Distance Learning with Hands-on Exercises: Physical Device vs. Simulator

Mikko Myllymäki
Kokkola University Consortium Chydenius
University of Jyväskylä
Kokkola, Finland
mikko.t.myllymaki@jyu.fi

Ismo Hakala
Kokkola University Consortium Chydenius
University of Jyväskylä
Kokkola, Finland
ismo.hakala@jyu.fi

Abstract— **This Research to Practice Full Paper presents a comparison between a physical device and a simulator in a distance learning context. Programming embedded devices is very commonly taught using embedded hardware. One of the most used solutions is the Arduino microcontroller platform, which allows small embedded applications to be built and commanded in a programming language. However, there are some challenges in using physical devices for educational purposes. These challenges are particularly acute in distance learning or when the course needs to be scalable to a varying number of students. To address these challenges, we explored the potential of a simulator as a replacement for a physical device. We implemented the course using both the physical device and the simulator and collected student and lecturer feedback and experiences. The results showed that the physical device is somewhat more concrete and motivating, but the simulator is also very well suited for the purpose. The technical solution did not seem to have an impact on course completion or workload. There are also some advantages of using a simulator over a physical device, such as the possibility to test electronic connections without fear of breaking down the equipment**

Keywords—Embedded Device, Simulation, Distance Learning, Arduino

I. Introduction

A common question when organizing distance learning is how to implement courses with hands-on exercises. There is a need for this type of activity, for example, when teaching IoT (Internet of Things) and embedded systems. One solution is to implement the course using physical devices. In the case of distance learning, the devices must, of course, be sent by post to students. This approach involves scheduling and scalability challenges. Another option is to take advantage of a simulator. In this case, the focus is on whether a simulator can pedagogically replace a physical device.

The course Introduction to Embedded Systems was delivered five times at the University of Jyväskylä during 2020–2021. It is a beginner-level course, and its main goal is to teach students how to command microcontroller hardware by programming. The course was intended to be hands-on, so it took advantage of the Arduino environment. The course was developed iteratively according to a design science model. For the first two course implementations, physical Arduino packages were sent to students, and they also had access to an Arduino simulator. In the latter three implementations, students had access only to the Arduino simulator. Students were required to make the necessary electronic connections themselves, whether using a physical device or the simulator. Another option would have been to provide students with preassembled hardware or a simulation platform.

This study takes a close look at student opinions on the use of physical devices and a simulator in learning. The paper also highlights the challenges and benefits of solutions from the educator's perspective.

II. Related work

Active learning and learning by doing increase learning motivation. Especially in learning programming, a deeper understanding also requires practical programming exercises. The efficiency of knowledge acquisition increases when a student can see and understand the practical application of what they have just learned [1][2]. Various electronic platforms offer the possibility to illustrate certain phenomena. Creating software using sensors, LED lights, and interactive sensors and components such as push buttons is more interesting than typical console-based programming [1].

Electronic platforms can be used for teaching purposes as physical devices or computer programs that simulate a physical device. There is a wide range of simulators available online, either open source or paid. An online simulator allows students to use a personal computer to practice programming embedded devices anytime and anywhere, as long as an internet connection is available.

Simulation is often used in the business world and, perhaps somewhat surprisingly, computer science education is not exactly at the forefront of using simulation in an educational context [3]. Falloon [4] found in his literature review that while no single agreed-to definition of computer simulations can be found, some characterizing features that are commonly associated with simulations can be identified from studies. These characteristics include the ability to manipulate variables in a virtual environment; the ability to form manipulable, computational representations of real or hypothetical situations or phenomena; and the ability to provide a dynamic, interactive, visualized learning experience. Often, simulations also include computer-based animations (like models, simulations, and virtual experiments) of scientific phenomena.

Although the results are often highly context-specific (i.e., the age of students, the application domain, and the techniques used vary widely), many studies have suggested that simulations can help learning [5][6][7][8][9][10]. Simulation-based programming instruction promises many benefits in contexts such as self-directed learning, learning by doing, and conscious and repetitive practice [3]. However, the difference between computer simulation and physical hardware, from a learning and teaching perspective, is not entirely clear. Nonetheless, it seems that the majority of science teachers and researchers define experimentation with physical hardware as a real "hands-on" activity, and the use of a simulation environment is more or less a trade-off that one has to make for one reason or another.

