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Raffaele De Amicis
Giuseppe Conti *Editors*

Future Vision and Trends on Shapes, Geometry and Algebra

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Editors

Future Vision and Trends on Shapes, Geometry and Algebra

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Editors
Raffaele De Amicis
Giuseppe Conti
Fondazione Graphitech
Povo, Trento
Italy

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Introduction

This volume collects the results presented in the context of the final workshop of the project SAGA—“ShApes Geometry Algebra,” a four-year long Initial Training Network that had been funded by the European Commission within the Marie Curie Action. Its aim was to introduce young researchers to interdisciplinary and inter-sectorial research and development issues in the areas of classical and computational geometry, approximation theory, numerical analysis, and computer graphics and—most notably—their implications in the context of Computer Aided Design and Manufacturing (CAD/CAM) systems.

In fact, over the last few years, disciplines such as computational geometry or computer graphics have undergone a profound evolution essentially driven by the ever-increasing computational power and by the availability of new hardware and software technologies. This, in turn, is having profound effects, either directly or indirectly, on a significant range of domains including, but not limited to, digital content creation and creative industry (e.g. performing arts, film, animation movies, video gaming, digital libraries), multimodal interfaces and natural computer interaction, scientific visualisation (e.g. medicine, chemical and pharmaceuticals), policy making (e.g. planning, environment, public sector information), engineering and manufacturing (e.g. civil, manufacturing, automotive and aerospace engineering), marketing (e.g. digital signage, advertisement campaigns), finance, safety and security.

Furthermore, due to their horizontal nature, any development in fields such as computational geometry, approximation theory, numerical analysis and computer graphics brings a number of direct and intermediate implications on a very large range of which are not directly related to CAD/CAM, ranging from pedagogy to neurosciences, from digital storytelling to social and cognitive sciences, to name but a few.

The aim of the project SAGA was to bring such a broad-range perspective to the community of young scientists and, through a comprehensive four-year training programme, promote the growth of a new generation of researchers capable to address a wide range of requirements emerging from both the academic and the industrial standpoint.

A three-day long workshop, which took place in Trento, Italy at the end of 2012, marked the end of the SAGA project. The event had been articulated to give project fellows the opportunity to showcase research achievements and meet with top experts from domains of relevance, who addressed, in the context of several keynote speeches, the following research and industrial challenges:

- Detecting Hidden Curves Using Algebraic Schemes (Prof. Lorenzo Robbiano from the University of Genoa, Italy).
- Virtual Conceptual Design (Mr. Gino Brunetti from CASED—Center for Advanced Security Research Darmstadt, Germany).
- Polynomial Splines over Locally Refined Box-Partitions (Dr. Tor Dokken from SINTEF, Norway and SAGA coordinator).
- Numerical Algebraic Geometry and Differential Equations (Prof. Andrew Sommese from the University of Notre Dame, USA).
- The Case for Alternatives to Interactive Design (Dr. Thomas A. Grandine from BOEING Research and Technology, USA).

The majority of the works collected within this volume were presented during the aforementioned workshop and span across several relevant domains, including:

- Mathematical algorithms for geometric and solid modelling.
- Scientific issues in the context of classical algebraic geometry.
- Industrial applications of mathematical models, for instance required deforming surfaces when animating virtual characters, to automatically compare images of handwritten signatures, or to improve control of NC machines.

Their multifaceted nature well reflects the cross-disciplinary nature of SAGA, which was funded upon four main pillars: change of representation, geometric computing and algebraic tools, algebraic geometry for CAD applications and practical industrial problems.

Raffaele De Amicis
Giuseppe Conti

Future Shape Modelling Scenarios

Current Trends and Possible Evolutions Within the Industrial Domains of Engineering and Manufacturing

Raffaele De Amicis, Giuseppe Conti and André Stork

Abstract The purpose of this chapter is to present a broad analysis of the recent developments that characterize the domain of CAD/CAM/CAE and, starting from the current state of the art in terms of scientific achievements, to analyse technological trends that regard the interactive visualization domain, and eventually define a number of possible scenarios that are likely to unfold in the next few years in the context of 3D shape modelling for industrial applications.

