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Applying a design approach to robotics in education

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Abstract

The integration of robots into classroom settings has a long-established presence in both general and vocational education. With the developments in Industry 4.0, the importance of robotics in schools has also increased, which has become clear through various funding programmes. Especially in general education, there is often a focus on utilising robots as a tool to provide learners with an interactive learning experience centred around feedback. This approach effectively connects theoretical concepts from the curriculum to practical real-world applications through the utilisation of robots. However, the emphasis often overlooks the robots themselves and their design elements. It is important to note that the possibility for learners to design robots for self-set goals is often limited by this traditional approach. This article introduces a methodological approach that promotes a design-oriented perspective within robotics in education. In addition to outlining the methodology, the article also presents initial examples on the implementation of this design-oriented approach in training future technology teachers.

Keywords

Design orientation, Technology education, Educational robotics, Design process

Introduction

Robots have long been the subject of teaching, both in general education and in vocational training. However, there are differences in the type of robots used in the educational context: in vocational education, the robots used are those that will be worked on later, mostly in industrial applications. In general education, on the other hand, robots are used that can be described as a didactic reduction of mobile robots with wheels (e.g. Lego Mindstorms) and which usually do not have tools comparable to industrial robots and therefore cannot perform any productive tasks. They are so simplified that the connection to real robots (e.g. to industrial robots) is not always obvious. Nevertheless, they fulfil an important function in the classroom and have so far been an important medium for digital education because they have made it possible to link the virtual and real worlds in the classroom. The code created by the students themselves in the virtual world controls the movement in the real world. The sensually perceptible actions of the robot constituted a form of feedback learning that has since captivated generations of students. In didactic research, the positive effects of using Mindstorms, Arduino etc. have been highlighted in many studies (a systematic review regarding the use of robots in education can be found in Darmawansah et al., 2023). However, these studies also show that robots were primarily used as a model for computer science education. Their reactions can be used to learn how to program and to experience the mistakes made in the process. The robot itself did not automatically become the subject of the lesson, as this requires a reference to real robots (Röben et al., 2023).

In this regard, the implementation of robot models that come close to real robots poses great challenges, especially in connection with decisions about what students should learn, which is particularly related to the diverse developments and applications of robots.

A previous study with teachers in the related project in which a total of 54 schools were equipped with robots has shown that even when schools are equipped with models of real robots, there are difficulties in implementation (especially in finding suitable contexts that motivate the students to engage with the robots as such) (Hamade & Landherr, 2023). In particular, the aspect of increasing demands in the creative use of robots will be addressed in this article and the question of the extent to which a design-oriented approach (Röben, 2023) to robotics can be promoted in general education will be explored. The robots used here were Dobot Magicians, which are based on real industrial robots and were purchased by the schools in the project. More information about the project realisation, the funding etc. can be found in Hamade & Landherr (2023). The approach presented here is based on the findings of this article (published in the course of the PATT40 conference) and on the project structure described there. The design approach was piloted with future secondary school technology teachers (for grade 5-10 (from age 10 to 16)).

Literature review: Design orientation and robotics

Technology and technological determinism

It is noteworthy that the design-orientated didactics of technology (Rauner et al., 1988; Schudy, 1999) has developed in confrontation with an opposite pole, technology determinism (MacKenzie & Wajcman, 1999). According to this view, developing technology is a social force to which societies must adapt and adjust. Any attentive newspaper reader will be familiar with calls such as: “Don't miss the boat on AI now!”. Technical products with AI are spreading rapidly in society; Amazon, Facebook, Apple and Google are bringing AI into every household (e.g. in the form of Siri, Alexa). From the past, many may remember the demands on schools to introduce computers into the classroom or CNC technology in the vocational sector. In country comparisons, the progress in the spread of mostly digital technologies is presented, the position of one's own nation is viewed with favour or criticism and one thing becomes clear: there is no discussion about the “whether”; the debate is ignited by the “how”. Surprisingly, one of the fathers of technological determinism, the American sociologist William Fielding Ogburn (1886 - 1959), formulated his thesis a long time ago. Influenced by Thorstein Bunde Veblen (1857-1929), he was one of the first to formulate the thesis of technological determinism.

