One Mill per Student

Designing a low cost prototype mill for architectural use

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Abstract. The linking of planning and production is today of crucial importance in architectural planning processes. Though the teaching of techniques and methods of rapid prototyping in universities is not up to date, since the needed machinery is too expensive and the students' direct and perpetual access to a sufficient number of systems cannot be granted. This paper describes a teaching project where architectural students tried to plan, build and test a 3-axes mill for themselves and their fellow students. It further describes the motivation and realization of the class and the possibility to integrate self-made and low cost milling machines in the education of architecture students.

Keywords. Rapid prototyping; computer aided manufacturing, CAD-CAM.

Motivation and background

The interaction of computer aided modelling and digital production is changing the architectural production line in a sustainable way. It influences the reliability of planning, production and logistics and changes the interaction of those involved in the planning processes. Furthermore it widens the possibilities in architectural design and opens the industrial production line for one-of-a-kind productions (Schodek 2005).

The impact of these technologies on the building industry is a main focal point of our research and teaching. Yet, the enhanced or changed possibilities of designing architecture as a solitary topic for teaching and research is deemed to be off minor interest. We predict in contrast, that more crucial impulses will originate in the changed interaction in planning and production. Obviously the digital production line in modelling, construction of prototypes and individual one-of-a-kind production is challenging the traditional way of planning and logistics in building, leading to thoroughly changed requirements concerning the different processes and their actors.

In this context digital production depends on other technologies that are relevant for the planning process and cannot be considered without them. Especially digital scanning and reverse engineering of objects with 3-D scanners is of high relevancy to facilitate an iterative optimization. Our experience shows that only an elaborate combination of these methods enhances the quality of each component in this process.

In general our projects target the integration of digital production into planning to gain a coherence contact with the methods in 3-D scanning and product modeling. The resulting strategies of planning provide tools that allow a geometrical-semantic modeling of buildings which can be transferred into haptic reality quickly and at any time. There, manual supervision and any correction on the real object can be re-integrated in the digital process by 3-D scanner. This cyclic process is not restricted to architectural models, is repeatable as many times as needed and constitutes an integral part of the planning.

We try to test and establish this principle in teaching as well as in research by several measures. In teaching our working environment IT-learning-pool has proved to be a valuable didactic tool. The pool is a collection of one-day workshops dealing with several computer applications for planning and simulating. The training courses provide practical approach to the respective topic and enable the students on this basis to tackle themselves more complex software applications. Usually 15 to 20 of those workshops in the field of CAD, simulations, 3-D scanning and computer aided manufacturing are hold on a semester. The students choose the workshops according to their preferences and interests and attend lectures that provide theoretical preparation and interconnections. With this combination we try to offer a broad variety of up-to-date applications to the students and satisfy the institute's goal of providing a comprehensive and forward-looking education.

It is crucial for the work with the CNC applications in the IT-learning-pool that the students work is as closely as possible to the machines and that the tools for digital production are combined with reverse engineering techniques to high-efficiency workflows. As a safeguard for students and machines there are three step courses providing a theoretical basis, supervised production in groups, leading to a driver's license for the respective machine. Therefore we do not provide services for printing, cutting or milling, instead the students with the respective licenses have direct access to the machines.

At the beginning of students' occupation with CNC applications we use in the field of 3-D scanning, 3-D printing and 3-axes milling self-build and therefore inexpensive machinery. These are 3-D scanners based on the project 'David' of the Technical University Braunschweig [1] and a 3-D printer based on the Fab@Home-initiative [2]. This minimizes operating costs, risks of damage on the machines and it provides the possibility for the students to closely explore tools and methods by themselves. Moreover the concept of integration low cost rapid prototyping machines in building and planning processes considers the special requirements of the Architecture, Engineering and Construction sector (AEC) better than transferring unadapted methods and tools from other realms. It respects the less required accuracy, the rough environment and the principle characteristics of the one-of-a-kind production. Furthermore the students can be involved in the building of the machines and gain a deep knowledge of its functionality and potential that way. The production of a 3-axes milling machine as a complement to these low cost elements seems to be obviously in this concept and allows us setting up didactical experiments in direct connections of 3-D scanning and milling.

It is the goal in our research projects with focus on digital production to perceive the possibilities inherent in these technologies, to interrelate them to existing methods and to prognosticate chances for future use via prototypes. The projects deal with the aforementioned influence of these technologies on planning processes and on the other hand with a changed logistics of the production processes. For instance, the project 'Basys' implemented this concept in the coupling of massive wood technology for densified housing with the integration of the technical equipment in CAD-CAM planning processes (Zwölfer 2004) (figure 1).

