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Didactics

The Other Mathematical Bridge

Abstract. This paper contextualises, describes and discusses a student project which takes a particular exploratory approach to using mathematical surface definition as a language and vehicle for co-rational design co-authorship for architecture and engineering. The project has two authors, one from an architectural and one from an engineering educational background. It investigates the metaphorical and operational role of mathematics in the design process and outcomes.

1.0 Introduction

1.1 Architecture and engineering

Within design, there appears to be, once again, a keen interest in a type of organicism that emerges from an underlying 'system', complexity from simple roots, form that follows certain growth criteria and responds 'intrinsically' to constraint systems such as gravity and site conditions or the external forces of weather and use. Perhaps this is to be expected in the time of the fine-grain decoding of life as DNA.

This appears fertile philosophical soil in which the curiously estranged disciplines of architecture and structural civil engineering can grow together. Accepting that the coexistence of these two fields with apparently similar objectives has a historical foundation, it is clear that the points of distinction have not remained consistent throughout history. Robin Evans notes a passing of the baton in late eighteenth century as descriptive geometry, specifically stereotomy, a minority but virtuoso technique in architecture, was passed, in the influential writing of Monge, from the architect and stonemason to the engineering community, to be taken up in their new roles as designers of steam ships and locomotives in the nineteenth century [Evans 1995: 328]. The means of representing and describing spatial conceptions, the particular preoccupations with materials, the types of value ascribed to various attributes of the design within architecture and engineering may always have followed separate paths but these wandering paths have crossed.

1.2 Architecture without mathematics

To some extent the particular disciplinary approaches to description can be said to have fed back into the conceptual process of form making. It is not hard to defend the observation that many architectural education courses have progressively eschewed any interest in the deployment of formal mathematics. Spatiality and spatial organisation may be innately mathematical but consideration of proportion, statics, and the manual construction of perspective views have now largely left the pedagogy, following mathematical description of surface, now long departed. Projection remained (and largely

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remains) an important conventionally prescribed conceit that bears heavily on the conceptualisation and realisation of architecture, but the strict Cartesian stranglehold on design has been relaxed as it has been internalised and obscured in hidden algorithms [Pérez-Gómez and Pelletier 1997: 378]. Now that much of the work of projection has been subsumed by the machine, the allusion to full shifting-perspective occupiable space, freed from its three imposed axes and fixed view points, makes formal and spatial complexity outside a single framework more accessible. The orthogonally grided world may still be the most prevalent procurement reference frame but conceptual spatial design need not set up its relationships according to this universal locator. The whole of Euclid is now not only available as a conceptual framework (as it always was) but is relatively effortless to deploy; manifolds that exhibit non-Euclidean characteristics at large scale are also within reach of the three dimensional virtual modeller. 'Digital clay' is still relatively geometrical or, at its most analogous, still influenced by the particular surface algorithms available. However, it is possible, with a little effort, to work in earthen clay or plaster[1] and find a geometrical description or controlled surface rationalisation method later through semi-automated processes that help realise tactile scale models at architectural scale and complexity.

Contemporary conceptual design space in education is potentially a no rules space or, at least, the search for appropriate rules systems has opened up with the technological means to appropriate more complex geometrical structures and programs from other fields. In place of truth, designers seek and use what is productive, and enjoy dialectics. Aesthetic arbitration holds less interest than defining the framework from within which it is being exercised. Liberated from any one universal constraining context, designers can choose their tools and their goals for their exploration of spatial possibilities. Some exercise this choice.

1.3 Structural economy

While the means to explore structural economy are ever more computationally sophisticated, this cornerstone of modernist ideology may be seen to have slipped from architectural prominence. The idea of a graph of relative use of steel by weight against the covered area of new Olympic stadia since Günther Behnisch and Frei Otto's revolutionary lightweight proposal in 1972 would be instructive in this regard.[2] In main stream practice, economy may commonly be met by reducing the overall number of standardised structural members used or finding an effective mean span but there are more subtle approaches to conceptual structural design that may also align with biological metaphor. D'Arcy Wentworth Thompson provides explanations for the scale and form of the living, demonstrating the diversity and specificity of evolutionary outcomes all conforming to the same Newtonian physics [Thompson 1992]. Cell growth too is a stimulating, potentially useful metaphoric process to consider in relation to *designing the design* for structural systems, conforming as it does to the genetic blueprint while, at a micro level, cells are laid down and removed in response to local structural exigency. What is the computer for if not to test these ideas by simulating, or at least emulating, the binary aspects of such processes to find structures that obey the same basic principals of getting the best performance for the least? What are the aesthetics of this kind of minimalism?

1.4 Form finding systems

The terms 'form finding' and 'generative design' refer in a general way to investing creatively in the design of a system to define possible formal/spatial outcomes according to specific relationships and criteria rather than in the more deterministic design of specific spaces or forms.[3] They are to some extent generic descriptions of several specific processes with different objectives. One manifestation is a graph of geometrical relations that supports a consistent topology that can generate many different contextually responsive forms and selecting forms from this field of possibilities through optimisation for certain ranges of values of particular parameters or relationships between them. An example of this might be a roofing element with sculptural qualities that admits indirect light into the building applied in a grid across a changing undulating roof structural system and optimising the roof form so that the largest percentage of the rooflights are within a value of a particular compass point. This might yield a range of solutions better and worse for different reasons. The actual geometry and dimensions of every roof element can be unique while conforming to the topological blueprint and recognisably similar across the field of instantiations, much as individuals vary in a population of oysters across an oyster bed. This looks like a return to highly Platonic concept of a contingent perceptual world of (imperfect, imprecise) copies of ideal forms.

