Robotics Education Under COVID-19 Conditions with Educational Modular Robots

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Abstract. The COVID-19 pandemic forces many robotics teachers to rethink their approach to education. Distance rules and the constant threat of a partial or complete lockdown leading to limited access to classroom equipment make it challenging to plan for hands-on education where students experience robotics by experimenting and studying with robotic hardware. On the other hand, this hands-on active learning experience is one of the strengths of robotics education and the ability to handle hardware equipment a substantial learning goal of study programs on robotics. In this paper we present and discuss the approach taken for the course Robotics and Embedded Systems at Maastricht University. The course had been adjusted to meet COVID-19 safety regulations and to allow for a fast seamless transition between onsite education at university and online education where students can work with robotic hardware at home. We share experience, best practice advice as well as educational material to help other teachers benefit from our developments. A key contribution is our custom-made, low-cost, educational modular robotic system for teaching kinematics, locomotion, and PID control that we make publicly available for replication through the website https://www.maastrichtuniversity.nl/edmo.

Keywords: Robotics in Education, COVID-19, Active learning, Blended learning, Personalized Learning, Modular Robotics

1 Introduction

In robotics education, students benefit from hands-on experience with robotic hardware that helps students engage in an active learning process [1] where students apply, test, and gain new knowledge by experimenting on real-world systems. This hands-on experience is beneficial for their learning and understanding as students learn best when they (I) experience course content in multiple modalities, (II) connect new knowledge to existing knowledge, (III) focus their attention on the learning experience, (IV) stay motivated to learn, (V) receive appropriate feedback early and often, and (VI) work on engaging collaborative

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and authentic experiences [2–4] - modalities that are facilitated by lab sessions where students actively interact with robotic hardware.

However, due to the COVID-19 pandemic and the consequentially required safety measures to protect the health of our students and teachers this core concept of robotics education, the intense hands-on experience, faces serious challenges. These challenges range from social distancing (i.e. keeping a minimum distance of 1.5 meters) during all educational activities to not being able to disinfect electronics and several types of robotic materials making it hardly possible for students to share robotic equipment and thus debilitate group work. Also due to the constant threat that countries or at least some regions have to undergo a complete or partial lock-down at short notice, educational institutions and teachers must be prepared to quickly adapt education to scenarios where onsite education in class is no longer feasible and students have to be taught at home. As a consequence of all these conditions, robotics education must be designed in such a way that a quick adaptation is possible while maintaining high educational standards and while meeting intended learning outcomes.

This paper describes the approach of and experience from the course "Robotics and Embedded Systems" of the Bachelor study program "Data Science and Artificial Intelligence" at Maastricht University, The Netherlands. The course has been taught during the COVID-19 pandemic from beginning of September until the end of October 2020. The course had been heavily adjusted to successfully address the aforementioned challenges of robotics education under COVID-19 conditions. With this paper, we share our experience in teaching robotics in higher education and provide other teachers with advice and open-source educational robotic hardware. We share experience and hardware in the hope that this provides meaningful insights and support for other educational institutions and colleagues. In particular, we are describing how we adapted the course to meet the conditions of the COVID-19 situation and to be able to switch between onsite and online education at short notice. A key tool that allowed us to maintain high safety standards and to let all our students study with their own robotic hardware is our custom-made, low-cost, robust modular robotic system EDMO. EDMO stands for EDucational MOdular robot as we developed the EDMO system particularly for robotics education. EDMO can be rapidly replicated through 3D printing and by combining low-cost off-the-shelf components. These are ideal properties if, like for our course, a large number of robotic setups have to be created to provide all students with personal hardware equipment to meet COVID-19 safety regulations. With this paper we extend our previously published EDMO setups [5] by additional and upgraded modules that we again make openly available for replication through the website https://www.maastrichtuniversity.nl/edmo.

2 Course overview and intended learning outcomes

An overview of the main components of the course on "Robotics and Embedded Systems" is provided in Fig. 1. The core of the course is formed by tutorials and

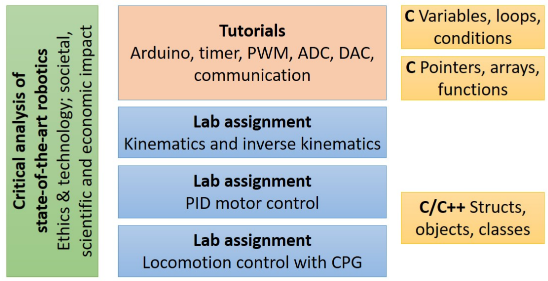

Fig. 1. Overview of course elements and content.