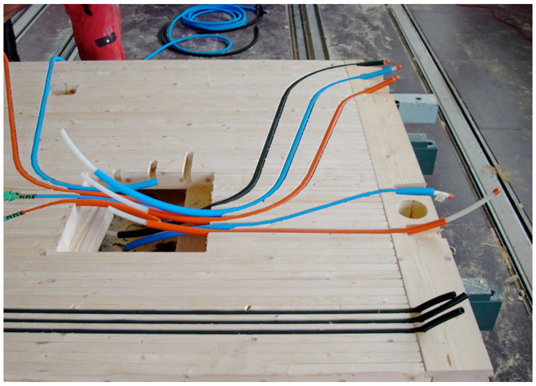

Figure1
Basys project: Integration of technical facility equipment in CAD-CAM

Our teaching projects today have in common that they leave the traditional domain of architectural concepts by our selection of topics, tools or methods and that we try to learn from other realms like car, ship or airplane production (Kieran 2004). We deem this approach reasonable and promising, because we reach out for the experiences of other disciplines and benefit of established strategies of mechanical engineering, electrical engineering and computer science. The concept effects enhanced expertise of the students in interdisciplinary cooperation and opens new spheres of activity for architects.

Why Rapid Prototyping?

The capable handling of rapid prototyping technologies (RP) is nowadays of key importance for students of architecture. Not only the production of work models and presentation models will be changed through the linking of digital planning with industrial fabrication but also the planning and construction process in the life cycle of a building itself. There are three reasons why architectural students have to learn techniques and methods of RP and train them intensively during their studies:

1. Usually the techniques and methods of RP provide better results. It leads to quality intensification in precision, completion time, costs and the overall quality of the products.
2. Rapid prototyping technologies allow generating new shapes and new ways in design by high precision manufacturing of individual parts and the possibility of parametric control of the machine.
3. Rapid prototyping technologies influence many processes in architectural planning and is changing interaction, order and relevance of design steps.

Linking of planning and production influences model making in both conceptual and planning stages as well as in the realization of buildings. The methods and impacts introduced by RP therefore can be found in architectural model making and also in processes and details during the realization of the build environment.

Why building a low cost milling machine?

The project ‘One Mill per Student’ was primarily initiated with three different motives. Main aspect was driven by the assumption, that low cost elements in RP fit the needs of

AEC sector better than exclusive, very precisely and therefore expansive environment provided e.g. in mechanical engineering. On the other hand we tried to design efficient low cost milling machines to counteract the bottleneck of our faculty in this technology. Simultaneously the handling of the machines needed to be designed as easily as possible that students of architecture, who are beginners in the use of RP technologies, are encouraged to start getting in contact with it. Finally, highly interested students, who understand already the principle functionality of the machines and are able to implement the specific demands of architects on this technology in a prototype, should be supported by this project.

Since the main aspect in our work concerns the influence of these technologies in planning and cooperation processes it seems to be necessary not only to apply RP in conventional workflows, but also to understand it in detail, setting it in contact with other available application and defining new methods and workflows for architectural use. By designing and building these machines ourselves, it is more probably to recognize the potentials of this technologies and use it more effectively.

Due to the described reasons, in our project 'One Mill per Student', we tried to introduce students of architecture very close to rapid prototyping technology. They received the task to get to know the technical basis of the milling technology and afterwards to design their own self made 3-axes milling machine. It was of very high importance to design a low budget milling machine which is suitable for everyday use and can easily be reconstructed and handled by other students. The overall cost of the machine, software included, should not exceed €2.500,00 for a mill with 70x40x10 cm work space in x,-y- and z-direction. The simple handling of the machine should also enable students to operate it on their own responsibility after a brief introduction rather than expecting the production of milled parts to be a pure service. Finally, particularly interested students with an understanding of the fundamental functionality of the machine and the ability to implement the very specific needs of architects into a prototype should be encouraged.

Application areas

Integrating RP into architectural planning has various purposes. The current use of this technology during the planning period, especially of 3-axes milling machines processing wood and plastics, focuses mainly on architectural model making. Therefore it is both reasonable and necessary to differentiate the distinct applications of models in architectural planning in order to specify the machine's requirements. Regardless of whether the model is created by hand or by means of CNC machines the following general classification can be made:

- Rapid production of working models for review and evaluation of design ideas. The essential requirement for this category is a fast and smooth connection to the planning tools in terms of an efficient CAD-CAM interfacing.
- Manufacture of presentation models for display and presentation of design ideas. They mainly require a high level of precision and workmanship.
- Models to verify the structural and technical feasibility of building details. In these cases it is important, that models are manufactured in a size sufficient for evaluation and the use of materials, which match the structural properties of the original parts closely.