Keywords CAx · 3D modelling · Virtual engineering · Future trends

1 Introduction

Global competition is continuously forcing manufacturers of industrial products within the automotive, aerospace or other production engineering domains, to introduce faster, cheaper and more agile processes to facilitate the creation of better performing and more personalized products. This trend has produced a significant strain to the whole production development process. In recent years the different models used to represent the various facets of the design and manufacturing processes have been profoundly transformed by a continuous evolving technological landscape.

R. De Amicis(✉) · G. Conti
Fondazione Graphitech, Via Alla Cascata 56C, 38123 Trento, Italy
e-mail: raffaele.de.amicis@graphitech.it

G. Conti
e-mail: gc@giuseppeconti.com

A. Stork
Fraunhofer Institute for Computer Graphics Research IGD, Fraunhoferstr. 5, 64283 Darmstadt, Germany
e-mail: andre.stork@igd.fraunhofer.de

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Over the past few years, the domains of Computer Aided Technologies (CAx)—in general—and Computer Aided Manufacturing and Computer Aided Engineering (CAD/CAM/CAE)—in particular—have been significantly influenced by several technological trends. These include deployment of cloud-oriented services for engineering and product data lifecycle purposes as well as the widespread availability of mobile IT devices.

The forthcoming large-scale availability of low-cost ubiquitous gesture tracking technologies, allowing for more natural interaction paradigms, together with the evolution of the computing scenario, will most likely have significant implications to 3D shape modelling.

2 An Overview of Recent and Current Trends for Shape Modelling in the Domains of Engineering and Manufacturing

2.1 From CAx to Virtual Engineering

As highlighted by a recent report by Jon Peddie Research, the domain of Computer-Aided technologies, often simply referred to as CAx, is "more dynamic than ever" [1] and can be accounted as the main responsible for a major evolution—within several engineering domains-towards Virtual Engineering (VE).

This evolution, which is often associated to the industrial uptake of Virtual Reality (VR) and Virtual Prototyping (VP) applications, is having profound implications across various design phases from concept to simulation and manufacturing [2]. A notable example of this evolution has been the all-virtual design of the Boeing 777 airplane [3, 4]. Such a milestone or achievement has been made possible through extensive use of CAx in the context of an extremely complex and collaborative set of design and simulation processes that involved experts, customers and manufacturers.

Several relevant projects funded by the European Commission within the fifth, sixth and seventh framework programs have specifically addressed Virtual Engineering. Some of the most relevant initiative include, but are not limited to, AIT VEPOP "Advanced Information Technology Virtual Early Prototyping Open Platform", VERDI "Virtual Engineering for Robust Manufacturing with Design Integration" and VEGA "Virtual Reality in Product Design and Robotics".

Despite the undoubtedly significant number of advantages, however, the use of VE and VR has also introduced a few critical drawbacks. One of the most notable examples is the false sense of security, conveyed by such an apparently deterministic approach. This clearly highlights the importance of developing modelling techniques that can intrinsically support variable levels of uncertainty as well as methodologies to formalize the degree of uncertainty across multiple modelling or processing/simulation steps.

The current limited awareness on the different degrees of uncertainty that characterized different components of a complex design solution may mislead to overconfident decisions made on top of only apparently precise datasets. Furthermore, as a result of the pervasive adoption of VE, the “fuzzy front end of the design process may be cut short—to the company’s long-term disadvantage” [19].

Furthermore, the intrinsically high collaborative and interactive nature of these environments may lead to the dangerous—if uncontrolled-growth of number of changes with the consequent poor control over them. The potential impact of this factor has been dramatically demonstrated during the design of the A380 model airplane by Airbus [20], whose release to the market was significantly delayed due to the continuous changes of the design.

2.2 *From Virtual Factories to Augmented Business Visualization*

If we further expand the scope of our analysis, from the early stages of the design process to the whole manufacturing process, we can observe that the increasing complexity of manufactured products, e.g. in the automotive or aeronautics domain, requires high levels of flexibility, maintainability, and customization which is being increasingly addressed by Virtual Manufacturing (VM) systems.

