Teaching Cyber-Physical Systems in Student Project Groups: How Do Alumni Assess the Experience in Retrospective?

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Abstract: The development of Cyber-Physical Systems (CPS) requires software engineering competences in an interdisciplinary context including physics, mechatronics, and electrical engineering. In addition, social skills and teamwork competences are necessary since the current complexity of CPS exceeds the capacity of a single human. The Computer Science faculty at the University of Oldenburg offers project groups (PGs) in the Master's curriculum to particularly strengthen these competences. To this end, small teams of students work jointly during two semesters on large software or systems engineering problems, which are often inspired by research projects with industrial partners.

In this paper we report on a survey that we conducted among alumni of a set of nine PGs that worked on different challenging CPS problems. The main questions were how alumni who already started their professional career assess the learning experience and different aspects of the design of the CPS PGs in hindsight. The responses indicate a good learning success on the main learning objectives of the considered CPS PGs, and a large majority of respondents considers the course to be comparably relevant or very relevant in the overall Master's curriculum.

Keywords: Software Engineering, Systems Engineering, Cyber-Physical Systems, Project Group, Alumni-Survey

1 Introduction

Cyber-Physical Systems (CPS) are already omnipresent in our daily lives and are still increasingly entrusted with safety-critical tasks in domains such as transportation systems, medical devices, or factory automation. Among the characteristics of CPS are the aspects that they need to interact with a physical environment in a reliable, timely, and safe manner. Hence, the development of CPS requires competences from many different disciplines including physics, mechatronics, electrical engineering, and of course computer science. The latter contributes competences from areas such as embedded HW/SW design, real-time systems, control theory, and software and systems engineering methods that deal with the high quality demands, the particular care that is needed for functional and extra-functional properties, as well as mixed criticality components and Safety Integrity Levels (SIL). Last

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but not least, CPS development needs to be economic in the sense that the necessary quality is achieved with bounded time, effort, and costs.

Education for research in methods and tools for CPS as well as for the development of CPS is correspondingly challenging in a traditional curriculum which only relies on instruments like lectures, exercises, seminars, individual projects, and single term practicals. Each of the above areas of knowledge and competence can easily define its own module, but time constraints usually do not allow adequate application of the techniques to more than rather small toy examples. In addition, there is the challenge to address one aspect that is particularly relevant to CPS development: That CPS development is not only about technology but about humans [LL07]. Today's CPS have reached a complexity level that by far exceeds the intellectual capacity of a single human engineer thus CPS development requires particularly strong soft skills such as social interaction, written and oral communication, and adequate attitudes towards responsibility. The Computer Science faculty at the University of Oldenburg has a long tradition of approaching many of these challenges with an instrument called *project group* (PG) in the graduate studies (optional since the 1990s, compulsory with the introduction of the Master's degree). A PG is a module that runs for two semesters (one year) with a workload of 24 ECTS (or 16 hours per week). The enrolled 6-12 students stay together for the whole duration and complete a project in a team. The team starts from a given, relatively open problem definition, which needs to be detailed by the students for a complete development cycle up to the complete realisation of the solution. Similar modules are offered, e.g., at TU Dortmund or the Universities at Bonn and Paderborn.

In this paper, we consider a particular PG design with the purpose to address the above mentioned educational challenges of the domain of Cyber-Physical Systems. We report on an effort to investigate one of the most relevant questions in teaching: How well does the module meet its challenges? Do students learn a lot and do they acquire the right knowledge and competences? As it is notoriously difficult for students to help in an assessment of these questions *during* their studies, we have taken the effort to conduct a survey among students who have already completed their studies and started their professional career. To obtain an as large as possible data set, we approached participants from nine completed CPS PGs and invited them for a questionnaire on how they look back on their PG experience.

2 Related Work

Marwedel et al. and discuss different curricula in the direction of CPS [Ma20]. The authors talk about the challenges in the CPS area and an important one was the interdisciplinary education. The authors also see a problem in the usually limited resources in terms of personnel, time and often also financial means. It also reads that teamwork is the key to bridging the different disciplines needed in the CPS field. However, long-term team-based projects were only marginally mentioned and not sufficiently discussed.

