Designing Robotics Student Projects from Concept Inventories

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Abstract. Student projects play a crucial role in current tertiary education. Projects help students to verify their understanding of technological and scientific concepts by applying them to practical problems. Typically they represent a phase between a consumptive and active learning or between acquiring and applying knowledge. This phase is of paramount importance to education, especially in science and engineering. However, there is no systematic way of designing robotic student projects. With this paper we want to propose a method of deriving student projects from concept inventories (CI), listing the concepts that are necessary to comprehend in order to actively contribute to a scientific or engineering domain.

Keywords: Robotics education · Concept inventory · Student project

1 Introduction

Student projects play an important role in modern education. This holds for the engineering studies and specifically for teaching robotics, which is a highly trans-disciplinary field of education. Typically the projects are centered on a specific application or robot or robot kit that is available for a project.

Researchers emphasize the importance of student projects in order to increase the self-motivation of students and improve their ability to handle the engineering design process, consisting of the following steps: problem definition, invention, evaluation, decision, implementation and review [1]. Projects should help to encourage students to enter scientific and engineering careers [2]. These clear statements underline the necessity for a systematic approach to design student projects.

Student projects are part of almost every engineering curriculum. They serve as means for motivating young students [1]. Attached to a lecture and often more like a lab exercise than a complex task that stretches over several days or weeks and requires planning, they serve as a measure to foster cooperation among students in teams or with others, external to the home university during an internship or company placement. They allow digging deeply into a scientific or engineering problem as a final project.

Still the design of projects often appears to be random. Final projects and those for mature students are derived from, possibly changing, research projects or projects with

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companies. Early projects, typically for a larger number of students, are driven by available infrastructure and optimized for an effective assessment.

However, accounting for the importance of projects in modern STEM education, the design of at least part of the projects should be guided by the objectives of the course of studies, as listed in the concept inventories [3, 4].

The remaining part of this paper is organized as follows: After this introduction we will detail the role student projects play in university curricula. Then we will revisit concept inventories and present two sets of projects that were derived from concept inventories. Finally we will present our conclusions.

2 Projects in University Curricula

In our curricula, robotics projects appear in different forms. We have Robotics projects:

- As an integral part of a robotics module (typically done in student groups)
- As a module on its own (typically done in student groups)
- As part of a working group (done alone or in student groups)
- In the form of the bachelor or master thesis (typically done alone)

In this paper we would like to concentrate on robotics projects as part of a lecture as well as a module on its own.

Robotics projects as part of a lecture - In our curricula, a robotics module consists of a lecture (typically 2 h per week) and a lab (2 h per week as well). In this context, the robotics project is part of the lab – besides the repetition of course content, deepening discussions, and exercises. In addition to the mentioned 4 h per week, students are asked to work additionally at home or at the lab. Altogether, the workload is around 150 h per semester.

Robotics projects as a module on its own - Students have the opportunity to choose a robotics project in terms of an elective module. The workload of such a module is also around 150 h per semester – this kind of project has a far greater complexity than the first project type.

Projects play a certain role in our curricula – but our curricula are far away from a curriculum completely based on project-based learning ideas.

3 Concept Inventories – The Robotics CI Example

This section shortly repeats the ideas behind concept inventories. Concept inventories list the relevant concepts of specific scientific fields and a single or a series of multiple-choice tests, related to those fields. Concept inventories serve as orientation for teaching and as a pedagogical measuring device to measure the levels of students and the gain of understanding, independent of the student's background and the actual method of teaching. This section will only give a very short introduction to the domain of concept inventories in general and to robotics concept inventories. For more details on concept inventories, please refer to the respective publications, e.g. [5, 6].

The list of concepts is assembled from the feedback of teachers and practitioners. It undergoes a lengthy period of revision and quality checks to make sure, all relevant concepts are covered. Within a scientific domain concept inventories may be adjusted for the level of students (e.g. school or university) and for sub-domains (e.g. analogue and digital).

