CAN BOTTOM-UP MODELLING IN VIRTUAL REALITY REPLACE CONVENTIONAL STRUCTURAL ANALYSIS METHODS?

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ABSTRACT
Conventional structural analysis methods are typically based on describing the structure as a system of simultaneous algebraic equations, and solving the system by iteration. A common feature of such methods is a top-down approach to modelling, where there is a global algorithm that controls the solution process. The top-down approach requires the knowledge of the entire state-space of the model in order to program the solution, which often involves simplification and consequent inaccuracy, whilst its computational intensity does not allow user interaction in the real time.

This paper describes an alternative, bottom-up approach, in which the solution process is controlled by local interaction of the structural components, acting as independent objects in virtual reality, and where the system model is created spontaneously, by interaction of the component models. Early results of this research show that it is possible to have analogue virtual reality models of structures capable of real time user interaction, from which forces and other design parameters could be obtained through measurement, without conventional calculation.

KEYWORDS
Bottom-up modelling, Complexity, Structural analysis, Virtual reality, VRML

INTRODUCTION

Conventional analysis and design of structures is based on describing the structure as a system of algebraic equations, and solving the system simultaneously by iteration. Although the definition of the equations is based on Newton's Laws, the solution method usually requires a simplification of the system of equations in order to be able to calculate the solution. Furthermore, the solution process is typically based on matrix manipulation and inversion. It can be argued that the simplifications of the system of equations, and the matrix calculus are an artificial process that is somewhat removed from the underlying physical system that it describes.

Interestingly, there is no general solution for a system of non-linear differential equations, and the fact that simplifications are needed to make the system solvable raises the question of whether the mathematical formalism that is invented in the past is still adequate.
It was therefore decided to look for an alternative approach to analysis, that would involve the creation of models of structures in virtual reality analogous to those in reality, and that will avoid the use of a globally controlled solution method and a system of simultaneous algebraic equations. Whilst virtual reality was chosen as the most suitable and inexpensive medium for creation of analogue models of structures and Newton's Laws were still the basis for modelling the physics of the system, the inspiration for the mathematical formalism was sought in the field of Complexity.

The Science of Complexity teaches us that order and chaos are two opposite states of systems consisting of a number of components (Waldrop, 1993), and that such systems would always reach a different state under different initial conditions (Fig. 1). The transition between the order and the chaos is defined as the "edge of chaos" or "complexity". Systems at the edge of chaos exhibit complex behaviour and are called complex systems. These systems have a tendency to develop a behaviour that is unexpected from the rules that define the system components. Through this unexpected behaviour a complex system appears to self-organise. This self-organising behaviour is called emergent behaviour. There are many examples of systems with emergent behaviour: crystal formations, molecules, flocks of birds, multi-cellular organisms, Darwinian natural selection, and others. None of these examples have been modelled successfully with deterministic (top-down) models, but have been modelled very successfully with emergent, bottom-up models.

Reynolds (1987) created an emergent model of a flock of artificial birds called "boids". He proved that very complex systems such as formations of birds, animals, or fish could be modelled by creating simple models of system components and making them interact. Jankovic & Dumpleton (2000), showed that emergent modelling of a number of different complex systems was possible in low cost virtual reality (Fig. 2) using VRML97 and JavaScript programming languages, running on inexpensive Pentium PCs.
DEVELOPMENT OF BOTTOM-UP MODELS OF STRUCTURES

Model Description

A model of a simple triangle truss was developed using VRML97 and JavaScript (Fig. 3), and consisting of joints and bars as main components. Following the principles of structural dynamics, the assumption was made that the mass of the truss was concentrated only in the joints. The joints and the bars were modelled as separate, independent components, each considered as an object in terminology of the object-oriented programming. The objects were connected through inputs and outputs only, in a similar way in which they are connected in reality. The bars were modelled as weightless springs. A viscous damping mechanism was adopted, and the damping force modelled to act in the opposite direction to the joint's velocity. Each component was defined on the basis of the Newton's Laws.

Component Model Architecture

The component architecture involved the use of PROTO(types) and Scripts (Fig. 4). The component PROTO was responsible for dealing with external components and the Script inside the PROTO was responsible for implementation of simple rules that determined the component behaviour.

The parameters and variables from the PROTO interface declaration were mapped to the Script parameters and variables. This enabled the prototype inputs to access the Script inside the PROTO directly.

All components of the emergent model were created by a process of instantiation (creation of working copies) of the same PROTO.

To ensure the compatibility of inputs and outputs so that outputs of one instance of the PROTO could be connected to inputs of another instance of the same PROTO, the PROTO's inputs and outputs were chosen carefully to be of matching data types.
The Script inside the PROTO was mapped to its geometric properties in order to effect the visual representation of behaviour of individual instances. This created a generic component model suitable for interaction with other components.

**System Model Architecture**

It was found that complex interactions between system components are best handled using a separate "container" PROTO(type) named Environment, capable of dealing with the influences between a large number of pairs of components (Fig. 5, Fig. 6).

