INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

PROTOTYPING WITH LASER CUTTERS IN LARGE ENGINEERING DESIGN CLASSES

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Keywords: prototyping, laser cutter, design education

1. Introduction

A key element of today's engineering design education considers the effective working with virtual and physical design representation. Especially in the context of project-based learning, it has become common practice to early train students in visualising their design ideas – first by sketches, later by CAD models – to support exploring and communicating design solutions. In addition to visualizing, several educational design approaches also attach great importance to physical prototyping, because it allows moving from the world of abstract ideas, analysis, theories, plans and specifications to the world of concrete, tangible and experiential things [Coughlan et al. 2007].

Although several studies have shown the positive effects of prototyping on learning and motivation [Ericson et al. 2012], the application of prototyping in education is often limited to low-fidelity prototypes made of low priced, but impermanent materials (e.g. paper or cardboard). These prototypes are most helpful in ideation, but they are not suitable to allow students experiencing the manufactability or the operability of the system they finally designed. This is where high-fidelity prototypes are required. High-fidelity prototypes are usually very expensive, because they are made of stiff and durable materials that are machined by manufacturing systems. Consequently, to minimise costs in education, high-fidelity prototyping is only applied in small and often specialized engineering design classes. Thus, a basic challenge in education of large engineering design classes is to afford students the opportunity to experience design as realistic as possible in line with acceptable costs.

This paper presents an educational approach that introduces laser cutters for application in large engineering design classes to cost-efficiently realize high-fidelity prototypes and thus, allow several hundred students to early experience the interdependencies of their technical system's design and its functionality in manufacture, assembly and operation.

The above mentioned laser cutters are small machine tools that are used to cut sheet material, made of wood or acrylic glass up to a thickness of 8 mm. Laser cutters are most suitable to be applied in large engineering design projects, because (1) they are sufficient accurate to realize critical design details, (2) they provide a professional data interface to CAD files, (3) they process very quickly and are sufficient durable to be operated by a large number of students, (3) they are well suitable to cut material characterized by a good fidelity-to-cost ratio and (5) they provide manufacturing constrains, but also a relative high degree of design freedom.

This paper investigates the question of how prototyping with laser cutters affects a first-year engineering design project conducted in 2013 with 456 mechanical engineering students, who designed and manufactured more than 80 high-fidelity prototypes. Based on a document analysis of 456 individually written reflections on most important experiences during the project, six clusters of key learning are deduced and discussed in the context of laser cutter prototyping. In order to illustrate single aspects of the key learnings, these are accompanied with exemplary student statements.

2. Trends in engineering design education

2.1 Trend towards project-based learning

Project-based learning is an educational approach that affords students the opportunity to personally experience subject matter contents by solving authentic problems in a realistic project environment. Blumenfeld et al. [1991] describe that within the framework of project-based learning students pursue solutions to non-trivial problems by asking and refining questions, debating ideas, making predictions, designing plans and experiments, creating artefacts, collecting and analysing data, drawing conclusions, communicating their findings to others and asking new questions. This process allows them to meld prior knowledge and experience with new learning, and develop rich domain-specific knowledge and thinking strategies to apply to real-world problems.

According to Dym et al. [2005] project-based learning currently is the most-favoured pedagogical model for teaching design. They also noticed an emerging trend of applying project-based learning in first-year cornerstone courses that especially aim for early enable basic design competencies as well as social skills, which arise from practical team work.

2.2 Trend towards Conceive-Design-Implement-Operate (CDIO)

The CDIO initiative bases on the finding that during the 20th century scientific and technical knowledge expanded rapidly and thus, engineering education evolved into the teaching of engineering science, whereas teaching engineering practice was increasingly de-emphasized. As a consequence Crawley et al. [2007] addressed the necessity to rethink engineering education and thus, they initiated a sustained trend towards an educational approach that allows students to personally experience conceiving, designing, implementing and operating engineering products. According to Crawley et al. the key criterion for such an experience is that the object created is designed and implemented to a state at which it is operationally testable by students.