lab assignments that allow students to practice with electronic and robotic hardware. We let students practice with hardware, rather than simulations, so that students learn to create robust robotic control systems and to deal with physical effects like friction, backlash, and noise, which is one of the important intended learning outcomes (ILOs) of the course. Further ILOs - addressed by tutorials, labs, and lectures introducing knowledge on robotics, control, and mechatronics - include the ability to program embedded systems under real-time constraints for reading sensors, communication, and robot control. After successful conclusion of the course, students are able to apply three main control concepts: (I) control of kinematics and inverse kinematics [6] of a robot arm, (II) closed-loop PID motor control [7], and (III) locomotion control with central pattern generators [8]. Thus students can apply a variety of useful, widely used control concepts. Students also gain a better understanding of important techniques from mathematics and artificial intelligence including parameter identification and optimization as well as the application of (coupled) differential equations and numerical mathematics for modeling and controlling robotic systems. Next to control concepts, students receive a step-by-step introduction to learn to program in C/C++, an ability that students directly practice as part of tutorials and lab assignments. Every week students get introduced to additional state-of-the-art robotic systems that are critically analyzed and discussed regarding their technology, ethical implications as well as their societal, scientific, and economic impact. We included these discussions into the course because we want our students to be well aware of the impact of robotics and artificial intelligence on our society so that students can make ethically well-justified decisions during their professional career.

Despite the impact of COVID-19 conditions we were determined to maintain meeting all ILOs of the course. That included also those ILOs described before that require hands-on experience with electronic and robotic hardware. To meet all ILOs of the course and to prepare properly for a possible lock-down that would only allow for online teaching, we upgraded both our EDMO hardware and our teaching approach. Both adjustments are being discussed in the following sections.

3 EDMO Hardware Setups

During the course, each student was provided with three custom-made EDucational MOdular (EDMO) robot modules (EDMO-RM, Fig. 2b) and one custom-made EDMO DC motor module (EDMO-MM, Fig. 2g). Together, EDMO-RM and EDMO-MM form the educational modular robotic platform EDMO. All EDMO modules have been designed to meet the requirements of low costs production with small size, low-cost hobby 3D printers. The printing process requires only a single extruder and no support material.

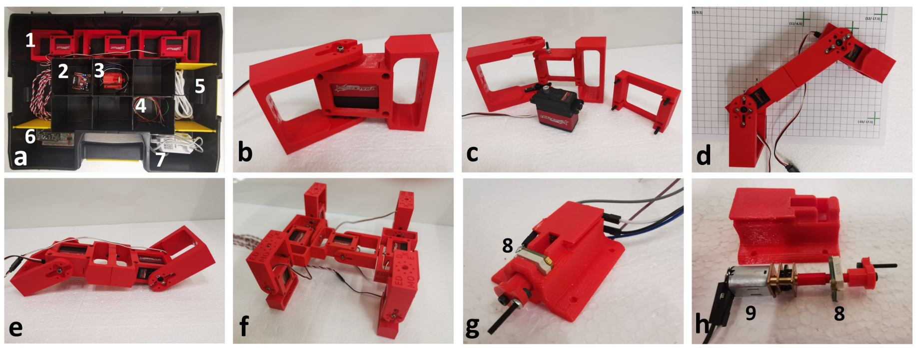

Fig. 2. EDMO hardware: (a) EDMO box ready for shipping to students. Box contains {1} three EDMO-RM, {2} DC motor driver, {3} EDMO-MM, {4,5} cables, {6} microprocessor and breadboard with electronic components, and {7} a DC power supply. (b) Assembled and (c) disassembled EDMO-RM. (d) EDMO robot arm made of EDMO-RM for studying control of (inverse) kinematics. (e) Snake configuration for studying locomotion control. (f) EDMO quadruped. (g) Assembled and (h) disassembled EDMO-MM containing {8} a rotary encoder and {9} a DC motor with gearbox.

3.1 EDMO Robot Modules

EDMO-RMs (Fig. 2b) were designed to create robust, versatile robotic modules from which a variety of robotic morphologies can be achieved including robot arms (Fig. 2d) for studying control of (inverse) kinematics and snake-like structures (Fig. 2e), but also full biped and quadruped configurations (Fig. 2f) for studying locomotion control. Also due to the modular design approach, without in-depth knowledge on the mechanic design of a robot, students can easily repair non-functioning robot configurations by exchanging malfunctioning robot modules.