The system had a Starter - essentially an event generator, used to start an event cascade. The subsequent interaction of the components gave rise to emergent behaviour.

**RESULTS**

**Snap-through Behaviour**

The snap-through behaviour is one of the most difficult problems to model in non-linear structural analysis, although it is possible to solve it using incremental iterative solution in combination with the Finite Element Method. This was the reason why the snap-through behaviour was chosen as one of the test cases for the bottom-up model.

The system shown in Fig.7 is a shallow two-bar truss with two hinges. The system has three possible equilibrium states under the load, but only two of these are stable and
they are shown in Fig. 7a) and Fig. 7b). After applying downward load, system shown in Fig. 7a) returns to the original equilibrium state or to the alternative stable equilibrium position shown in Fig. 7b). If the system under the load reaches a critical state, it will soon settle in an alternative stable equilibrium (Fig. 7b), after dynamic snap has occurred. There are always two dynamic snaps, from one stable equilibrium state to another. It is also possible to achieve the dynamic snap by applying upward load on the system shown in Fig. 7a, or by applying downward load on the system shown in Fig. 7b. This example is at the edge of chaos, and a slight change of initial conditions at some initial state may result in the system resting in an alternative equilibrium position.

A virtual reality model of a shallow two-bar truss was developed (Jankovic, 2000) using the approach described earlier in the paper (Fig. 8). The model consisted of joints and bars as main components. The joints and bars were modelled as independent components, each being an "object" in the terminology of object-oriented programming. The objects were connected through inputs and outputs only, in a similar way to which they are connected in reality.

As originally assumed, the interaction between the model components did indeed give rise to emergent behaviour. The resultant model was not governed by any conventional solution method, except the basic Newton's Laws, and neither the Finite Element Method or the incremental iterative solution were used. Effectively, an analogue model of the real structure was created in virtual reality and enabled the user to interact with it in the real time.

**Two-dimensional truss**

In order to test the generality of the modelling method, a more complex structure was modelled using the same approach. Figure 9 shows an example of a two-dimensional truss, before (a), and after (b) application of load.

![Fig. 9 Bottom-up model of a two dimensional truss](image)
It was found that the system behaved realistically, and returned to the original state after a short period of time. The co-ordinates on the side of the joints were changing as the system went from the initial state, to the maximum displacement state, and back to the equilibrium. As in the previous example, the user was able to interact with the model in the real time, and examine its behaviour.

**EVALUATION AND VALIDATION**

The finding that the bottom-up model was capable of simulating the shallow two-bar truss with snap-through behaviour is believed to be significant. The conventional analysis of the same problem involves the Finite Element Method and the incremental iterative solution, and is a difficult problem to solve. The bottom-up model was able to solve this problem dynamically, allowing the user interaction in the real time.

A similar real time solution with user interaction was achieved with a bottom-up model of a two-dimensional truss. The interactive display of co-ordinates of the joints indicated that measurement of forces was possible from this analogue virtual reality model.

Another significant capability of the bottom-up model is believed to be the ability to simulate both static and dynamic behaviour of structures.

The model was tested with a small number of components only (up to 30), and therefore its performance for simulating large structures is not yet known.

Some of the structures modelled using the bottom-up approach were also modelled in parallel using LUSAS, a standard Finite Element Method software. The results obtained from the bottom up model, and from LUSAS were almost identical.

The benefits of the bottom-up modelling method described here are believed to be best summarised in the words of one the project's industrial partners: "To set up a 3D model of a design, poke it, pull it, see what happens, change bits of it, would be a complete change in our method."

**CONCLUSIONS**

Conventional structural analysis methods based on systems of algebraic equations involves simplifications and inaccuracies, and its computational intensity does not allow user interaction with the model in the real time. Inspired by more efficient bottom-up models in other disciplines, the authors developed bottom-up models of various simple structures.

It was found that this method was capable of solving the snap-through behaviour of a shallow two-bar truss, normally a very difficult problem to solve with the Finite Element Method.

A more complex truss was also modelled and it was found that its behaviour was realistic. The model enabled user interaction in the real time, and was able to simulate
static, and especially dynamic behaviour of structures, the latter being often neglected by engineers. However, the model was only tested with relatively small structures, and its efficiency of simulating large structures is therefore not yet known.

The behaviour of some of the structures was also modelled in parallel using a standard Finite Element Method package, and the results obtained by the two methods were almost identical.

Can therefore bottom-up modelling in virtual reality replace conventional structural analysis methods? From the analysis presented in the paper it would appear that it could. However, the success of the method will depend on its ability to handle as complex structures as the current methods do, and also on adoption by the structural engineering profession.

The future work will concentrate on developing a library of standard components, such as beams, bars, and joints, and also on investigating and improving the capabilities of the method to handle structures with a large number of components.

As far as the adoption of the method is concerned, the authors believe that this approach to spontaneous modelling of structures, which integrates the modelling method and visualisation into one, could revolutionise our approach to structural analysis.

REFERENCES


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