In [BS12] a 12 week course about CPS design is described. The authors write, that CPS design requires a broad field of knowledge and often there is not enough time to teach all aspects in detail. In [Go15] a 17 week project-based learning approach is used. The authors support the claim, multi-disciplinary projects can help to learn optimization across different engineering disciplines. [LSJ12] reports about capstone projects, which are 2 semester single student projects. They mention the impact on the career trajectory of students. In [TH16] the authors observed that interpersonal skills like working in cross-disciplinary teams are important in the CPS domain. They also believe that capstone projects are an important part of CPS education, which is a bit contradictory as they are handled by individuals. Student projects in team size 4 are described in [Li13]. The project covers the steps of requirements analysis, implementation and testing. [Sc11] describes one semester student group tasks with a size of 8 students. The paper places particular emphasis on the importance of group work. Our PGs often have a team size of 12 people and runs for two semesters. This allows us to pose a much more complex problem formulation. In addition, the size of the group means that there is a much greater need for coordination. Capstone projects, on the other hand, cover relatively complex problems but do not include the very important aspect of teamwork. Also in [Wa15] the challenge of interdisciplinary education is mentioned. The authors describe their approach to implement a 4 course approach on education in CPS. The courses cover the complete life cycle of a system and it also seems to be a complex system. However, the project theme seems to be the same in each cycle. The topics of our project groups are always different.

In [St20] a survey is done about a project-based course design afterwards. The course design was well accepted and the students found it very interesting. Repetitive interviews and questionnaires are used in [Ri17] for evaluation of a 16 week model-driven engineering CPS project class. In [Be22] a survey is done to evaluate a practical oriented one semester classroom and lab approach. None of the surveys mentioned above includes the alumni perspective and thus the effects of such projects on the later job.

3 Project Groups for Cyber-Physical System Education

The PG module in the Master's program at the University of Oldenburg in general has two major learning objectives. Firstly, to strengthen competences related to teamwork (cf. [Ma20]), including (self-)organisation and management of teams, resolving conflicts, taking responsibilities, and information and document management. Secondly, to provide an environment where students can experience larger problems than what can be handled by tiny teams of 1 to 3 persons. This includes the challenge to deal with imprecisely stated, hardly manageable requirements, the possible need to develop partial solutions, and the need to establish appropriate quality assurance measures.

In this paper, we consider a particular design of such PGs that includes particular challenges from the domain of Cyber-Physical Systems. The most obvious particularity of this PG design is the consideration of (special purpose) hardware and its interaction with a physical

environment together with the necessary software software development. Fig. 1 gives brief outlines of some concrete instances of the PG design reported on here; the experience of PG 'AA', for example, even turned into a publication [Sc15] which gives many more technical details. From the descriptions, we see that the considered problems have been designed to include embedded hardware and aspects of control theory, hard real-time constraints, and mission or safety-criticality. Such problems allow us to address a number of learning objectives that are specific to the domain of Cyber-Physical Systems. Firstly, to include budget planning in the project management (students need to buy parts of the equipment from an available budget) as well as time management for resources (there needs to be a schedule of who is using the prototype hardware for testing when). Secondly, to deal with interdisciplinary projects and address particular challenges to the organisation of the work (PG participants need to specialise to solve the problem but have to be sufficiently familiar with other specialisation areas to integrate the partial solutions; also, CPS PGs need to use a much more heterogeneous set of development tools than pure software PGs). There are also higher demands wrt. thorough risk-analysis and management. It is, for example, a risk that hardware is not delivered in time, that electronic components are harmed by electrostatic discharge effects, or that the whole system is damaged in trial runs. Overall, students should experience the importance of well-defined roles (at least project manager, test manager, and document manager) and the importance of thorough requirements analysis, component specifications, and quality assurance measures (errors in these activities can usually not just be work-around-ed in software in CPS projects).