Some studies have found that real-world experiments are more effective than virtual experiments [11]. On the other hand, opposite results have also been reported [12][13]. Some studies have found that both are equally effective [14][15][16]. One perspective is provided by Jaakkola and Nurmi [5], who concluded in their study that combining a simulation environment with hands-on laboratory activities led to the best learning outcomes, but there were no statistical differences between outcomes for simulation and laboratory environments. Winn et al. [17] also came to a conclusion that favored combining both approaches. Kurniawan et al. [16] found that although there was no difference in learning outcomes between those using a physical device and those using a simulator, the physical device elicited greater interest in learning computing and increased student engagement. Similarly, Wu et al. [15] and Brauner [18] found that the use of a physical device promoted a more positive attitude toward the subject matter being taught. However, Kurniawan et al. [16] identified disadvantages associated with the use of physical devices. For example, students have to deal with hardware issues, and troubleshooting can be more difficult and time-consuming than using a simulator. In practice, therefore, more hands-on time is needed with a physical device than with a simulator.

III. Course Implementation

Over the years, a unique approach to teaching [19] has emerged in the context of a master's degree in computer science in University of Jyväskylä's joint institution Kokkola University Consortium Chydenius. In practice, there is no face-to-face teaching or real-time lectures. Instead, teaching is offered in the form of short thematic videos, where each video contains one subject area [20]. Teaching is done using a virtual learning platform and video-conferencing technologies for guidance and seminar-style teaching. Education is therefore entirely distance learning. Learning can take place in a flexible way, practically independent of time and place.

The specialization option for the master's program is Smart Systems. Students applying to enter a degree program must complete an introductory course prior to student selection. The course is called Introduction to Embedded Systems. The aim of the course is to provide a basic understanding of embedded systems and how to control them through programming. The course is based on lecture recordings and exercises. The first exercise is a written report on a scientific article in an area of the student's choice. The remaining four exercises are Arduino device programming exercises that build on each other and become increasingly difficult.

A few constraints have influenced the way the course is taught, as well as its content. The course was not intended to be entirely theoretical but to include hands-on activities. The course also has a strict timetable (due to the student selection process); it must be delivered in a relatively short time frame of approximately two months.

The number of students in a course can vary greatly and cannot be known in advance largely because the number of applicants is not known in advance. In addition, the number of already enrolled students attending the course varies greatly. These students may have a different specialization or minor in the subject. The subject matter of the course is such that there are also plans to offer it as an open course to large numbers of students in the future. For these reasons, all educational solutions for the course must be implemented in such a way that they can also be scaled up as required.

As mentioned, the course is not intended to be purely theoretical, but to combine a theoretical basis with learning by doing. For this reason, the course has made use of the Arduino platform. As the program is based on distance learning, the use of a simulator has been considered alongside the physical device. A wide range of Arduino simulators is available for use online. Some are paid, but open-source solutions are also available. We chose to use the Tinkercad simulator (www.tinkercad.com) because of its ease of use and visual appeal. Both the simulator and the physical hardware can be provided to students as a pre-installed configuration, or the students can be required to make connections themselves. The course used the latter approach.

The course was implemented five times. In the first two implementations, students were provided with the Arduino platform as a physical hardware package. They also had the opportunity to use the Arduino simulator from Tinkercad. In the latter three implementations, the students had access to the simulator only.

A. Physical Device

The physical device used for the course was the Arduino K000007 starter kit (https://www.newark.com/arduino/k000007/starter-kit-arduino-with-uno-board/dp/47W2965). In addition to the Arduino UNO board rev.3 and breadboard, the kit includes several common components that allow the implementation of a wide range of projects. The kit also includes a project book, where the projects presented provide learning tips for the course exercises.

B. Simulator

The Tinkercad simulator is a free program that runs in a web browser. It allows one to develop and test software code and circuits as if on a physical hardware platform and is compatible with the same IDE (integrated development environment) that real Arduino hardware uses. The Tinkercad simulator allows students to take advantage of an extensive list of off-the-shelf components. Components can be dragged onto a breadboard and connected with wires to a virtually modeled Arduino board. If desired, the connections can also be viewed as an electrical circuit diagram.

