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Balancing Theory and Practical Work in a Humanoid Robotics Course

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In this paper, we summarize our experiences from teaching a course in humanoid robotics at Chalmers University of Technology in Göteborg, Sweden. We describe the robotic platform used in the course and we propose the use of a custom-built robot consisting of standard electronic and mechanical components. In our experience, by using standard components, the students obtain a deeper understanding of robotics hardware than would be possible with the use of (some) commercially available robot kits such as e.g. Boe-Bot or Lego Mindstorms. Furthermore, we propose a division between time spent on teaching the theoretical background and time spent on robot assembly and programming, which, in our view, provides the optimal balance between theory and practical work. Summarizing briefly, for a seven-week course, we propose two weeks of theoretical background lectures, followed by five weeks of practical work, in which each practical session starts with a brief theory demonstration.

This paper concerns the authors' experiences from teaching a university level course in humanoid robotics in an international masters programme at Chalmers University of Technology in Göteborg, Sweden. In courses that involve both theory and practical work, as do many robotics courses, the teacher faces the problem of weighing the theoretical and practical aspects against each other. On the one hand, at least in the authors' view, it is important to give the student a solid theoretical background before they embark on practical work. This is especially important in our international master programme, where the students usually have very different background knowledge. On the other hand, since the duration of the course is limited (in our case, the duration is seven weeks), if too much emphasis is put on the theoretical side of the course, the students' practical work may have to amount simply to assembling a robot without having proper time to actually use it. In this paper, we describe how we have dealt with this problem in our humanoid robotics course. In addition, we also briefly describe the robotic platform used in the course, motivating the use of a custom-built robot rather than a commercially available, off-the-shelf robot.

The Complex Adaptive Systems Master Programme

Following the trend toward increased internationalization, Chalmers University of Technology offers about 50 international master programmes in various fields. One of those programmes is the Complex Adaptive Systems (CAS) master programme. The courses in this programme range over a wide spectrum of academic fields and cover topics such as stochastic processes in physics, chemistry and biology, dynamical systems theory, information theory, computational biology, stochastic optimization algorithms, computer modeling and simulation, artificial neural networks, and the study of mobile robots. Consequently, graduates from the CAS programme have found employment in a wide range of areas in industry such as software development, management consulting, research and development, product development, and in the financial sector. Despite these opportunities on the employment market, many students have chosen to continue in academia towards a PhD. It is our strong belief that our students will become even more attractive on the job market if their analytical skills acquired in the programme are also augmented with studies of engineering methodology and practical problem solving techniques. Making the connection between analytical skills and practical work is one of the main purposes of the course in humanoid robotics, which will now be described briefly.

The Humanoid Robotics Course

The Humanoid Robotics (HR) course is offered as an elective course in the CAS programme. Students taking this course have often (but not always) taken the course Autonomous Agents, which is also offered as a part of the CAS programme. In the Autonomous Agents course, the students put together and use a Boe-Bot developed by Parallax Inc. Due to its simplicity and the high quality of the documentation and manuals, the Boe-Bot is a suitable starting point for robotics work. However, the Boe-Bot's limitations soon become evident. For example, its simple Basic Stamp microcontroller cannot handle tasks such as image processing. By contrast, in the HR course, the students are given the opportunity to work with a custom-built humanoid upper body robot (described below) involving several degrees of freedom as well as the use of a motor controller (which is not needed for the Boe-Bot) and a camera.

In addition to providing a useful platform for the application of analytical skills in practical work, the use of a humanoid robot is motivated by the fact that, in the coming era of autonomous robots, it is generally believed that humanoid robots will play an important role, since such robots can be more naturally adapted to environments primarily designed for people. Furthermore, sociological studies have shown that people perceive such robots as easier to interact with than wheeled robots without humanoid characteristics (Brooks, 2002).

The students of the CAS programme come from many different countries and generally have rather different background knowledge. Some students have a background in engineering physics, whereas others have studied electrical or mechanical engineering or computer science. Regardless of their detailed background, the students generally have a solid foundation in mathematical analysis, programming, and computer modeling (topics that are included in the requirements for admission to the CAS programme).