The following list gives an overview of the different domains of concept inventories with the number of available concept inventories [3]:

- General Science and Learning (15)
- Force, Mechanics, and Materials (17)
- Electricity and Magnetism (12)
- Geosciences and Astronomy (5)
- Optics and Waves (4)
- Thermodynamics (8)
- Chemistry and Biology (7)
- Mathematics (10)
- Electrical Engineering (3)
- Computer Science (3)
- Other (6)

Central components are the concept inventory tests, one for every concept inventory, that allow assessing the understanding of students of the relevant concepts independently of the actual knowledge. Students typically undergo the test twice, first as a 'pre-test' at the beginning of the course and second as a 'post-test' at the end.

After an initial development phase, the tests typically do not change over some time or only develop slowly. This way, a single test can be used to measure the relative level of students of different years. In combination with a post-test after a class it allows assessing the concept learning gain of a specific course.

Noteworthy to mention is the fact that concept inventory tests must not be used for grading. Otherwise there may be strong incentive for students to specifically prepare for the tests, e.g. by memorizing the answers without working on the concepts. Therefore, test are carried out anonymously.

Evaluation of the test results can be very informative. Above the aggregated numerical values, the overall spread of answers and possible clusters of wrong or right answers often are interesting for teachers to know. With a second test development of understanding can be inferred. Figure 1 visualizes the gain for different teaching approaches in 'Signals and Systems' courses [7]. The learning gain is calculated by the following formula:

$$gain = \frac{post - pre}{100 - pre}$$

with post and pre representing the aggregated results of pre- and post tests.

Furthermore, the development of individual students may be interesting to follow. For this, a 'magic value' that does not allow to refer the two tests to a specific person, but to each other, is used. It may show improvements on some concepts and acquiring miss-concepts on others.

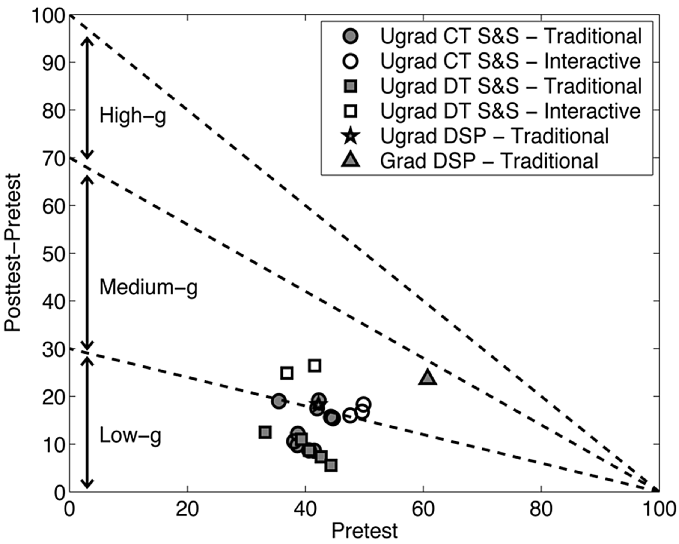


Fig. 1. Gain for different teaching approaches [7]

Figure 2a shows the development of understanding on a specific question. Whilst answers in the pre-test were more or less randomly distributed, in the post test the students demonstrated the understanding of the targeted concept by choosing the correct answer (b), which can be considered an outcome of the course.

A negative example is given in Fig. 2b In this case, answer "a" was the correct one. This example shows how student, after answering the question correctly in the pre-test, got detracted and picked a wrong answer in the post-test. This result may indicate a wrong approach to teach specific concepts. However, this kind of 'unlearning' may also be a necessary step for students to overcome incorrect concepts.