Another specific and contrasting example is the deterministic optimisation method called 'Evolutionary structural Optimisation' [Xie and Steven 1997: 97]. This is an iterative structural optimisation tool, closely analogous to processes in nature. It uses finite element analysis to identify and remove the least stressed material in a structure. This process is repeated many times and a highly structurally optimised form emerges. The form is determined by the way that the loads have been applied and the way the object is supported. Only one particular optimised form can be found within a particular set of conditions. A simple and classic example shown to illustrate the process by Prof Y. M. Xie is the evolution of a cube suspended from one central top point. At the end of the process it appears the shape of an apple. In reality this method has been developed to generate complex three-dimensional structural forms, the current version allowing both the subtractive and additive processes in response to both compressive and tensile stresses. This process is essentially non-geometrical by its treatment of structure as finite elements.

2.0 The project

2.1 Context of the project

Form finding lies within the broad territory negotiated between architecture and structural engineering where the paths are likely to cross. Potentially this crossroads should be a most fruitful and emergent social and operational locale for conceptual design activity for built systems. *Dissolving the Boundaries between Architecture and Engineering* is the name of one of the eleven research projects under the broad umbrella of the Virtual Research and Innovation Institute (VRII) for Information and Communication Technology (ICT) at RMIT University to research ways to broaden this shared activity. It brings together the Spatial Information Architecture Laboratory from the School of Architecture and Design and the Innovative Structures Group from the School of Civil and Chemical engineering, from different faculties.

Although the two professions work together continually, in practice there is a deep cultural and epistemological chasm running between the disciplines that is established and maintained in the education system. This is not limited to any particular university or even country – it appears common, for instance, to Australia, New Zealand, USA, Canada and UK. The institutions where this is patently false are the exceptions in these fields. The gulf may be linked to or exacerbated by the nature of accreditation by the respective professional bodies. As part of the research into dissolving these boundaries a research–based, experimental joint design studio for final year undergraduates from both disciplines was proposed and given the title Re-engineering. This was a loosely structured research project supported by a team of staff from both disciplines with the overriding and much emphasised brief to explore the concept of *co-rational design*. This is the idea that there is a third way as an alternative to either taking a structural system as a point of departure – the *pre-rational* approach – or designing a structure in response to a pre determined formal solution – the *post-rational* approach – or '*please make it stand up'* . The studio provided an environment in which to explore structural systems in synthesis with other design drivers. Each architecture student was paired with an engineering student. One partner (the architecture student) had four years experience of being immersed in a progressively more student-led vertical studio context continually challenged to initiate conceptual design and speculate, all projects focused around the built environment. The other (the engineering student) had been trained for a similar length of time to be a focused problem solver, seeking appropriate solutions to problems posed in a range of engineering contexts of which building structures was one, reporting rigorously on the outcomes of applying solutions and accustomed to a well-defined problem as a starting point.

2.2 Educational methodology

The architecture students were enrolled in a course that requires a speculative semester of supported research in preparation for their Major (or thesis) design project. The engineering students were enrolled in an investigation project, their final project leading to the submission of a written research report. There was no proscription as to the means of communication and sharing, but there was a heavy emphasis placed on the co rational design objective of finding a means to co–authorship. The studio was uncompromisingly process driven and divided into three phases. The three stages were articulated to encourage continual return to the origin throughout the semester, albeit with a more developed focus each time, and to suppress the inclination to develop designs more fully or diverge into separate disciplines in the process. These courses were chosen as the setting for the experiment in collaboration for their emphasis on research. They are open ended, requiring the engineering students to prepare a formal written research report, the architecture students, a more graphical representation of their research findings and their design intentions. In distinguishing between method and methodology, this is action research, generating knowledge through design, by working together on projects. The central research question for all the students concerned a third way of designing that was neither formally reactive to a structural approach nor structurally reactive to a formal approach. The sub-questions were to investigate methods of 'labour' that supported early "*co/*labor*ation"* between the designers of the two disciplines and how this collaboration impacted on the quality of their design outcomes.

The weekly classes were structured as a space to present and reflect collectively on the week's work, exploiting 'the mind's ability to ponder its own reflections' (Locke, quoted in [von Glasersfeld 1991: xviii] and to develop 'consensual domains' (Piaget, quoted in [von Glasersfeld 1991: xvi] in a mediated conversation between the students engaged actively in design and staff as research facilitators, critics and commentators.

2.3 The project

Here we chart the development and outcomes of one particular architectural research project undertaken in the context of this course, curious to locate this with regard to the multifarious relationship between mathematics and architecture. In the project described, the overall objective of finding a co rational way to work together conceptually was most successful in the intense closing stages of the project.

The first phase was a series of weekly investigations, each starting with a new program and structural concept chosen or devised by the students. The ground work for this project was wide ranging. First, experimental use of the 2D Evolutionary Structural Optimisation (ESO) tool developed by Prof Mike Xie provided structurally optimised cross sections for an extruded or extrapolated 'Hanging Tower' followed by calibration of the tool by reverse engineering the cross section of Frank Lloyd Wright's Falling Water in order to move on and find a series of varying structurally optimised cross sections responding to local support conditions for the free form envelope of a suspended space in a Melbourne laneway. In subsequent weeks they further experimented with the laneway proposal, developing an undulating shell structure attempting to minimise the surface area and to learn how to use finite element analysis to resolve this into a compression structure, in a way analogous to the funicular model used by Gaudí to find the lines of force and hence the form for the church for the Colonia Güell [Bassagoda Nonell 1989]. They modelled it using the vacuum former and applied physical loads to measure the deflection. They also considered material strength testing.