In the Tinkercad simulator, the user can change the properties of components such as resistors. Similarly, the user can change the data measured by sensors, such as light and temperature conditions, by moving sliders to adjust the simulated inputs. Components that require user intervention, such as potentiometers and weight buttons, can also be operated using the mouse during the simulation. Arduino can be simulated by programming the desired functions. Programming can be done in text-based C/C++ code or in Scratch using block programming. The simulator also includes a serial monitor to which the output of the code to the serial port can be directed.

Both the built circuits and the code associated with them can be easily replicated in Tinkercad. This makes it easier to perform multiple exercises if the work is constructed in such a way that the same electronic circuit is used in several exercises. The code can be exported in Arduino's own file format (.ino), making it easy to return the code from the exercises to the learning platform or to transfer it to the Arduino device for execution.

Tinkercad also enables the use of the so-called Tinkercad Classroom. It allows one to create a virtual classroom for students in a simulator environment, where students can be assigned tasks and the teacher can browse, edit, or comment on student work. The Classroom feature was not used in the course because it already used a learning platform that is widely used in the curriculum and students did not want to use a new platform for, for example, assignments or feedback on assignments. Each student therefore used Tinkercad as a personal simulation environment.

The Tinkercad Arduino simulator and the physical Arduino device are shown in Fig. 1.

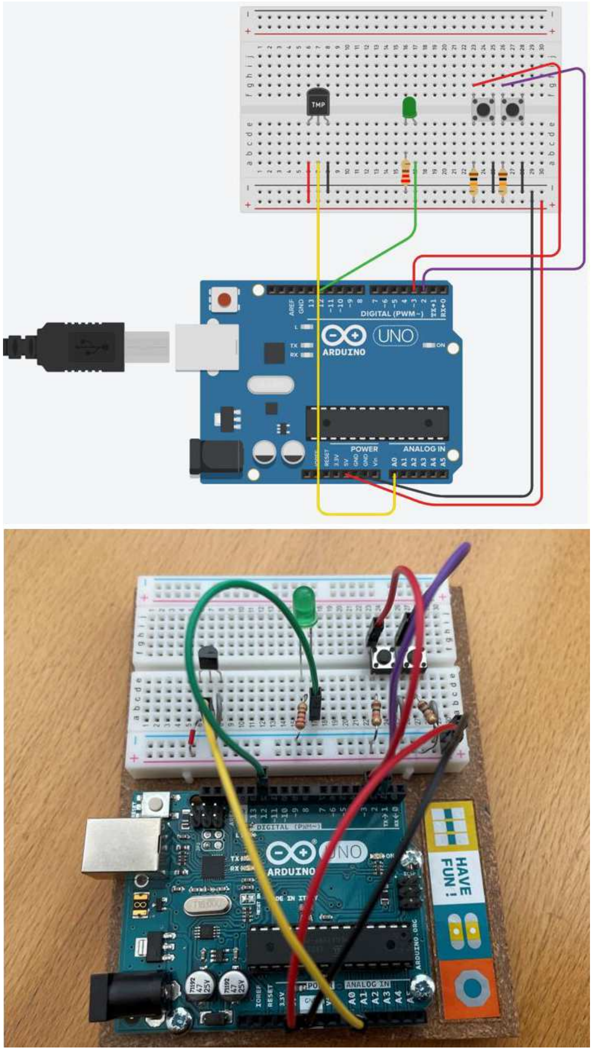

Fig. 1. Tinkercad Arduino simulator above and physical Arduino device below

IV. Study Design

The main research question of this study is whether the physical Arduino device can be replaced by a simulator when teaching embedded device programming at a basic level. To this end, the aim was to find out what the students' experiences are of using the simulator and the physical device and what are challenges and benefits of using simulator instead of physical devices from the educator's perspective.