The goal of VM is to pursue the integration of computer modelling for product development purposes within a manufacturing system. VM allows simulating all manufacturing operations to be performed on actual production lines and, as a discipline, it was borne out of the integration of many domains including CAD/CAM, Virtual Prototyping (VP), Virtual Reality (VR), production planning and control, Product Lifecycle Management (PLM), Product Data Management (PDM), Manufacturing Process Management (MPM), Computer-Integrated Manufacturing (CIM), Component Information System (CIS), Knowledge-Based Engineering (KBE), Manufacturing Process Planning (MPP), Electronic Design Automation (EDA).

Particularly relevant have been the implications emerging from the use of wide networked collaborative virtual manufacturing system [22] as in these cases the definition of product may require the cooperation between a large number of different experts using different tools. Referring to the aforementioned example of the design of the Boing 777 airplane, this required the definition of 130,000 parts, through the involvement of 6,800 internal and 10,000 external experts.

Furthermore, in the last few years, increasing use of Web Services and Grid computing has expanded the use of CSCD—Computer Supported Collaborative Design technologies. The importance of this trend in terms of shape modelling is significant as proved by the development of several commercial visualization systems for collaborative design, including Oracle AutoVue (formerly Cimmetry Systems), Actify SpinFire, Autodesk Streamline and SolidWorks DraftSight developed by Dassault Systèmes.

This trend is leading, as a result, to a new generation of applications that are designed for what is referred to as Augmented Business Visualization (ABV), which can be regarded as the application of Visual Analytics to the engineering and manufacturing domain.

2.3 The Importance of the Concept Design Phase

If we analyse the relevance of shape modelling research across the whole design and manufacturing lifecycle, we can observe that traditionally, significant effort has been paid to the development of visualization and visual computing technologies specifically designed for the early stages of the design process. In fact, particular attention has been paid to improving quality and efficiency of Computer Aided Styling (CAS) systems. The reason for this is to be found in the high market value of styling features in particularly important markets such as automotive or industrial design where products tend to be often remembered more for their aesthetical properties and "emotional features" than for their physical or mechanical properties. CAS software have been typically engineered to interactively support the designer along an evolutionary process that starts from a conceptual model or an initial—often vague—idea, which is iteratively refined until it is consolidated into a design "concept". Therefore, the main goal of CAS has been to free designers from very constrained graphical languages accounting, at the same time, for increasingly performing materials and manufacturing processes, which have allowed manufacturing of increasingly complex 3D shapes.

Virtual Prototyping (VP) tools, to a certain extent, have represented the natural evolution of CAS, in that they allow interactive simulation and optimization of products or concepts, assessment of design features through design reviews [5] or assessment of the impact on manufacturing processes. VP tools are now well established within advanced engineering fields, for instance within the automotive and aeronautical industries, and can allow considerable savings in the range of up to tens of millions of euros for each product.

In the past, several research groups have developed VP tools that leveraged on Virtual and Augmented Reality (VR/AR). The results were a number of three-dimensional environments that combined sketching and modelling within a natural seamless action. These environments allowed interactively creating and modifying 3D shapes at the early stages of the design process. First examples of these developments include the work of Butterworth et al. [6] and Steed et al. [7] while later works include those of Fiorentino et al. [8] or De Amicis et al. [9], to name but a few. More recent developments on interactive drawing of 3D models include, among others, studies at Fraunhofer IGD [12] on dynamic simplicial meshes [13], on physically based interactive simulation techniques for deformable objects Falcidieno and Léon [14], the work by Alexa [15], the work by Liverani [16] and the work by De Amicis [10].

2.4 The "Massification" of Virtual Engineering

Recent industrial trends in the domain of shape modelling have also been characterized by the need for mass-customization. It should be noted that the concept of "mass-customization" within this context could be considered from different standpoints.

The first "massification" trend sees the use of IT technologies to improve the design and manufacturing processes by extending the range of possible product configurations. With regard to this trend relevant works include the development of flexible vehicle manufacturing solutions and architectures that have been carried out, for instance, by the Smart Customisation group at MIT Media Lab [23].

The second approach to "massification" sees the possibility to create new IT-based services (especially in the context of web-services, for instance for marketing or commercial applications) that by themselves represent a customized form of product, resulting from a complex software engineering process. Examples of this second approach are the 3D services developed by My Virtual Model Inc., a Canadian company that allows creating virtual avatars of real people that can use their virtual counterparts to test or assess products (from garments to objects) in a virtual manner.

