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# Optimised building

Architectural geometry is a cross-discipline combining elements of mathematics, computer science, engineering and architecture. **Professor Dr Helmut Pottmann** has worked on a number of exciting contemporary buildings and interesting projects and explains more about this emerging field

**As an introduction, could you briefly give an overview of the new field of architectural geometry?**

Architectural geometry is a reaction from the mathematics/computer science community to the emergence of complex geometric structures in contemporary architecture. The design of these structures is less of a problem, but their actual construction and financial feasibility are big challenges. Here, geometry plays a key role and it is applied at a level which hasn't been used before in architecture.

**What led you into this emerging field?**

I am a mathematician with a particular interest in geometry and its applications. I am also very much interested in art so I find architecture very appealing. I have been teaching geometry to architects for 20 years, but I only realised in 2005, through attending

a conference of the Smart Geometry Group in Baltimore, that architecture is also a promising research area. The aesthetics of the application is a great motivation for me, and also the fact that one can see results on a large scale, and typically in very prominent locations.

**What are the main aims and objectives of your project Architectural Freeform Structures from Single Curved Panels (ARC)?**

The main objectives of ARC are the development of methods and algorithms for the optimised use of single-curved panels in architecture. In architecture, single-curved panels, applied in the right way and under the right constraints, give enough freedom to achieve a rather smooth appearance, and they offer a good trade-off between surface smoothness and cost of manufacturing.

**Are there other projects that meld mathematics, engineering and architecture, or is this the first of its kind?**

To the best of my knowledge, only in a few projects do mathematicians take

# Smoothing the lines

Designers and architects are pushing the boundaries of what is achievable in building structures with modern materials. Mathematicians have led the way in realising these dreams using cost-effective materials, and have been able to bring together a multitude of disciplines

**THE RECENT TREND** towards freeform and irregular structures has presented new challenges to architects and designers. Take, for example, a curved glass wall. The simplest and least expensive way of creating such a wall would be to use many connected flat triangular panels of glass. Whilst simple, this solution leads to a faceted appearance, mainly visible as a discontinuous reflection and refraction pattern on the surface.

A much more aesthetically pleasing solution would be to use panels that are curved. Single-curved surfaces are the first step beyond planar, or flat surfaces. Curved panels reduce the discontinuities seen in the reflection from the curved glass wall and can be made as single long strips. A plain piece of paper can be used to demonstrate the many single-curved surfaces that can be created. It the initiative and play a leading role. We previously worked with a group of architects and engineers on a project that focused on the use of flat quadrilateral panels in architecture. In some ways ARC is a natural extension of that project, but on a larger scale and more ambitious.

**Technology developed within ARC has been used by project partners Evolute and RFR in the redevelopment of the Eiffel Tower Pavilions on the first platform of the Eiffel Tower, designed by the architects Moatti-Rivière. Have there been any challenges in this work?**

Through ARC, our partners Evolute and RFR have had the fantastic opportunity to apply research findings directly to this prestigious project. The main challenge was the realisation of a double-curved facade using affordable materials. ARC's research played a substantial role in providing a cost-effective and elegant solution. I was involved in developing the scientific methodology and was a scientific advisor to Evolute. The project is scheduled for completion in summer 2013.

**What are the most ambitious geometric designs for real-world structures that you are currently working on?**

One project which used technology developed within the ARC project is the Centre Culturel et Touristique du Vin de Bordeaux. This building, designed by X-TU Architects, features a 9,000 $m^2$ freeform facade, which will be realised using flat and single-curved metal and glass panels.

Another remarkable project is the Arena de Sao Paulo in Brazil, which will host the opening match of the 2014 World Cup. The west glass facade of the stadium follows a 5,400 $m^2$ double-curved freeform surface, which will be achieved using mostly cylindrical panels.

**What have been some of ARC's greatest achievements to date?**

From a technical perspective, our greatest achievements are rationalisation with developable strips, its realisation with cylindrical panels and a novel method for surface cladding by bending (nearly) rectangular flat panels. Some of this research has been presented at Special Interest Group on GRAPHics and Interactive Techniques (SIGGRAPH), an annual conference on computer graphics, which is by far the most prestigious publication avenue for computer graphics and related areas.

On the practical side, I like the Eiffel Tower Pavilions the most; they are a perfect realisation of ARC's core results. Explaining some of the geometry is like a lecture in applied differential geometry!

**The project consortium is made up of partners from academia (Vienna University of Technology), geometry consulting (Evolute) and engineering (RFR). Have you found it challenging combining the various expertise and different languages of these sectors towards a common goal?**

Evolute is a spin-off from Vienna University of Technology and employs some of the best architectural geometry researchers worldwide. They have expertise in working with architects and engineers, especially with those from RFR. Hence, cooperation is easy and very effective. Fortunately, we dealt with the language problem early on when we began architectural research at the University.