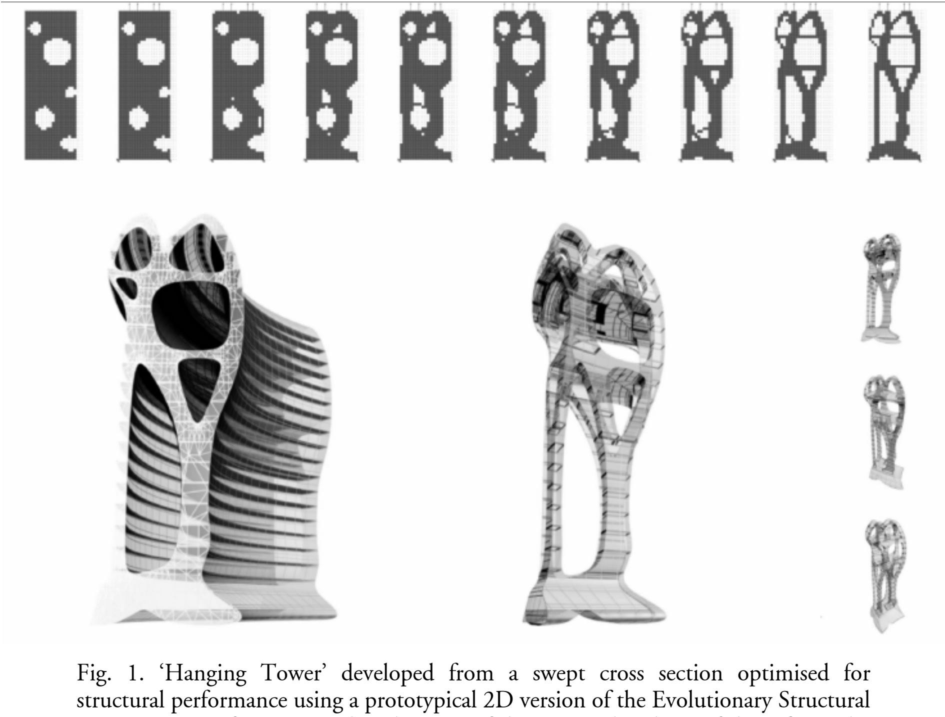

Fig. 1. 'Hanging Tower' developed from a swept cross section optimised for structural performance using a prototypical 2D version of the Evolutionary Structural Optimisation software. Initial exploration of the potential and use of the software by Steven Swain, RMIT architecture pre-major student 2005

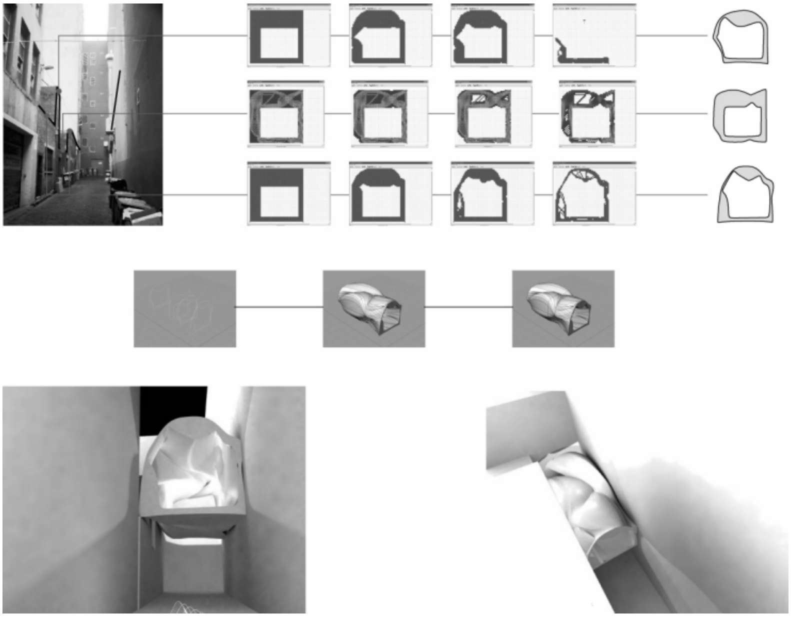

Fig. 2. China Bar showing the same ESO tool used to define a surface from differentiated optimised structural sections for changing support conditions along its length. Joint project by Steven Swain, RMIT architecture pre-major student 2005 and Andew Rovers RMIT final year civil engineering student 2005, in which they also investigated generating catenary forms and framed, tensile and shell structures. They tested a shell structure in structural analysis software and using physical weights on a vacuum-formed model. (Images shown prepared by Steven Swain)

The second phase narrowed the focus to one particular structural approach, possibly one of the first phase experiments. The partnerships changed. The architecture student considering shells and continuous surfaces was now teamed with an engineering student who saw his own strength in mathematical understanding. The 'architect' immediately adopted some difficult, mathematically-derived surfaces. A number of equations were selected including a combined Jacobi elliptic function and hyperbolic cosine function. They were chosen from a library of surfaces on criteria of aesthetics and spatial potential. Through very simple manipulation of these 'found' surfaces – Booleans to create edge boundaries and openings and differential scaling – a series of formal articulations of program were suggested, an interpreted railway station roof, a sinuous tower development. The most compelling was the use of a surface in its most raw state as the shell structure of the *Hybrid Cathedral*. In this proposal the surface mediated between a soaring sacred space of monumental proportions at the heart, and multilevel apartments nestled in the sinuous peripheral undulations. It was prototyped in wax to enjoy its engaging formal-programmatic encounter at a more sensory level. At this point, the differences between the software and processes introduced by the architects and engineers became very apparent and divergent. Apart from the usual issues of format compatibility and transfer, the rigid 'yes or no', 'right or wrong' solution inherent in the engineering software compared to the forgiving nature of the architectural modelling software in supporting speculation, meant the engineer struggled at this stage to define a role.