However, the students usually only have a very limited experience in applying their engineering knowledge to practical problem solving. Like several other universities, Chalmers University of Technology generally encourages teaching activities aiming at bridging the gap between scientific and practical engineering education. An example is the CDIO initiative (Andersson *et al.*, 2005). The CDIO framework is a generalized description of a complete product or system life cycle called *Conceive-Design-Implement-Operate*. In CDIO-based education, the teaching is organized around the engineering disciplines but with the CDIO activities intermixed. The four stages in the CDIO framework are: *Conceive*, a stage that includes definition of the need and technology, considering all possible constraints; *Design*, in which the focus is on generating the design, i.e. drawings and algorithms; *Implement*, in which the design is transformed into the actual product, including manufacturing and testing; and *Operate*, in which the implemented product is used for generating the intended value, including maintaining, modifying and retiring the system. An important goal with these activities is to provide industry with highly skilled engineers who are trained both in theoretical and practical engineering as well as goal-oriented project management. In the HR course, the students are given the opportunity to develop their problem solving techniques in a assignment involving the construction and programming of a humanoid (upper body) robot.

Related Work

Using mobile robots as a tool in science and engineering education has been a common approach in recent years (Horswill, 2000). The use of robotics as a teaching tool has been reported both for the education of young children and high school pupils (Mataric, 2004), (Movellan *et al.*, 2007), (Nourbakhsh, 2005), (Sklar & Eguchi, 2004), as well as in the teaching of various subjects on the university level (Billard, 2003), (Horswill, 2000), (Kay, 2004), (Koller & Kruijff, 2004), (Verner *et al.*, 1999).

The motivation for introducing mobile robots in the educational curriculum varies from case to case. Given the great deal of attention that robotics has received in recent years (movies, public robot competitions, etc.), robotics can be very appealing as a pedagogical tool for teaching mathematics and science for school children at all ages. Thus, by introducing robotics at younger ages, the recruitment situation regarding the science and engineering programmes at the university level is likely to improve (Mataric, 2004). Furthermore, there are several studies that report cases in which robotics is used at the university level as the main motivating factor for the students to learn various topics from the fields of computer science and artificial intelligence (Horswill, 2000). For example, Koller & Kruijff (2004) have reported a study from a course in computational linguistics in which the students created simple but interesting talking robots, based on LEGO Mindstorms, in the limited time of only seven weeks. It turned out that using robots in this course was very motivating for the students. Kay (2004) reported the use of robotics lab exercises in an introductory course in robotics for undergraduates with little or no experience in robot construction. The focus of the course is software development, artificial intelligence, and algorithmic aspects, rather than low-level hardware control. Therefore, the lab exercises in this course are based mainly on LEGO Mindstorms. This curriculum resulted in significant student enthusiasm and interesting projects, which were also presented at a local student research symposium.

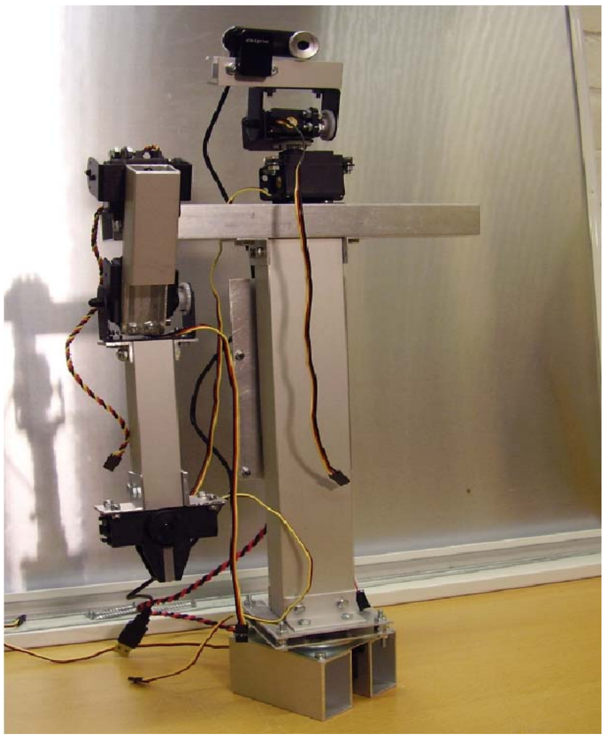
Another aspect of using robotics as a teaching tool is that this topic provides great possibilities for the integration of classical engineering subjects (e.g. mechanics, electronics, software development, control theory, machine vision) with topics more oriented towards psychology and cognition (e.g. human-robot interaction) within one interdisciplinary curriculum (Billard, 2003), (Verner *et al.*, 1999). The topic of robotics does not replace courses in, for example, control theory or machine vision but offers the students an excellent opportunity to use the concepts learned from these courses for a specific application (Billard, 2003).

