QuickCam Color II and has been a very popular camera on the PC market because of its low price and good image quality. To be able to run the computer vision algorithms sufficiently rapidly, we employed a separate processor for this purpose, the TMS C31 digital signal processor (DSP) from Texas Instruments. This processor communicates with the camera and runs all computer-vision algorithms. The final results of the image processing can then be transmitted to the 68HC11board through a parallel interface. All decisions concerning the control of the actuators and the interpretation of the other sensor data are made by the 68HC11 board. Thus, the DSP board, in combination with the camera, can be regarded as a *smart sensor.* This is illustrated in Figure 3, which gives an overview of the system. The PC is only used during development.

Hardware

The QuickCam camera is equipped with a parallel port interface, thus making a framegrabber superfluous. However, this however leads to relatively low frame rates due to the limitations of the interface. For example, it takes 0.3 s to transmit one RGB image of 160 × 120 pixels. The RGB images have a maximum resolution of 320 × 240 pixels. A rectangular region of interest can be chosen freely anywhere in the image, as illustrated in Figure 4. It is also a possible to obtain sparse images; for example, a decimation mode of two leaves out every second pixel, thus leading to an image of 160 × 20 pixels [3]. This makes it possible to overcome the problem of the limited communication bandwidth between the camera and the DSP by reducing the number of pixels that must be transferred.

The computer system, belonging to the vision system, is built around a single board computer equipped with a TMS320C31 32-b floating-point DSP. We use the so-called starter kit from Texas Instruments because of its very competitive price of US$99. It has pinned out data, address, and control signals that allow a simple expandability with daughterboards. To be able to connect the DSP board with the camera with the HC11 board and with the PC for development purposes, we designed our own daughterboard equipped with two additional parallel ports, eight binary inputs, and eight binary outputs.

We also put 64-kB word expansion memory on the daughterboard for storing the image-processing programs and the image data. The total cost of the vision system was about US$450 in 1998: US$250 for the camera, US$99 for the starter kit, and about US$100 for the daughterboard. This vision system is illustrated in Figure 5.

Development Environment

The students' development of the image-processing software can be done in two steps, where the first step can be omitted or done with another software package:

- *Step 1:* The RGB images from the camera can be imported to MATLAB and analyzed with the image-processing toolbox [4] and user-written functions, making it possible to efficiently test different algorithms.
- *Step 2:* The most suitable image-processing algorithms can then be programmed in C and downloaded to the DSP. The results can be displayed on the PC screen through a special monitor program.

Programs for assembling, downloading, and debugging programs are provided in the starter kit. We have added a commercial C compiler to be able to program the DSP in a high-level language. We wrote a special program that runs on the PC and communicates with the DSP to be able to control the camera and display the images and the results on the screen of the PC. This program gives full access to all the programmable functions of the camera.

Software

This section describes the C functions available on the DSP. To start with, we developed all interface routines for grabbing images at a desired resolution and region of interest as well as to set and get all possible camera parameters, such as brightness and contrast. Second, we provide routines to store the images in a buffer. One RGB pixel is stored in each data word. When the image is grabbed, the intensity for each pixel is calculated by the DSP and stored in the upper 8 b, as illustrated in Figure 6. Finally, we also provide communication routines to communicate with the 68HC11 board.

Experiences with the Vision System

"Election Campaign" Robot Competition

The first contest with the vision system, held in the spring of 1998, was called the election campaign. The task robots' task was to locate "voters" in an arena and bring them into the voting station. The arena was 2×2 m and contained a "voting station" in two of the corners, one for each robot. The voters are DUPLO bricks, where three different types of voters are distinguished by red, blue, and yellow. The robot's goal is to place as many voters, either red or blue, as possible in their own voting station, marked either with a red or blue color, as illustrated in Figures 7 and 8. Yellow voters give no points. Their role is to act in tipping the scale if the two teams collect the same number of voters.