A tentative list of categories for a robotics concept inventory is given in Table 1 [5]. The 'math' and 'numerical methods' category covers the mathematical foundation, which typically is related to linear algebra, differential equations and representation of multi-parameter properties by means of vectors and tensors. The 'mechanics' category covers all aspects of Newtonian mechanics. 'Stability' covers mechanical stability that keeps a robot from falling, control theoretic stability that keeps systems from un-intended oscillation and the stability notion of decision making, to consequently follow a plan. 'Kinematic' concepts are required for intentional behaviours of complex mechatronic systems and have some theoretical links with systems of linear equations and trigonometry. 'Dynamics' addresses the field of rigid body dynamics and dynamic behaviour. 'Sensing' of physical parameters requires signal estimation and filtering. 'Perception' can be seen as the level above sensing that turns sensor data into information for planning and decision-making. 'Planning' includes tasks like path planning. Concepts of artificial or computational intelligence are port of a separated concept inventory.

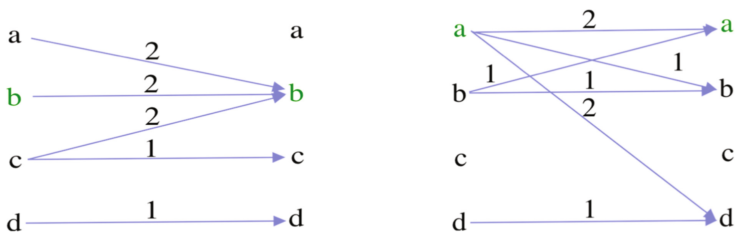


Fig. 2. Differences between pre- and post-test answers, (a – left) improving, (b – right) 'unlearning'

Table 1. Tentative list of robotics concept inventory category list

#	Category	Concepts
1	Math	Transformation between different coordinate systems: select the transformation matrix that transfers a point from one coordinate system to another
2	Math	Time shift: given a plot of p[n], select the plot of p[n + 1]
3	Math/Numerical methods	Difference equations: Given a sequence of equidistant distance measurements, select the values for speed and acceleration
4	Numerical methods	Linearization: Given a curve, select a suitable stepwise linear representation
5	Mechanics	Spring-mass-damper system: give a specific configuration, select the steady-state configuration
6	Mechanics	Robot control: select a suitable configuration of a differential drive wheeled robot that would follow a specific trajectory
7	Control theory	Control parameters: Identify the a most suitable control response for a specific task
8	Stability	Static stability: Given a set of rigid bodies on different slopes, select the (un) stable one
9	Kinematics	Trajectory: given a differential drive robot with both wheels rotating at different speed with a fixed ratio, select the trajectory the robot takes
10	Kinematics	Building space: Given a specific robot arm configuration, select the sketch of the space the robot can reach with its tool
11	Dynamics	Motor momentum: given four robot configurations, select the one that requires the lowest motor momentum for a given task
12	Sensing	Drift: Assume a measuring system that adds a fixed, ever increasing value to the measured value, determine the time after which the measurement will be unreliable
13	Perception	Object properties: Given a four different objects, determine the number of properties to identify the objects
14	Planning	Path planning: given a specific environmental configuration (obstacles and path), derive a suitable cost function that describes the situation
…		

4 Requirements for Student Projects Derived from Concept Inventories

Whilst concept inventories must not be used directly for teaching, they may serve as a good orientation for defining student projects, which we will demonstrate with a small example. Assume the partial list of concepts listed in Table 2.

Table 2. Partial list of concepts resp. questions

	Concept/Question	Refers to category (Table 1)
1	Transformation	Math
2	Time shift	Math
3	Acceleration	Math
4	Small-signal/linearization	Numerical methods
5	Mass-Damper	Mechanics
6	Segway	Kinematics
7	Maze	Planing
8	M-Bot	Dynamics

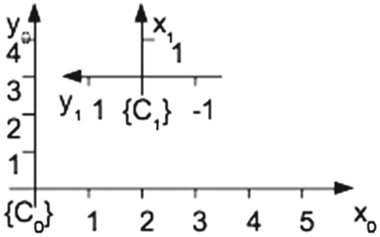
The first question is related to the coordinate transformation between different coordinate systems or frames of reference, e.g. an inertial coordinate system and one that is statically or dynamically transformed with respect to the inertial coordinate system. The transformation concept has different levels of complexity. In mechanics it could be a displacement along a single or multiple axes, a rotation around a single or multiple axes or a combination hereof. Image acquisition and processing adds aspects like scaling and perspective. Depending on the maturity of students, the project may make use of different levels of complexity. The transformation between two coordinate systems may depend on a single parameter, e.g. the angle of a single robot arm experiment – like an actuated pendulum or it could be a mobile robot with a local (mobile) and a global (fixed) frame of reference. Figure 3 shows details of the question related to transformations.