The course Introduction to Embedded Systems was implemented five times between spring 2020 and autumn 2021. A total of 110 students participated in the courses. In the first two course implementations, students were sent physical Arduino kits by post and had access to a simulator. In the second three implementations, students had access only to the Arduino simulator. At the end of each course implementation, feedback was collected from students. The course feedback survey consisted of both open-ended questions generating qualitative data and questions generating quantitative data. This feedback was responded to by 44 students, of whom 19 were users of the physical devices and 25 were users of the simulators. In addition, the students kept a learning diary, which complemented the information provided by the students.

The data collected was analyzed using textual analysis. The qualitative data were supplemented by descriptive statistical analysis. One of the authors of this study was also a lecturer on the courses. However, the other author has no connection with the course. In this way, the bias of a single observer has been removed by a triangulation of investigators.

V. Results

The results approach the use of the simulator first through the students' opinions and then from the educator's perspective.

A. *Student Opinions*

The way the course was delivered was generally perceived as very motivating. Students in courses using the physical device gave the course a score of 4.6 on a scale of 1 to 5 for motivation, while students in courses using a simulator gave it a score of 4.4 for motivation. The implementation of the courses remained identical over the study period, except for the switch from the hardware to the simulator.

Of all the students who responded to the survey, 60% considered the simulator to be a fully functional solution for the course. The simulator was seen as particularly suitable for an initial, less demanding, embedded device programming course. This is illustrated, for example, by the citation below:

> *"The Arduino simulator was sufficient for the needs of the introductory course and was a good solution pedagogically. The postable devices are better suited for advanced courses."*

Opinion on the suitability of simulators was more pronounced for students who did not have access to the physical device. Almost 90% of these students considered simulators to be a more viable solution than physical devices. Some of these students' opinions, such as the one below, highlighted, for example, that the simulator always worked in the same way.

> *"Even with the limitations, I think the simulator works more consistently, so it's better for this initial stage of learning."*

As can be seen from the following two comments, other important factors for students were the accessibility of the simulator anywhere and at any time and the fact that it allowed them to carry out experiments without fear of the hardware breaking down. In particular, accessibility is a feature that students value in a training program, where flexible participation is a fundamental principle of learning.

> *"This [simulator] was a good solution. Certainly cost-effective and parts were not wasted, and work could continue anywhere. It was also good to see right away if the code worked or not."*

"This worked well. There was no fear that I would break the real physical device by connecting things incorrectly."

Of all students, 19% felt that it was possible to run the course using a simulator, but at the same time, they noted that there was an added value to the physical equipment that would be lost. In general, the added value of the physical device was seen as an increase in concreteness and meaningfulness. The students' responses reflect this:

"[The course] could be done well without a physical device. But then it might not feel so concrete. What excited me was that I felt like I was doing something real."

"It is always more meaningful to do it with real device, but if necessary, the course could be done on a simulator."

Some students, however, felt that a physical device would be a better solution for their needs and could not be replaced by a simulator; 21% of all students shared this opinion. As before, these students were of the opinion that the advantages of a physical device were mainly related to increased concreteness and motivation, as the citations below show:

"I prefer a physical device because tinkering with it is more meaningful and motivating than simulator wiring."

"I think that the tasks are more concrete when done on the device."

"Getting the right hardware to work is many times more motivating compared to a working simulation."

The opinion on the irreplaceability of physical equipment was more pronounced among the 19 respondents who had access to the physical device. Of them, 37% shared this view, while only 9% of those who had taken the course with the simulator agreed that a physical device would have been a better solution.

Student opinions on the suitability of the simulator for the course are detailed in Table I.

TABLE I. CAN THE COURSE BE DELIVERED IN A PEDAGOGICALLY MEANINGFUL WAY USING A SIMULATOR INSTEAD OF A PHYSICAL DEVICE?

	Yes	Yes, but something is lost	No
Physical device course (n=19)	26%	37%	37%
Simulator course (n=23)	87%	4%	9%
All (n=42)	60%	19%	21%

Although the importance of the physical device was slightly more pronounced among students who had access to it, they also saw added value in the simulator. About half of the students who had access to both the simulator and the physical device used the simulator, at least to some extent. For example, they used the simulator to test the connections before actual implementation. However, only a fraction of these students consistently used the simulator instead of the physical device. The simulator was used particularly for initial testing and in problem situations to ensure that the fault was not in the connections.