- Models for experimental generation of design ideas. These working models serve as 3D sketches for experimental spatial experiences in the design process. Parametrically modeled buildings can be quickly verified in physical models, build with RP technologies, changed by hand and brought back to virtuality.
- Finally there are models created for architectural teaching in order to directly experience a specific material such as wood or metal.

What is crucial to the implementation of our project is rather the opportunity of detailed experience in the field of computer-aided manufacturing by fabricating the milling machine itself, than the character and quality of the models producible by the machine. Thus both the impacts and potentials of this technology in architectural planning can be appraised better, which leads to an additional, very important reason why students should produce models in training:

- By fabricating models using RP technologies students get to know innovative technical treatments in order to identify and practice the related planning methods. These methods in some respects differ fundamentally from the previously known architectural strategies.

Precisely this last point is important for our project. In our opinion, the RP technologies not only have an impact on the quality characteristics time and precision, but also influence the whole workflow of the planning and production of architecture strongly. In this respect the computer-aided fabrication by 3-axes milling machines is connected with further techniques of CAD-CAM interfacing. Particularly the comprehension of three-dimensional structures using 3D scanners with a subsequent interpretation by mathematical algorithms and the consistent computer-aided modelling play a decisive role in this context.

Project

The different objectives of model making are important as they determine the demands on the used materials, the required precision and the used technologies and machines. The main focus in constructing our machines was set on the creation of a basically functional machine that is driven by three simultaneously and independently controlled axes and its capability to work on wooden material up to a depth of 5 mm. The produced machines needed to have at least work model standard. The second important aim was the precision and permanent reliability of the machine and its realization investing not more than 2.500,00 € for a fully functional and safe mill.

The basic principles of 3-axes mills are easily demonstrated by simple constructions. The initial stage of the project meant for the students to analyze a simple machine and copy it. The small 3-axes plotter based on LEGO-Mindstorm-technology is easily built with public domain plans and manuals [3]. This machine is well-suited to demonstrate the working principle of a 3-axes mill.

The students then analyzed and assessed pre-existing projects, such as the self made milling machine TRON-CNC [4] (figure 2). By following the detailed descriptions and step-by-step manuals of this well documented project, students get familiar with basic construction principles and important design parameters of a milling machine. This second step has been completed by further exploratory on popular platforms like e.g. cnc4free [5].

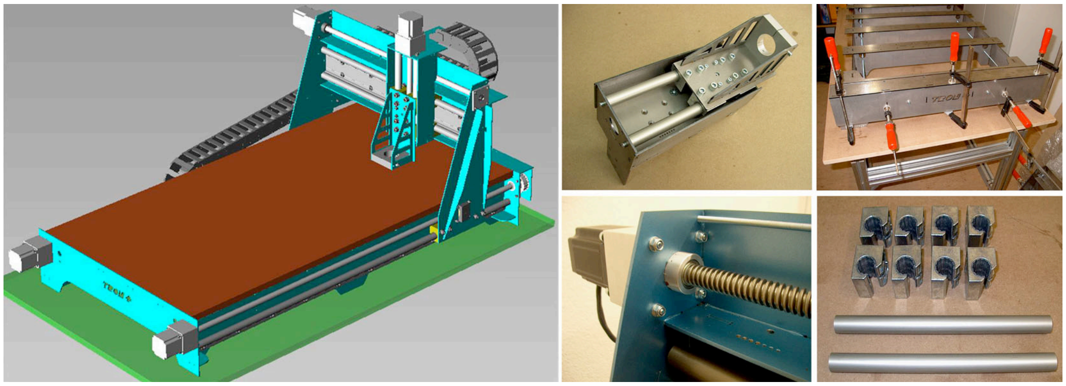

Figure2
Construction sample CNC Router Tron+ [4]

In the following processes we decided not to use existing construction manual from internet but to work on the spot with standardized and individually manufactured components on the basis of the specific requirements of the architectural model-making and of our work environment. In the process of the conception and realization of the machines the quality improvement and the durability of the construction was of growing importance.

Construction, planning

As a starting point we used low-cost spindles and check rails. Already then, a initial decisions were made concerning the dimensions of the machine that was to be built. Architectural students should be able to work with retail sales available panel materials. Therefore we decided to limit the tabletop size to 100 x 50 cm.