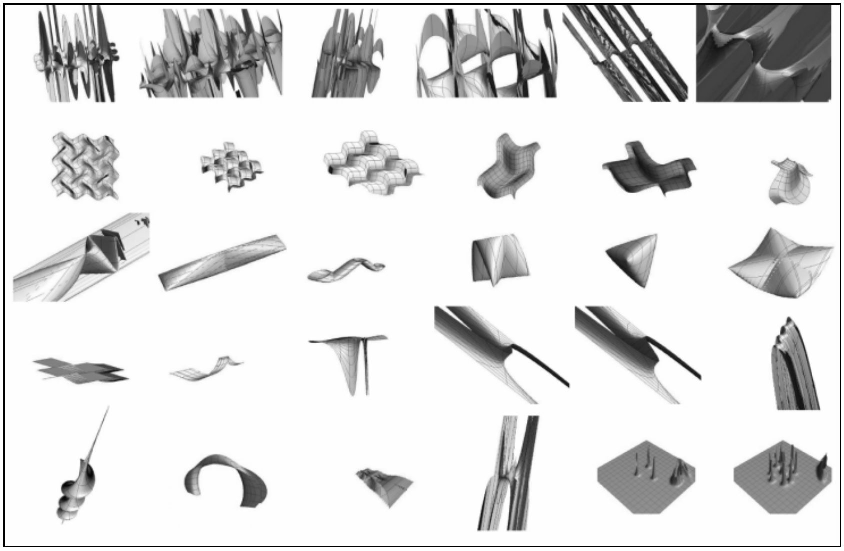

Fig. 3. One of the pages from the collected 'library of surfaces'. Steven Swain (final year architecture) and Sean Ryan (final year civil engineering) experimented with shell structures based on surfaces from a gamma function. Sean researched the function, varied the coefficients in Maple and exported geometry files

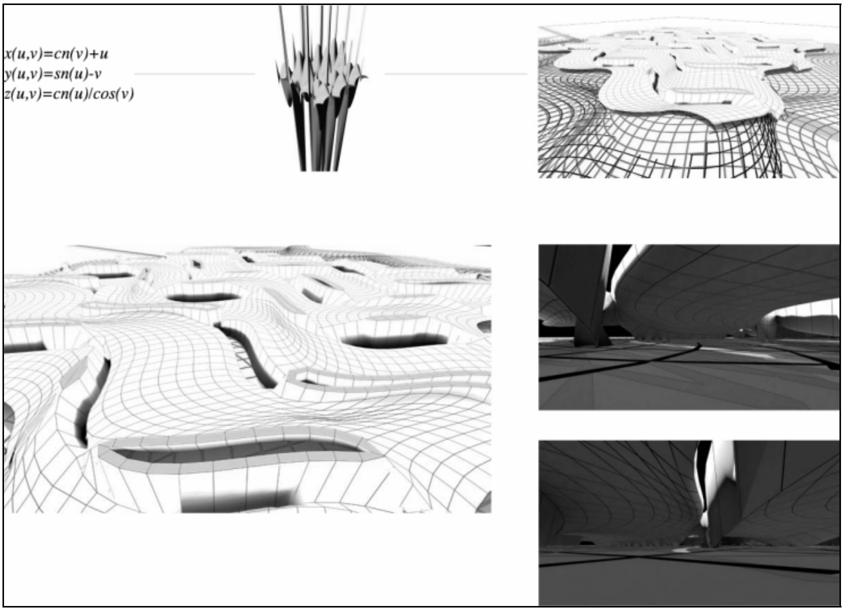

Fig. 4. 'Functional' Railway Station roof using Booleans and scaling to create a programmatic surface from a mathematically defined surface. (Design and images Steven Swain)