His book “Social Change” from 1922 contains the famous thesis of cultural lag (Ogburn, 1922). Incidentally, he already stated in the introduction: “Never before in the history of mankind have so many and such frequent changes taken place” (Ogburn, 1922). Culture is understood here in a broad sense, which also includes industry and technology in the sense of material culture. Ogburn sees the changes in technology as the pressure generator that exerts pressure on other instances of society, including the education system, to adapt. These instances are determined by it. He sees the cause of the acceleration already observed in 1922 in the increase in inventions, which is based on the accumulation capacity of material culture. Ogburn presents the material culture of a society as if it were simply a given and had to be accepted like the next rain shower. He does not address the fact that it is the work of people, that decisions and interests are behind the spread and implementation of technology in society.

This acceleration of change in material culture is a relatively recent historical phenomenon - especially in the USA at the time of Ogburn. It only began with the start of the industrial revolution and continues to this day.

Remarkably, the birth of the robot takes place just one year before the publication of his book. This refers to the play Rossum's Universal Robots by Karel Čapek (1890-1938), in which the term robot was coined from the Czech roboti (for hard labour) and was adopted in many languages around the world. This play was performed around the world and 184 times in New York in 1922/23 and was widely commented on. In this play, the independent existence of technology assumed in technological determinism finds artistic expression and makes the robot known before it even exists technically (Jordan 2019).

What challenges does the education system face as a result of the ongoing technological revolution?

In summary, the following can be said about technological determinism:

Firstly, the use of technical artefacts in society has nurtured the illusion that technology has a life of its own. Dispelling this illusion is and remains a challenging educational task. Secondly, there are different ideas about the nature of this life of its own. While Ogburn assumes a given material culture to which intellectual culture must adapt, dystopian ideas were already developing in his time that ascribed hostile tendencies to technology. This is where representatives of the Frankfurt School such as Habermas meet conservative representatives such as Schelsky. Habermas, for example, reproaches Marx for what he believes he did not understand: “Marx never realised that this 'machinery' (and the entire social system in its wake), that technology itself and not just a certain economic constitution under which it operates, covers people, both workers and consumers, with ‘alienation’.” (Müller, 2018). In the scenarios so far, people have hardly featured as decision-makers and actors, but rather as sufferers and passive acceptors or drivers of technology. We must therefore turn to the social side of technology in the following.

Technology and the human being as a social being

In view of the penetration of information technology into everyday professional and private life, it is easy to fall prey to the theory of technological determinism. Dystopian visions have long dominated science fiction, and with the development of robots, which are also becoming increasingly present in everyday life, this development is receiving a new boost. Without ignoring the driving force behind this development, it must be a task of technical education to reduce this apparent superiority to what it really is: balance of power in which technology is shaped according to economic interests. But even classic technology, which plays a major role in a robot, is barely recognised.

Every car driver, every airline passenger on the way to their holiday destination uses technology and benefits from it, does not experience the consequences of technology on nature, but views it in terms of its benefits. The consequences of this use are not experienced through the use itself, but must be developed through intellectual work. Anyone who works with their students on topics such as ecological footprint, life cycle assessments and life cycle analyses knows how difficult this educational work is. It is an urgent educational task to make this apparent superiority of technology transparent. After all, appearances must not be taken for reality.

Getting to the bottom of appearances means, for example, examining the existence of a technical artefact in terms of its history, who designed it, who benefits from it, what effects its use has and what resources have to be used for it.

Design-orientated technology didactics

The concept of design therefore encompasses both past design, when it comes to illustrating how development has progressed up to the present, and the identification of alternatives: sustainable (co-)design of technology in a socially responsible manner, both in the present and towards future generations. The concept of design is thus also linked to de Haan's design competence (De Haan, 2008) but must prove itself in terms of technical and methodological competence in the field of technology. According to Rauner (2006), this development process is the confrontation between what is socially desirable and what is technically feasible (see Figure 1). What is technically possible in the mouldability of the material world, which is limited by the laws of nature but constantly expanded by science. Here, malleability refers to the mouldability of technical apparatuses and structures.