From the teaching perspective, there are two main challenges towards reaching these learning objectives. One is not to over- or under-strain the students: At the beginning of the project it must be clear that the problem (or a sufficiently large sub-problem) can be solved with the given amount of work (6-12 students, 24 ECTS each)and taking into account the uncertainties mentioned above. The second one is fair marking/grading since students need to obtain individual marks/grades by the study regulations. The first challenge is addressed on different levels. Problems for CPS PGs are usually inspired by subjects of active or completed joint research projects including the University of Oldenburg, research institutes, and partners from the industry. Most of the PGs considered here were carried out in close corporation with the research institute OFFIS e.V.[1] This approach ensured the availability of domain experts who were able to conduct a preliminary analysis and develop a sketch of a "shadow plan" before offering a PG to the students. Integrating members of the research institute as supervisors (and in some cases industry representatives as external mentors) was perceived very valuable since all nine PGs from Fig. 1 completed in time with impressive results. Individual conversation during and directly after the PGs indicate that students understand that they are working on scaled-down variants of real, industrial CPS problems, which, together with the creation of a real, tangible product and the self-determined work in the project, have a very positive effect on the motivation, the enthusiasm, and creativity. Consulting the "shadow plan" helps in assessing the progress of the PG and can be a basis to

[1] In 2022 the transportation department of OFFIS e.V. transferred to German Aerospace Center, Institute of Systems Engineering for Future Mobility.

SmartSystems – 4Wheeler (2004/05). This PG developed a 4-wheeled, remote-controlled robot capable of mapping. They used several sensors (ultra sonic, camera, laser), and combined FPGA implementations and real-time algorithms.

Eye Fly (2007/08). This PG developed a steady camera system inside of a rolling ball. Part of this project was to merge 12 camera images via image processing to one all-round view.

Mobile Solar Power Plant (2012/13). The PG Mobile Solar Power Plant developed a solar driven power plant involving ether a Stirling motor or a solar cell. The system included an automatic sun position adjustment mechanism.

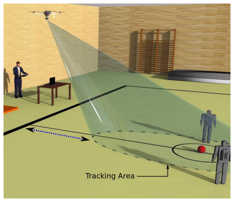
ViDAs (2009/10). The PG *Virtual Driver Assistance* developed a driver assistance system for use in simulation environments with a model-based approach using Simulink. The functionality included a lane change assistant, traffic sign recognition and an adaptive cruise control which considered the detected traffic signs. The students also had to develop sensor models based on real sensors.

Guardian (2016/17). This PG implemented a satellite control system on four Xilinx Zynq-7000 FPGA boards and simulated an asteroid interception mission in a simulation called Kerbal Space Program. The students also had to develop a fault injection methods for their testing phase.

MHA2 (2005/06). This PG developed an FPGA-based mobile PDA capable of running a special hearing aid development software (MHA: Master Hearing Aid). The students developed their own FPGA circuit board and implemented several audio filter functions in hardware.

Micro Urban Challenge (2008/09). This PG developed a small scale autonomous car using a simulation-based development approach. Highlight of this project was stereo-camera based traffic light and traffic sign detection system.

AA (2014/15). The PG *Avionic Architecture* specified, implemented, and tested a mixed-criticality multi-rotor system. The task was to integrate a safety-critical flight control algorithm with a mission-critical payload processing on a single chip. The topic was inspired by an industrial use-case in the research project CONTREX (https://contrex.offis.de).



EmBrAAC (2018/19). The PG *Emergency Braking Assistant for Fully Autonomous Cars* developed a safe evading manoeuvrer for an autonomous vehicle based on the F1TENTH car with guaranteed execution times. The students modelled the system with contracts to ensure correct timing requirements and verified their system through measurements later (correct-by-construction method).

Fig. 1: Goals and achievements of nine PGs on Cyber-Physical Systems.

decide on when supervisors need to intervene (which was only necessary once so far due to a system dynamics model that turned out to be too optimistic compared to the reality). This pre-planning is not visible to the students. They obtain the problem in an intentionally brief and imprecise form during a few introduction sessions. The students acquire the necessary knowledge to analyse the problem in a seminar phase, and develop a system specification, a project plan (with own milestones) for a fixed deadline within the first months and structure their way of working on their own, Results are presented at a mid-term and a closing event. In addition, there is continous supervision in the form that a small team of supervisors offers counselling in weekly or bi-weekly project meetings. While the students are supposed to

take all decisions on their own, the supervisors may recommend re-assessments if the plans seem to over- or under-ambitious.