Image Processing

The robot task required a robust segmentation of different colors. A well-known method [5] for achieving this is to normalize the RGB color signals with intensity signal I according to the following operations, which are done for every pixel:

$$I = (R + G + B)/3 \quad (1)$$

$$r = R/I \quad (2)$$

$$g = G/I \quad (3)$$

$$b = B/I. \quad (4)$$

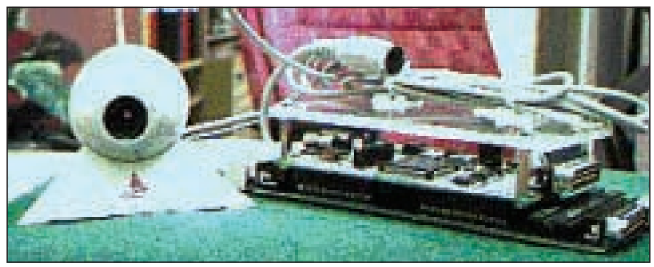

Figure 5. *The low-cost color vision system with an estimated cost of US$450.*

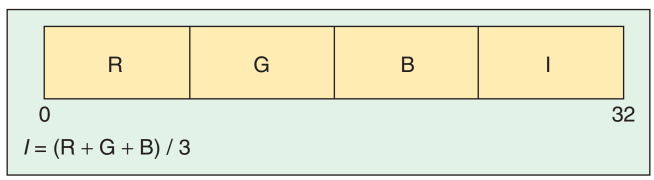

Figure 6. *Contents of a 32-b word in the image buffer.*

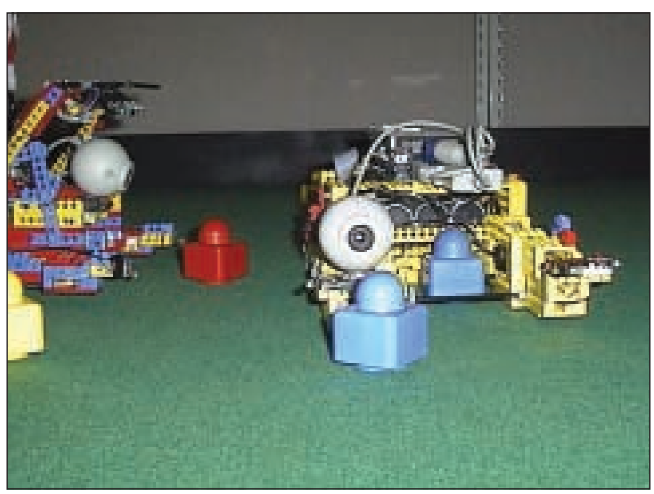

Figure 7. *A LEGO robot detecting a blue DUPLO brick.*

Low-cost sensors and high computing power make it possible to hold highly advanced robot competitions.

Each of the normalized components is linearly dependent on the other two (as $r + g + b = 1$), so the normalized color space can be represented by two normalized colors, for example, red (2) and blue (4). Each possible color has its unique position in this two-dimensional space, which is independent of the light intensity. This makes the method robust against variations in intensity caused, for example, by shadows, as it only focuses on the real color of the object. A minimum distance classifier can be used for the segmentation. Every RGB pixel in the image is then converted to a normalized color pair—r, g—and the distance is calculated to the predefined average normalized color of the object ($r0$, $b0$) according to:

Figure 8. The arena, with the voting stations in the upper left and lower right corner.

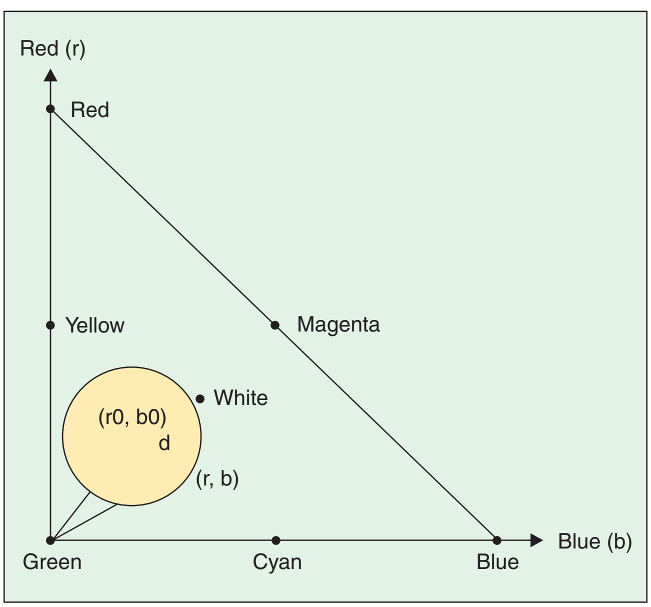

Figure 9. Normalized color space.

$$d = \sqrt{\left((r - r0)^2 + (b - b0)^2\right)}. \quad (5)$$

If the distance, d, is smaller than a predefined threshold, the specific pixel is labeled as belonging to the object; otherwise, it is a nonobject point (see Figure 9). The resulting binary image can be used for further processing, for example, to calculate the area or the position of the area center of the object. Dark pixels can give incorrect results because I is almost zero and the normalized color is determined mainly by noise. It is also possible that single bright pixels are misclassified as a result of specular reflections and other sources of noise. These misclassified pixels can be easily removed by some kind of filtering, such as a median filter.

