A LEGO/FPGA-Based Platform for the Education of Cyber-Physical/Embedded Systems

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ABSTRACT

This article reports an ongoing project, an educational platform for cyber-physical/embedded systems by using Lego equipments and Fpgas. The platform targets the projects in lab exercise and practical training for both undergraduate and graduate students with a multidisciplinary background. The current version of the platform has been firstly applied to a lab course in the summer semester 2013 and an updated version will be used for both a practical training at the summer break and winter semester lecture of the same year. A first-hand feedback is also presented from the students that jointed the lab course.

1. INTRODUCTION

Cyber-physical systems (Cps) refer to the integration of computation with physical processes [8], where embedded computers monitor and control the physical processes. The design of such systems, therefore, requires knowledge of computer hardware, software, and system integration. The education for qualified engineers for Cps/embedded system design needs to consider multiple disciplines with hands-on experience thereof. There are several universities that offer graduate level programs in embedded systems. A few prominent ones are, e.g., [15, 4, 14]. The corresponding practical syllabus is also reported in e.g., [6, 1].

The platforms used in the aforementioned programs are course-specific, i.e., lectures at different semesters will use rather independent experimental platforms. Our concern is that whether there is a systematic platform that can be used for both graduate and under-graduate education, such that students can use this platform in a more consistent manner for different practical exercises during their studies. A few requirements that we have in mind are: a) The platform can be reused/extended for practical exercises and courses at different education levels, from basic `C` programming to high-level hardware/software co-design. b) The cost of platform, including both hardware, software, and development toolchain, must be low. In this regard, open source tools are preferable. c) Most important of all, the platform itself has to be interesting enough to motivate the students. It should not be too complicated for junior students, at the same time, not too toyish for senior students.

Another observation is that, within only 30 years, the amount of software has evolved from zero to tens of millions of lines of code in a typical modern vehicle. Additionally, the number of Electronic Control Units (ECUs) have grown from less than ten to dozens [2, 3] in the same time period. A current premium car, for instance, implements about 270 functions that a user interacts with, deployed over about 70 embedded platforms. Altogether, the software amounts to about 100 MB of binary code [2]. The next generation of upper class vehicles, hitting the market in about five years, is expected to run up to 1 GB of software. Therefore, we consider the Cps/ES development for vehicles will become a major job market for EECS students. To cope with this trend, the newly established School of Mobile Information Engineering (SMIE) [13] of Sun Yat-Sen university, for example, has developed a such division specific for vehicle intelligence.

Being aware of all these facts, we started this project, building a Lego/Fpga-based vehicle platform, a primary version of which is shown in Fig. 1. The original idea of using Lego is inspired by the Lego Technic 9398 offroader [9] released in March 2012. The Lego 9398 is a crawler with dual live axle suspension, quad portal axles, and all wheel steering, which is “cool” for students. Based on the 9398, we developed a new version, integrating the Siemens eCorner concept [5], where each wheel unit consists of a traction and steering motors. With this design, arbitrary numbers of wheels can be attached to the chassis depending on the requirement. This design provides a scalable setup for the lab platforms, from simple control of single wheel to more challenging control for multiple wheel units.

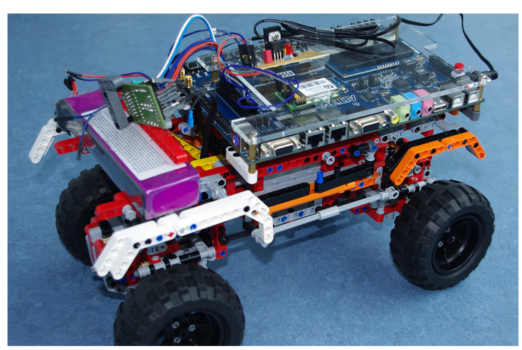


Figure 1: A version of the Lego/Fpga-based vehicle.