Within a larger configuration, each EDMO-RM forms one module with a single hinge joint. Fig. 2c shows a disassembled EDMO-RM. EDMO-RMs combine a low-cost servo motor integrated into a custom-made 3D printed body and were designed so that their assembly and the replacement of the servo motor requires little skill. As a result, educational institutions can i.e. perform the production of EDMO modules at low costs with the help of student assistants that do not need to have a technical background. Alternatively, the assembly of EDMO modules can become an integrated part of a robotics course where students get asked to assemble those EDMO modules, that they are afterwards using during their lab assignments. We updated EDMO-RM version 1.0 (originally published in [5]) and created version 1.1 around the TrackStar TS-411MG digital servo motor with metal gearbox. Featuring a torque of 11.2kg·cm, the EDMO-RM version 1.1. is five times stronger than EDMO-RM 1.0 at an additional cost of €10.10. Due to the extra torque, EDMOs now support the construction of larger robot configurations and longer robot arms. Both EDMO-RM versions can be operated together in a single robot configuration. During the course, both EDMO-RM versions proofed to be robust in their application. All experiments could be carried out with only two EDMO-RM. We provided all students with three modules to allow them to quickly repair a robot arm or snake in case of a module failure. However, despite intensive use by about 40 students, no EDMO-RM was damaged. So in the end, students used replacement modules only to try larger and more sophisticated robot configurations, not to replace damaged modules.

3.2 EDMO DC Motor Module

In past years we have tested a variety of hardware configurations for education on PID motor control. A key challenge during implementation of PID control is that students have to take care of mechanical limits of servo motor components. Our strategy in past years involved supplying our students with low-cost servo motors from which we had removed the motor control electronics. Students would then read the angular position from the potentiometer inside the servo motor and drive the embedded DC motor through a separate motor driver board (L298N). If students would break some internal components of the servo motor, they would learn from this experience and would have to start with a new servo motor. With the risk of running into a shutdown of the university, we found this strategy of supplying replacement motors too risky and went for designing a new custom-made 3D-printed DC motor module, the EDMO-MM. EDMO-MM is designed to be very robust by combining a DC motor with metal gears with a N15TS-103A3030 rotary encoder from Amphenol Piher (Fig. 2g,h). By design, EDMO-MM supports continuous rotation and is operating without those mechanical limits that are typically found in standard position-controlled servo motors and that led to servo motor damages in past teaching. As a result, with EDMO-MM we did no longer encounter any motor failure during the course, despite intensive use, just two cases of not properly soldered cables that could be quickly fixed and can be avoided in the future.

3.3 EDMO Box

Situated in the heart of Europe and within 30 kilometers from the German and Belgian borders, Maastricht University attracts students that commute across country borders on a daily basis. The result is an international educational environment that is highly appreciated by both students and staff. However, during the COVID-19 pandemic where European countries prefer their citizens to avoid cross-border travels and where we experienced that safety and travel regulations can spontaneously change during a weekend, this forced us to develop additional strategies to ensure that all students would remain access to robotic equipment in case of strict travel restrictions. Also, several students from within the Netherlands faced the problem that they spontaneously could no longer come to class as they had been instructed to quarantine by Dutch health-care authorities at short notice.

Even if onsite education in class could have been maintained, during our course preparations it was not clear how long the COVID-19 virus can survive on surfaces of robotic and electronic hardware. Standard disinfection strategies are not applicable to electronics and robotic hardware since e.g. typical disinfection fluids and sprays can harm electronics and dissolve 3D-printed material. As a result, after careful consideration of alternative strategies we decided that our best option was to provide all students with their own hardware setups. Here we benefited from the chosen robotic and electronic setups that support rapid fabrication at reasonable costs. Through this rapid fabrication we have been able to provide all 41 students of our course with personal robotic setups. No sharing of hardware between students was necessary. Hardware production time was less than one month with a team of only three people. An item and cost list highlighting the main components as well as an upper cost limit can be found in Table 1. A detailed bill of materials is provided online at https://www.maastrichtuniversity.nl/edmo. We found that we can provide each student with a full robotic setup at a maximum costs of 145€ per student. Total costs can be further reduced i.e. by using mass production or by purchasing off-the-shelf components in large volume.