One essential element of practice-oriented approaches, like CDIO, is physical prototyping. Prototyping supports design in different ways. Low-fidelity prototypes are simple prototypes made of materials that are easy to handle. Their basic purpose is to quickly illustrate key functions or interfaces to the user and the product environment and they are usually used to improve communication and understanding within design teams by making ideas tangible [Lande and Leifer 2009]. In contrast, high-fidelity prototypes are not just manifestations of design ideas, they are physical representations that are quite close to the final design and thus allow testing its functionality in implementation and operation. However, high-fidelity prototyping usually requires more valuable materials (e.g. wood, plastic or metal) and accordingly, also more professional manufacturing tools [Leutenecker et al. 2013].

2.3 Trend towards large classes

Technical universities all around the world are faced with challenges involved in educating an increasing number of engineering students. In fact, from 2002 to 2011 the number of bachelor degrees in engineering increased by 24.3 % in the US [Yoder 2011] and by 28.4 % in the EU [Eurostat 2013]. In China or India the growth rates are even considerably higher [Gereffi et al. 2008].

As a consequence, today’s engineering undergrad lectures are attended by several hundred students and teaching such large classes is challenging. In order to meet the challenges of large-class teaching at university Mulryan-Kyne [2010] claims to move beyond the ‘traditional’ lecture to more active forms of teaching and learning. She emphasizes that serious attention needs to be given to finding creative ways of dealing with the challenges, especially those related to levels of interaction and feedback. Chalmers [2003] addresses another view on this topic. She describes that especially the management of large classes is a crucial issue and that the importance or coordinating and preparing other teaching staff and tutors to ensure cohesiveness of the curriculum and use of effective teaching and learning activities in classes cannot be underestimated. This statement is especially true for large engineering design classes applying both project-based learning and high-fidelity prototyping.

3. Prototyping in ETH Innovation Project

The Innovation Project is a first-year engineering design project annually conducted at ETH Zurich, which intends to combine the three educational trends presented above. This means, the Innovation Projects represents a large-class, project-based learning approach that involves conceiving, designing, implementing and operating a technical system. In 2013 a number of 456 mechanical engineering students participated in the Innovation Project. In this year the student's task was to design a cable car that is able to collect different goods spread all across a mountain landscape (model size: 2500 x 600 x 1580 mm) and transport these goods to the upper station (cf. [PDZ 2013]). One central element of the project was high-fidelity physical prototyping, which allowed the students to experience the effectiveness of their design at first-hand and furthermore, to compare the performance of their altogether 82 systems in a final contest. The manufacturing of these prototypes was realized by two laser cutters fulfilling all the requirements regarding accuracy, durability, safety, costs and ease of operation. In order to guarantee that all students have same conditions, the access to of the laser cutters was restricted to sharp time slots of 30 minutes per team and week.

Figure 1 depicts 1 of 82 cable car systems that were designed in the Innovation Project 2013. The single magnifications exemplary illustrate typical machine parts that were designed and manufactured by the students. Amongst others, laser cutters allow prototyping gearing mechanisms (e.g. gear wheels, gear racks or gear belt), structures (e.g. lightweight structures) and connecting elements (e.g. form locked or frictionally engaged connections).