Students liked that the course included making electrical connections on the Arduino platform in addition to programming. Almost all students (Table II) were positive about the fact that the connections had to be made by the students themselves and not be given as pre-installed. The positive attitude is well illustrated by the comment below:

"Making electrical connections is definitely a plus, it adds a lot of interest to the tasks."

TABLE II. SHOULD THE DEVICE BE PRE-INSTALLED?

	Yes	Neutral	No
Physical device course (n=19)	11%	11%	78%
Simulator course (n=23)	4%	4%	92%
All (n=42)	7%	7%	86%

Making electrical connections was perceived as useful regardless of whether the physical device or simulator was used, although the willingness to make connections was slightly higher among students in simulator-based courses. In the case of physical devices, students highlighted the challenges related to contact failures in electrical connections, which made it difficult to solve problems. The students did not always seem to know whether the problem was hardware-based or code-based. This problem did not occur with the simulator, of course.

Understanding the characteristics of electronics and components was considered important, especially when talking about IoT solutions. The students described the added value as follows:

"I think that building hardware helps to understand better how the hardware and software work together."

"[Making the connections] helps to understand the relation between the program and the environment and how the hardware works."

Students gave feedback on the time they spent on the exercises. Looking at it, it was possible to see that some students spent a lot of time on the exercises, while others spent quite little time compared to the scope of the course. There was no big difference in the amount of work between courses using a physical device and courses using a simulator. The average time spent on a single exercise in simulator courses was around 5 hours, with a median of 3 hours. In contrast, the average for those using physical equipment alone was just under 6 hours, with a median of 4 hours. However, the variation was very large. In both methods, students with the good previous programming experience gained in studies or work spent a minimum of only about an hour on a single exercise, while students with the lowest background knowledge spent several tens of hours.

B. Educator's Perspective

According to the course lecturer's observations, adding learning by doing to the course seemed to increase student motivation compared to previous teaching experiences. It was therefore a clear choice to use either a physical device or a simulator in the course.

The education program has been implemented in a location-independent way, and students are located all over Finland. Therefore, physical devices must be sent by post. With a tight timeframe, sending them poses scheduling challenges. As the number of students in the course can vary widely, it is difficult to estimate the number of devices needed for the course in advance. However, the devices should be ready to be sent to students as soon as the course starts, in order to minimize scheduling challenges. Sending several dozen devices by post is also a somewhat additional workload factor. This factor can become significant, especially if the course is to be scalable to a large number of students.

Sending devices to all course participants would also increase the cost of running the course. Approximately 25% of the students enrolled on the course did not complete it. The majority of these students never even started the course properly and did not return to the first exercise. One possibility would be to send the equipment only after the first written exercise, thus avoiding the need to send devices to students who had no real intention of completing the course. However, this would also pose a scheduling challenge, as in practice the devices would reach the students when almost half the course had already been completed.

Clearly, using a simulator instead of a physical device increases the scalability of the course. When using a simulator, the variation in student numbers is irrelevant, and the posting of devices does not pose problems in terms of scheduling or workload.

According to the performance statistics, the course was exceptionally well completed with high marks. There are several reasons for this [21]. From the point of view of grades, the use of physical devices or simulators does not seem to make a significant difference. For courses using both physical devices and simulators, the average grade was 4.48/5 (n=24), and for courses using only simulators, the average grade was 4.62/5 (n=80). Six students failed the courses. The failures were evenly distributed between the physical and simulator-based courses.

In general, the Tinkercad simulator used in the course worked very well from a technological point of view. There are, of course, a few differences between simulator and physical devices. For example, the simulator's internal clock runs occasionally at a different speed relative to real-world time and the Arduino's internal memory behaves slightly differently. However, these are mainly differences that may need to be considered at some level when instructing the exercises.

VI. Discussion

In a distance learning program, physical devices must, in practice, be delivered to students by post. In an intensive course, this poses scheduling challenges. Furthermore, if the course is such that it is difficult to predict the number of students participating and therefore the number of devices to be sent, the use of physical devices is not a very meaningful solution. On the other hand, physical devices sent for one course could potentially be used in several other courses in the program to carry out exercises. From this point of view, sending devices to students selected for the program would be justified.