For the control electronics, Fpgas are chosen. The reason for choosing FPGAs, rather than the popular low-cost credit-card-sized BeagleBone, Raspberry PI, and Arduino boards, is that the FPGA vendors usually provide sophisticated toolchain and IP libraries for software and hardware design. For instance, the ALTERA Quartus II web edition, the one that we currently use, is free of charge and provides most of the needed functionality for our use cases. The integrated toolchain also allows students more focus on the design itself, rather than tedious tooling, e.g., setting up cross compiling environment. Currently, the DE0-nano and DE2-115 development boards are used, the academic prices of which are $ 59 and $ 299, respectively. Choosing the DE0-nano board is essential w.r.t cost, as one of our use cases, the 10-day SMIE practical training in the summer break of 2013, will involve 288 under-graduate students.

This platform is currently served as a reference design for a lab course (10 ECTS) [7] in the summer semester of 2013. We also design a set of software/hardware exercises for the fresh-man practical course in the summer break at SMIE as well as the "Networked Embedded Systems" lecture (5 ECTS) for 5th semester students at the Munich School of Engineering.

In the rest of the paper, we will present the mechanics (Section 2), electronics (Section 3), and overall system integration (Section 4). A set of software/hardware exercises and a first-hand feedback are presented in Section 5 and Section 6. Section 7 concludes the paper.

2. MECHANICS

The original idea of using LEGO is inspired by the LEGO Technic 9398 offroader [9] released in March 2012. The LEGO 9398 is a very cool design with dual live axle suspension, quad portal axles, and all wheel steering. Another reason of choosing LEGO is that LEGO is well recognized and is probably available allover the world.

Based on the 9398, we followed the Siemens concept of eCorner [5] and built a LEGO version using the 9398 components. Basically, an eCorner wheel unit consists of a traction and steering motors. With this design, arbitrary numbers of wheels can be mounted onto the chassis upon requirements. Thus, the design also provides a scalable setup for exercise platforms, from simple control of single wheel to more challenging synchronization for multiple wheel units.

(a) 88003 L-Motor (b) 88004 Servo Motor

Figure 2: LEGO motors (Figures from LEGO website).

2.1 Traction Motor

The traction motor that we use is the newest 88003 L-Motor [10], as shown in Fig. 2a. The motor is driven by a 4 pins 9V connector. It delivers a maximum torque of 45.4 mNm (450 mA). Without load, its rotation speed is around 380 rotations per minute (RPM) and current consumption is 120 mA. The actual current consumption depends heavily on the load it is driving. Under normal conditions it can be around 225 mA and the official website does not recommend a continuous use above 450 mA.t The motor is also tested under 12 V and 1.3 A with which it works fine for a short time period[1].

For the 4-pin connector, only C1 and C2 pins (see Fig. 6) are used as power lines. By applying PWM to one of C1/C2 while setting the other to 0, the motor turns with the speed according to the duty cycle of signals. Changing the signal line will change the rotation direction. The working frequency is 10 Khz.

2.2 Steering Motor

The steering motor that we used is the latest 88004 Servo Motor [11], shown in Fig. 2b.

The Servo Motor can turn from -90 degree to 90 degree and it receives PWM with duty cycle from 0% to 100%. According to the official website, it has in total 15 positions, i.e., 1 center position, 7 clockwise positions, and 7 counter-clockwise positions. Based on our measurement, its initial state is in the middle and its stable states are corresponding to the duty cycle of -5%, -15%, -30%, -45%, -60%, 0%, 5%, 15%, 30%, 45%, and 60%. Negative values represent counter-clock direction.

The controlling signal is also PWM but in which the width of the pulse determines the position (angle) of the motor shaft and the amount of increment or decrement in the pulse width determines the speed of rotation. The signal must be sent every 20ms (50 Hz) and the range of duration for the motor is 0.5ms (0 degree) to 2.5ms (180 degree).

The Servo Motor uses the same 4 pins 9V connector. It can accept the PWM frequency upto 10 Khz.