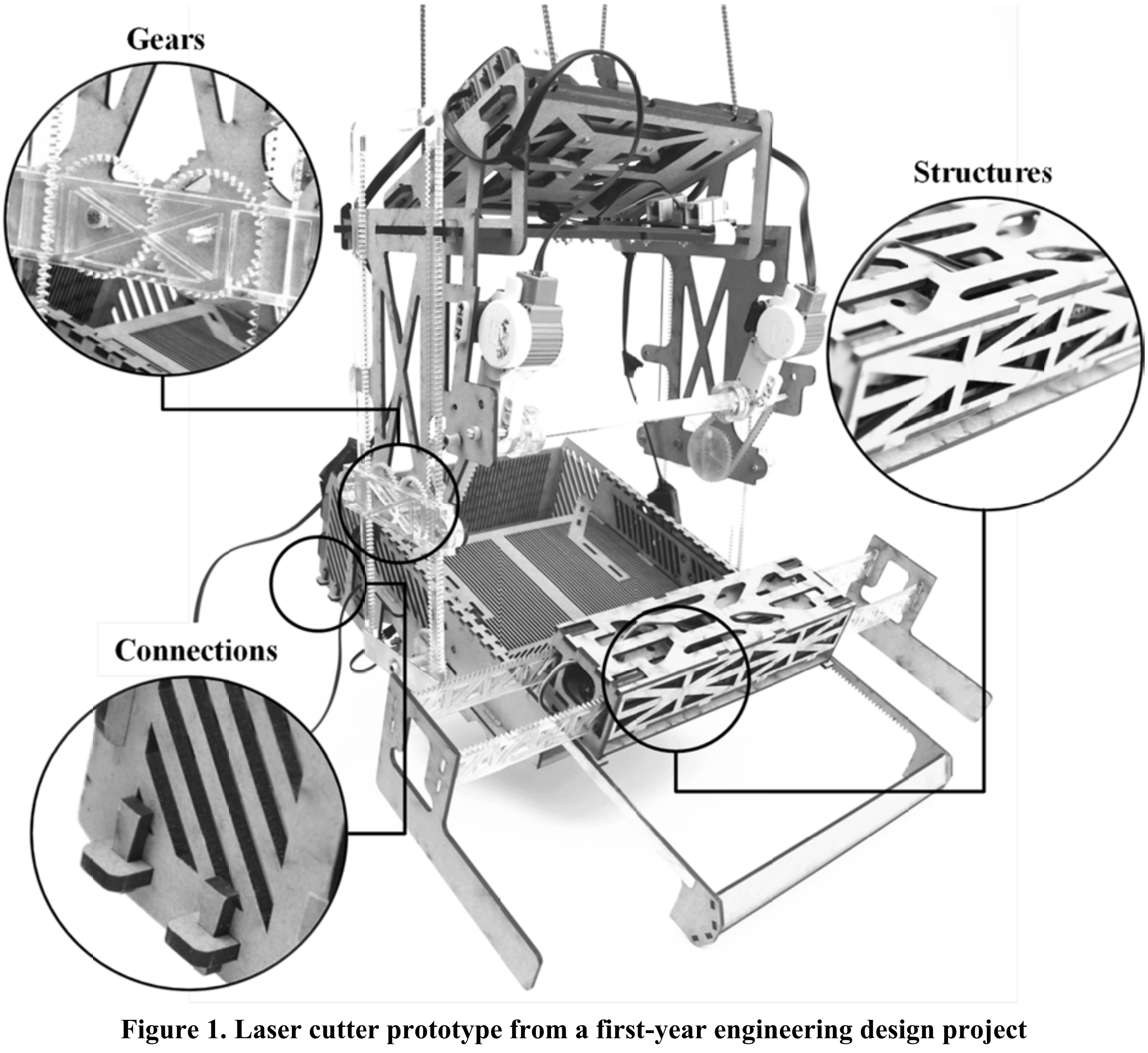

Figure 1. Laser cutter prototype from a first-year engineering design project

4. Key Learnings

In the end of the Innovation Project 2013 all student teams were assigned to write a final report that also includes an individual reflection on personal key learnings. The 456 resulting one page reflections were then analysed with a focus on key learnings associated with laser cutter prototyping. As a result six clusters of key learnings were identified: (1) Dealing with uncertainty, (2) consequences of design decisions, (3) illusion of reliability, (4) impact of design details, (5) risk of complexity and (6) relevance of testing. In the following these clusters are described in detail. In order to illustrate the students' personal experiences and insights during the project, the single key learnings are exemplified by individual statements made in the reflection.

4.1 Dealing with Uncertainty (There is no such uncertainty as a sure thing)

The first key learning the students report considers dealing with uncertainty. In engineering education students are often confronted with theoretical problems that are well-defined and have exactly one standard solution. In contrast to this kind of problems, practical design problems are mostly ill-defined and thus especially characterized by a high level of uncertainty. Uncertainty is caused by both a lack of knowledge and a lack of definition. In project-based design education students learn to deal with this uncertainty: they learn how to work with estimations, how to gain relevant knowledge and how to iteratively specify their system during the design process:

"The most valuable experience I have gained in this project is the knowledge of how to deal with such uncertain situations I also will face in my future career."

"An additional challenge is the pervasive uncertainty, which remains throughout the whole design process."