The third, and perhaps most challenging, approach to "massification" regards the massification of the design process itself through the involvement of large community of stakeholders, typically customers, within the design process, through very complex participated design process. This has profound implications in terms of shape modelling in that it requires development of complex participative interaction mechanisms and tools for collaborative shape creation and editing.

The fourth and last approach, which is also referred to as "consumerisation", sees the use of non-professional (consumer) applications being used for industrial or engineering use. The most notable example in the domain of shape modelling is the widespread use of the 3D modelling and visualization SketchUp package by Google for professional uses. Such a very significant (from a market standpoint) trend has been essentially fuelled by the interactive nature of these applications that offer a very easy-to-use interface at low cost and dramatically proves the importance of simplicity of use, within certain applications, even beyond the absolute quality of the final representation.

2.5 The "Cloudification" Trend

If we analyse the 3D modelling scenario from a different standpoint, the need for high-performance environments for 3D shape modelling and simulation has also driven the research community to explore the use of cloud-oriented software paradigms. An interesting example of this trend is the COVISE service-based platform [21], which extends the coSimLib interface for high-performance visualization for CPU/GPU systems for fast post processing tools, to allow interactive access through the web to results of 3D simulations.

Most notably, in fact, the result of the simulation can be visually manipulated through a WebGL client that renders a scenegraph created by a service-based post-processing tool on top of the results of the simulation. Although this approach does not yet allow for full simulation-steering, based on interactive manipulation of 3D shapes, it undoubtedly represents a significant step forward towards a fully interactive visualization and simulation environment.

Other examples of this trend include PythonOCC, a Python-wrapper for Open-CASCADE, which delivers CAD-based functions as a service—including visualization and simulation—through the web [20]. The resulting CAD/CAE web-based library introduces a logical layer between end-user-oriented CAD software, which provides end-user scripting and access to software-developer-oriented CAD kernels.

3 Existing Barriers and Opportunities

Based on the aforementioned trends it is possible to identify a number of barriers that need to be overcome by research in the next few years. If we start our analysis from the early stages of the product design lifecycle it clearly emerges how, in the medium-term, the role of tool superficially designed to support the styling phase is set to increase in terms of importance.

This will be mainly due to the wide availability of consumer technologies supporting more natural forms of interactions (e.g. multi-touch interaction technologies and low-cost motion sensing devices). The availability of low-cost consumer devices, instead of expensive customized setup used by research community and industry in the past few years, will eventually determine a rapid uptake of new interaction paradigms.

This is extremely important when we analyse the early stages of the design process, which is characterized by the use of CAS tools. Current CAS tools are in fact mainly designed for expert use and often make use on non-intuitive interaction process, for instance based on interactive manipulation of shapes through control points. However, users at this stage, typically designers, have limited mathematical knowledge of the underlying mathematical representation used by the system. For this reason it is difficult for them to acquire complete control overall shape definition process. This is particularly critical at the early stages of the design process when the operators needs very unconstrained ways to generate and modify shapes, for instance based on sketching and free-form modelling.

Among the several existing technological barriers to less constrained design process, few are worth particular attention. One the main barriers that limits the transition from physical to a totally virtual environments, is the development of experience augmentation technologies that can convey the sense of physical matter through interactive feedback mechanisms closely associated to the shape creation or editing action.

To this extent, new approaches based on emerging hardware (multi-touch devices, miniaturized portable gesture tracking systems) are required to fill the gap between virtual and physical scenes. Paradoxically, up to now, existing sketch-based modelling systems can be still considered at their infancy since they do not fully exploit the potential of emerging 3D or multi-touch/multi-hand interaction devices.

However bridging this gap is essential to help operators move beyond the level of usability achieved today by Computer Aided Styling (CAS) systems. This can be achieved through the development of both new mathematical models and novel forms of virtual feedback augmentation that can leverage on natural manipulation skills.

Traditionally, the use of multi-dimensional interaction and haptic devices, including motion capturing systems, gesture recognition technologies and haptic feedback devices, has been expensive, unpractical for desktop or mobile scenarios or has yielded unconvincing results. However, this is set to change rapidly, since the availability of low-cost, accurate and miniaturized feedback technologies will promote widespread adoption of 3D interactions at the consumer level.

