PUSH: Generating Structural Form with Haptic Feedback

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This paper looks into the use of haptic feedback (also known as force feedback) in helping generate and evolve structural forms, a process that is important to students of architecture and engineering. Force feedback provides these students with opportunities to "feel and manipulate" virtual 3D structures in a very natural and intuitive way. It also makes it possible to have real time holistic evaluation of structures in a qualitative rather than quantitative manner, something of particular importance to introductory-level students. Furthermore, the incorporation of force feedback into a highly interactive multimodal structural behavior application furnishes students not only with a means to observe virtual structures but also a tool to help generate and develop efficient, innovative and alternative ones. This also is of vital importance to students of architecture as they are often challenged to explore non-conventional forms.

Implementing force feedback systems for these purposes need not necessarily require sophisticated and expensive VR hardware. This paper describes a structural behavior application called *PUSH* which utilizes a simple force feedback joystick connected a reasonably fast desktop computer.

Introduction

Computer based evaluation of structural performance has often relied heavily on graphical representations to depict structural response. Indeed the most readily observed facets of structural behavior such as deformation and vibration do lend themselves naturally to being visually conveyed. There are, however, other aspects of structural response such as force, stress and stiffness, which are also usually depicted graphically albeit in a much less intrinsic way - through indirect mapping representations. Force feedback, a form of haptic interaction currently receiving much attention in various research communities, presents an alternative means of portraying these particular structural aspects more intuitively. It is for this reason that haptic feedback has been incorporated into PUSH, an interactive, multimodal, real time structures simulator developed to aid students understand, evaluate and generate structures.

PUSH is basically a design and teaching tool intended for students of architecture in particular. It is meant primarily to assist them in generating and evaluating structural forms through a tactile experience. It basically provides an opportunity for them to physically pull, push, nudge, feel or even sway their 3D virtual computer modeled structures just as they would their physical study models. The system requires relatively simple and inexpensive hardware, which comprise mainly of a fast desktop computer and a two-axis tactile force feedback joystick.

The paper will discuss how the haptic interface (together with the visual and audio interface) is used to evaluate, generate and improve structural forms with the aid of information conveyed through a constant stream of force feedback sensations. In general, the generation or improvement of form is achieved with the aid of constant real time monitoring of a structure's three-dimensional stability as structural topology and attributes are manipulated. The application accommodates different levels of abstraction to account for structural hierarchy thus making it useful simulating not only overall structural behavior (usually helpful at the conceptual stages of design), but also behavior of more detailed structural assemblies.

The structure of the user-computer interface will be discussed. It basically consists of simultaneous occurrence of haptic force input, haptic stiffness feedback, and structural response conveyed through the visual and audio modalities. Inversely, haptic stiffness input and force feedback are also involved. The paper will also examine how the force feedback interface can be used to help show second order, inelastic behavior in a direct and intuitive way thus providing an alternative means of experiencing accurate and realistic structural performance.

The paper will likewise look into the relevant issues regarding parameter mapping. These include, among others, discussion on the techniques used for selective mapping of the tactile device's 2 degrees of freedom to the structure's 6 degrees of freedom, as well as and mapping of stiffness parameters (shown on table 1).

Force feedback application

Several studies are now being made on the advantages of using force feedback in virtual environments most particularly in the areas of medical training, entertainment, telerobotics and the military (Burdea, 1996). An example of a medical application is one developed creating realistic force sensations in a virtual environment for a widely used medical technique called lumbar puncture (Popa, Singh, 1998). Several studies on force feedback and manipulation of simple deformable objects and surfaces have also been undertaken (Thalmann, 1995 ; Yokoi, Yamashita, Fukui, Shimojo, 1994; Vedula, Baraff, 1997). Another example is a system providing data visualization methods for the blind using a bimodal interface consisting of force feedback and sonification (Grabowski, Barner, 1998). Several other studies and applications use haptic interaction without necessarily requiring force feedback. An example of such application is one that enables design of a free-form surface using a pen-based force display where-in manipulation of both the congenital and acquired characteristic of a shape can be performed (Iwata, 1997).