In this context, it became apparent that laser cutter prototyping is most valuable to be applied in design education, because it allows students to tangibly become aware of the high number of interdependent impact factors that need to be considered within their design. The analysis of their physical prototypes supported the students in identifying the most relevant factors and helped them evaluating the correctness of their estimations:

"It was interesting to see that in reality most designs behave differently than previously imagined. It is very difficult to foresee all the relevant factors and to estimate them correctly and truthfully."

"We absolutely misjudged the weight. When we built our first real prototype, we started with 5.5 kg. Actually, we could reduce the weight by 2 kg without affecting the functionality of the system."

In their project work most students also underestimated the time and effort that was necessary to solve the assigned design task. They especially misjudged the number and the impact of design problems occurring during the late development stages of manufacture, assembly and operation:

"The project showed me that often there is a huge difference between coming up with a solution and putting it into practice. An idea may sound very obvious and easy, but if you want to implement it, you will notice that it comes along with a lot of problems."

Due to laser cutter prototyping the students, who participated in the project, directly experienced dealing with the design challenges that arise when trying to make a system work or when trying to optimize its performance. As a result of this insight, most students intended to consider learning cycles in scheduling their future projects:

"The most important lesson I have learned is to always plan a project by taking into account additional time slots for solving initially unknown problems."

4.2 Consequences of Design Decisions (Decision is a risk rooted in freedom)

The second key learning the students highlighted in their reflection is about the consequences of their design decisions. Educational projects running over a longer period of time, in general allow students to experience these consequence. However, working with high-fidelity prototypes can intensify these experiences, because students can directly recognize the functional insufficiencies of their design and they personally have to make efforts for required improvements:

"The consequences of the decisions we made in the planning turned out to be enormous."

"I became aware of the responsibility I have as an engineering designer: Small mistakes in designing can cause big consequences."

Most students report about their right decisions very briefly and about their wrong ones very extensively. Their personal key learnings are often referred to descriptions of the mistakes they made, the consequences they experienced and the final insight they gained. The consequences described by the students are usually related to either a technical impact on the system design or an organisational impact on the project:

"We noticed that mistakes in the design of single parts can heavily impact entire assemblies."

"Mistakes in the final design are devastating in regard to the schedule, since they can cause delays of whole weeks."

Decisions during design usually result in design changes. These changes used to be improvements of design. Thus, they can be understood as important steps towards a well-performing system. In design education, laser cutter prototypes can relativize this understanding. The students learned that changes are required in design, but they also learned about the costs and the risks of changes:

"I learned that changes at an early stage of the design process are much easier to realize than in the end of the project."

"In the last project week we decided to optimize our system's lightweight design. Although our final system looked quite impressive, it also lost a lot of its stiffness. Due to this, it broke in operation."

Based on these learnings, the students started to systematically estimate the consequences of their design changes and, in the final stage of the project, they especially focused on finding design solutions barely impacting the system's embodiment, but heavily improving its functionality:

"Sometimes big problems can be solved by making small changes!"

4.3 Illusion of Reliability (All that Glitters is not Gold)

The third key learning results from the opportunity to compare the expressiveness of virtual and physical prototyping in practice. In their project work the students were assigned to apply both a CAD-tool to develop the virtual design model and a laser cutter to realize the physical counterpart. As a matter of fact, a high number of students reported that their technical system, represented as CAD-model, was expected to be absolutely reliable. By testing their laser cutter prototypes, most of them revealed this as an illusion of reliability:

"The project showed me that theory and practice often are far away from each other. I noticed this most clearly during the implementation of the CAD concepts. On screen everything looked so beautiful perfect, but when we tried to assemble the parts, we recognized all the mistakes".

"Designs that in sketches or CAD appeared to be simple, in practice suddenly turned out to be very complex or even unfeasible. This probably is the most important insight I gained during the project."

Thus, the students directly experienced the limited expressiveness of CAD-models, which are most suitable to spatial represent geometrical characteristics, but usually do not consider those physical effects strongly influencing a technical system's functionality and reliability:

"We have noticed some really critical points such as friction or deformation."

"In assembling I recognized the laser cutter's high level of accuracy and I became aware of the fact, we simply can frictionally engage the parts without using any glue or clamps."