2.3 eCorner and Chassis

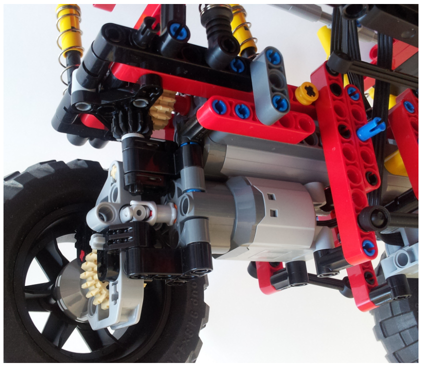
The original 9398 uses one Servo Motor to steer all four wheels and two L-Motors to drive the front and rear axles, respectively. To bring in more flexibility, we followed the eCorner concept from Siemens and integrated a wheel with one L-Mortor and one Servo Motor.

The basic concept of the Siemens eCorner is to combine the drivetrain, steering, shock absorbers, and brakes into the wheels. This concept is promoted by the well recognized drive-by-wire technologies where the mechanical controls are replaced by electronic ones. This design allows more freedom to design electronic controls which perfectly fits our needs.

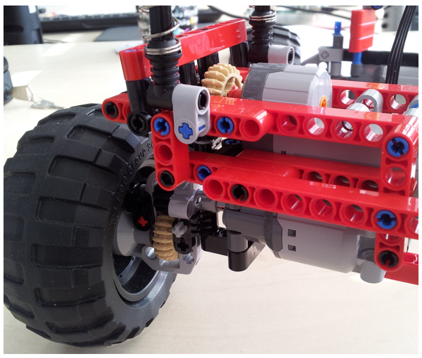
Designing our LEGO eCorner was however not easy. The main reason is that we intended to use only the components shipped with the 9398 package. Under the limited space and the predefined components, the design of the drivetrain was challenging, especially, fixing the transaxle of the the drive shaft for both motors. Nevertheless, we found a way to cope with this challenge. The design is shown in Fig. 3.

With the eCorner, the design of the chassis is rather simple, as the drivetrain has been integrated into individual wheels. The chassis is, basically, a frame which only needs to be strong enough to hold the electronics that are put on top. We used the 9398 suspension components to connect the wheel units and the chassis. A 4-wheel version is shown in Fig. 4.

[1]Running the motor with this setup is at ones own risk.

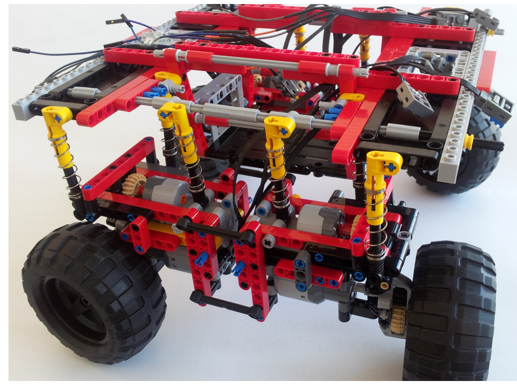


(a) Inner view



(b) Outer view

Figure 3: LEGO eCorner wheel unit.



(a) Top view

(b) Side view

Figure 4: Design with 4 eCorner wheels.

With this design, one can actually mount arbitrary numbers of wheel units to the chassis to build different types of vehicles. This opens the opportunity for advanced exercises, like controlling and synchronizing multiple wheel units to steer the vehicle with different moving patterns.

3. ELECTRONICS

For the control electronics, FPGAs are chosen. The reasons for choosing FPGAs, rather than the popular low-cost credit-card-sized BeagleBone and Raspberry PI boards, are that the FPGA vendors usually provide sophisticated toolchain and IP libraries for software and hardware design. For instance, the ALTERA Quartus II web edition, which is free of charge, provides functionality for most of our use cases. For software exercise/lab, the ALTERA Nios II soft core can be used as the microprocessor to run the software code. For hardware exercises, customized designed IP can be directly rendered to the FPGA.