In the second step the machine was constructed along the basic parameters to gain a maximum traverse path. Starting with the z-axis we dimensioned the carriage big enough to mount a common mill engine (Kress [6]). It should be exchangeable and be mounted to allow maximum drilling depth.

The next step involved the planning of the portal allowing movements along the y-dimension. It has to combine low weight with high torsional stiffness. The precision in its construction is mandatory for the resulting tolerance and precision of the whole machine. To reduce costs we choose solid aluminum 10 x 10 mm, which can be delivered cut to size. Furthermore, additional holes for fastening e.g. energy chains, distribution boxes, dust shields, exhaust mountings etc. are easily drilled.

For the tabletop we choosed standardized aluminum profiles, which are very planar due to low manufacturing tolerances and can be easily exchanged in case of damage. The flute profiles are very accurately fitting and grant a high stability when built in. A broad variety of materials of any size can be mounted on the table. Furthermore, the parts are delivered cut to length.

Lastly we placed failsafe limit switches, and installed covers to reduce the danger of contusion. Additionally we placed kill switches and installed exhaustion.

Software

We process the milling data in several steps. The students develop the drawing data with the aid of common CAD applications. For the milling ways we choose MeshCAM [7], a simple program to create contours in STL format for 3-D data. The application is handy to demonstrate the basics, due to the reduced amount of adjustable parameters. Furthermore, it is cheap, yet, it is possible to develop complex forms with it.

The machine itself is controlled with Mach3, an established control software that is applicable for many machines and also well documented [8].

Controlling

We used a low-cost kit by Benezan Electronics [9], which can control up to four axes, thus allowing extension in future projects.

Problems and prospect

Since this was our first step in planning and building a RP machine, we encountered e.g. problems concerning the dimensioning of parts. In future projects the experiences we made allow more precise planning of the parts themselves and to match their respective application. Furthermore, we aspire synergy-effects in the used software applications, though right now a consistent applicable software, especially in conjunction with the University's existing machine pool, is difficult to implement.

Figure3
Construction and test of the prototype

Next steps

Based on our experiences so far we plan to develop the project and prototype new levels in future:

- A public manual and lessons is planned to facilitate other students copying the machine. We intend to enhance the construction manual with a basic schedule and an information pool with student cooperation.
- Certain suggestions for improvement of the machine will be discussed. The focus of this discussion would be cost reduction, reliability and security of the machine. Furthermore the possibility of scaling the machine based of the same construction will be analyzed.
- Subsequently the machine will be tested considering its interaction with planning methods and processes. Especially the coupling of the machine with product data modeling based on the Industry Foundation Classes and the integration of 3-D scanning will be tested for its didactical value.

- Finally we test, if the experiences made in this project can be transferred into the field of 3-D printers on the basis of the Fab@Home [2] and RepRap [9] initiatives and can lead to similar didactical environments.

Conclusion

The architecture students have learned the required skills of electrical and mechanical engineering to construct the milling machine by themselves or they cooperated with experts from other realms. The cooperation with other departments and the integration of expert knowledge can be therefore designated as an important didactically learning effect of the class. After completion and testing our machine we are furthermore sure that the construction and application of self-made 3-axes milling machines is a practicable method to increase the number of available machines in a sufficient quality and to get in deep touch with the technology itself. As a first obviously aim we can now produce based on these experiences a 3-axes milling machine with a labour input of 2 students for 1 month and a budget of 2.000,00 € each. We achieved a fully functional prototype, with an adequate precision for architectural model building. Currently we have reached a testing phase in which we gain experience considering different materials and the development of workflows. Altogether the machine shows a good relation between costs, precision and capacitance, which allows students to work by themselves with the machine. The used construction and materials allow easy alteration and additions of elements in the future.

Second and more important is, that by constructing this mill we are now better prepared to go further on in connecting rapid prototyping technologies with other available procedures and combine them to efficient planning environments for architectural use.

Low cost rapid prototyping machines are not complex and can be constructed also by laypersons in a sufficient quality and with permanently precise results. We furthermore assume, that since getting cheaper, more effective and easier to use, RP technologies like milling machines, 3D printing, 3D scanning applications and lasercutter are today before a breakthrough and will be affordable soon also to smaller architectural offices and students. The project 'One Mill per Student' wants to achieve, that every students has a deep comprehension and direct personal access to these technologies. The professional interaction with rapid prototyping technologies should be a matter of course for architectural students and the technology must have a higher availability in architectural schools.

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