The marking/grading approach is based on a scheme with three parts. A student's final mark is determined by a mark for the overall result, a mark for teamwork, and a mark for individual work. The mark for the overall result is based on the project report. Here, it is in our experience important to communicate to the students that even if the PG problem is not perfectly solved, this can still be a very good PG result if the technical reasons are well understood and documented. Otherwise, students may assume that a non-perfect solution counts as a failure which would cause unnecessary strain. The mark for teamwork is assigned by the supervisors according to a detailed marking scheme (including aspects like presence/absence of complaints, responsible assumption of roles, offered or refused cooperation, etc.). The individual mark is based on the contributions of the student to the project as declared by the student. Interestingly, this step has been remarkably smooth in all nine PGs: the teams were always able to agree on who takes credits for which parts. In addition to informal feedback during the team meetings, there is one mid-term review where each student receives individual feedback; earlier interventions are conducted on demand.

All nine PGs from Fig. 1 were successful measured by the marks and the organisers' impression and were subject course evaluations. The design has also been refined over time, for example, later PGs did not schedule all students' seminar talks into a fixed slot in the beginning of the PG time but scheduled the presentation closer to the point in time where the expertise was needed. Yet, course evaluations usually only take place *within* the study times, so a long standing question was how former participants of CPS PGs perceive the learning experience and success in hindsight, after some time or professional work experience.

4 Alumnis' Assessment in Retrospect: Survey Design

The goal of this study was to collect data on the retrospective view on previous PGs on Cyber-Physical Systems. To this end, we have considered participants of nine already completed PGs from a time period between 2004 and 2019 with 93 participants in total. Of these students, 65 were approached individually using the mechanisms of career-oriented social networks. We sent a contact request first which, if accepted, was followed by an explanatory email including a link to the online survey site. with the questionnaire. The site was online for 4 weeks, participants did not receive any reminder after the first message.

Data was gathered by an online survey without the possibility to identify the particular participants. The questionnaire is structured into five parts (cf. Tab. 1). The first block consists of questions for demographic data (current age, and sex). The second block asks for the context of the current employment (where multiple of the three options 'Research', 'Development', 'Teaching', and 'Other' can be selected) as well as the current branch (to be selected over a list of standard branch names). The third and main block asks for a subjective assessment of the learning experience in the PG wrt. nine competence areas,

- How old are you? [..25/..30/..35/..40/..45/..50/50..] • Sex? [f/m/d/prefer no answer]
- In which context are you currently working?
  [Research/Development/Teaching/Other; multiple choice]
- In which branch? [single choice over a list of standard branch names]
- During the course of your PG, how much did you learn wrt. the following topic: Project management (leading projects, approach, . . .), self management (own way of working, time management, . . .), taking responsibility, presentation of results, social interaction, documentation, programming, development of hardware, testing?
  Each rated on a six-valued Likert scale from ‘nothing’ (1) to ‘a lot’ (5).
- Did you get to know new management tools during your PG time? [y/n]
  Conditional (if ‘y’): Which? [free text] How often do you use one or more of the previously named tools? [five-valued Likert scale from ‘not at all’ to ‘a lot’]
- Same questions as before for “dev. tools” and “technologies (languages, hardware, etc.)”.
- How relevant do you consider the project group in comparison to other modules in the Master’s studies? [five-valued Likert scale from ‘not relevant’ to ‘very relevant’]
- How did you perceive the grading/marking in your PG?
  [five-valued Likert scale from ‘not fair’ to ‘very fair’]
- What did you particularly like about your PG? [free text]

Tab. 1: Questionnaire design.

namely project management, self management, taking responsibility, presentation of results, social interaction, documentation, programming, development of hardware, and testing. The fourth block asks to name tools and technologies that participants got to know during their PG time, and requests a subjective assessment of how often at least one of the named tools the participant uses at the time of the questionnaire. The fifth block focuses on the didactic aspects of perceived relevance of the instrument of PGs in the curriculum and the perceived fairness of markings. The last question is an open question for particularly liked aspects about the respective PG.