LEGO NXT is another option widely used as an education platform. However, there are some drawbacks of this platform considering CPS/ES education. The drawbacks are summarized as follows. i) The cost of single unit is considerably high. Considering the prices for LEGO-specific peripherals, the total cost of a system will rocket up. ii) The LEGO NXT does not support `C`. Since `C` is the mostly widely used programming language for CPS/ES systems, the support of `C` is essentially important. iii) The computing power of LEGO NXT is limited. As modern embedded systems demands high computing power and are moving towards multiple cores, the educational platform should reflect this trend. iv) The LEGO NXT is a toy that most of the students in the western world have had during their school years. It is now time to move beyond. Otherwise, the students will lose there interests.

3.1 FPGA-based Control

The DE0-Nano board is a low-cost FPGA solution from Altera. Apart from the benefits of availability of free tool-chain and IP libraries from the vendor, the FPGA is an ideal platform for education. Typically, students learn in a bottom-up approach. They are introduced to the complexities of current digital ICs and the lowest level logic. Due to available resources in "nano" size on this board, they learn to use resources in an efficient way. For example, during our course, students realized that their ELF[2] was too large for the available on-chip memory and they had to optimize their code. Moreover, apart from different core components (caches, FPU etc) they also got familiar with the peripherals such as I/Os, processor interconnects, JTAG UARTs etc. The students also learned about various sensing components, such as accelerometer, Analog to Digital Converter (ADC) etc. FPGA development is, sometimes, very frustrating as well. That helped us in teasing patience of students.

Considering the future extensions, the FPGA is an ideal solution for control applications. Following are some of the advantages. i) Pulse counters for motor encoders

[2]ELF(Executable and Linkable Format) is standard file format for UNIX-like systems

can be efficiently implemented without over-loading the processor. ii) Controllers, such as PD, PID can be efficiently implemented. The core is only responsible for setting parameters. iii) Response time is negligibly small.

The DE0-Nano board features the Altera Cyclone IV 4C22 FPGA. It can be powered by either USB or a battery. The board contains one 8 channel ADC and an accelerometer. Numbers of I/Os are provided using three expansion heads. Moreover, the board contains 32 MB SDRAM and 2 Kb EEPROM as off-chip memories.

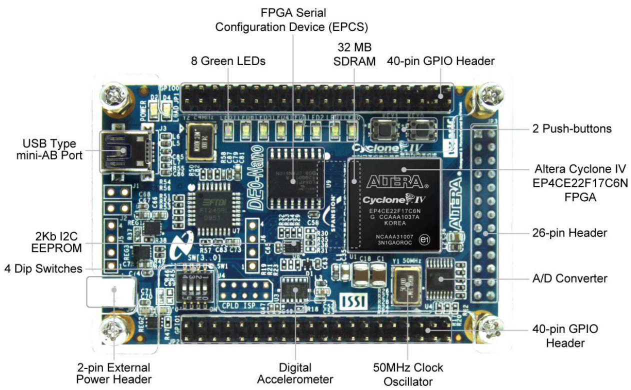


Figure 5: The top view of Altera DE0-Nano board (Picture from Altera website).

The Fig. 5 depicts the board and its components.

3.2 PWM IP

A hardware Pwm generator is designed to control the motors. The Pwm generator is implemented in VHDL and conforms to the Altera Avalon specification. This PwmIP can be configured by software running on the Nios II core to generate Pwm waveform with different duty cycles and frequencies.

This PwmIP generates 2 output Pwm waveforms. Ideally, it is designed to control the two motors of an eCorner wheel unit. To support more wheel units, additional Pwm IPs have to be instantiated in the Fpga.

Now we can see the advantage of using Fpga, as synthesizing more Pwm IPs into the system is rather straightforward. On the other hand, designing a software Pwm component on BeagleBone, Raspberry PI, or Arduino boards may be cumbersome, as one may face situation of lacking hardware timer or multi-thread runtime environment.