Research has also shown that the incorporation of force feedback into various applications has many advantages such as reduction in dependence on visual tasks, reduction in errors, training and task completion time, and increase in the sense of immersion in virtual environments (Hasser, Massie, 1998). The potential impact of force feedback technology in the realm of education is likewise significant since it involves multiple senses, offers "self-paced and semi-autonomous learning", and provides an efficient and flexible use of a single haptic device for interacting with many virtual physical models (Hasser, Massie, 1998).

Overview of the PUSH system

The *PUSH* system was developed with Delphi 3 and can run on Pentium-based systems under Windows NT. It is a multimodal application that requires a force feedback joystick, sound card and speakers, and reasonably good color display. The general process of interaction between user and structure in the *PUSH* system are illustrated in Figure 1. The user is at liberty to manipulate both the structural form and the forces acting on it. Form manipulation is accomplished either through general adjustments or reorganization in overall topology or through individual or collective changes of element attributes. Force manipulation on the other hand is achieved through gradual increments /decrements in force magnitude and/or direction. The corresponding structural behavior (taking into account second-order, inelastic effects) in response to these form and force adjustments are then determined. Force feedback, deformation and stress distribution are imparted back to the user in real time to enable the closed loop process to continue naturally and unabated.

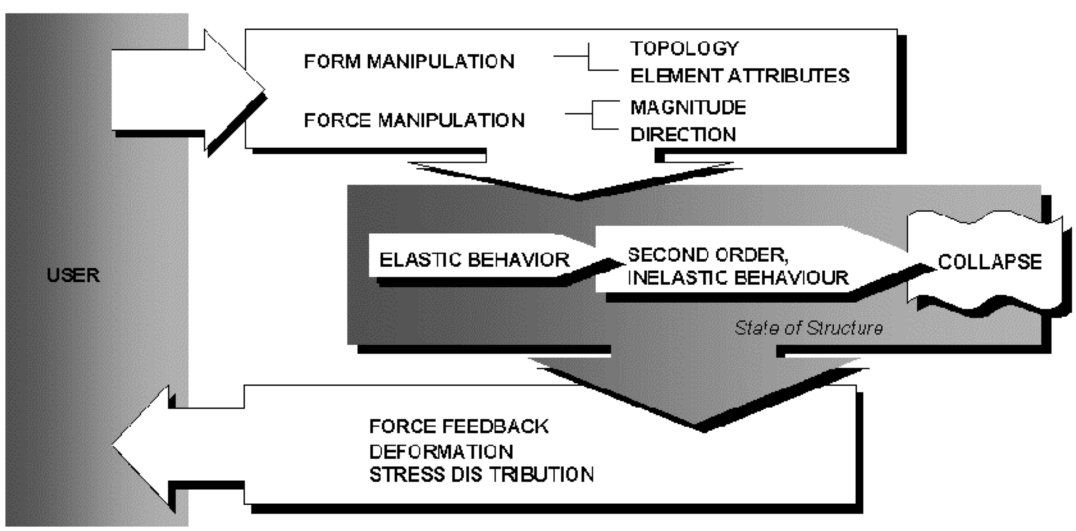

Figure 1. User-Structure Interaction

The force feedback joystick

The implementation of force display can be achieved through three basic approaches, namely, exoskeleton, tool-handling, and object oriented type (Iwata, 1997). The exoskeleton and object-oriented type of force displays are much more complex and therefore more difficult to implement. Exoskeletons provide independent point forces to specific points in the fingers or hand through mechanical linkages. Tool-handling types provide devices which users grasp. A joystick, an example of a simple tool-handling type, is the device chosen for implementing force feedback in the *PUSH* system.

Joysticks, being simple and intuitive devices, have been very popular in the past many years. Those with force feedback capabilities are now readily available and relatively inexpensive. The force feedback joystick used in *PUSH* is a simple 2-degree of freedom spherical configuration haptic joystick. This device is capable of 2-dimensional feedback forces on the horizontal plane. However, *PUSH* simulates 3D structures, which means that 3 translational as well as 3 rotational degrees of freedom (DOF) have to be considered. Rotational DOF's are currently not supported in the force feedback feature of the *PUSH* system. In dealing with the 3 translational DOF's, transformation settings can be defined or selected to enable the user to apply and receive forces within any desired plane.