Different Solutions

After intensive evaluation, the students employed either the above described method of color segmentation or used the minimum distance classifier based directly on the average RGB value of the objects. Major differences occurred in the processing stage of the binary images. One group developed a function for self-calibration of the brightness to be able to adapt to different illuminations. Another group entered the area of sensor fusion and effectively combined information from the vision system and distance sensor to detect and locate the DUPLO bricks in the scene. Yet another group was able to reason about the distance of the DUPLO bricks relative to the camera based on perspective geometry.

The "Environmental Control" Robot Competition

The latest contest with the vision system, held in the spring of 2001, was called "environmental control," and the robots' task was to locate three different kinds of garbage in an arena and bring them to the correct container. The arena was 2 × 2 m and contained the "containers" at one side, three for each robot. The garbage was either a bottle, a battery, or a pack of newspapers. The color of the garbage was blue. The task involved object identification and localization. Figure 10 shows the battery and the bottle standing in the arena. The figure also shows a segmentation result based on color. The segmented image allows a calculation of how the robot should be directed to one of the objects. Our original idea was for the student to identify the object by means of the vision system. However, although all students started with this approach, one group tried instead to identify the object by means of three contact switches mounted at different heights. This was a robust solution, and all of the other groups copied it. Thus, the vision system was used to find a garbage object and guide the robot towards it. The contact switches were then used to guide the grasping process and identify the object. Finally, the vision system was used again to find the right container for the identified garbage object.

Experiences with the Vision System

The students found the system very easy to work with. Students with no major experience with computer vision were capable of achieving very good results and learned a great deal about the basic principles of computer vision. They also learned the difficulties of employing computer vision when illumination cannot be controlled, which results, for instance, in a frequent occurrence of specular reflectance. They also felt an extra motivation in the course as they experienced the integration of the vision system as being on the frontier of robotics. The vision system proved to be compact enough to be carried onboard the relatively small robots. A typical execution time of 0.4 s per image of 160 × 120 pixels was achieved, including grabbing and storing a frame (0.3 s) and running the segmentation and localization algorithms (0.1 s). This allowed the robot to be controlled in real time, i.e., the robot moved smoothly around while executing the vision algorithms.

Questionnaire

To be able to test whether the students had, in fact, learned the things we intended them to in the course, we distributed a questionnaire in the autumn of 2001 to students who had attended one of the past seven courses. The total number of former students is about 120 students. We had current addresses for 65 of them and received 39 answers (60% response rate). Of the respondents, 28 are now employed as engineers in different areas of Sweden, and 11 are still studying. We presented several statements to which they could respond on a scale between 1 and 5, 1 meaning "I totally disagree," and 5 meaning "I totally agree." The statements are listed here together with the average response. They are listed in descending order according to the degree of agreement.

- It is important to apply theory in practice in order to learn the limitations of the theory, e.g., sensors and computer-vision algorithms.
  Average answer: 4.6.
- It is important to have a project in the curriculum in which the students can integrate and apply knowledge from several previously attended courses.
  Average answer: 4.6.
- A competition is a good work form as it provides students a specific and stimulating goal.
  Average answer 4.5.
- Students learn a great deal from pursuing a project all the way from idea to prototype, with respect to how to approach an open-ended problem and test it along the way.
  Average answer: 4.4.
- An open-ended problem, such as the robot-design competition, is beneficial as it stimulates creativity among the students.
  Average answer: 4.4.
- The project was fun and stimulating so that the motivation and desire to make an effort in the course was high.
  Average answer: 4.2.
- The project course is important as students learn how to cooperate in a group.
  Average answer 3.6.

Robot-design competitions are a popular and effective way to teach system integration in engineering curricula at universities.

- The project takes too much time in relation to what the students learn from it.
  Average answer 2.5.
- The project course should be removed from the curriculum because students do not learn very much in it.
  Average answer 1.5.