Due to the high quality of geometrical representation, CAD-models in practice are especially used to prepare manufacturing introductions, such as technical drawings. The transformation from a CAD-model to a technical drawing usually is accompanied by the exact definition of all geometrical dimensions. The following statement indicates that by the application of laser cutters in educational project work this important purpose of CAD-models was recognized:

"Until the project, I was convinced that designing all parts in CAD is unnecessary, because it served for illustrative purposes only. Due to the usage of the provided materials and the laser cutters, I now have applied CAD for its intended purpose."

4.4 Impact of Design Details (The devil is in the detail)

As an additional key learning the students participated in the project personally experienced the impact of design details. In this context, design details is an umbrella term including geometrical details as well as functional details. Most students broach the issue of design details by reporting that they initially underestimated their impact and finally spend a lot time and effort adapting design details to improve their system's performance:

"It was interesting and instructive to learn how complex and relevant the smallest details can be."

"When we first tested our system, we were confronted with new problems that we never could have imagined. We had to deal with so many little things heavily impacting our system's functionality."

Due to the high-fidelity prototypes manufactured by laser cutters, the close interdependencies of function and embodiment design became more tangible. This allowed the students to experience the impact of design details on the system behaviour depending on smallest geometrical adjustments. A good example is given by the following student statement:

"We used the laser cutter to manufacture our gear wheels. They looked great and fit perfectly on the servo drive. However, during assembly we noticed that the distance between the gear wheels was just a little bit too long, which massively increased friction and thus overloaded the servo drive."

Some student teams even paid nearly all of their attention to the pick-up mechanism and consequently neglected the design of a sufficient durable mounting between the cable car and the hauling rope. Although the mounting is just a small part of the system, its function is most critical. The failing of this part can cause the failing of the complete system:

"I have learned that the smallest parts can cause a breakdown of the whole system."

In order to guarantee the functionality of such parts the students tried to design these elements as simple and reliable as possible. And this can be a quite ambitious aim:

"It turned out that the details, in particular, are anything but negligible. Especially trivial appearing parts are really hard to design working simple but also effective."

Lectures in engineering design sometimes misleadingly suggest that the early stage of the design process is the most challenging part, where all important decisions are made and all relevant problems are solved. In turn, designing the details might be misunderstood to be a diligent but routine piece of work. Here, educational project work, which includes both ideation and implementation, provides the opportunity to practically teach students the difficulties of different design stages and make them aware of the fact that being creative can be even more challenging in the hard constrained final design, than in the fuzzy early stage:

"As soon we had solved one problem, the next problem appeared. But exactly this challenge caused a lot of motivation to conjointly search for creative ideas and clever solutions."

4.5 Risk of Complexity (Keep it simple)

The fifth key learning addresses the risk accompanied by a complex design. In the project, many students tended towards designing complex structures. This trend often results from their intention to design a high-performing system that is able to quickly collect all kinds of goods. Due to the fact that the goods varied in geometry and material, the students decided to design single sub-systems that each are specialised in collecting one specific good. Consequently, they designed quite complex systems, which were composed of a high number of diverse parts. In this context, the students reported that the laser cutters were most suitable to manufacture such individually shaped parts:

"The laser cutter allowed us to realize a nearly endless number of possible designs."

"It was especially interesting to work with the laser cutter. You can manufacture plenty of possible parts and thus, you are really motivated to realize innovative designs."

Although most students already in designing were aware of their system's increasing complexity, they usually have not seen its risk until they tested the system's physical realization. Due to the laser cutter prototypes the students experienced that each additional component as well as each additional interaction of components, in reality represents an additional source of errors. In order to minimize the occurrence of errors and malfunctions, they learned to avoid complex designs and to spend more time in searching for simple and reliable solutions:

"In retrospect, I would probably attach more value on simple and robust mechanisms leaving no room for errors."

"A system with limited functions working reliable, is much better than a system that theoretical fulfils all functions, but practically fails."

Based on these insights, some students even deduced design strategies supporting them in the design of simple systems. The following student statement gives an example. It was made referring to the final design stage that is especially characterized by the sudden occurrence of various interdepending and unforeseen problems:

"You must always keep in mind that an occurring problem should not be solved by making everything more complicated, but by leaving something out."