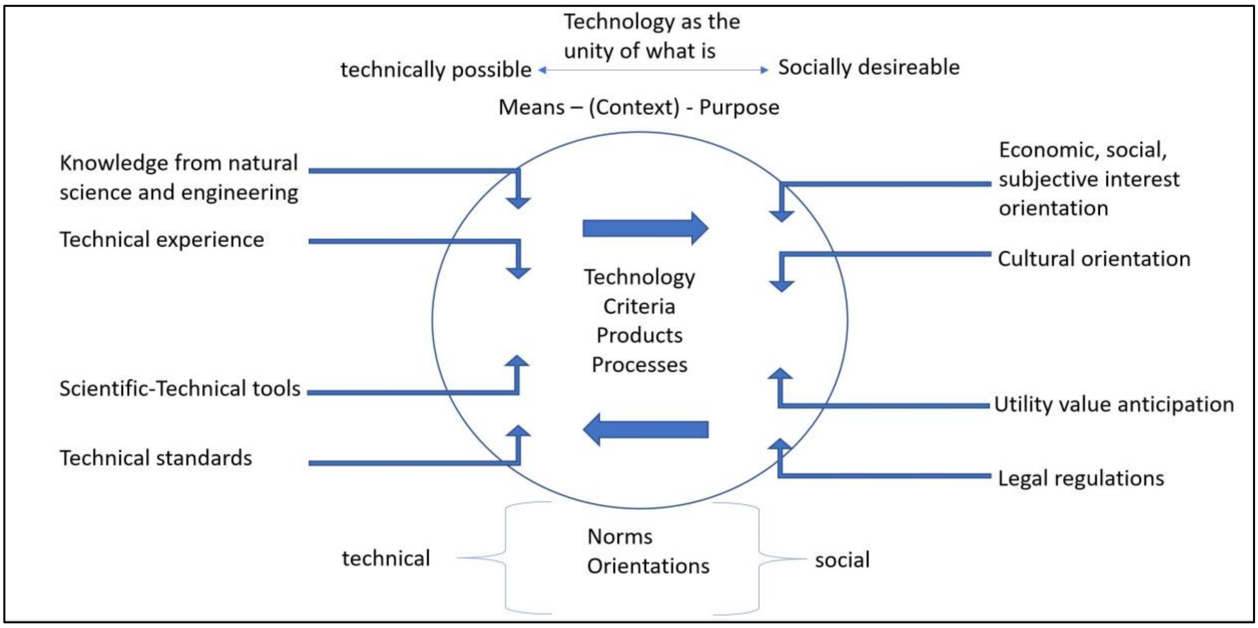

Figure 1. Technology as an end-means context according to Rauner (2006)

In the field of technology, there is a permanent, economically driven confrontation with previous limits, which is very often successfully overcome. This is because limits are not only to be found in nature, but also in the state of the natural and engineering sciences. And the experience of technical specialists in operational practice very often promotes the further development of technical systems and machines, which is why no large company refrains from awarding prizes for suggestions for improvement. However, scientific progress is at the centre of innovation research, and an entire branch of science deals with the search for applications for new findings. The social forces that characterise the process of shaping technology lie in the formulation of what is socially desirable. However, these forces are distributed very unevenly in society.

It is certainly not desirable, for example, to leave the mobility sector to the automotive industry alone. It alone is not even capable of effectively curbing fraud, as the Volkswagen emission scandal (the so-called Dieselgate, see Aichner et al. (2020)) shows, which is wrongly associated with just one company. The car industry as a whole has not stopped overproducing cars but has increased competition immeasurably. Without social control, without (co-)shaping the future of mobility, there will be no solution to this social problem.

The technical artefact as a unit of the objective, which on the one hand can be represented in scientific categories such as mass, energy and information and on the other hand has a use value that can only be grasped anthropologically with categories such as utility and satisfaction of needs, is the irreducible basic unit of technology. This is because the form and function that technical products take on in the manufacturing process cannot be traced back to science and mathematics alone. Their view of technology is truncated. The robot is a good example of a technical artefact. On the one hand, it can be analysed in the dimensions of matter, energy and information. On the other hand, it cannot be understood unless we are clear about the purpose for which it was constructed. Robots are therefore designed technology.