According to the experience and feedback of students, the physical Arduino kit was perceived as very useful and motivating. On the other hand, students who had physical hardware in addition to the simulator generally felt that the course could also be delivered using the simulator alone. However, replacing the physical device with a simulator would reduce concreteness to an extent. In this case, meaningfulness and thus motivation might be slightly lower. The students using only the simulator, on the other hand, were almost unanimous that it was an adequate solution for this basic course. Among other things, the simulator was found to allow various experiments and incorrect electrical connections without fear of equipment failure. From an administrative perspective, the use of the simulator naturally increases the scalability of the course. Thus, the implementation of the course in a simulation environment allows the course to be developed toward a widely offered MOOC (Massive Open Online Course) delivery.

Based on the above, it was decided that in the future, the exercises in the Introduction to Embedded Systems course will be carried out using a simulator. However, the course material will also include instructional videos related to the physical device, for example on how to install the hardware and the necessary software. In this way, students who are willing to purchase the hardware themselves or who already have it will be able to make use of it.

The simulator can be used by providing students with a ready-to-use hardware setup, with the necessary sensors and actuators connected to a microcontroller platform. Alternatively, students can be required to select components and make electrical connections themselves. In the course under study, students were required to make the electronic connections needed in the exercises themselves. Electronics was not really part of the learning objectives of the course, but making connections was seen as increasing understanding and helping to see the connection between the program and the operation of the hardware. This was found to be useful when programming. The situation was the same for students who used the simulator as well as the physical device. The simulator will continue to be used in the course, with the students making all the connections and component choices themselves according to the requirements of the exercises.

This study and some previous studies [5][17] have shown that both physical hardware and a simulator have advantages and, in fact, their combined use could potentially offer added value. Although the target group in Jaakkola and Nurmi's study [5] was elementary school students, both [5] and [17] also looked at the combined use of simulation and the real environment on which the simulation is based. In this respect, the setting was similar to that of this study. In the context of the current education program, it was therefore decided to send the physical device to all students selected for the program during the course following the introductory course. If needed, lecturers can use physical devices alongside the simulator in teaching.

VII. Conclusions

The Master's Program in Computer Science at the University of Jyväskylä's joint institution, Kokkola University Consortium Chydenius, is implemented as a distance learning program. The program relies heavily on educational technologies, without face-to-face teaching and with learning material consisting mainly of video recordings. In accordance with the teaching practices of the program, an Introduction to an embedded systems course, which teaches the programming of embedded devices, is also implemented as distance learning. The course is hands-on, which poses challenges for distance learning. Learning by doing can be supported through the use of a programmable microcontroller platform. This can be either a physical device or a computer program simulating it.

Physical devices pose challenges in terms of time, cost, and scalability. A simulator can address these challenges. However, the question remains whether a simulator is a suitable pedagogical replacement for a physical device.

The Introduction to Embedded Systems course was implemented five times, with the first two sessions carried out by posting the physical device to students and providing them with a simulator, and the latter three sessions carried out by experimenting with the simulator alone. The aim was to obtain feedback from students on the suitability of the simulator for course development. Comments from students who had used the simulator in particular suggested that the simulator was a good solution. Those who used a physical device said that it was more concrete and possibly more motivating, but they also shared the view of those who used the simulator that it was a suitable solution for this course. The feedback from students was positive to the extent that, in future, the simulator will be used to complete the exercises. The physical devices will be sent to the students selected for the training program later in the program, allowing for accurate prediction of the number of devices and delivery without time constraints. Also based on the feedback, it was decided that students would make the electronic connections required for the exercises themselves rather receive them as pre-installed implementations.

Although this study showed that the simulator works well for its purpose, some of those who had used physical equipment had also used a simulator and found it to be an effective approach. In the future, it may be worth considering whether the joint use of a simulator and a physical device should be encouraged, rather than using either one alone. Furthermore, the scalability of the course could be further improved by introducing some form of automation in assessing the exercises carried out on simulators.

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