The materials used in connection with the robotics courses ranges from standard off-the-shelf robotic kits, such as e.g. LEGO Mindstorms and the Boe-Bot from Parallax Inc., to more specialized and custom-built equipment, such as a bipedal humanoid robot (Takahashi *et al.*, 2003) or a research-grade mobile robot platform (Horswill, 2000). For the curriculum presented here, we advocate an intermediate approach: We have developed a relatively simple humanoid upper body, combined with a basic microcontroller for low-level motor control and a vision system in the form of a web camera.

Educational Robot Platform

The state-of-the-art in humanoid robotics involves complex robots such as Honda Asimo (see, for example, http://corporate.honda.com/innovation/asimo.aspx). Needless to say, robots of that level of complexity are beyond the financial and practical reach of a university course such as ours. Instead, in this course we have used a custom-built humanoid upper body robot named Hubert with a greatly simplified design. Hubert’s size is roughly that of a small child (age 2-3 years). The total height of the robot's upper body (excluding the rotating base) is about 0.47 m.

Figure 1
Hubert, the Humanoid Upper Body Robot.



Two robot prototypes were designed for the course. Four copies of the second version of Hubert, shown in Figure 1, were then produced. Each robot contains on the order of 400 parts (including nuts and bolts). The total time needed for producing one copy of Hubert (given detailed drawings and appropriate tools) is around 20 hours. Figure 2 shows the complete set of parts for a Hubert robot. The robots are delivered to the students in the form of a kit (i.e. disassembled).

Mechanically, the robot consists of four main body parts, namely a rotating base, a torso, an arm, and a head. The robot's skeletal structure (frame) is made of rectangular cross-section aluminium tubes. In order make it possible for the students to carry out the assembly of the robots, complicated operations like welding should be avoided. Therefore, the aluminum beams are joined using standard machine screws and L-shaped aluminum brackets. In order to keep the costs down, the robot is only equipped with one arm, consisting of three main parts: (1) an upper arm segment, (2) a lower arm segment, and (3) a gripper. On top of the robot is mounted a web camera, providing the robot with vision. Altogether, this configuration results in a robot having one arm, a head with vision, and six degrees of freedom (DOFs) in total.

Hubert’s main onboard microcontroller consists of a Board of Education (BoE) from Parallax Inc., equipped with the Basic Stamp 2 (BS2) microprocessor from the same manufacturer. Henceforth, the complete main microcontroller, consisting of the BoE and the BS2, will be referred to as the BoEMC. The BoEMC is connected to another onboard processing unit, the Parallax Servo Controller (PSC), which is used as the servo interface. The onboard microcontrollers (the BoEMC and PSC) are used for low-level control tasks such as servo control. The main robot application, implementing high-level control algorithms, runs on a standard desktop PC placed next to the robot. Thus, in the current configuration of Hubert, the sole task of the low-level program is to transfer signals sent by the high-level program (using RS232 serial communication) to the servo controller (PSC), which then sends the actual control signals to the servos. The high-level program is responsible for image processing and decision-making, as well as generating the signals sent to the BoEMC.

Course Curriculum

The course includes basic theoretical studies of humanoid robotics as well as experimental work with the Hubert robot. The use of the robot is centered on human-robot interaction (HRI) and image processing. The course runs over one quarter (seven weeks) and begins with two weeks of theoretical studies. In

Figure 2
The complete Set of Parts for a Hubert Robot

Upper left panel: The parts for the base. Upper right panel: The parts for the torso. Lower left panel: The parts for the arm. Lower right panel: The parts for the head.

addition to the lectures, the students are also required to solve two home assignments. The remaining five weeks of the course consist of robot construction and programming work.

Table 1.
The Course Schedule.