4. SYSTEM INTEGRATION

To put things together, we still need a motor driving circuit to transfer the controlling signal from the Fpga to motors while isolating the control unit from the high voltage units.

The driving IC that we choose is L298N. The L298N is an integrated monolithic circuit in a 15-lead Multi watt and PowerSO20 packages. It is a high voltage, high current dual full-bridge driver designed to accept standard TTL logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors. Two enable inputs are provided to enable or disable the device independently of the input signals. The emitters of the lower transistors of

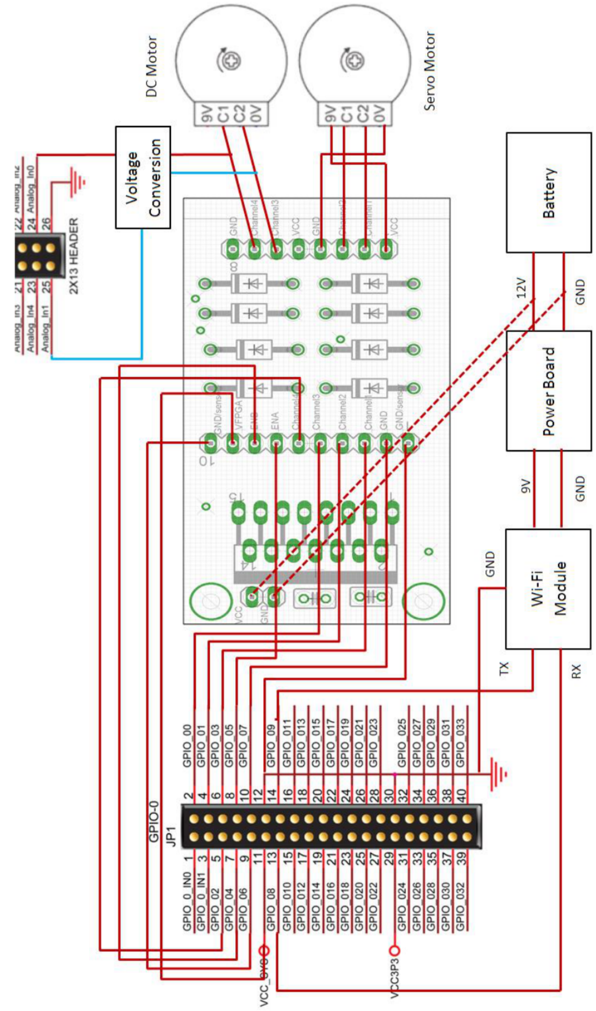


Figure 6: Block diagram of the final setup

each bridge are connected together and the corresponding external terminal can be used for the connection of an external sensing resistor. An additional supply input is provided so that the logic works at a lower voltage. The maximally operational current and supply voltage are up to 4 A and 46 V, respectively.

The final setup of the platform for one eCorner consists of a power supply unit, the DE0-Nano Fpga board, the RN131 Wi-Fi Module, the motor driver circuit, and the voltage conversion circuit. The connections between the Fpga board and the aforementioned components are shown in Fig. 6. All connections are on the GPIO 0 of the DE0-Nano board. The back EMF is measured using the on board ADC. the voltage conversion circuit is used to convert the back EMF signals to the Fpga board. The Wi-Fi module is connected to the FPGA board using UART. Note that the DE0-Nano board has sufficient GPIO pins to connect four eCorner wheel units.

With respect to the price, the total cost of a 4-wheel platform shown in Fig. 4, including all the Lego components and electronics, is less than $ 300. Considering it is a full-fledged vehicle platform with 4-wheel steering and drive, we believe that this platform is cost effective.

5. LAB DESIGN

This platform will serve as the experimental platform for the fresh-man practical training at the summer break 2013 at SMIE [13] as well as the "Embedded Networked Systems" lecture (5 ECTS) for the winter semester at the Munich School of Engineering (MSE) [12] of Technical University Munich..