**And finally, do you believe that Industry-Academia Partnerships and Pathways (IAPP), such as ARC will be more common in the future?**

We are certainly very positive about it and Evolute and Vienna University of Technology are already cooperating in another IAPP project in a similar area – Geometric Manufacturing Solutions for Freeform Shapes. I like the direct channel from academic research to the forefront of industry, as we obtain direct feedback and inspiration from industry. Industry benefits through enhanced technologies and opening up new markets, business opportunities and synergies. The ARC project is now moving into technologies which may be highly relevant for ship building, a new area for both involved companies.

can be bent into numerous shapes without needing to be folded.

## INCREASING COMPLEXITY

The best solution to the glass wall would be to produce double-curved panels. These panels are a custom shape that precisely fits the specifications, producing a perfectly smooth reflection. However, this visually arresting alternative comes at a high price in terms of production cost.

Single- and double-curved surfaces are the building blocks of freeform structures on a massive scale, such as the Guggenheim Museum and other iconic modern buildings. However, there is a limitation to this design technique as, although the imagination can conjure a variety of amazing surfaces, a balance has to be found between cost, approximation and quality. Solving these problems by finding optimal solutions to different structures and specifications has led to the new field of architectural geometry, a cross-disciplinary subject combining elements of mathematics, computer science, engineering and architecture.

## ARCHITECTURE MEETS MATHEMATICS

Professor Dr Helmut Pottmann and colleagues in the Architectural Freeform Structures from Single Curved Panels (ARC) project are leading the way in developing novel techniques to allow construction of such shapes as envisioned by designers. ARC was formed as a result of Pottmann and his team realising that appropriate mathematical representations and algorithmic solutions could provide answers to the problems posed by architects. Notable assignments they are working on include the double-curved facade that will be seen on the newly constructed Eiffel Tower Pavilions, and the Arena de Sao Paulo in Brazil, which will host the opening game of the 2014 FIFA World Cup. Others have realised the importance of mathematics to modern architecture too, and the popularity of the field is rapidly increasing; with the biennial conference Advances in Architectural Geometry showing an increase in the number of participants from 130 in 2008 to 220 in 2010, and most recently 400 in 2012. ARC has sponsored the two most recent conferences, and is hoping that by building partnerships between academia and industry they can establish a broad range of tools that will assist with real-world projects.

## PARTNERS IN INNOVATION

At present, the design and manufacture of complex freeform shapes is highly reliant on techniques and technologies developed by other industries, such as the automotive and aerospace sectors. The requirements of architects on such computer-aided design and computer-aided manufacturing (CAD/CAM) technologies varies in a number of ways, most notably the scales employed and materials used.

To bridge the gap between academia and industry in the ARC project, an Industry-Academia Partnerships and Pathways (IAPP) contract has been signed between Vienna University of Technology, Evolute and RFR. Pottmann enjoys working in partnership: "The direct channel from academic research to the forefront of industry means that we obtain direct feedback and inspiration from industry". The partners all bring unique skills to the project: academics involved are able to provide a deep fundamental knowledge of geometric computing and applied geometry; Evolute offers high-tech research, services and software to all industries facing challenges related to complex geometry; and RFR has world-renowned knowledge and experience as an engineering company that specialises in the design of complex structures and of sophisticated envelopes for buildings.

## RATIONAL APPROACH

Through these partnerships, a new company – bform Technologies – is being formed. Its aim will be to fuse design, engineering and mathematical rigour in order to deliver tools that will allow designers and architects to realise concepts that will push the boundaries of form, material and structure. It is by combining expertise and knowledge in such partnerships that it is hoped that the next big problem in the field of architectural geometry can be solved – that of delivering tools that allow for construction-aware geometric design without the need for a redesign phase after the initial geometry definition. This is known as rationalisation.

The rationalisation process involves re-computing the geometry of a design, whilst minimally deviating from the original specification. At the same time, requirements on panel types must be met, including considerations of smoothness, aesthetics and cost of production. From a purely mathematical perspective, rationalisation amounts to the solution of often highly nonlinear and computationally expensive optimisation problems. As such, the development of efficient optimisation algorithms and user-friendly software tools are two of the most substantive research challenges in architectural geometry.

Work within the ARC project conducted by Evolute is already beginning to offer a broad range of powerful rationalisation tools, which have proven to be highly efficient in, for example, the Eiffel Tower Pavilions project. Pottmann admits there will always be special designs that demand non-standard solutions, but perhaps more intriguingly there are still questions for research: "One example would be the combination of rationalisation with energy and sustainability considerations".