5 Alumnis’ Assessment in Retrospect: Survey Results

Of the 65 students that were contacted, 47 completed the form. Hence, the survey achieved a remarkable response rate of over 72 %, even without a reminder message or particular incentives connected to filling in the form, and for some students years after finishing their studies. The distribution of sexes in the group of respondents matches the one in the set of candidates and is about equal to the overall distribution in the Master’s programme. There is thus no indication that certain sexes particularly choose or avoid CPS PGs. There were responses from almost all age groups so we can assume that the responses refer to multiple

different PGs. Age below 30 was reported by 15 participants, between 30 and 35 another 8, and over 35 the majority of 22 responses. The exact age was not asked for since the answers should not allow to conclude to the particular PG a respondent referred to.

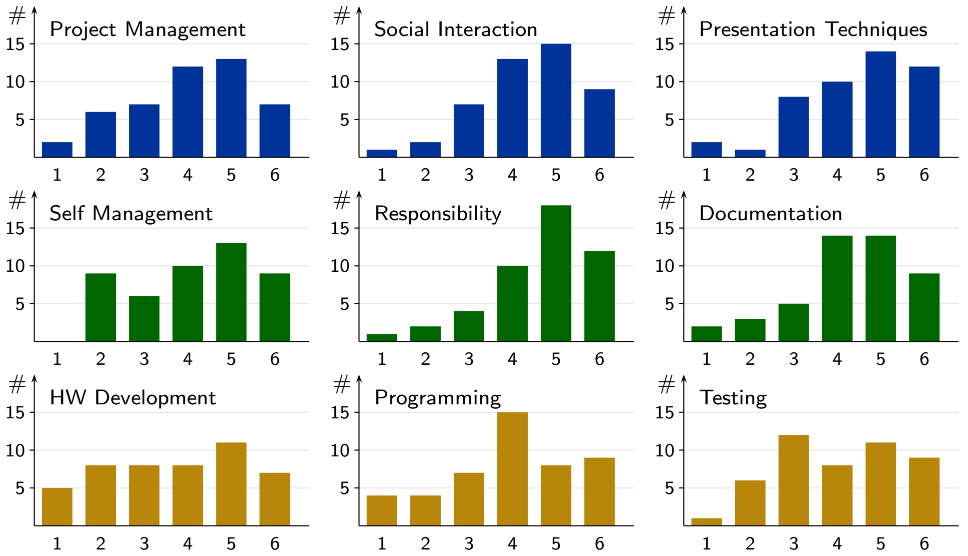


Fig. 2: Subject area learning experience (abs. number of responses, cf. Tab. 1 for the scales 1–6).

Responses regarding the current branch were less informative, probably by a sub-optimal choice of pre-defined branch names. The highest number (29.8 %) is for ‘automotive’, followed with a distance by ‘service’ (8.5 %), ‘transportation’ (6.4 %), and ‘maritime’ (4.3 %). Under ‘other’ (31.9 %), respondents reported ‘energy’ (3) and ‘mechanical engineering’ (3), ‘software’ (2) and ‘robotics’ (2), and one each for ‘university’, ‘navy’, ‘home automation’, ‘agriculture’, and ‘online sales’. The remaining branches were not selected in any response. Regarding the context of the current employment, 16 respondents named ‘Research’, the majority of 30 named ‘Development’, and 5 named ‘Teaching’. Multiple choices were possible, there are 5 overlaps between ‘Research’ and ‘Development’, and 4 overlaps between ‘Development’ and ‘Teaching’. Five participants did not answer this question at all.

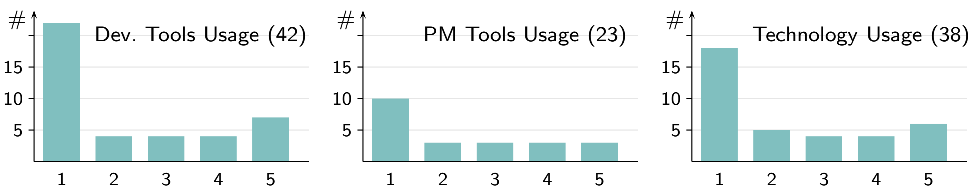


Fig. 3: Usage of tools and technologies met *newly* in PG, hence the number of responses here (in parentheses) is lower than overall questionnaire responses (cf. Tab. 1 for the scales 1–6).

