Experience of teaching geometric modeling at schools and universities

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Abstract. This paper presents the requirements to specialists willing to work in state-of-the-art mechanical engineering as well as the related requirements to teaching geometric modeling at school, where students are supposed to learn the principles behind 3D modeling of natural and man-made objects and to study the issues of making 3D model-based parts on CNC machines. The paper also covers an elective course program designed to teach high school students to model and manufacture parts. Students of Samara Aerospace Lyceum have made projects as part of such learning, which are also presented herein. The article further dwells upon the scope and the curriculum of the geometric modeling course taught at the Engineering Graphics Department, Samara University, as part of the Aircraft and Rocket Engine Design degree, and analyzes the students’ projects made on individual assignments. The authors conclude on the effectiveness of said training.

1. Introduction
State-of-the-art training of engineering students implies broad use of IT, in particular to enable specialists to collaborate in a uniform information space (UIS) [1, 2, 3]. When working in a UIS, a well-trained designer needs to use CAE systems for modeling, which simulates the environment, in which the new product, its units and parts will operate; CAD systems to create 3D models; to set reasonable technical requirements to the assembly and manufacture of individual parts; and to draw up technical documentation kits [4].

Technologists use 3D models of products, parts, assemblies, machinery [5], tooling, and tools to design optimal processes for manufacturing parts, workpieces [6], tooling, etc. on state-of-the-art high-performance machinery; besides, such models help perform engineering analysis of the thermal, power, and other patterns of machine operations involved in converting a workpiece into a finished part, control the geometric parameters of complex-shape parts using state-of-the-art instrumentation [7, 8], and implement automated release of the necessary process documentation.

2. Experience of Teaching Geometric Modeling
The principles behind the innovative development of the Aircraft and Rocket Engine Design major at Samara University imply, among other things, targeted courses for innovation-seeking pre-university institutions (secondary and vocational schools), broad use of cutting-edge computer-assisted design tools in teaching, and training students to work on CNC machines to help them learning machining and rapid prototyping (additive manufacture).
Two approaches are distinguished depending on how complex the geometry of the part to be designed is:

- 2D model-based part and manufacture process design;
- 3D model-based design.

2D geometric modeling is the natural evolution of the conventional pencil-and-rule drawing method. 3D modeling, albeit a novel tool, can also be used to automatically generated 3D-associative 2D models. However, 3D models are more natural to human eye, as the world is three-dimensional, which is why it makes sense to start teaching graphical language early, e.g. in Grade 5.

The following should be borne in mind when implementing such an approach:

- learning the laws of microcosm and macrocosm from the point of view of geometry in addition to physics, chemistry, or biology helps students gain a broader understanding of the world;
- 3D modeling course for schoolchildren should be based on teaching them the graphics creation methods. All stages of learning should be thoroughly implemented. Creativity should be involved in all parts of the course;
- computer-assisted modeling of physical objects is inseparable from cognitive training. Geometric modeling classes involve diverse problem-solving to boost school students’ visual, logical, technical, and heuristic thinking. Computer-assisted geometric modeling helps schoolchildren develop the analytical and synthesizing components of creative thinking;
- modeling training is based on the following principles: the knowledge it gives should be in demand and of applied nature. When making new assignments, the teacher should make sure their scope and content are similar to what engineers in production do, whilst the graphic models should be based on actual existing objects as prototypes. The course should be tied to Art & Craft, Mathematics, Visual Arts, Mathematics, IT, and other school disciplines;
- learning the fundamentals of computer-assisted geometric modeling of 2D and 3D objects is integral to further studies of how IT innovations are used in design, engineering, and manufacturing;
- knowledge of the fundamentals of geometric programming and mastering the state-of-the-art model-based manufacturing tools and methods help advance one’s understanding of computer-assisted geometric modeling.

3D modeling develops schoolchildren’s spatial ability and facilitates the learning of geometry, arts and crafts, which in turn helps with career choice during teenage years, among other things.

Geometric models derived from their physical prototypes and the drawings based on such models could be of use as handouts for arts and crafts lessons, including the development of control programs for CNC machines.