Session	Duration	Contents
W1S1	2 hours	Introduction and motivation. Examples of humanoid robots
W1S2	2 hours	Locomotion (and other movements) in humanoid robots
W1S3	2 hours	Human-robot interaction
W2S1	2 hours	Image processing for humanoid robotics
W2S2	2 hours	Delphi programming for humanoid robotics
W2S3	2 hours	Introduction to robotics hardware (mechanics and electronics)
W3S1	4 hours	Robot construction
W4S1	4 hours	Robot construction and experiments
W5S1	4 hours	Robot experiments
W6S1	4 hours	Robot experiments and project demonstrations
W7S1	4 hours	Robot experiments and project demonstrations

W1S1 = week one, session one, etc. As can be seen, the first six sessions (two weeks) of theoretical studies are followed by five weeks of experimental work with the Hubert robot.

Lectures

The six lectures given during the first two weeks of the course cover the topics (i) introduction to humanoid robotics, (ii) kinematics of humanoid robots, (iii) human-robot interaction, (iv) image processing for humanoid robots, (v) programming humanoid robots, and (vi) introduction to robotic hardware (mechanics and electronics). The detailed schedule is presented in Table 1.

Home Assignments

In Assignment 1, the students are required to derive the equations of forward kinematics for the robot used in the course, given the detailed measures of the robot. The task in Assignment 2 is to make a case study of an existing robot with marked HRI capabilities, namely the PaPeRo robot from the NEC Corporation. The students carry out a literature study and then summarize it in a written report. In both assignments, the students are required to work independently.

Robotics Assignment

In the remaining five weeks of the course, the students are required first to assemble their robot kits and then to program the robot in order to solve a particular task. The students are divided into groups (the 13 students taking the course during our study were divided into three groups), and each group is given a Hubert kit. The students are required to formulate their own tasks, both as a training exercise and as a means to increase their motivation for the work. The teachers review the suggested tasks before approving them. During our study, changes included limiting the complexity of the tasks, something that is needed since the students (in our experience) tend to formulate unrealistically complex tasks.

Each of the five four-hour practical work sessions are supervised by two teachers. The students are given considerable amount of freedom to work on the robotics assignments, but they are required at least to show up at each four-hour session to report on their progress. By the middle of the second practical work session (i.e. week four of the course), the groups have completed the assembly of the robot and spend the remaining time programming it. Final demonstrations are carried out in the last two weeks of the course. All students are required to attend the final demonstrations.

Course Evaluation

Towards the end of the HR course, the students were given a questionnaire regarding their experiences with the course, including the hardware construction part. The questionnaire, which was anonymous, consisted of a number of multiple-choice questions and also permitted the students to give their own comments directly on each question. (See Appendix A for the questionnaire and the distribution of the comments obtained from the students.)

Disposition and Goals

The first three questions (Q.1-Q.3) concerned the disposition and goals of the course. Regarding the disposition, i.e. the division between theory and practical work, all students were positive, but only three had a very favorable view. The teaching goals, which were communicated on the course web page and during the first lecture, appear to have been clear.

Lecture Quality and Level of Difficulty

The topics of the six lectures given in the beginning of the course are presented above. The quality of the lectures (Q.5) was generally perceived as high or very high, with only one student giving a low grade. However, it appears that the level of difficulty (Q.4) could have been raised somewhat. This is an important lesson for the next HR course (2009). However, as described in the beginning of the paper, the students' educational backgrounds vary quite significantly, and one should therefore be careful not to raise the level of difficulty too much.

Home Assignments

As described in above, the students were given two home assignments, one regarding humanoid robot kinematics and one involving a case study of a personal robot (PaPeRo). The level of difficulty of those assignments appears to have been about right, even though some students found them to be rather easy. In the most recent HR course, several students were from a different master programme in which they had taken a course on robotic manipulators, thus making the first theory assignment a simple task for them. Overall, the home assignments appeared to raise the students' interest in the topic of humanoid robotics.

Robot Construction and Use

The level of difficulty of the robotics assignment seems also to have been appropriate, and the assignment clearly increased the interest for the topic among the students (Q.8-Q.9). Most students seem to be positive about the format of the project groups, although some claimed that not all of the students contributed to the work as much as the others (Q.1, Q.10, Q.12). Furthermore, almost half of the students thought the time allocated for the robotics project was insufficient (Q.11).