The small form factor of all hardware components allowed us to integrate and properly organize them into off-the-shelf plastic boxes (Fig. 2a) with a size of 44.2 cm x 33.2 cm x 9.2 cm as they are offered by standard hardware shops for storing and organizing hardware items. The box was chosen so that it could be shipped by mail to students that are prohibited to come to class. During onsite education, the outside surfaces of the box could be disinfected by students and staff while only students would have access to material inside. Thus, this organization would allow meeting safety standards during onsite education and would have enabled us to rapidly switch to online education without dropping intended learning outcomes that require hardware experiments.

4 Adapted Teaching Approach to Meet COVID-19 Conditions

Until before the COVID-19 pandemic, the course featured interactive onsite lectures, tutorials, and lab sessions. During tutorials and lab sessions teaching staff was moving in between students and joined them in debugging code and experimenting with robotic hardware. To challenge interested students and to provide additional support for those students requiring extra help, we applied aspects of differentiated instruction (DI). According to [9], DI involves providing all stu-

Table 1. Material costs (upper limits) for EDMO box and components

Component	**Costs [€]**
EDMO 1.0 robot module	
3D-printed body parts and fasteners	4.50
Turnigy^{TM} TGY-50090M servo motor	5.50
EDMO 1.1 robot module	
3D-printed body parts and fasteners	4.50
TrackStar^{TM} TS-411MG servo motor	15.60
EDMO DC motor module	
3D-printed body parts	3.00
RS PRO 6V brushed DC geared motor	15.20
Amphenol Piher N15TS-103A3030 rotary encoder	2.40
Electronics	
Adafruit Feather M0 Proto board	18.00
Adafruit Feather servo wing	9.00
L298N DC motor driver board	5.00
5V DC - 2A Raspberry Pi power converter	6.80
Breadboard, resistors, LEDs, switch, cables, and wires	16.80
Plastic box/organizer	20.00
Screwdriver	4.00
Total costs of box with 2x EDMO 1.0 robot modules	**<125**
Total costs of box with 2x EDMO 1.1 robot modules	**<145**

dents with a range of different opportunities for understanding new information and developing teaching materials so that all students of a course can learn effectively, regardless of differences in their ability. We applied DI i.e. by inviting all students to our robot lab, the DKE SwarmLab, where students struggling with tutorials or lab assignments got extra practice time and guidance. Excellent students got opportunities to explore and study material that went beyond core content of the course. Often students would also implement own project ideas with support by teaching staff.

When preparing the course during the pandemic we knew that we would no longer be able to maintain this open teaching approach where students could come to the lab whenever they wanted while properly considering COVID-19 safety restrictions. To provide all students with the opportunity to gain some onsite study experience at university including personal contact to teachers and fellow students, Maastricht University followed the guideline: "On campus, if possible, online, if necessary." To prevent infections, students had to keep a minimum distance of 1.5 meters at all times considerably reducing the maximum amount of students allowed in university buildings and lecture rooms. To meet these safety guidelines, classes had been split into smaller groups and students were no longer allowed within campus buildings outside scheduled class hours. Thus, concepts like our open lab were no longer possible. In addition during the pandemic, all courses must plan for the constant threat of a transition to fully online education that might come at short notice. During the first wave of the COVID-19 outbreak in Europe before summer 2020, we experienced that during a lockdown students travel to their home countries to escape loneliness. Since our study program proudly attracts international students from all continents we had to prepare education for students suddenly living in different time zones.

When replanning our course we asked ourselves how we can best get students engaged in active learning by experimenting with robotic hardware while closely following COVID-19 safety guidelines as well as prepare for a rapid switch between onsite to full online education if that would become necessary. Also, we wanted to use the limited contact hours at class (and online) in such a way that students benefit most from guidance by experienced staff. Finally, we wanted to maintain an effective form of differentiated instruction and personalized learning that targets the different needs and strengths of our students. To achieve these goals we reorganized the course following a variation of blended learning (BL) [10] and the flipped classroom approach [11]. BL is known for aiming to optimally integrate face-to-face teaching with online learning [10] with the goal of "using the web for what it does best and using class time for what it does best" [12]. BL does so by replacing or enhancing aspects of face-to-face classroom learning by online or technology-based experiences [10].

In our course, we combined elements of online learning with onsite hands-on tutorials and lab sessions supported by online group discussions and personal onsite discussions. For interactive online communication we used video conference tools like Zoom. Also, all onsite tutorial, lab, and discussion sessions had been planned in such a way that teaching staff could support students online through video communication while students would be working at home if a transition to full online education would become necessary. Course content was provided for self-studies online through a CANVAS platform in form of video lectures and reading material. The course was carefully planned so that students had enough time for self-studies and labs.