Understanding design as an analytical act in technology lessons

The design approach is not limited to the students' own design of technology, even if this is given great importance in this didactic approach. If you do not design the technical artefact yourself, but analyse the reasons for its design, you go back to the time of its creation. We enter the life cycle of a technical artefact and switch from the context of application to the context of production. The context of use refers to the appropriation of the technology in the professional or private sphere for the purpose of utilisation. The production context refers to the development of the technology. Both contexts allow different levels of social aggregation to be analysed. One can choose a micro level, on which the interaction of an individual with a concrete technical artefact is examined, but also a meso level, on which the interaction of social groups and institutions with technical systems is analysed. At the macro level, technological complexes that affect society as a whole, such as energy supply or transport networks, can be analysed (Häußling, 2014).

Analysing the development process of technology also makes it possible to understand how engineers work. An educational goal that has so far been little associated with technology lessons, but which is highly relevant in the upper secondary school in particular, which is fed by the resulting understanding of the development of technology as well as the need to reduce ignorance about the occupational field. A recent study summarises: “However, neither the girls nor the boys really know what is or can be hidden behind this occupational profile. [...] The engineer has nothing to do with the reality of young people.” (Cajacob & Herzig-Gainsford, 2019). However, the retrospective analysis of the design of technical products must be supplemented by a prospective assessment of future effects. Looking at the consequences of technology and empowering students to (co-)design technology is a necessity, because every technical product and artefact not only shows the intended consequences of its commissioning and use, but always also side effects, which often have unexpected consequences, especially in the case of networked technologies. The technical design task must therefore always be expanded to include a social dimension; technology must not appear as an innocent neutral in educational processes.

The creative forces at work throughout the entire life cycle must not be ignored in an enlightened technology education, nor must the social and ecological consequences of the use of technology.

Design as a generative act in technology lessons

Design appeals to special powers in people that are not awakened in purely reproductive tasks. Design intentions place demands on the technical possibilities, but these must also be realised in relation to the material and the technical possibilities.

The process of realising what was previously only imagined and the experience of this process and its result have great didactic potential both for the acquisition of technical skills and abilities and for personal development. The work processes closely associated with technology, such as inventing, designing, constructing, manufacturing, measuring, testing, repairing and recycling, also reveal insights about oneself and one's own preferences, talents and dislikes. Career guidance in technology lessons can and must build on this.

Methodology: Design process and first approach

Design process

There are already established models for the creative design process upon which the methodical sequence derived here is based. The classic model for design processes includes a divergence phase, transformation, and a convergence phase (Jones, 1970). In the divergence phase, the design space is expanded as the designer deepens their understanding of the design context, decomposes a problem, and identifies underlying issues and variables. This space is then explored through the transformation of ideas, materials, and situations in creative ways to identify new “solutions”.

Eventually, solutions converge as the designer restricts the design space by imposing constraints, removing assumptions, and realising a final design (Cameron-Jones et al., 2008). Various factors such as lateral thinking, experience, and cultural background influence the breadth of the design space. Design decisions are based on requirements and available knowledge, but often also on incomplete knowledge. The designer's experience, preferences, and willingness to take risks shape the solution space (Mader & Eggink, 2014). Building upon these models, Mader and Eggink (2014) developed a model of the design process for Creative Technology.

Their model aligns with the aforementioned aspects of design-oriented teaching but is particularly adaptable to the present basic idea from a teaching perspective due to its focus on “design beginners”, which makes it very attractive for our approach, as the students have often had no previous contact with such robots. Furthermore, the given approach fits very well, as it provides for iterative improvement loops in the design process, which is of great importance for the development of creative applications for the robots (these are particularly necessary when the first transfer of the application reaches the kinematic limits of the robot). Mader and Eggink (2014) divide the creative design process into the “ideation phase, specification phase, realisation phase, and evaluation phase.” At the outset, the design question takes the form of a product idea, a client's order, or a creative inspiration (similar to the divergence phase in the classic model described above).