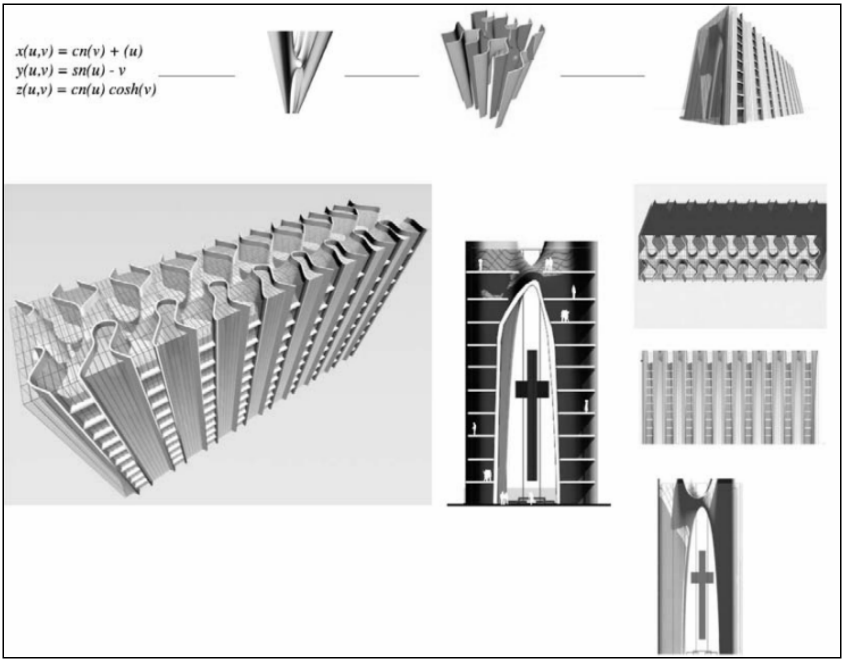

Fig. 5. The Hybrid Cathedral: worship space and the apartments to fund it mediated by a single mathematical surface. It was proposed for an environment such as Hong Kong, with scarce land and burgeoning population and economy; collaborative project between Steven Swain (architecture) and Sean Ryan (engineering). Steven developed the spatial and programmatic concept, they both worked on refining the surface and Sean endeavoured to undertake finite element analysis of the structural shell and then design a discrete frame structure for analysis in more familiar software

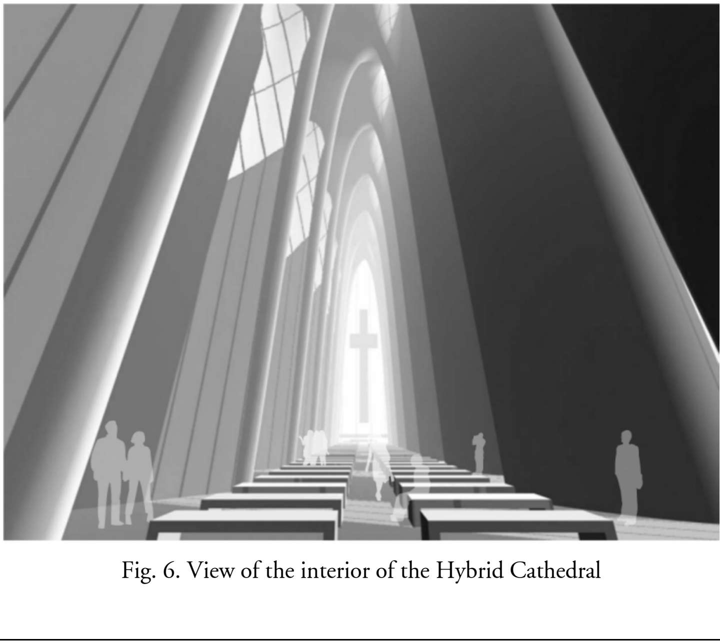

Fig. 6. View of the interior of the Hybrid Cathedral

1.3 The final stage of the project

The third phase introduced site and location, subtly inverting the program-seeking form experimentation earlier. It led this same partnership to the development of an inhabitable bridge that could be mathematically defined. Architectural and structural parameters were identified as they embarked on writing an equation that would satisfy both parties and the program that they had jointly defined. At this stage, a much more intense interaction with the mathematics unfolded.

A publicised but short lived proposal to divert the Geelong freeway across the entrance to Corio Bay was reawakened to advance the concept of a single mathematically controlled surface as structure, rich space defining boundary and interface between monumental scale and domestic infill. The real world requirements of maintaining and spanning the dredged shipping channel, also allowing small craft to pass between Corio Bay and its parent Port Philip Bay, maintaining the tidal flow, observing the spatial, gradient and curvature constraints of the freeway and separating the habitation with its services and access roads from the freeway, intensified the quest to develop the relationship with the surface equation that would allow detailed manipulation of the parameters without relinquishing the emergent qualities and aesthetic coherence of the surface itself. It introduced all the architectural dialectics around the intensity of the experience of crossing the bay at the historic fording point and the iconic and environmental impact of the bridge as it reshaped the view and context for Geelong. It also engaged with the specific engineering challenges of exceptionally long spans, building in water, and site conditions at the springing points.

Simply editing the variables within the original function had a similar impact to scaling the surface using external software algorithms; for instance, it altered the distribution of bridge piers but continued to create repetitive, regularly-spaced piers. To be able to create the large opening for the shipping canal but find more optimised structural intervals for the other parts of the bridge it would be necessary to add a second function to disrupt the rhythm. Various functions were overlaid, some causing too much disruption and surface distortion. Finding a satisfactory addition through empirical experimentation imbued a situated awareness of the power of superposition of different functions, and it was possible in the same way to overlay a fine grain to the surface, a detailed level of surface undulation or corrugation for combined aesthetic and structural opportunity. The formula was then simplified in experimentation to find out how to control the level of detail and hierarchy of peaks, calibrating it to control the height of the peaks in the undulating surface (varying this in relation to the width of the bridge and spans) and a further function superposed to vary the height of these peaks. By this stage, the designers had entered or immersed themselves in equation or function building as their design environment. At each iterative step, the formal elegance and subtlety of the model increased with the increasing control and mastery over its potential to vary. In order to curve the bridge in plan into the sinuous 'S' needed to meet the freeway routing at each abutment, and make the crossing at the old fording route, some of the existing components of the function could be used but had first to be rearranged and separated or their impact altered through denomination. The peaks then had to be controlled in a way that specifically reduced their height at the springing, where short piers were required, and at the main shipping canal, where the vast span would require stiffness but all possible reduction in the weight. This variation could be periodic but the period relative to the pier intervals needed to be controllable in a specific way. This required the further superposition of a specific function for u and v in Z. Although the formal mastery now extended to understanding how to vary not simply the parameters but the function itself, the means to arch the bridge deck following a specific curve from springing to springing was not yet clear.