The time shift question is related to the delay of signals. This is a common problem in processing sensor data. Pre-processing and evaluating sensor data may result in significant delays between the occurrence of an event and its perception by a control system. Similarly, actions may be delayed due to processing and communication times. However, delays may be neglected by using an ideal simulator, such that the related concepts can be excluded from the learning process by choosing a respective project setup.

The third question is related to changes in speed of mobile systems. Typically, there is at least one instance when mobile systems experience an acceleration, which is when they start or stop moving. Often, the moment can be neglected, if there is a simple on-off-control of robot locomotion. However, there are scenarios, e.g. a soccer-playing robot to avoid interception by an opponent that may require consideration of deceleration and acceleration.

Question 1

Given coordinate systems C_0 and C_1 as in the following image:



For transformation of the coordinates of a point P from coordinate systems C_1 to C_0 we can find a system of linear equations. Identify the suitable equations to calculate x_0 and y_0 values of point P with its coordinates given in x_1 and y_1 values.

a) $x_0 = x_1 + 2$, $y_0 = y_1 + 3$,
b) $x_0 = - y_1 + 2$, $y_0 = x_1 + 3$,
c) $x_0 = - y_1 - 2$, $y_0 = x_1 - 3$,
d) $x_0 = 2y_1 -3$, $y_0 = -3x_1 + 2$.

Fig. 3. Example question 1 [6]

The small-signal and linearization question is related to the concept of acceptable error. With high computation power or long processing times, imprecise computations can be avoided. However, small computers and hard real-time requirements may need to sacrifice accuracy.

The mass-damper question is related to the concept of stability and oscillation. However, oscillation requires specific classes of systems and setups, which are subject to the design of the project.

The Segway and the M-Bot question relate to the kinematic concepts of mobile robots, as well as to the concept of friction which is a crucial prerequisite for accelerating masses. Kinematics is introduced by requiring drives with the typically inherent parameter of the axis angle to control a parameter like a position by means of a transmission. Friction can be introduced to a project by the overall use case, e.g. requesting the robot to move on slippery surfaces or requiring it to climb slopes.

5 Student Projects Derived from CIs

5.1 4-DOF Bipedal Robot

The task is to implement a bipedal robot with as few degrees of freedom (DOF) as possible. Aside of the Jansen mechanisms, the artist uses for his mobile installations [8] and of ‘Toothbrush robots’ with only a single degree of freedom and without control of orientation, legged robots require a minimum of 4 drives or degrees of freedom (DOF). Making them move requires understanding of multiple concepts of the robotics, mechanics and other concept inventories.

Figure 4 shows a 4-DOF bipedal robot built by computer science undergraduate students as practical part of a robotics lecture. The robot was assembled from a mechanical kit with conventional scale modeling servo controllers, a raspberry PI mobile computer and a power bank. The main objective was implementing a locomotion scheme. The timeframe was very tight with only few hours allocated to the task. The project thus covered only a few concepts. For example, no sensors were involved in the project such that no data pre-processing, delays, control stability issues where involved. However, there have been some design considerations as can be inferred from the ‘face’ applied to the robots ‘head’.