The authors refer to this process as “tinkering,” aiming to identify novel applications for existing or new technologies, thereby bridging the gap between technology and user needs. As a second phase, they define the specification phase, in which prototypes are developed to explore the design space. The prototypes are evaluated within the phase, allowing for the creation or discarding of multiple prototypes. Following prototyping, the realisation of the previously developed approach ensues, which is then evaluated in the final phase. Preceding the design process in our approach is the phase of engagement with a specific technology. In the context of robotics, this phase mainly involves becoming familiar with the robots by exploring their capabilities and limitations (e.g., introduction to the technical structure and handling, peripherals, and programming of the robots).

This phase is essentially still tightly guided, as it aims to build a basic knowledge of the system, thereby enabling the design process for “design beginners” to be meaningfully initiated. Regarding the basic model of design thinking described at the outset, this upstream step is justified by the nature of the convergence phase, as design decisions must be made based on given requirements and available knowledge how it is described by Jones (1970). Ideas for designing the robot for self-set goals are gathered in the divergence phase (quantity over quality/brainstorming). In the convergence phase, the ideas for designing the robot are condensed and merged with the experiences gained in the first phase. Thus, the question of the fundamental feasibility of the ideas is pursued based on the insights gained with the robot beforehand, ultimately leading to a decision. In addition to engaging with the existing robot itself, engagement with the diversity of robots is meaningful (where are robots used, how are they categorised, what current issues exist, and what ethical debates surround robotics? What are the future predictions regarding dissemination, areas of application, etc.?). Once the basic engagement with robotics has been completed, the actual design process as described in Mader and Eggink (2014) begins. The learners have learned about a specific system and independently define a problem based on the insights gained and their individual interests (concrete examples are provided in the following section). After defining the problem, the learners (analogous to the phases after Mader and Eggink (2014)) begin to develop solution approaches (prototyping). The design space is limited here due to the robots themselves (the focus is more on designing end-effectors and the “robot-environment” to solve individual problems).

Subsequently, the prototypes are realised, and the realised solution presented and evaluated. The design process already undergoes several iterations during processes such as prototyping or realisation. It would be beneficial if there is still room for further revision after evaluation. It is plausible that an appropriate solution may not be attainable for the given problem. In such instances, it is prudent to reflect on this observation and deliberate on optimisation strategies. If the problem exceeds the capabilities of the available robot, then consideration should be given to revising or refining the problem statement, or alternatively, the development of additional prototypes may be warranted following the creation of the initial solution.

In our approach we made a course with prospective technology teachers over 14 weeks with four hours each week. The first block (two hours) of the seminar deals with the field of robotics, various types of robots and applications, which are considered from both technical and other perspectives, such as ethical perspectives. The second block (also two hours) involves practical work on the robots.

The beginning with a still very closely guided introduction to the Dobot Magicians as models (programming, networking, end effectors, sensors etc.) is followed by the actual design process in which the students realise their ideas. Examples of this can be found in the following section.

The design process itself is not a novelty in technology education, but it is intended to show the extent to which it is possible to co-design robotics on the basis of current issues, in contrast to classic approaches in robotics that focus on coding. Teachers stated that they tend to use the classic approach focussing on coding and that they lack methods to motivate pupils. The following section will illustrate this using an example.

Findings and first implementation

In order to analyse robots, we first have divided the contents regarding robotics in the seminar into the following categories (see Table 1).

Table 1. Categories of robots and robotic related content discussed in the seminar

Technical aspects	Contents
Motorisation	e.g. Electric drive, pneumatics, hydraulics
Kinematics	What movements can the robot perform with its arms, legs, wheels or wings?
Actuators	Which tools can the robot use to perform which actions?
Sensors	What signals does the robot receive from itself (e.g. torque sensor) and from its environment (e.g. LIDAR, video camera)?
Programming	What digital processing is the robot capable of (e.g. learning ability)?