Force feedback within the context of multi-model interaction

PUSH was originally mainly bimodal in its output interface having both visual and audio channels. Haptic force feedback was incorporated into the application to provide stronger, more intuitive user-structure interaction. Figure 2 illustrates the role of haptic force feedback within the context of the multimodal interface. All three output modalities (haptic, visual and audio) are imparted simultaneously in parallel to achieve a greater bandwidth of conveyed information. The structural response information from the three modalities are both supplementary as well as redundant. The redundancy is intended to provide the user with greater sensitivity to the structure's behavior. Previous studies have shown that when such redundancy provided, the haptic channel increases the effectiveness of the multimodal interface (Richard, Coiffet, 1995 ; Fabiani, Burdea, 1996).

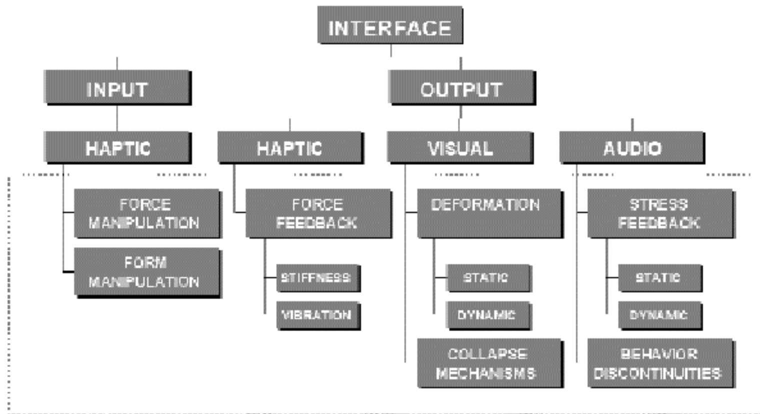

Figure 2. The multimodal interface of PUSH.

Shown on the left side of figure 3 are examples of the visual interface, which depict simple 3-dimensional pre-stressed cable structures viewed from different angles. The virtual structures can be deformed and loaded laterally and vertically. The diagrams on the right of figure three indicate typical examples of the state of force feedback in the joystick. Large arrows indicate large resistance to joystick movement therefore indicating adequate stiffness in that direction. Small arrows indicate otherwise. The force feedback joystick allows the user to manually feel and explore the structures (or substructure's) stability and stiffness along various degrees of freedom and enable him to detect directions of weakness or strength disparities.

Sensing structural stiffness and stability

In the PUSH system, structural form is continuously generated through evolution. Force feedback provides a sense of the structural stiffness and stability in various directions and as exploration proceeds, changes in overall structural form or elemental proportions take place either automatically or under the user directed manipulation. In either case, structural optimization is approached with a significant degree of user guidance.