The practical training for the SMIE is 10 days full-time course during the semester break. The students to be trained would have just finished their first year bachelor study, with basic knowledge of `C` programming and digital circuits. Therefore, the goal of the practical training is to provide hands-on experience to what the students have learned on a real-world platform.

The "Embedded Networked Systems" lecture is a 5^{th} semester lecture for bachelor students at MSE. The MSE is based on the innovation concept of combing interdisciplinary research and cross-faculty teaching. Therefore, although the lecture is scheduled in the 5^{th} semester, the students have similar hardware/software knowledge to the SMIE students.

Being aware of the background of the students, a set of software/hardware exercises are designed. The software exercises mainly focus on the control of I/O peripherals with `C` program. For instance, exercises on simple control, interactive control by polling and interrupt, and PWM control of external motors, are designed. Standard `C` exercise like memory overflow and volatile variables will also need to change. Note that all exercises are designed to run on the DE0-Nano boards.

For hardware exercise, we have different setups. Since the SMIE students are at end of their first year, the exercise we planed is to assemble the system presented in Section 4 with all pre-available components. In this way, the students will have a clear understanding of what a CPS/embedded system looks like. For the MSE students, in addition to the integration exercise, we design advance tasks, like adding new PWM IP to the system and feedback control for the motors.

6. FEEDBACK

The current version of the platform has been applied for a smaller scale lab course (10 ECTS) for hardware/software co-design at the summer semester 2013. The lab course hosted 14 students who are split into three groups. Each group works on a specific topic. In principle, the students are expected to work on their projects 6 hours/week during the semester.

The platform previously presented served as a reference design, based on which the students can mount different sensors, e.g., camera, infrared, and laser, to assist the driving systems. The students are also allowed to change the mechanics of the vehicle.

We just got the first-hand feedback from the students. The statistics of the feedback is graphically shown in Fig. 7. From the figures, we have the following observations.

- Figs. 7a-7f are about the setup of the lab course. From these figures, we can find out that the students like such kind of lab course and consider the experience obtained from course useful. Indeed, the students were initially attracted by the LEGO platform to attend the course, as reflected in Fig. 7f.
- Figs. 7g-7i are related to the task setup. Fig. 7g is particularly interesting, where 71% students were highly interested in their tasks. This is a strong evidence that our platform is successful for educational purpose.
- Figs. 7j-7l are related to the course materials. This set of figures does not show the same good reviews as other sets of figures. The reason is mainly due to the late shipment of the required electronic components, as also reflected in Fig. 7i.

In general, we consider the designed platform a success for attracting the interest of the students and introducing them to CPS.

7. CONCLUSION

This paper presents a LEGO/FPGA-based platform for the educational purpose of CPS/ES systems. The platform is powerful and flexible, at the same time, low cost. With around $300, a full-fledged toy car can be built. With the eCorner design, the platform can be extended to x-by-wire vehicle models of different shapes. Feedback from a lab course shows the popularity of the platform. In fact, the course has been so attractive that the number of student registrations is twice the capacity for the same course in the following semester. In the second half of 2013, two other types of courses will use this platform for exercises. We will continue on the development of the platform and keep track of the students feedback.

8. REFERENCES

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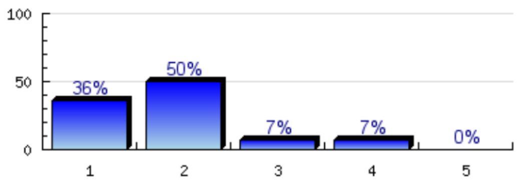
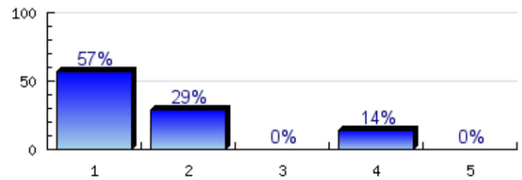
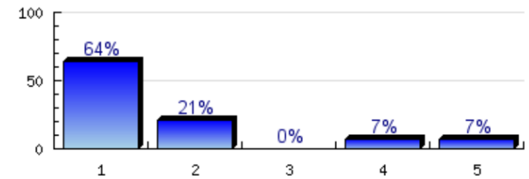


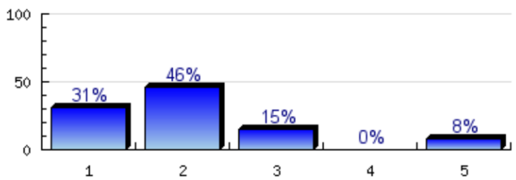
(a) The class met my expectations.