Besides the high value of a simple design, the students also experienced that it is usually more challenging to solve a complex problem by a simple solution than by a complex one. In this context they also learned that, even if a solution seems to be trivial in the end, the process of developing this solution might have cost a huge amount of effort and time:

"In my opinion, the difficulty of designing an efficient system is not to design very complex, but to design as simple as possible and still meet all the requirements."

4.6 Relevance of Testing (Testing leads to failure, and failure leads to understanding)

The sixth and last key learning includes all previous ones. The five statements presented in the following indicate that due to laser cutter prototypes the students understood that in engineering design (1) testing is a consequence of uncertainty, (2) testing provides an adequate basis for making right decisions, (3) testing reveals illusions of reliability, (4) testing pinpoints the impact of design details and (5) testing is required to deal with complexity.

"Even in most sophisticated systems, unpredictable minor or major problems occur during or after manufacture and assembly. Only if scheduling includes time slots for extensive testing these problems can be solved before the final milestone."

"Our system perfectly showed that in practice not everything works as predicted in theory. In order to early detect and solve these discrepancies, regular testing is required. Testing is a precondition for developing the optimal solution."

"An important insight I gained concerns the relevance of testing. For a long time, I was convinced that our subsystems will work anyway and besides, they looked great in CAD. The first time I have noticed that a component did not meet the expectations was in testing."

"The project showed me how much time and effort is to be spend on testing and optimizing a system in order to meet the desired output."

"We limited ourselves to build and test only single components. Instead, we should have also assembled these components and tested them on a system level."

As a matter of fact, the relevance of testing was continuously discussed in lecture. Nevertheless, for most students it was essential to personally experience testing in project work to really understand its relevance. Some of them even emphasised this aspect in their reports:

"I finally became aware of how important it is to plan well and test extensively. I think this is only learnable by personally experience it."

5. Conclusion and Outlook

5.1 Conclusion

The analysis of 456 student's personal reflections on the Innovations Project 2013 revealed six groups of key learnings that are closely related to the introduction of laser cutter prototyping as one essential didactical element in engineering design education.

The above presented student statements indicate that the laser cutter machine tools allowed even first-year students to physically realize a system their designed on a high level of fidelity and thus, afforded them the opportunity to personally experience the system's functionality in implementation and operation. Based on the identified key learnings, it can be concluded that laser cutter prototyping decisively supports understanding:

- that designing is not a straightforward process, but a progression of iterative learning cycles characterized by uncertainty-affected decisions and clarifying tests,
- that designing the details is not routine work, but continuous and multifaceted problem solving characterized by various hard constraints and increasing time pressure,
- that designing is not modelling virtually, but effectively using virtual and physical models to realize a physical product operating reliable in real environments.

Although the applied laser cutters are not able to manufacture parts made of typical engineering material, such as steel or composites, they do represent a sufficient realistic and moreover cost-efficient manufacturing technology to make students understand the design process in its whole from the idea to production and testing, and this even in large classes of several hundred students.

5.2 Outlook

The Innovation Project 2013 showed that from an educational point of view, it is most beneficial to apply laser cutters in engineering design courses. Based on the insights gained from teaching the class and from analysing the student reflections, it seems to be important to facilitate the access to the manufacturing machines in future projects. This is planned to be achieved in two different ways. On the one hand, students need to become familiar with the laser cutters earlier, in order to purposefully consider prototyping and testing activities in their project plan. Consequently, in future projects the students will be assigned to deliver first laser-cut parts already at early project milestones. On the other hand, the completed project work revealed that the capacity of two laser cutters nearly reached its limit. In order to guarantee that even more than 456 students are able to build high-fidelity prototypes at the right time, in future projects more laser cutters will be made available to the students. Another need for improvement results from the laser cutters' limit to just allow manufacture two-dimensional parts. Especially in mechanical engineering, students need to learn designing basic machine elements and these usually are not flat. In contrast to gears and connecting elements, for example, shafts are parts that cannot be easily realized by laser cutters. Due to this, in future projects students will additionally get access to 3D-printers that are able to physically realize selected three-dimensional parts like shafts. Based on these measurements, the implementation and operation of high-fidelity prototyping can be successively improved and thus, practically experiencing engineering design can be further intensified.

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