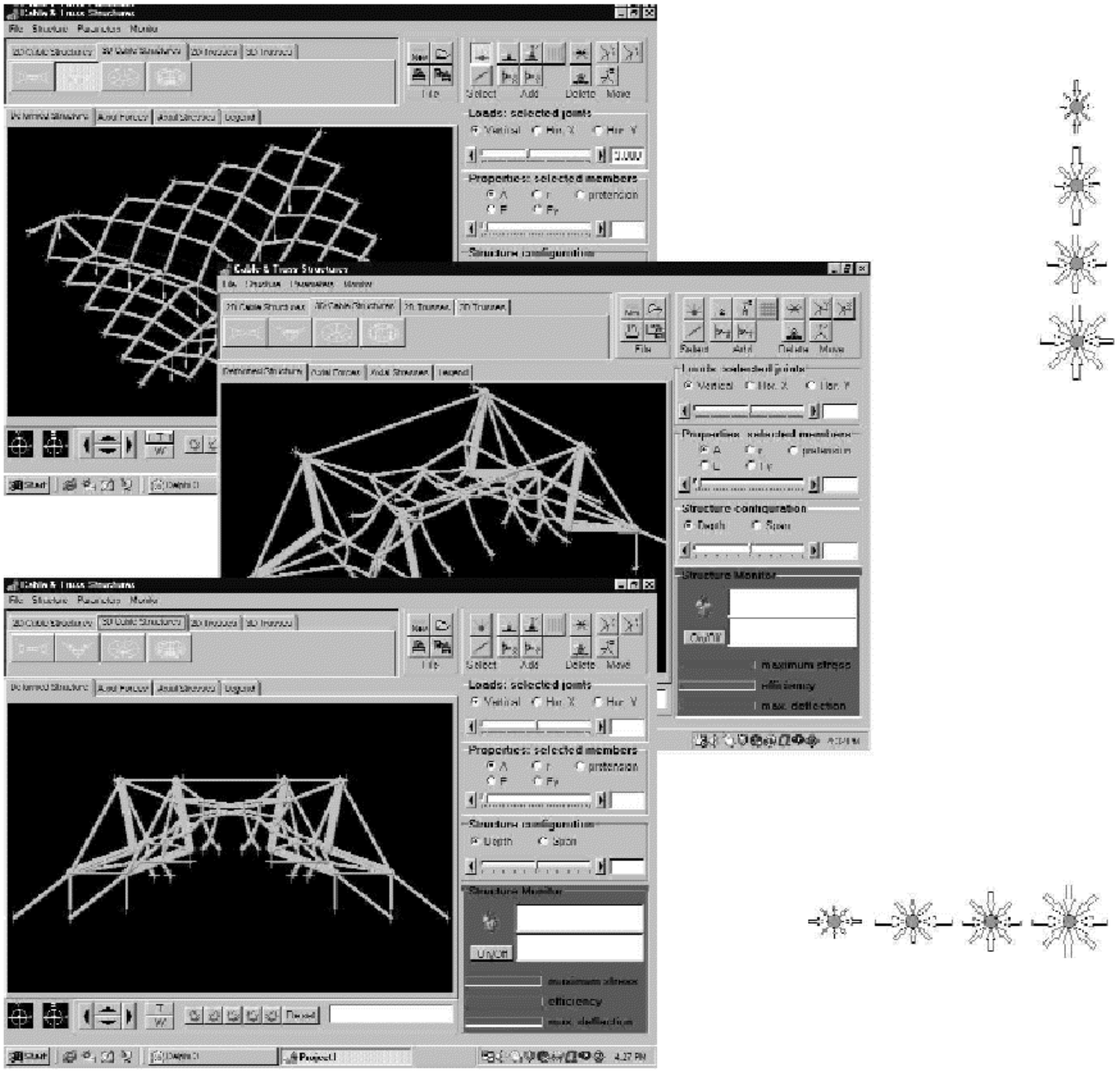

Figure 3

Sensing stiffness through incremental loading

Figure 4 shows in greater detail, a typical second-order, inelastic behavior of a structure. The right of the figure shows the structure's load-deflection diagram. A typical time-history simulation would show the non-linear behavior of the structure as loads are gradually incremented over time. Elapsed time and magnitude of applied loads are directly proportional and thus both parameters are placed on the vertical axis of the diagram. The non-linear nature of the behavior is apparent from the diagram as indicated by the formation of plastic hinges/zones in the structure. The formation of plastic hinges/zones are significant events in the simulated behavior and result in loss of stiffness as well as redistribution of internal stresses. The onset of each plastic hinge therefor marks a new state for the structure, with each state shown as being subdivided in time by the