The plots in Fig. 2 give the absolute numbers of responses on the Likert scale for three aspects of learning with three questions each. The first aspect (blue in Fig. 2) is the way of

working in a team, including project management (leading projects, methods, . . .), social interaction, and presentation or communication techniques. The second aspect (green) is the own way of working, including self-management (time management etc.), taking and delegating responsibility, and the documentation of results (for oneself and for team members). And there are the technical aspects (beige), here programming, testing, and (as a particularity of the PGs considered here) hardware development.

In total, 42 respondents (89.4 %) stated that they did got to know new development tools, namely modelling tools (Matlab, Simulink, Stateflow, Scade, CAMeLView; 28 mentions overall), chip development tools (Xilinx Vivado, Altera Quartus, etc.; 16 mentions overall), and more generic development tools (LaTeX, make, git, Redmine, etc.; 8 mentions overall). Some project management tools were new to 23 respondents (48.9 %), including Redmine, Jira, MS-Project, Traq, and Slack. Some technologies were new to 38 respondents (80.9 %), including programming languages[2] (C, C++, Ruby, Python, Assembler; 15 mentions overall), CPS hardware (development) technologies (VHDL, FPGA, System-on-Chip, microcontroller; 13 mentions overall), and specific solutions (CAN, I2C, SPI, etc.; 4 mentions in total). Fig. 3 gives responses to the question for how often at least one of these tools and technologies are used; note that these questions were only presented to those participants who stated that they did got to know a new tool or technology.

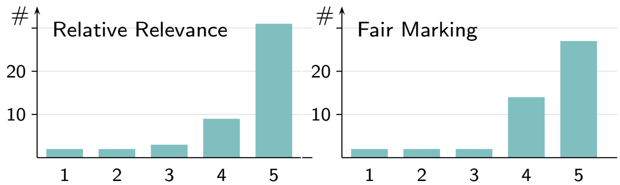


Fig. 4: Relative relevance and fairness of marking. (See Tab. 1)

Regarding the questions on teaching aspects of the considered PGs, only 7 responses consider the PG (much) less or equally relevant compared to other modules in their study plan (except for the Master's thesis). Only 4 respondents indicated that they perceived their marking to be not or less fair (cf. Fig. 4). For the free text question on what participants particularly liked, about half of the respondents named the cooperation in the team (40.4 %). A larger number of responses named the practical experience (14.9 %), the large size of the problem worked on in the PG (17.0 %), and the long duration of the module (6.4 %). Other aspects were the dedication of the supervisors (6.4 %), that new topics were addressed (8.5 %), the possibility for a related Master's thesis (4.3 %), and the degree of freedom that the task statement permitted (4.3 %).

6 Discussion

The survey presented in Section 4 is designed to investigate three main questions: Firstly, how do alumni assess the learning success in hindsight, after completion of their studies, and with some experience from a working environment? Secondly, how do alumni assess

[2] Java is the most taught language at the University of Oldenburg.

the relevance of the teaching instrument of PGs in hindsight and how do they feel about the fairness of their marks/grades? And thirdly, how appropriate is the choice of CPS problems, tools, and technologies for the PGs?

Regarding learning success, Fig. 2 shows that that a large majority of responses leans towards 'learned a lot' (Likert values of 4 and above) for project management (68.1 %), social interaction (78.7 %), and presentation techniques (76.6 %). If we consider the values of 5 and above, we still have 42.6 %, 51.1 %, and 55.3 %, respectively. These results indicate that the CPS PGs presented in Section 3 clearly reach the learning objectives in the perception of the responding alumni. Recall that the PGs take place in the graduate studies, hence the students have clearly been exposed to opportunities to practice social interaction and presentation techniques before and still report to have learned a lot in the PG. Whether these results can be attributed to the focus on CPS is unclear since we are not aware of comparable survey data from PGs that do not focus on CPS. By construction (cf. Section 3), CPS PGs clearly provide particular challenges in these aspects.