To optimize required contact time between teaching staff and students and to limit the number of required teaching assistants during tutorials and lab assignments, also for tutorials and labs we provided short videos with step-by-step instructions as well as videos with background information that students could watch on demand. For each tutorial session, basic and challenging tasks were provided targeting the different skill levels of students while ensuring that all students could reach the intended learning outcomes of the course. This organization of tasks in addition to providing all students with own hardware setups and by having teaching staff available to answer individual student questions led us to create a personalized learning environment [13] for all students that could be seamlessly transferred to full online education. Due to our experience from past years, we had been able to foresee and address many student questions in our video lectures. As a result, online and onsite contact hours could be focused on helping students who needed extra support or had additional questions.

A standard tutorial session was organized as follows: Each tutorial was separated into smaller sub-tasks and experiments. In preparation for a tutorial, students watched short introductory lecture videos at home and studied the required background material. Lecture videos were organized to address students with different background knowledge. All students were asked to study the core material. Additional background material was provided in text and video form to support the understanding of the core material where we expected that some but not all students would require additional information. Also during tutorials, students were watching short videos containing instructions using headsets to not disturb colleagues. There was a separate video for each sub-task. Each tutorial started with short, simple tasks that would become increasingly complex to provide an easy but rewarding start as well as some complex material for more experienced students. For the teaching staff, it initially felt strange to see students watch video instructions silently and to conduct experiments on their own without the involvement of any staff. However, we quickly found that this approach was rewarding both for students and staff. Students followed the tutorials at their own pace without feeling the pressure to keep up with or to wait for colleagues as they had during tutorials before COVID-19. Staff benefited from close interaction with students on interesting questions that often went beyond the standard lecture material, rather than answering basic questions repetitively. Students asked freely since they did not feel observed by colleagues. Also because students went at their own pace, students did not finish a sub-task at the same time. Thus, bottleneck situations where all students required support at the same moment could be reduced, a situation that we encountered more frequently before using video instructions in tutorials and labs. This unloads teachers and enables better communication with students.

During course preparation, we feared that video lectures used by students for self-studies according to the flipped classroom approach [11] would be less motivating for students to follow than the interactive lectures that we used to provide before COVID-19 and that as a result, students might delay their studies to a point where an effective exam preparation would no longer be possible. However, we found that hands-on tutorials and lab assignments significantly helped and motivated students to stay on track since to successfully work with electronics and robotic hardware, students had to study a well-defined amount of video lectures every week. Providing both basic and challenging tasks for all lab sessions helped significantly both students and staff to (self-)assess individual study progress and to identify content that required additional explanations. Typically students could remove study delays by themselves by concentrating on the essential parts of tutorials, skipping advanced content, and by gaining extra support by teaching staff. Since all students worked with their own hardware setups supported by video tutorials, we could provide enough flexibility so that students could shift content from one week to the next where required. In a few cases where students could not catch up and did not meet study progress requirements (typically caused by external circumstances, partially due to private COVID-19 situations) we offered an additional lab session targeted more specifically on the needs of the individual students and with intensified support by teaching staff.

Individualized hardware provided to each student played an important role in fraud prevention. Due to individualization of hardware setups, e.g. by using different motor gear ratios, different alignments of servo motors and rotary encoders, control parameters could not be copied one on one from one hardware setup to another. Students thus had to work intensively on their own setups to be successful.

During direct contact, students and staff have been wearing face masks and kept a distance. We also experimented with the use of video lecture tools like Blackboard Collaborate Ultra and Zoom to allow staff to ensure the correct wiring of electronics from a distance and to allow students sharing their computer screen either with teaching staff or to help each other with coding problems. In case of a lockdown where students would no longer have been able to come to class, we would have used these tools to keep supporting students at home.

Students were graded based on two lab assignments (PID control and locomotion control) that counted in total for 20% of the final course grade as well as a written paper exam counting for the remaining 80%. Depending on their preferences and conditions, students could take the final written exam onsite or as a proctored online exam. Lab assignments were graded based on software code and experimental results that students submitted in form of a video. We decided for video submissions as we made good experience with them in the past years and as they (I) allow good protection against fraud as students are asked to comment and explain their experiments with their voice and (II) allow for the documentation of moving robots. (III) In addition we chose for video submissions as they become a more and more common addition of scientific publications i.e. in robotics journals and conferences. Thus, it is essential that also students gain the skill to prepare such video submissions (course ILO).