The source of the original kernel of the function and surface led to the Astro Physics department of Swinburne University. The function was rewritten in a way that clearly parametricised it for the variables already identified and an additional Gaussian function now gave the arch to the road to allow it also to rise up 70m over the shipping channel from its low lying springing points.

The designers could now rewrite the equations satisfied by the x, y and z values of each u, v point on the surface with the list of variables in Table 1.

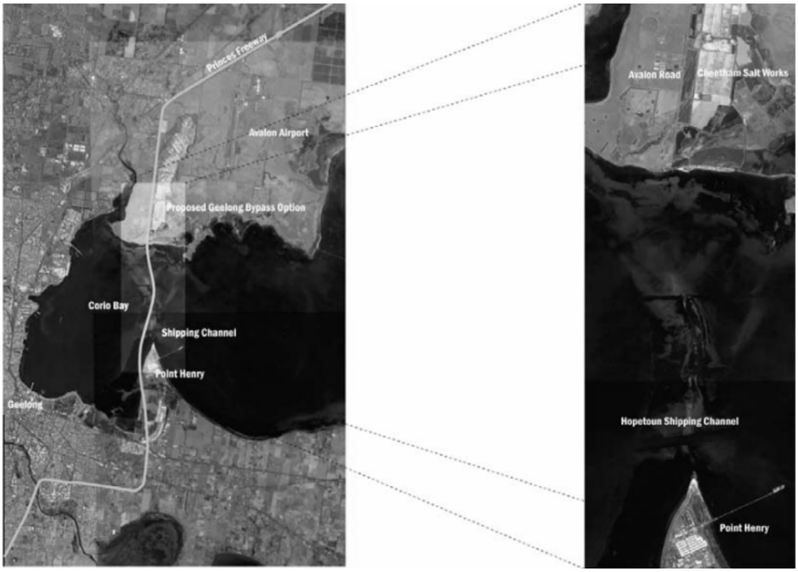

Fig. 7. The Geelong Bypass bridge site. The bridge proposal in this project was to be a 5-kilometre long, one-street highway town, with prime views and real estate helping to fund its construction. The freeway and bridge city were to be separated by a surface generated to test a particular mathematical function. Ferry terminals at the base of the piers allow the residents to reach Melbourne and Geelong without entering the freeway. This was the final collaborative project by Steven Swain (architecture) and Sean Ryan (engineering); image by Steven Swain

	Variable parameters in bridge surface function
1	Number of piers
2	Height of the piers
3	Width of the road
4	Length of the road
5	Number of cycles in the x-y plane (controlling the plan curvature of the road)
6	Amplitude of cycles in the x-y plane (also controlling the plan curvature of the road)
7	Number of cycles in the secondary function controlling the varying heights of the piers
8	Amplitude of the this secondary function
9	Height of the road arch (number of cycles will be constant for the single arch)

Table.1

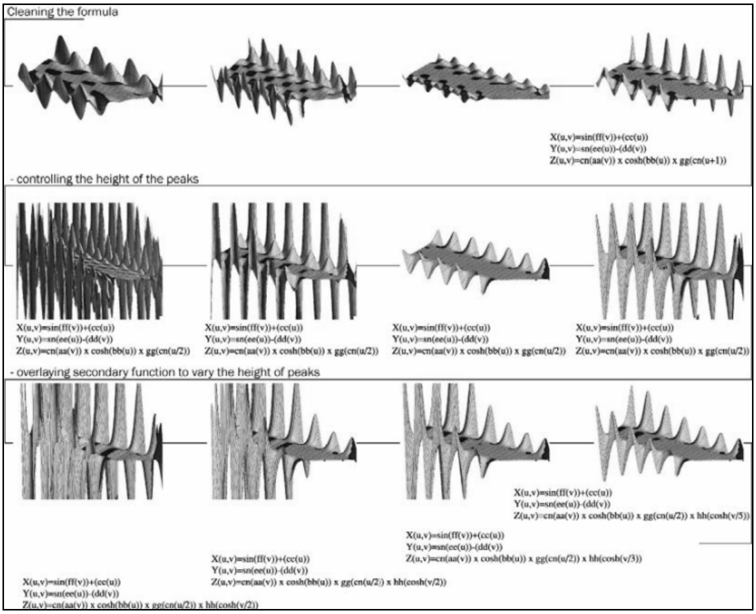

Fig. 8. Manipulation of the function showing the effects of superposition of functions, restructuring the function and parameter value changes. (Project: Steven Swain and Sean Ryan, images: Steven Swain)

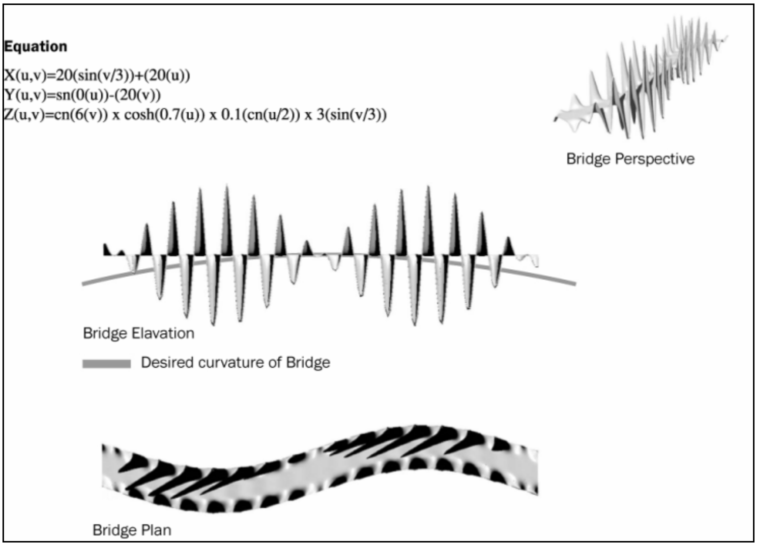

Fig. 9. The bridge surface showing its potential for manipulation for all required characteristics except achieving the necessary arch from its springing up seventy metres over the shipping canal without causing surface distortion. (Project: Steven Swain and Sean Ryan, images: Steven Swain)