A general conclusion is that the students emphasize surprisingly strongly that they feel they have learned all the different aspects we wished to teach them in this course. The moderate response of 3.6 to the statement "The project course is important as students learn how to co-operate in a group" might be explained by the fact that the courses given at Halmstad University often include some kind of project work. Some students commented on this statement that, while they felt it was true, it was not really specific to this course as they had other courses as well that trained them in working together.

Conclusion

Robot-design competitions are a popular and effective way to teach system integration in engineering curricula at universities. A questionnaire distributed to former students confirmed this surprisingly well.

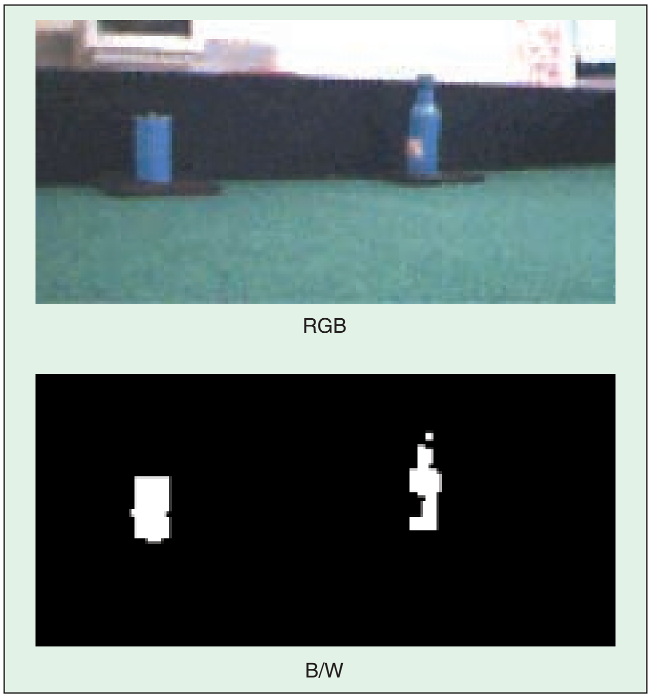

Figure 10. *Garbage collection. RGB-image of a battery and a bottle together with the corresponding segmented image based on color segmentation.*

Today's availability of low-cost sensors and high computing power makes it possible to hold highly advanced robot competitions.

Today's availability of low-cost sensors and high computing power makes it possible to hold highly advanced robot competitions. We designed a low-cost color vision system intended primarily for robot design competitions. The estimated cost is about US$450, including the color camera, and the system is small enough to be carried on board mobile robots of a typical size of approximately 30 × 15 cm. The system is built around a TMS C31 signal processor. Experience with the system has been very good. We are currently designing the next generation of a robot control and vision system, consisting of only one processor, a DSP C6211, with a daughterboard containing the necessary I/O units. An important extension will be the possibility to connect real encoders, allowing more sophisticated motion control and dead reckoning. We will also employ a smaller camera able to exchange data about ten times faster, i.e., one image per 20 ms. The A/D converters, now with an 8-b resolution, will be given 12-b resolution.

Finally, a wireless connection (Bluetooth) will be available to communicate with a host PC. The total cost per system, including the color camera, will be about US$700 per kit. We are confident that it will allow us to design very challenging robot competitions in the future.

Keywords
Robot design competition, mobile robot, computer vision, color vision.

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Albert-Jan Baerveldt is a professor of mechatronic systems at the School of Information Science, Computer, and Electrical Engineering at Halmstad University in Sweden, where he holds the Getinge Chair of Mechatronic Systems. He received the Ph.D. degree in mechatronics from the Swiss Federal Institute of Technology, Zurich, in 1993, where he conducted research mainly in the field of vision-guided robot arms. During this time, he also won the first world championship for ping pong playing robots in Hong-Kong in 1992. His Ph.D. work on the bin-picking problem was awarded with a grant to exhibit the work at the "Research and Development Exhibition" at the Hannover Fair 1992 in Germany, which is one of the largest industrial fairs in the world. In 1994, he had a postdocoral position at the Institute of Automatic Control at Lund Technical University, Lund, Sweden. Since 1994, he has been working at Halmstad University in Sweden. Currently he is leader of the Intelligent Systems Lab. His research interest include robotics and computer vision.

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Björn Åstrand received his M.S. in computer system engineering in 1995. He is currently a Ph.D. student at the School of Information Science, Computer, and Electrical Engineering at Halmstad University. His research interests are in mechatronics, robotics, and computer vision.

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