It is also promising to build associations between geometric modeling and IT, where geometric models (the basic shapes) created in a CAD environment could be described in any text editor using high-level languages.

This research involved high school students, e.g. those of Samara International Aerospace Lyceum; as a rule, these were Grade 10 students who started the 32-hour Geometric Modeling and Manufacture of Parts course, a two-classes-per-week elective, in the fall semester. Before the course began, its content had been discussed with and approved by the school’s Principal and other officials.

Each of the four classes of the year attended a lecture on the role of 3D modeling in today’s manufacture; among other things, the lecture presented the goals, objectives, and curriculum of this elective course, exemplifying every statement.

The goal of the course was to teach students to use human-computer interaction so as to create solid 3D models of man-designed and natural objects, as well as to apply this knowledge to creative tasks associated with making new things.
Students were expected to develop their spatial thinking by manipulating 3D models of basic shapes (spheres, cubes, cylinders, etc.) and man-made objects, by arranging these elements in space without sketches or drawings, by learning to make and use electronic product models, to work in state-of-the-art CAD/CAM/CAPP systems to ultimately implement their creative designs on CNC machinery.

ADEM VX, a Russian CAD/CAM/CAPP system, was used as the working environment. Practice sessions took place in the specialized interactive classroom of the Engine Manufacturing Department, Institute of Engine and Power Plant Engineering, Samara University; this classroom features modern computers and small-size Wabeco CNC machines. Four parallel groups of students (50 persons at first) spent 16 hours in this classroom to study the fundamentals of 3D modeling, to compare canonically shaped natural objects (cylinders, cones, parallelepipeds, etc.) against their quasi-3D images on a flat screen, which were picked from a library of parametric models of basic shapes; they learned to recognize objects by the model, to unambiguously detect the shape and metric parameters of an object, and to run affine model transformations adjusted for the spatial position of the object, see figure 1; students also performed 'local operations' by simulating clay sculpting or altering the spatial position and shape of individual model elements, see figure 2; they further modeled the sequence of transformations, e.g. plane section to Möbius strip, cylinder to Klein bottle; they were tasked to model a predetermined composition of same-type objects, e.g. perfect crystallographic cells composing a solid, see figure 3; they mastered the design methodology behind creating complex objects from basic shapes on a physical prototype by running Boolean operations, see figure 4; finally, they revised the 3D solid modeling materials of students from previous years.

Figure 1. 3D PM library and affine BS transformations.

Figure 2. Local operations.
The students also had 14 hours of laboratory sessions, where the assignments were given in different versions; this helped students master the modeling of machining by CNC turning (figure 5) and milling, whereby they wrote and verified ADEM VX control programs, see Figure 6, learned the functionality of AGIE electric discharge machines (EDM) and 3D printers from various manufacturers. The students also took part in parts manufacture.

Figure 3. Crystal lattice modeling.

Figure 4. Modeling a fitting from a physical object.

Figure 5. Making a part on a CNC lathe: (a) a 3D model; (b) control program development; (c) machining verification; (d) finished part.

Figure 6. Making a part on a CNC milling machine: (a) a 3D model; (b) control program development; (c) machining verification; (d) finished part (die).
During the spring, the Lyceum students who had done the basic elective and wanted to do their own projects had individual classes. They got to choose the project topic themselves. However, each project followed the same algorithm:

- research the existing assembly designs on the Internet;
- make an optimal design and build a 3D model;
- develop a control program in ADEM for various CNC machinery;
- manufacture, assemble, and test the finished assembly.

Figures 7 and 8 below show some of the completed projects.

![Figure 7. Modeling, printing, and finalizing a Matryoshka design.](image1)

(a) (b) (c) (d) (e) (f)

![Figure 8. Handlebar fastener assembly design: (a) design model, (b) and (c) tool trajectory modeling, (d) and (e) finished parts, (f) completed assembly on a bike.](image2)

(a) (b) (c) (d) (e) (f)

The projects utilized solid 3D modeling and help schoolchildren learn how to design machine parts and assemblies, how to develop rational CNC machining processes, to manufacture, finish, assemble, and test the finished products. Such projects help make rational and conscious career choices. School training also helps with further studies of geometric modeling at university level. Over four semesters, each student of the Institute of Engine and Power Plant Engineering (IEPPE) needs to pass the first stage of learning (geometric modeling training, GMT) even though most of them do not have pre-existing experience of drawing. The design, manufacture, and organizational training is furthered in accordance with the student’s major of choice [9].