Within certain limits, the students were able to choose the robots they wanted to study in more detail (see categories of robots in Table 2). Both seminars were very exciting for students, as it became clear what an important phase of robot development we are currently in. The students were given the task of searching for reliable information (for each of the technological aspects in Table 1), researching data on the above-mentioned categories, determining the development status of the robot, and finding out which company or institute developed the robot. After the research, the students had to present their results. The starting point for the practical examination of robotics within the design-oriented approach is to demonstrate possible technical solutions within the framework of a defined problem. In this initial phase, students are introduced to various programming possibilities (Teach-In & Playback, visual programming with Scratch or Blockly, textual programming in Python) and work on tasks with a defined solution path (e.g., the use of sensors, controlling conveyor belts and linear axes, sorting cubes by colour, or stacking objects with iterative increases in object height). They learn how programs are structured and which commands can trigger specific actions of the robot. This first phase serves as preparation for analysing the robot according to the design approach.

Table 2. Robot categories and examples of robots covered in the seminar

Categories of robots	Contents	Robots covered in the seminar
Industrial robots	e.g. Assembly, handling, welding	Welding robot AA IRB 7600, Daisy (recycling robot at Apple)
Cobots (collaborative robots)	Human-robot-collaboration	Kuka LBR iiwa 7 R800, Bosch Rexroth APAS assistant
Mobile robots	e.g. Bipedal robots, robots with wheels	Da Vinci, Tesla-Car
Service robots	e.g. care and nursing, communication with people (social robots), logistic robots	Atlas, Spot both Boston Dynamics, Zeno (for use with autistic children), Digit (logistics from Agility robotics), Pepper, Sophia
Research robots	Curiosity, autonomous underwater vehicles	Mars rover Curiosity, Care-O-Bot (care, Fraunhofer),

In the second phase, students make the connection between the robot they have become acquainted with in the seminar and robots from various fields of application. Examples include robotic representatives from medicine and care, industry and logistics, self-driving autonomous systems, or the military. As they further specify the exact function of the robot in the given field of application, they learn about how the robot must be constructed to fulfil its assigned task. For example, a robot designed to assist in searching for victims buried in an earthquake should be equipped with an all-terrain drive and possess a manipulator as well as sensors. An industrial robot, on the other hand, does not need to be designed to move locations itself. Instead, it requires high precision with simultaneous high payload and reach. The students approach the robots from two directions inherent to the design-oriented approach: the robot as an object that can be described in scientific categories (mass, energy, information), and the robot as a utility value, useful because it can perform a task. The students inquire about the reasons for the design: why does the technical object look this way and not differently?

In the third phase, students consider what problems could be solved using a robotic system. They find examples from everyday life or reconstruct existing robotic systems according to didactic principles (e.g., by reducing complexity) and transfer the process for solving the problem into a Nassi-Shneiderman diagram. They learn that overall problems can be broken down into technically implementable individual steps or partial problems, which can then be transferred to the robot as instructions through programming. This phase of algorithmicising prepares the generative act of realising the conceived solution: what natural laws must I consider? what technical rules and procedures must be observed?

Once the students have adequately described the problem and devised a theoretical solution, they begin building a prototype. This prototype can consist of arranging known sensors and actuators in a new configuration, resulting in a new application. Or the students use additional sensors and actuators, integrating them through the robot's interfaces, possibly with the help of additional hardware, e.g. an Arduino. During the prototyping phase, the greatest non-technical challenge for students is dealing with frustration. For example, the coordinates were not accurate enough, the sensor outputs data that is not understood, or the experimental setup exceeds the robot's working area. It is important to support students in maintaining the original problem statement, rather than changing the problem situation so that the robot can now handle it. The goal is not to design the problem but the solution path using the robot. In addition to expanding the robot with new sensors and actuators, many students also design new end effectors to give the robot new possibilities for manipulating physical objects. In this phase, students learn that the possible is not always easily achievable but that its realization must be earned with effort and patience. This process, however, also has great didactic potential, as acquiring technical skills is accompanied by personal experiences stemming from the relationship between temporary failure and eventual success.