Teacher Support

All students were satisfied with the support provided by the teachers during the project part of the course, and a majority of the students now also feel more confident working with projects involving construction and programming of hardware (Q.13-Q.14).

Overall Rating

All students participating in the course would recommend the course to their interested friends (Q.15), implying that the course was mostly successful.

Suggestions from Students

The students were asked to suggest changes and additions for the course and provide general comments (Q.16-Q.17). In general, the students would like to go deeper into the technical details of various subjects such as image processing, hardware, and motion control. They also would like to see an upgraded version of the humanoid robot used in the course with a faster microcontroller and two arms instead of one arm.

Discussion

Effects on the Recruitment of Students

In order to succeed with a career in an interdisciplinary applied research field such as robotics, it is certainly necessary for the students to acquire some practical engineering skills at some point during their studies. The research carried out in our group is focused on autonomous robots, and it involves both construction and application (e.g. programming) of such robots. The recruitment base for our new master students and PhD candidates mainly consists of the students from the CAS programme. Therefore it is essential for us to seek to bridge the gap between theoretical knowledge and practical engineering demands at an early stage in the students' development.

From our point of view as robotics researchers, it is preferable that the students become acquainted with the tools and methods used in our research *before* they actually start with their master's thesis. Otherwise, too much time will be spent on such activities in the beginning of the master thesis period, significantly limiting the time being spent on the given thesis tasks.

Our aim for the masters students is that they should be able to give a real contribution to our research, thus giving us the opportunity to observe (or at least estimate) how well they would fare as PhD candidates should they wish to continue their studies. Following the completion of the HR course (in the Autumn of 2008), we have recently recruited two masters' students from the 13 students that took the course. One student is involved in the construction of a head for a humanoid robot which is to be used in our research, and the other is working on the topic of simultaneous localization and mapping (SLAM) using a wheeled robot equipped with a laser range finder. In both cases, we clearly note the benefits (from our point of view) of the students having completed the HR course: Both students are currently working on a level that may result in one or several publications being written (based on their work) at the end of their masters' projects.

Furthermore, being able to offer interesting and challenging master theses that start on a rather high level (achieved by means of courses such as the HR course) also enhances the reputation of the research group, thus making it easier to attract the very best students.

The Robotics Assignment

The high-level program for Hubert running on the desktop PC can, in principle, be written in any modern high-level language. In the 2008 course, Delphi (object-oriented Pascal) was used as the main language, although some students chose to use Matlab instead. Even though the experience with Delphi was favorable, in next year's course C# will be used instead. Given the prominence of C-like languages at Chalmers University of Technology, the students are more likely to be familiar with C-style syntax than with Pascal syntax.

Even though the robotics tasks suggested by the students had to be modified slightly, we believe that letting the students formulate their own tasks greatly increases their motivation for the work. Some of the tasks suggested by the students included face tracking, face recognition, simple game playing, and hand-eye coordination tasks such as grasping. Furthermore, working with realistic robot hardware instead of the more simple material used in other robotics courses (e.g. LEGO MindStorms) provides the students with a deeper understanding of robotics hardware (such as sensors, electronics, mechanics etc.). They will face the reality of robotics research and focus on the relevant problems for their learning.

Student Feedback

The answers given on the questionnaire clearly showed that the students found it both interesting and challenging to apply their theoretical knowledge, which they have acquired during many years of study, to a real problem-solving task involving hardware construction and robot programming. Comments from the students include: "It's fun to see the results and possibilities!" and "One of the few courses I've had that involve[s] building mechanical structure. I love it. Should be more courses involving that."

In addition, the questionnaire indicates that the level of difficulty of both the lectures and the home assignments could perhaps be raised somewhat. A problem in this regard is the fact that, due to the limited duration of the course and the need to have ample time for robot construction, only two weeks could be devoted to lectures. This, in turn, meant that the lectures could only skim the surface of the topics considered, perhaps rendering the presentation a bit too simple. Squeezing in additional lectures in the first two weeks is not an option for reasons involving both the budget of the course and schedule conflicts with other courses. However, another option would be to divide the four-hour sessions used for robot construction and programming (in the last five weeks of the course) into two parts: (i) A brief (30-60 minutes) theory session, in which the topics considered during the first two weeks are exemplified using the Hubert robot platform, and (ii) a slightly shortened (i.e. from four hours to around three to three and a half hours) practical session for robot construction and programming. Shortening the part involving practical work would hardly have any negative effect since the students do a significant amount of the practical work outside lecture hours. The questions they may wish to ask, and the feedback given by the teachers, can easily be accommodated in a slightly shorter session. Furthermore, the short theory sessions would, of course, be interactive, allowing the students to pose questions and make comments.