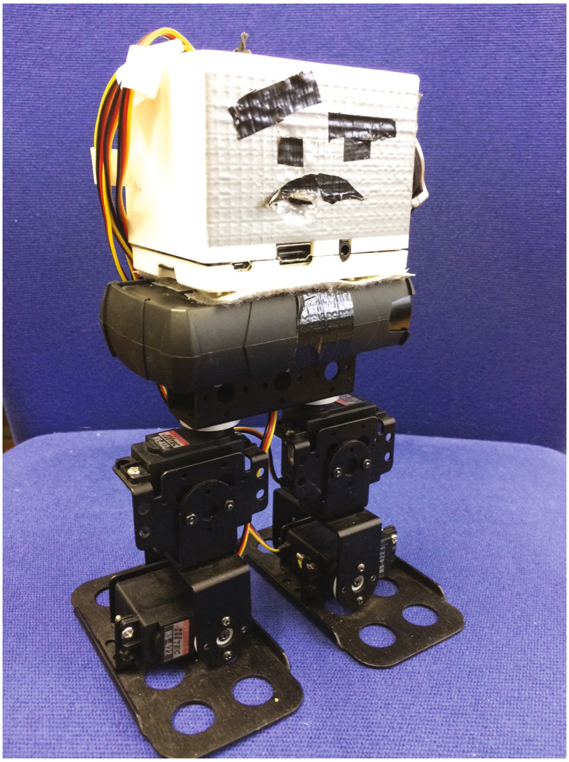


Fig. 4. 4-DOF bipedal robot

Still, students carried out calculations on Newtonian mechanics and mechanical stability. Figure 5a is taken from a student report to estimate the maximum angles of the two joints, which eventually lead to the zero momentum point (ZMP) approach that still is widely used in the robotics domain. Figure 5b, taken from another student report shows the region of stable stance for the possible combinations of the two joint angles.