This is a practical example of a student who considered how to use a robot to assist in surgery for a bone fracture through osteosynthesis. The student had previously delved into the history of robotics in medicine and discovered that as early as 1991, it was discussed how robots could be used to support the placement of implants. The problems of manual placement, namely inadequate precision and reproducibility, could thus be circumvented (Rall, 1991). To “generate” the problem, the student used a 3D printer to design and print two bone fragments of a humerus.

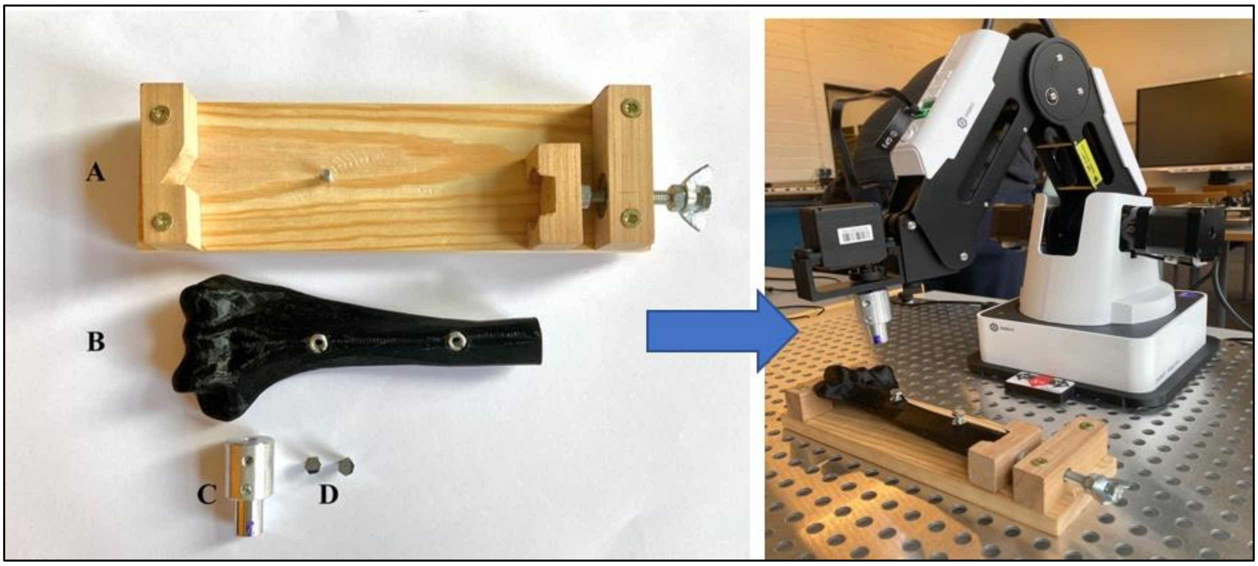

Figure 2. Left side (prototype): A: Bone mount, B: 3D-printed bone model, C: End effector, D: Screws. Right side: Testing the prototype on the robot (Mosebach, 2022).

Two internal threads were inserted to accommodate a screw, which would reassemble the broken bone using a technique known as plate osteosynthesis.

This method stabilizes the bone with a plate to increase angular stability. Additionally, she constructed a holder to securely position the object for manipulation. To enable the robot to screw into the internal thread, an appropriate end effector had to be chosen and installed. The end effector also needed an actuator to facilitate a rotating motion. Therefore, the student designed a socket attachment for a rotary servo.

Another example is illustrated in Figure 3. Here, a student addressed an issue observed in everyday university life. In the cafeteria, guests place their used knives, spoons, and forks on a tray, which is then transported to the kitchen on a conveyor belt. In the kitchen, the cutlery needs to be removed from the tray for cleaning. The student aimed to automate this process using a robot so that different types of cutlery could be sorted and cleaned separately. The student faced two challenges: Firstly, the cutlery was never positioned consistently on the tray, making it difficult for the robot to grasp using a standard end effector. Secondly, knives, forks and spoons have different shapes, requiring a solution that would allow the robot to pick them up effectively. The student solved these challenges by designing a device where the cutlery is positioned consistently for the robot to reach. Additionally, the student equipped the cutlery with points suitable for grasping using a vacuum suction cup. While the student had to adapt reality to fit the robot's capabilities to some extent, this approach represents an initial step towards designing a practical solution. By considering how the cutlery should be shaped for manipulation by a robot, the student also contemplated the reasons behind the current shapes of everyday objects.