This it is very likely to produce, as an effect, a cultural change whereby natural interactions will become part of the standard computer experience. As a result, this will eventually influence the development of more natural forms of interactions suitable for professional applications including those designed for the industrial domains.

These will have to move beyond past approaches that have only tried to mimic traditional techniques such as clay modelling. In fact it is very likely that in the near future, due to the flexibility allowed by forthcoming gesture tracking technologies (e.g. concurrent tracking of multiple users), mockup-modelling techniques such as clay modelling and sketching will play an increasing smaller relevance.

The availability of more natural interfaces within the product development process could shorten the product development time and improve the overall "quality" of industrial processes and products. The concept of "quality" here is regarded in very general terms, ranging from the quality of manufacturing processes (in terms of efficiency, safety and ergonomics) as perceived by the industry and by those working therein, to the quality of product life cycle (in terms of maintenance) up to the quality of the product itself (in terms of aesthetics, usability, ergonomics and functioning) perceived by the final users.

For this to happen it will be necessary not only to address more efficient interaction mechanisms but also new cooperation mechanisms to allow on interactive shape modelling by several concurrent users. This will require development of forms of concurrent modelling within a three-dimensional realistic environment, for instance to support cooperation and evaluation by operators from different sites, both inside and outside the boundaries of a company. This would allow more collaborative enterprises environment leveraging on knowledge coming from suppliers, whose operator would be thus able to better validate a product before it is physically realized.

The main challenge will be to deliver technologies characterized by extremely high usability based on very natural forms of interaction and dialogue with the system. This will also have implications in terms of support to mass customization in that it will help non-experts (e.g. final users) to model and/or modify 3D shapes of virtual products in a simple way. This would allow for instance final user to be able to participatively involved, through support of methods such Analytic Hierarchy Process—AHP or Multi-criteria decision analysis—MCDA, in the assessment and proactive designs of products.

Moving to a different issue, significant limitations still exist today when considering interactive and iterative tools addressing the real-virtual-real object transformation cycle. It is a matter of fact that the use of digitization techniques today is still not fully integrated with the virtual manufacturing pipeline. Alternatively, its extensive use may be unpractical in that it may either require significant manual work (for instance when scanning the interior of a vehicle) or time (for instance when acquiring the exterior of a vehicle).

Furthermore the use of 3D digitization systems requires significant post-processing and manual work to create a model from the initial point cloud or mesh based on transformations and re-modelling to ensure that the final shape can be further modified in an interactive manner.

A classical example of this can be appreciated when observing a point cloud resulting from a scanning process. The point cloud cannot be modified in an intelligent or semantically meaningful manner. Therefore its practical use within an interactive design process requires a time-consuming manual process to transform the dataset from a discrete to a continuous representation. This example clearly highlights the need for the development of new high-level shape models that can integrate, from a user perspective, both continuous and discontinuous representation. It is therefore clear that a significant barrier to be removed is the development of unified representation over the different incompatible or only partially compatible computer representations used today, which often hinder several operational activities.

Furthermore, future tools for shape re-engineering will require, for instance, new algorithms for shape semantic understanding and interpretation based on machine learning technologies, computer vision, swarm of communication systems and 3D descriptors, to allow for easy modification and account for downstream processes. The availability of these processes would be very beneficial to help users define hypothesis about the initial data structure, thus accelerating the transformation towards more usable representation.

In more general terms, it can be stated that there is a clear need for semantically rich 3D model descriptions that can account for intrinsic knowledge representations to facilitate both generation and transformation of 3D models in order to ensure that the representation used within a given context is best fit-for-the-purpose. To do so the research community will have to address the development of novel representation schemas such as unified models for NURBS, sub division schemes, locally refined splines, integrating semantics as an intrinsic feature of the geometric descriptions.

The development of more knowledge-rich models, in turn, would foster the creation of more intelligent tools to automatically facilitate manipulation or transformation tasks or to provide intelligent control mechanisms that do not require specific expert knowledge. This, in turn, would allow development of more intelligent systems