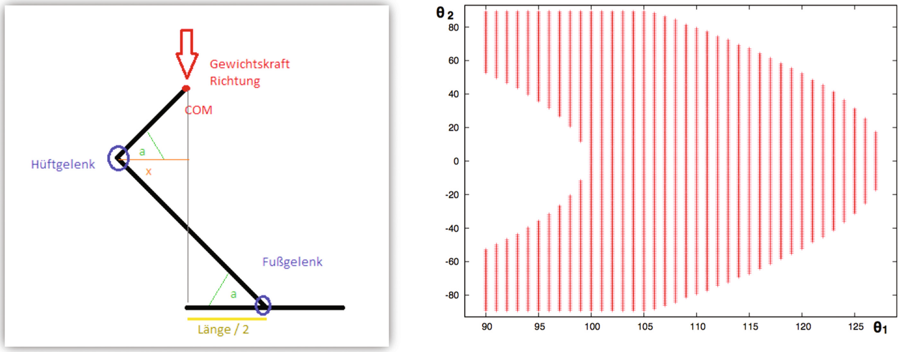


Fig. 5. Student sketches on stability issues related to bipedal robot

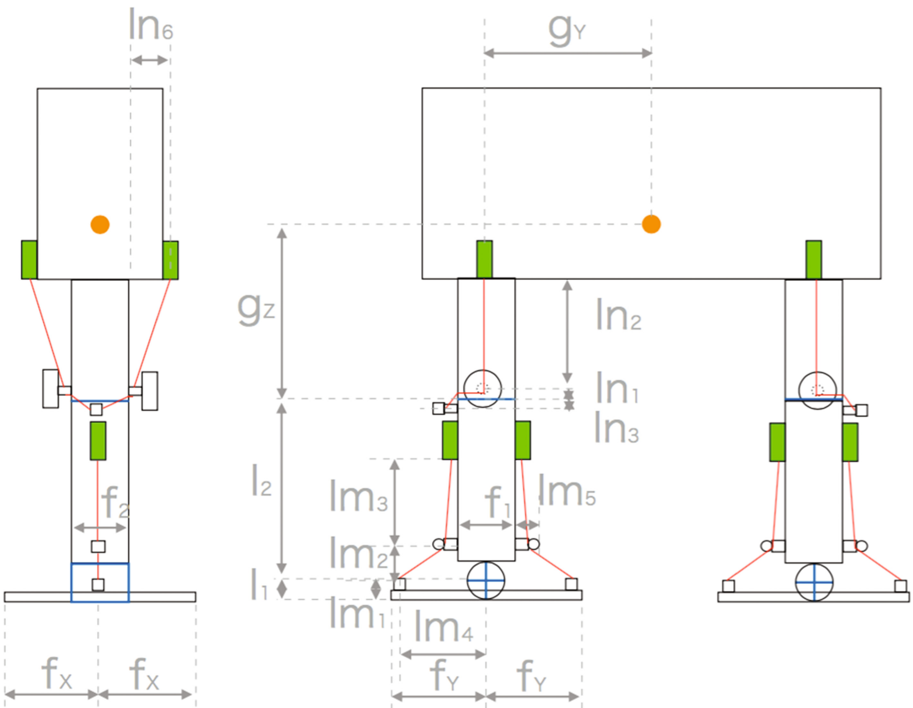


Fig. 6. Engineering drawing of bipedal robot with linear actuators

In a subsequent project, designed to for an even deeper involvement with mechanical concepts, students have been asked to replace the rotational motors by linear actuators and consider the mechanical and kinematic properties, e.g. maximum force required, as opposed to the previous project with all components given.

Figure 6 shows an engineering drawing taken from a student report indicating the linear actuators (green boxes attached to body and legs) and strings with a guiding system to transmit the forces (red liens, attached to the actuators). Furthermore, the dimensions, required for calculating forces and estimating the behavior are given.

Figure 7 shows another design with a rigid coupling of the drives and a spring to replace one of the motors on each leg. In order to address the kinematics the student added the local coordinate system to his sketch. Taken from another report, we see the sketch of the robot's path, used to estimate the step width and speed of locomotion (Fig. 8).

All projects were designed to deepen the understanding of specific aspects of the lecture. The two examples indicate how the focus of otherwise similar setups may be controlled by the design of the project.

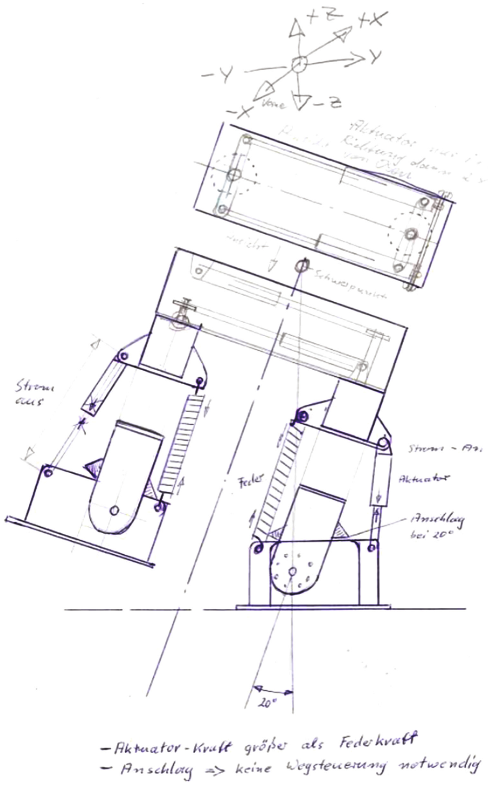


Fig. 7. Alternative bipedal robot concept

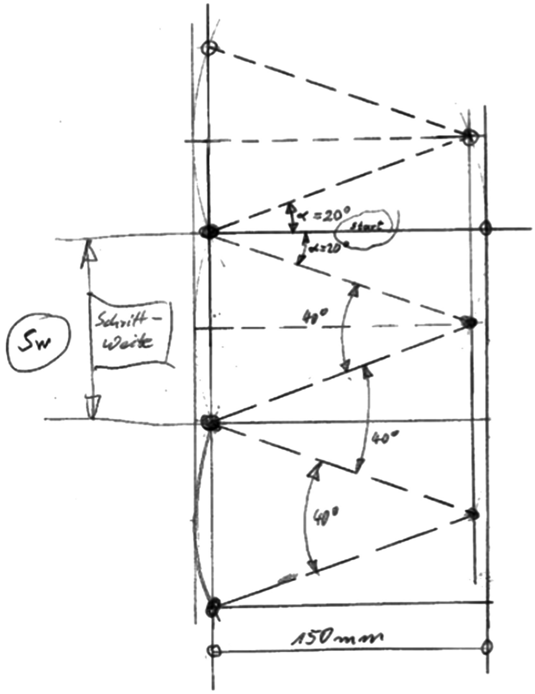


Fig. 8. Concept of locomotion

5.2 Mixed-Reality Robots

In this project, we aim to build and work with a number of cheap differential drive robots. These robots are remotely controlled. A central vision system provides the robots with pose and position. Each and every robot is controlled – independently from the other robots – via an infrared interface by a computer.