Geometric modeling training consists of the Engineering Graphics Department’s courses: Foundations of Geometric Modeling in Mechanical Engineering (replaces Descriptive Geometry) and Computer Graphics for Engineers (replaces Engineering Graphics).

These courses constitute the foundation, upon which the following design projects involving 3D and 2D modeling (electronic documentation) are built. In the first semester, as students take the Foundations of Geometric Modeling in Mechanical Engineering, they learn the fundamentals of creating and using geometric 3D models: how to visualize the basic shapes of the given geometric parameters, how to map models onto a plane, how to run affine, topological, and logical transformations, how to solve positional and metric problems in space, how to transform graphical elements on a place, how to do geometric drawings, how to model from a drawing, and finally how to make projective drawings, build 3D models of parts, and print them.
Thus, students complete their individual assignments, in which they solve four complex problems without supervision. These involve overlaying geometric objects and their developed views, and would be normally done as part of the Descriptive Geometry course; the students are tasked to present as-built drawings, 3D models, and associative drawings to the teacher to show how they solved the problems, usually done as part of the geometric and projective drawing modules of the Engineering Graphics course. When studying how surfaces are shaped, each student does their individual assignments, which involve not only modeling a surface, but also manufacturing it by 3D printing, see figure 9.

Figure 9. Möbius strip.

The second semester covers the following topics: CAD systems and how they can be used to make parametric 3D models of fasteners and standard parts; use of parametric models for modeling separable and non-separable joints, and for 3D modeling of custom-designed GTE parts from their physical prototypes plus making associative drawings of the parts.

During the practice sessions that follow the first year, students get individual assignments, where they are tasked to use parametric model libraries of standard parts and fasteners to create 2D and 3D models of the first stage of a helicopter reduction drive (Figure 10), where they need to bear in mind the technological particularities of making part components as well as the principles of modular assembly and disassembly of parts.

The third semester covers 3D modeling of planetary gear trains, final-stage modules, reduction-drive final stage cases, and frame parts; students are also taught to make general-view drawings. This part of the course revolves around individual assignments.

While studying computer graphics for engineers, students model and manufacture fasteners, standard parts like shafts, gears, bearings, cases, etc. They also make and assemble full-size mockups of various assembly units, see figure 11.

Figure 10. 2D and 3D models of the first reduction-drive stage.

The fourth semester connects GMT to engineering design as taught by the Department of Machine Design Fundamentals: developing the general-view drawing (i.e. making associative as-built drawings of the helicopter reduction drive parts), making specifications and assembly drawings.
3. Conclusions

Therefore, the specialist training course covered herein: takes into account the dominant role of 3D modeling for work in a uniform information space; differentiates such concepts as a computer-readable 3D model and its flat-screen representation as a human-readable quasi-3D model or flat (2D) model; teaches the principles of natural geometric modeling (3D based) using database technologies (no drawings); helps acquire geometric modeling skills by using various mathematical representations (structural, boundary modeling, or hybrid) and geometric modeling methods (parametric, direct, synchronous, associative, and object-oriented); implements 3D and 2D assembly of collapsible parts by bottom-up design based on parametric model libraries of fastening parts; teachers 3D modeling of parts and assemblies based on parametric models of complex representative standard parts while also explaining the peculiarities of manufacturing, assembling, and disassembling such parts; implements direct 3D modeling of hollow-body parts by means of top-down design; teaches methods for generating general-view drawings of complex assemblies consisting of over 80 items; explains the rules of making drawings by means of associative design from 3D models; explains how to make specifications and assembly drawings from 3D models; teachers efficient end-to-end virtual design and manufacture of finished products; contains individual project assignments where students model complex parts, assemblies, and objects, and then make them on CNC machines, mainly by rapid prototyping. The educational technology based on geometric modeling [10-13] improves the training of GTE design and manufacture specialists, making it state-of-the-art [14, 15].

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