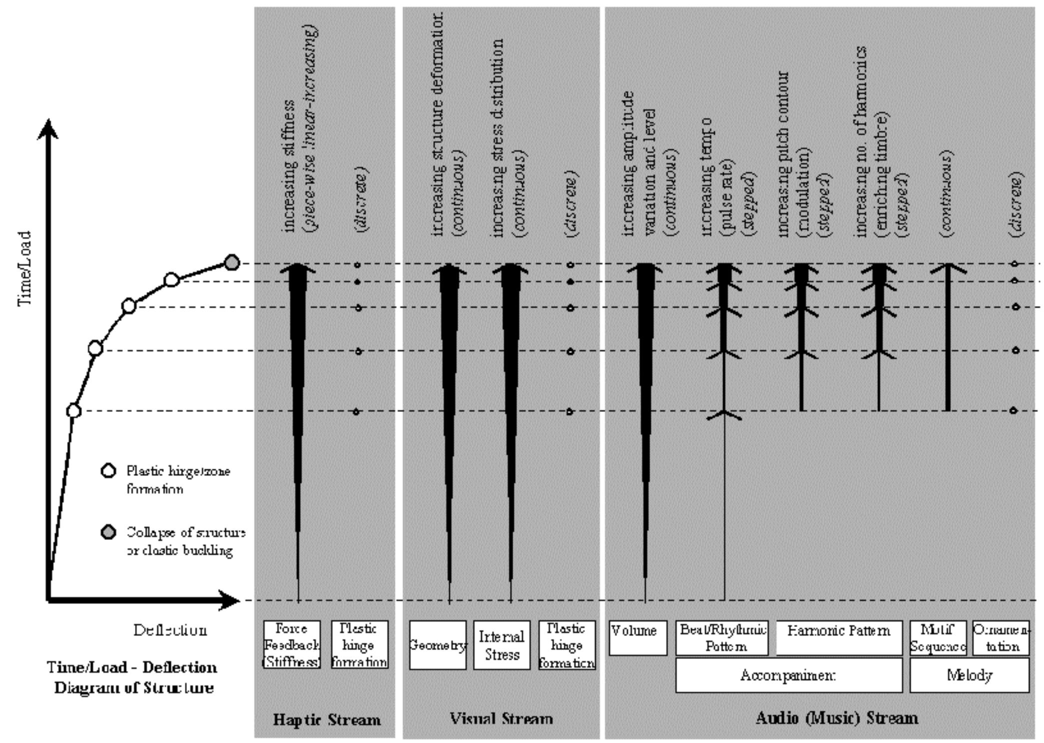

Figure 4

dashed lines. Force feedback through the joystick provides the user with an opportunity to directly experience the loss of stiffness.

Increase of external forces, animation of the structural deformation, distribution of internal forces/stresses as well as the location and spread of plastic hinges/zones are portrayed graphically through the visual channel of the bimodal interface.

The audio stream also conveys redundant information and injects affective qualities as well (Garcia, 1998).

Sensing stiffness through structure vibration

Stiffness of a structure can also be sensed through force feedback as it undergoes dynamic response (in the form of vibrations) due to load. The vibration of the structure as it responds to a periodic or transient load is conveyed to the user through the force feedback joystick. The frequency of the vibration gives a good indication of the structure's stiffness. Table 1 below shows the role of the Haptic channel within the context of the multimodal output of structural dynamic response.

Summary

The haptic force feedback computer interface incorporated in PUSH is envisioned to enable students of structures to generate, develop and improve structural forms by actively experiencing structural behavior with the aid of haptic sensations. Interactive real time 3-dimensional exploration makes it possible to explore the structure's stability and discover directions of inadequate stiffness and stability.

PUSH is not intended for quantitative structural

	Structural Data	Haptic Representation	Visual Representation	Auditory Representation
Dynamic Loading	Periodic, Transient		Dynamic Force Vectors	Flutter in sound amplitude (vibrato) & panning
Structural System Properties	Fundamental natural frequency	Force Feedback Vibration	Vibration	Tempo
	Partial frequencies	Force Feedback Vibration	Vibration	Tempo
	Damping	Force Feedback Dissipation	Vibration Dissipation	Decay
	Mass	Timbre	Mass	Timbre
Structural Response	Maximum stress envelope	Force Feedback Strength		Pitch and loudness
	Onset of Resonance			Earcon

Table 1

design and will therefore be inadequate in that regard. It is however meant to qualitatively explore and generate structures holistically through examination of overall and local stability. An added benefit provided by this multimodal interface is that it allows a realistic depiction of second-order inelastic behavior.

There are however several issues that still need to be looked into further such as the transformation of forces to human scale, scaling time when force feedback structural vibrations are used, and the inability to achieve real time in very large or complex structures.

A brief demonstration of the *PUSH* will also be shown during the conference presentation.

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