The project was so huge, that we split it up into a number of smaller sub-projects:

- Designing and building the robots
- Controlling the robot including implementing low-level operations
- Playing football with the robots

Sub-project: Designing and building the robots

The goal of this sub-project was to design and to build a cheap differential drive robot using a 3D-printer (see Figs. 9 and 10). Furthermore, the robots should be tested with focus on mechanical tests.

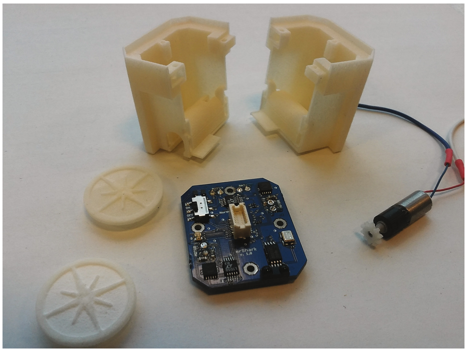


Fig. 9. Elements of the differential drive robot

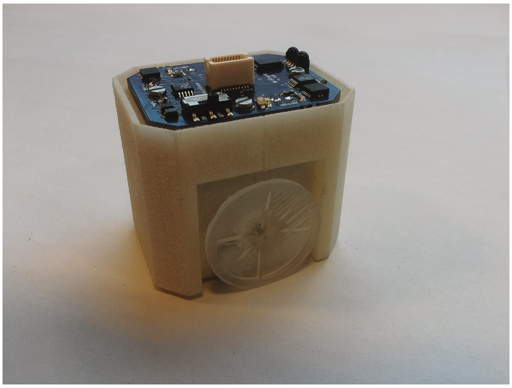


Fig. 10. Assembled differential drive robot

Sub-project: Controlling the robot including implementing low-level operations
The first aim of this sub-project was to establish the communication between the robot, the central vision system, and the computer – via a central server. Secondly, the most important low-level operations like moving forward, moving left, etc. have to be established. The functionalities should be tested performing some kind of integration test.

Sub-project: Playing football with the robots
In this sub-project the students should generate autonomous agents based on the results of the two precedent sub-projects. The goal is to build autonomous agents that are able to interact with each other in order to play football on a mixed-reality football field (see Fig. 11).

The sub-projects have been designed in such a way that the foci were on different categories of the concept inventory (Table 3). Test results – the tests were conducted in the first robotics lecture – helped us to build teams and to distribute them on the different sub-projects.

Fig. 11. Mixed-reality soccer game

Table 3. Categories addressed by the sub-projects

Category	Sub-project 1	Sub-project 2	Sub-project 3
Mathematics	×	×	×
Numerical methods	×	×	×
Mechanics	×		
Control theory		×	
Stability			
Kinematics		×	
Dynamics		×	
Sensing		×	
Perception		×	×
Planning			×
Navigation			×
Decision-making			×
(Dealing with) uncertainty			×
Robot Design	×		
Human-robot-interaction			
Artificial intelligence			×
Project management	×	×	
Electronics	×	×	
Programming		×	
Exploration			×

6 Conclusions and Outlook

In this paper we presented an application of concept inventories on project design. Categories of the concept inventory – we have chosen the robotics concept inventory as an example – have been taken as guidelines to design projects. This approach allows us to make a certain kind of internal differentiation in order to help students to eliminate weaknesses.

We have just started with this kind of project design. The first results of the described approach were promising. Nevertheless, we have to collect more data in order to get valid results.

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