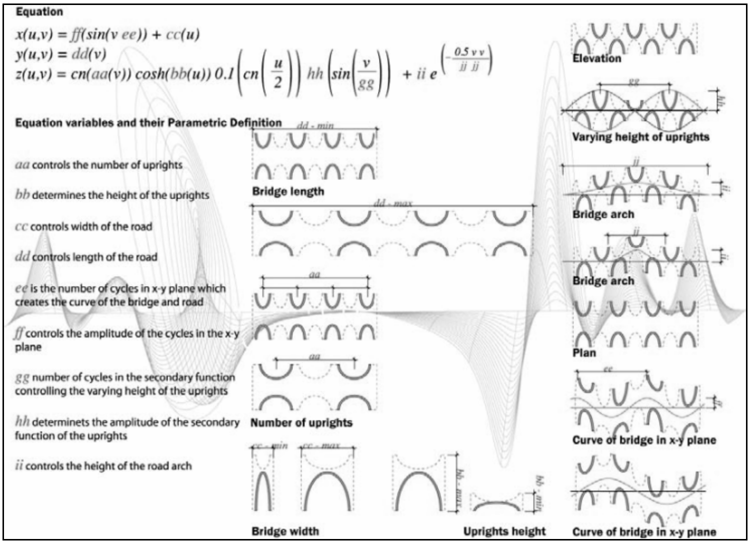

Fig. 10. Illustrated table of variable parameters for the definition of the bridge form. At this stage the architecture and engineering collaborators reported having a medium in which there were able to negotiate the design inputs, overcoming some of the earlier frustrations of the engineering student who felt at the second stage, that, unless detailed structural analysis was called for, he had little input. (Project: Steven Swain and Sean Ryan, images: Steven Swain)

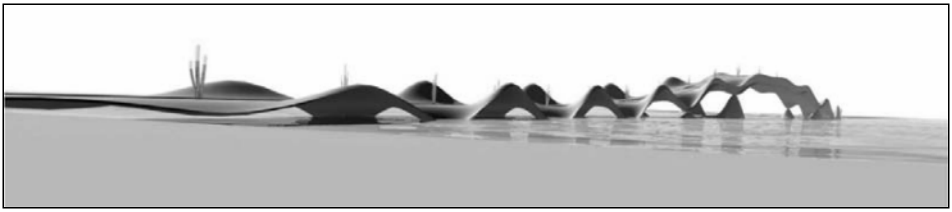

Fig. 11. One of the alternative experimental iterations of the bridge. (Project: Steven Swain and Sean Ryan, images: Steven Swain)

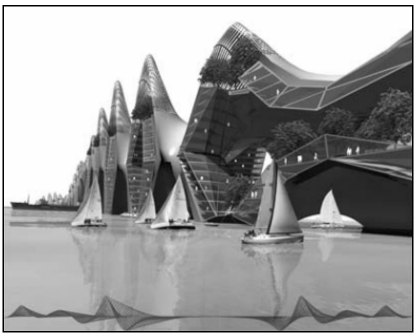

Fig. 12. View of the bridge in its final form. (Project: Steven Swain and Sean Ryan, images: Steven Swain)

A lower deck was needed below the freeway to provide access to the inhabited pier shells. For this the same functions could be used with a small change to the value of the last variable: altering one variable in the short Gaussian expression.

In summary every aspect of the bridge is periodic, determined by its tidy three line function but the superposition of these periodic 'behaviours' is formally subtle and variably aligned with programmatic constraints. Its description is simple and simply conveyed or *transmissible*; its spatial manifestation rich and animalistic.

3.0 Process, outcomes and reflections

While the ultimate requirement for a formal written report as the deliverable from the engineering students left much of the best graphical illustration of the projects in the portfolios of the architecture students, it provided more insightful written reflections than were garnered from the students' comments in weekly class discussions. The engineering authors were honest in expressing frustration when paired with an architecture student they regarded as less than conscientious or productive but also inferred that it was part of the learning process to become accustomed to other working styles. In their literature reviews they gathered strong evidence for the value of a 'co-rational' approach to architect-engineer design and were initially optimistic that this could be realised through a will to work together. They reported very successful outcomes at the end of the first project. One of the engineering students listed the criteria of success that he intuited by the end of the first project as "Understanding of Language, Understanding of Capabilities, Uncertainty, Data (interoperability) and Attitude (levels of openness and interest)". The same author was amazed to discover the differences in the common use of language by the two disciplines, the time taken to overcome this and the dangers inherent in trying to adopt terms one from the other. He observed that on each side the capability expectations were extremely high – he had assumed that architecture trained students would quickly and naturally create beautiful forms that worked and have these modelled rendered in 3D in no time while his architecture counterparts assumed there was nothing much to analysing a structure and expected instant results. They experienced software interoperability challenges and more fundamental ontological differences between softwares conceived to be speculative and those for analysis with little room for fallibility.