5 Discussion and Conclusions

In this paper, we share our experience in teaching robotics and embedded systems under COVID-19 safety conditions. By adapting to a flipped-classroom approach with elements of blended learning and by using compact, robust, custom-made educational robotic modules, called EDMOs, we transformed the course in such a way that even under challenging COVID-19 safety regulations, students achieved those intended learning goals that require experimenting with robotic hardware. The paper presents the design and use of two new EDMO modules: a second-generation EDMO robot module with hinge joint and a new custom-made EDMO DC motor module for rotatory movements. Through their modular design and by supporting a variety of configurations, EDMO modules allow students to explore, study, and practice approaches for position control, control of (inverse) kinematics and locomotion. We further use EDMOs to teach the application of mathematics and artificial intelligence. All hardware discussed in this paper is made publicly available for reproduction at other educational institutions. The educational approach and material described in this paper are specifically designed to allow for a seamless switch between onsite and online education. Video lectures would allow students to follow the course even in different time zones while all robotic and electronic equipment can be packed so that it could be shipped to individual student homes in case of a total lockdown where teaching at university buildings would no longer be possible.

While teaching robotics with EDMO setups during the COVID-19 pandemic, we found that students embrace the opportunity to have their own hardware setups and to use these setups also for independent problem solving. Providing individual setups for all students was possible for us due to our custom-made EDMO modules that we could reproduce rapidly with few staff members at reasonable costs. Although initially skeptical, we were positively surprised by how well education with robotic hardware is possible despite strict safety regulations. However, preparation time for the adaptation of a robotics course to the new format and for providing sufficient educational material is not to be underestimated. Throughout the course, our students acted in a very professional and responsible way. Students were very understanding that the teaching format had to be adapted. Students also agreed to wear face masks to protect each other and teaching staff even before strict regulations had been passed. Sometimes we had to remind students to keep a distance. However, this is very natural during communication with friends and colleagues.

Table 2. Course evaluations provided by students.

Academic year	**# students who took the course**	**# students who evaluated the course**	**Course grade [Likert Scale]**	**Standard deviation (course grade)**	**Teacher grade [Likert Scale]**	**Standard deviation (teacher grade)**
2015	28	16	4.5	0.63	4.88	0.34
2016	23	4	4.33	0.47	4.75	0.43
2017	41	22	4.68	0.55	4.91	0.28
2018	24	9	4.4	0.9	4.6	1.0
2019	47	28	4.2	0.8	4.1	1.0
Mean evaluation - before COVID-19						
	32.6	15.8	4.42	0.67	4.65	0.61
Evaluation 2020 - during COVID-19						
2020	41	21	4.7	0.5	4.8	0.4

After taking the course, students at Maastricht University are invited to anonymously evaluate the course, its components, and teacher performance on a 5-point Likert Scale [14], where a grade of 5 corresponds to the highest level of student satisfaction and is rarely given by students. The results of the student evaluations for the presented course are provided in Table 2. Comparing student satisfaction during COVID-19 (course grade of 4.7) and before COVID-19 (average course grade of 4.42) shows the success of the course adaptation. Student satisfaction increased in comparison to last year and slightly outperformed the best-reached value so far from the year 2017. Also feedback by students in personal discussions was very positive. No intended learning outcomes had to be dropped and the level of difficulty of examinations remained at the same high standards we achieved before COVID-19. Average performance of students during the final written exam was similar to previous years. However, the passing rate of students taking the exam decreased from 91.7% (before COVID-19) to 82.9% (during COVID-19). So more students failed the final exam but those who passed received on average higher grades. From personal discussions with students, we know that this decrease in passing the exam was at least partially caused by personal circumstances due to COVID-19. The increase in student satisfaction in the course and teacher performance on the other hand shows that students did not make the course or teacher responsible for having to take the resit exam.

Overall, we conclude that despite safety restrictions, high teaching quality with hands-on robotics experience for students could be achieved. We envision that some concepts developed and tested due to COVID-19 restrictions will even be maintained after the pandemic. In the future we envision to maintain video lectures for core and background material as well as instructional videos for tutorials and lab assignments as they allow students to study at their own pace and as staff gets to concentrate on activities to better support and challenge students, meeting their capabilities and needs. Still as teachers we are looking forward to more personal interaction with our students again without the need of keeping large distances to students that often generate awkward situations where we either have to speak to each other with an unnatural loud voice or communicate through IT infrastructure despite being in the same room. We also plan to come back to our flexible open teaching approach where students get invited to join our robot lab outside class to pursue their research ideas.

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