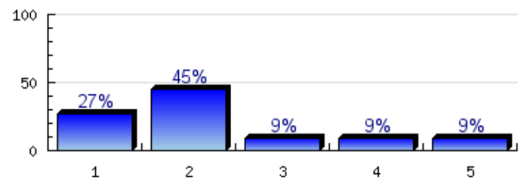
(b) Learned something new in the class.



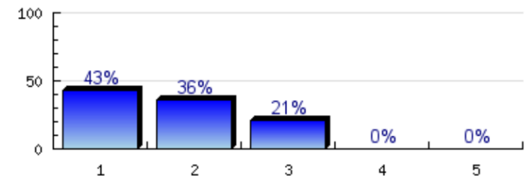
(c) Would recommend the class to a friend.



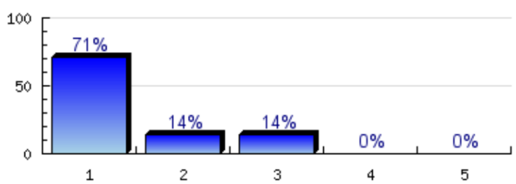
(d) I will be able to apply what I learned in this class in the future.



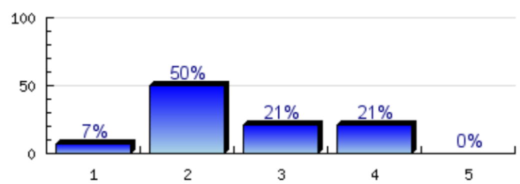
(e) I learned things that will be helpful for my future career.



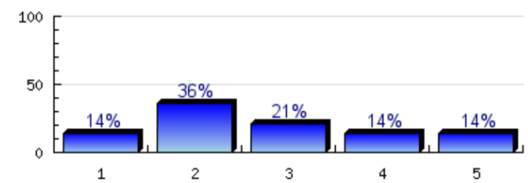
(f) The class was mainly a fun hobby course for me.



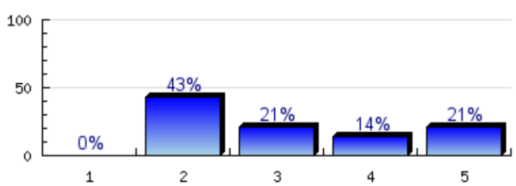
(g) The task was interesting.



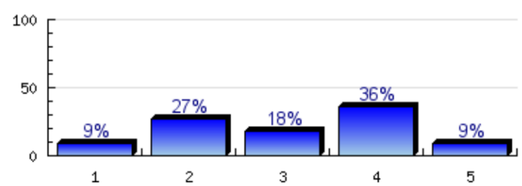
(h) The instructor made clear what the task for the work groups was.



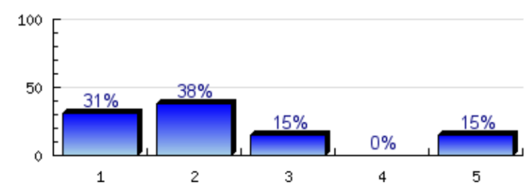
(i) I had all the resources I needed to successfully complete the task.



(j) The instructors presentation slides were well structured and contained the relevant information.



(k) The provided seminar material / written instructions / handouts were informative and helpful.



(l) The building material / equipment provided for the task was adequate.

Figure 7: Feedback from the lab course this semester. 1 to 5 represent degrees from "Yes, very much" to "No, not at all".