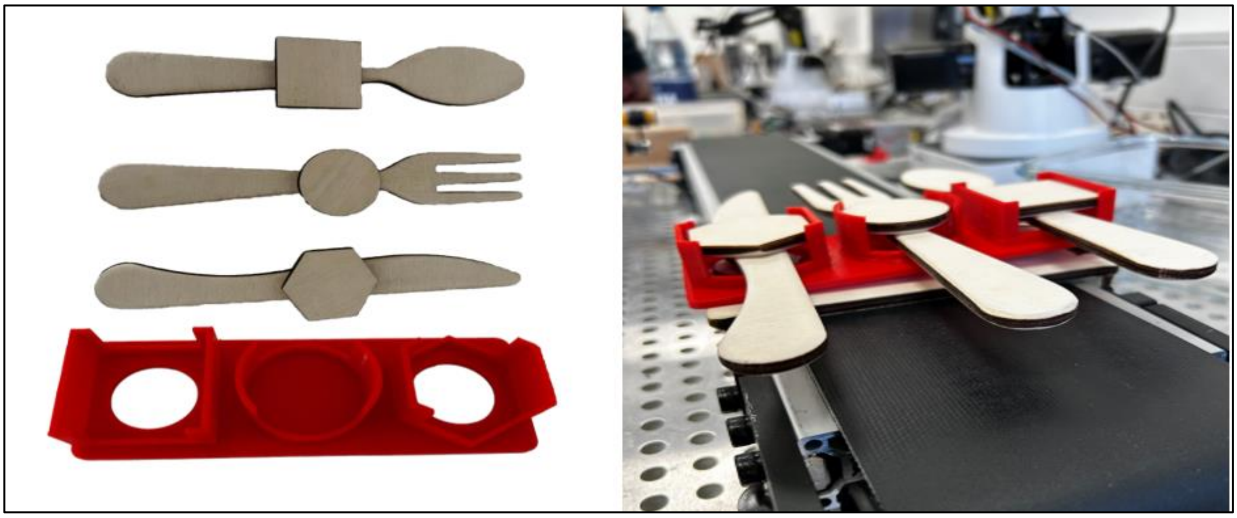

Figure 3. Left side: Designed cutlery and holder. Right side: Testing the prototype (Kleinelanghorst, 2024).

In conclusion, students thoroughly test and evaluate their prototypes by asking the following questions: Does the programming function as intended? Do the components synergize effectively to solve the problem not just adequately, but within a technically sound framework? The evaluation of prototypes goes beyond mere functionality assessments, encompassing additional criteria such as adherence to economic principles, potential social or ecological impacts, and integration of design principles.

Discussion

The design-oriented approach offers a promising avenue for creatively integrating robots into educational settings. Beyond its application in teacher training and schools, this model holds potential in engineering, product design, and science-based courses where design plays a pivotal role in learning. Departing from conventional methods, the approach places less emphasis on technical programming and more on fostering creative engagement with robotic platforms. Here, robot programming serves as a tool to realize imaginative designs. Initial implementations have demonstrated that the design-oriented approach stimulates critical inquiry and fosters innovative design practices in robotics education. Therefore, systematic investigation into observed phenomena and student feedback is essential. It is crucial to assess whether this approach effectively enhances learner motivation towards engaging with robotic technology.

Given its focus on future educators, it is imperative to extend this inquiry to broader educational contexts. Initial attempts at implementing this approach in schools highlight a trend towards openness and design orientation across different grade levels. Several critical factors merit consideration, particularly students' pre-existing mental models shaped by media portrayals lacking exposure to robotics. Tailoring the design-oriented approach to these contextual nuances requires comprehensive reconstruction of students' perceptions. This should be followed by the development and rigorous evaluation of interventions aimed at bridging the gap between existing perceptions and the transformative potential of design-oriented robotics education. Ultimately, these efforts will yield empirically grounded recommendations for effective pedagogical practices in robotics education.

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