By the end of the second project, they reported that, in general the partnerships had failed to achieve a 'co- rational' result. They attributed this to different causes: lack of time and opportunity to work together in the same space, interoperability challenges, poor level of interest from their partners in the particular challenges of their own discipline, working with new techniques beyond current capabilities, but the result seemed to be the same – the retreat of each partner to familiar territory within their own disciplines.

At the end of the third project, the view was expressed that "it is very difficult to develop or even define a formal co-rational design approach". They attributed this to a fundamental distance between architecture and engineering typified by respective emphasis on art and science and reinforced in the pedagogy. At the same time they reflected on the transformative nature of the experience which had given them a much greater appreciation of the work of the architect, greatly expanded their geometrical repertoire and interest in innovation in structures, enhanced their conceptual design skills and fundamentally changed the way they looked at problem solving and design issues.

It was interesting to read their own perception of *frustration* in the stated objective of designing co-rationally in relation to their preconceptions of how this might be, and contrast this to the collective academic's perception of *success* in relation to the same measure, because the students had found (in the example illustrated, mathematical) media in which to hold a design conversation and develop an outcome that was not clearly spatially or structurally led. In other words, they had uncovered a form of labour that supported *col***labor***ation*. It would have been interesting to have had equivalent written reflections from the architecture students. One measure of their evaluation of the way in which the collaboration contributed the quality of design outcomes was the verbal concern expressed about having to develop the work for their Major project the following semester without the further input of the engineering students. Another, in the illustrated example, was that work primarily representing research won State and National architectural student awards in design categories.

4.0 Discussion

What is the significance of this work? Clearly in the context of the particular academic studio in which it was taken, its significance lies in this *transmissibility*;[4] its power as a common vehicle for a student of architecture and a student of engineering from their strictly segregated educational cultures to work concurrently on formal conceptual design. 'In the long run what must be transmitted is not the object itself but its cipher, the genetic code for the object at each new site, according to each site's available resources' [Novak 1996].

In the context of architectural borrowing, inheritance, deep inspiration from science and mathematics, what is the significance of the experimental application of the discoveries of Carl Gustav Jacob Jacobi around 1830 and Gaussian number theory developed in the closing years of the eighteenth century in a joint architecture engineering studio in 2005?

Perhaps it is Antoine Picon's hypothesis that it is the similarity of operation between science and architecture that at certain points makes the relationship most productive. Picon and Ponte also write of 'a new type of connection between architecture and science' for which 'the computer, of course, is central' [Picon and Ponte 2002: 14]. The tradition of metaphorical and methodological exchange between science and mathematics and architecture goes back a long way. In the fifteenth century, Alberti took a philosophical and aesthetic lead from the contemporaneous revolution in astronomy and nature's preference for roundness [Wittkower 1952]. The terms 'structures', 'mathematical surfaces', and architectural examination of biological sciences all seem to lead back strongly in our time to the nineteenth century. 'What would nineteenth-century architecture have been without the notion of structure?' [Picon and Ponte 2002: 294]. So analogous to the model for this studio or of design itself, this architecture reaches back in an iterative cycle to retrieve largely nineteenth-century ideas that find new applications underpinned by the current state of technology. Martin Bressani writes that, '[t]he central problem with architecture's relationship with modern science is not the distance that separates the two disciplines but, on the contrary, a closeness that prevents free metaphoric exchanges.' He highlights the nineteenth century as a good illustration of the paradox. The French word 'structure' was first used in biology to denote the internal organisation of the body, and Violet-le-Duc's vast library contained no volume on the modern science of engineering: despite his advocacy of rationalism and structural determinism, his analogies and archaeological methodology were all drawn from physiology, anatomy and geology [Bressani 2002: 120].

What is compelling about mathematical surface definition or generative processes that bear a metaphorical resemblance to the 'laws of nature'? Clearly, there is a rationalist drive to define design objectives as a rule set controlling the configuration of space and form. This is a way to gain greater efficacy from the technology – using computation to achieve a set of complex spatial or geometrical objectives simultaneously through the definition of their relations. Then there is the matter of beauty. There is the rational scientific idea that underlying natural beauty is a profound system of law abiding relationships. By reconstructing a closely analogous system, not only the source but the resulting sensory delight will be rediscovered. Finally there is the distinct question of *mathematical beauty* : the authors' delight in a bridge of great spatial and programmatic complexity from a three line function. This aesthetic is so intensely felt yet so ineffable that even Paul Erdös said on the subject:

> Why are numbers beautiful? It is like asking why is Beethoven's Ninth Symphony beautiful? If you can't see why, someone can't tell you. I know numbers are beautiful. If they aren't beautiful, nothing is [Hoffman 1998: 44].

Acknowledgments

Steven Swain, Architecture RMIT pre-major student in 2005, prepared all the figures presented in this paper from his work for the joint projects with Andrew Rovers and Sean Ryan, final year Civil Engineering students.

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Notes

1. For instance: Frank Gehry's design process. Antoni Gaudí's process for the design and construction of the Sagrada Família church is a good counter-example where ruled surface geometry is used to construct the physical models and also used in their geometrical reverse engineering for continuing design for construction, employing computation for analysis and synthesis.
2. An idea raised by Robert Aish in conversation.
3. For further reading, see [Shea, Aish and Gourtovaia 2003]; [Burry 1998]; [Kolarevic 2003]; [Kilian 2003]; [Xie and Steven 1997].
4. This allusion to the work of Marcus Novak [1996] was included by the student in his project submission.

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