## CONTINUING THE UPWARD CURVE

The trend towards a high level of geometric complexity also has important implications for geometry in architectural education. The

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## ARC project partners

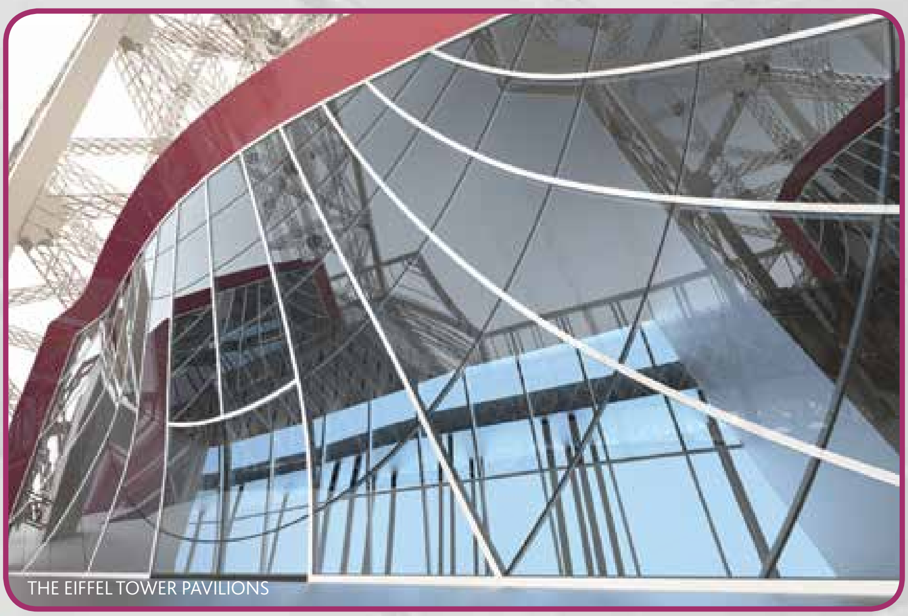
**Evolute** – consisting of mathematicians, computer scientists and architects, the company was founded in 2008 as a complex geometry services and software spinoff from Vienna University of Technology.

**Vienna University of Technology** – the Geometric Modeling and Industrial Geometry research unit in the Institute of Discrete Mathematics and Geometry performs application-orientated fundamental and applied research closely connected to geometry, particularly focusing on discrete and computational differential geometry; geometric optimisation; surface matching and registration; computational line and sphere geometry; and architectural geometry.

**RFR** – founded in 1982 by Sir Peter Rice, the company designs complex structures and sophisticated envelopes for buildings, relying on its staff's wide range of skills in engineering, architecture and industrial design. Diverse projects have been undertaken, including the design of structures of the 'Pyramide inverse' of the Musée du Louvre, the Avignon and Strasbourg TGV Stations, the Charles de Gaulle Terminal 2F airport in Paris, the complex skins forthe 'Fondation Louis Vuitton pour la Création' designed by Frank Ghery, the facades for the new three Pavilions on the first floor of the Eiffel Tower and the 'Musée de la Dentelle' with Moatti-Rivière.

effective use of powerful geometric design software already requires further knowledge of geometry than is traditionally taught in drawing or descriptive geometry courses, and an even deeper understanding of geometry is necessary to excel in the exploitation of parametric design technology. Pottmann has been the Director of the Geometric Modelling and Scientific Visualization (GMSV) Center at the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia since 2009. In this role, he has attempted to bring together renowned researchers and promising young talent across a variety of fields of expertise. The early signs of this work in improving education are promising, with the first evaluation recognising the quality of the research conducted as 'outstanding'.

The major challenge facing the architectural geometry community will be to move from pure rationalisation to a more integrated approach, where rationalisation and design are interactively coupled. Pottmann is optimistic that this challenge can be overcome: "It will take a few more years to come up with a powerful methodology and to arrive at user-friendly design environments," he explains. "Fortunately, architectural geometry is gaining more attention now from the relevant maths and computer science communities, and this will boost development."


THE EIFFEL TOWER PAVILIONS

## INTELLIGENCE

### ARC

### OBJECTIVES

To investigate the problem of building architectural freeform structures from single-curved panels.

### KEY PARTNERS

**Evolute**

**Vienna University of Technology**

**RFR**

### KEY COLLABORATORS

**Professor Alexander Bobenko**, TU Berlin, Germany

**Professor Niloy Mitra**, Center for Geometric Modeling and Scientific Visualization (KAUST), Saudi Arabia and University College London, UK

**Professor Johannes Wallner**, TU Graz, Austria

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### PROFESSOR DR HELMUT POTTMANN

gained a PhD in Mathematics in 1983 from Vienna University of Technology and his Habilitation in 1986. He then took several visiting faculty positions in Germany and the US, followed by a professorship in Hamburg in 1991. Pottmann returned as Full Professor to Vienna University of Technology in 1992, before rising to Director in 1994. More recently, he took on the position of director of a research center at KAUST in Saudi Arabia.