Conclusions and Future Work

Even though the number of students (13) is perhaps too limited to make far-reaching conclusions, based on our observations we advocate that the students' evident interest in applied robotics should be promoted, something that we believe will ultimately result in better engineers. In the long run, educational activities of the kind carried out in the HR course are also likely to have a positive effect on the recruitment (at the college level or even earlier) of students to the engineering profession.

Judging from the questionnaires that the students filled in at the end of the course, the majority of students appear to have been satisfied with the disposition and contents of the course. In particular, the robot construction project seems to have been a positive experience. All students answered that the robotics project increased their interest in the topic of humanoid robotics (Q.9).

Summarizing, we believe that a good balance between theory and practical work was achieved with the curriculum used during the course. Nevertheless, some improvements will be made in the next course offering (2009). Specifically, the sessions involving robot construction and programming (i.e. the last five weeks of the course) will be divided into an initial one-hour lecture and interaction part, followed by a three-hour practical part. By adding a short theory part in each session, the connection between theory and practical work can be made clearer. Furthermore, additional specific examples of robot kinematics, image processing etc. can then be given using the Hubert robot platform.

Due to the limited size of the statistical material, the conclusions given above should be seen as preliminary, and they will be followed up during the coming HR courses.

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Appendix A
Questionnaire with the Students' Answers

In this appendix the questionnaire given to the students is presented, together with the students' answers to the questions. All students answered the questions, and the distribution of the answers is given.

Q.1 How do you rate the disposition of the course (two weeks of lectures, followed by five weeks of robot construction)?
very positive 23%; positive 77%; neutral 0%; negative 0%; very negative 0%;

Q.2 Are the teaching goals of the course clear to you?
very clear 15%; clear 77%; a little 8%; not at all 0%;

Q.3 Are the teaching goals of the robotics project clear to you?
very clear 8%; clear 92%; a little 0%; not at all 0%;

Q.4 How do you rate the level of difficulty of the lectures?
very difficult 8%; difficult 0%; neutral 38%; easy 54%; very easy 0%;

Q.5 How do you rate the quality of the lectures?
very good 23%; good 54%; neutral 15%; low 8%; very low 0%;

Q.6 How do you rate the level of difficulty of the home assignments?
very hard 0%; hard 8%; neutral 61%; easy 31%; very easy 0%;

Q.7 To what extent do the home assignments increase your interest for the topic of study?
Much 15%; little 54%; neutral 31%; negative 0%; very negative 0%;

Q.8 How do you rate the level of difficulty of the robotics assignment?
very hard 0%; hard 23%; neutral 62%; easy 15%; very easy 0%;

Q.9 To what extent does the robotics project increase your interest for the topic of study?
Much 69%; a little 31%; neutral; negative 0%; very negative 0%;

Q.10 To what extent have the robotics assignments increased your ability to solve problems in teamwork?
Much 8%; a little 38%; neutral 38%; negative 15%; very negative 0%;

Q.11 Was there enough time allocated for the robotics project in the course?
too much 0%; yes 54%; no, too little 46%;

Q.12 How do you rate the size of the project groups?
too large 31%; appropriate 61%; too small 8%;

Q.13 Do the teachers provide enough support for the students to carry out the robotics project in the course?
too much 0%; yes 100%; no, too little 0%

Q.14 Do you feel more confident now to work on projects involving hardware than you did before you started this course?
yes, much 30%; yes, a little 47%; neutral 23%; no, less confident 0%;

Q.15 Would you recommend this course to your friends?
yes, absolutely 38%; yes 62%; no 0%; no, absolutely not! 0%;

Q.16 What additions or changes (if any) would you like to see in the course?
[Please refer to the main text.]

Q.17 General comments and suggestions:
[Please refer to the main text.]