For the learning aspects responsibility and documentation, the majority is even larger (85.1 % and 78.7 %, respectively for 4-and-above), yet a bit more diverse for the stronger criterion (63.8 % and 48.9 %, respectively for 5-and-above). The responses on responsibility indicate that CPS PGs can substantially strengthen this aspect, in particular as the numbers for 'learned nothing' are very low. The responses for documentation look comparable and indicate a good learning gain. This may be considered surprising because students practice (written) documentation from their first semester on in homework exercises, individual assignments, and the Bachelor's thesis. A difference to keep in mind is that these documents are usually prepared for a single reader (usually the teacher), while many PG documents need to be effective for multiple readers towards the project goal. Our observations during the project groups confirm that students can in particular learn a lot from documents that are not well written in their first iteration. The figures on self-management are a bit more balanced (68.1 % and 46.8 %, respectively). Still, it is interesting that graduate students in the Master's program report that they learned a lot on self-management given that the undergraduate studies already require quite good skills for this aspect.

For the more technical aspects, the results of the survey also do not indicate a strongly misguided PG design. The almost evenly distributed learning experiences wrt. hardware development match the PG design where each group develops a few hardware specialists who learn a lot while other participants are required to be able to at least follow the hardware development. Regarding programming, there is a peak of responses who lean towards 'learned a lot' but do not strongly agree. We take this as an indicator that the basic programming education in the previous study plan is well sufficient to participate even in challenging CPS PGs and that the special programming languages still provide learning opportunities for many participants. Similar for testing, here the previous education seems to have been even more successful since it is almost impossible to reach the results that the PGs considered here had without a very good test regime.

About two thirds of the respondents (cf. Fig. 4) selected the highest possible value for relevance of this module. This outcome is particularly remarkable, because the respondents of the survey state their impression in hindsight, after having completed their studies. The answers given to the free text questions further support the overall positive impression (cf. Section 5), among them some notable examples such as “the collaboration with the group members and also external partners strongly corresponds to my current working environment in research”, “the process of the project group was very much based on the development of a real product; I now work in software development and especially the application of process models helped”, and “in retrospect, I feel that the project group was by far the module in which I learned the most.” Responses on the question of fair marking indicate that these PGs can be conducted without sacrificing the need for fair individual marks at the end of the studies.

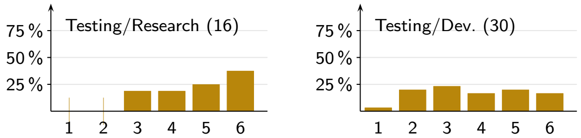


Fig. 5: Learning experience ‘Testing’.

Differentiating the data on learning experience (cf. Fig. 2) between the three contexts research, development, and teaching shows that the response distributions are not equal. Fig. 5 gives the distributions for the aspect ‘Testing’ as an example. It indicates that testing in development contexts has more aspects than can be covered in one PG while the majority is still on the positive side. Still, all responses for context ‘research’ report good learning success which indicates that the CPS PG design does not sacrifice the scientific aspect for the pure engineering part.

The majority (ca. 80 %) of responses states that some development tools or technologies were new in the PG. About half of the former students state that they still use at least one tool or technology that they got to know in their PG in their work environment, some even often. Those who do most often name Matlab Simulink, some even name the hardware oriented Xilinx tools. That only about half of the respondents got to know new project management tools does not come unexpected since the PGs employ lean project management approaches.

7 Conclusion

In this paper, we report the results from a survey to evaluate the effectiveness of our design of a project group that emphasises Cyber-Physical Systems education. The survey was conducted among alumni who participated in one of nine previously offered PGs. The survey had a remarkable response rate of over 72 %, given that the PGs ran many years back for some respondents. The responses collected here are particularly valuable since they come from former students who can assess the learning experience from the perspective of their current working environment. The results confirm that PGs on CPS provide good learning experiences with the main learning objectives focusing on aspects of teamwork and working with more complex problems. A large majority considers the course to be relevant or very relevant in the overall Master’s curriculum.

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