MATERIAL FEEDBACK IN DIGITAL DESIGN TOOLS

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Abstract. How do design tools feedback material behaviour to the designer? Digital design tools in use by designers today provide a rich environment for design of form but offer little feedback of the material that ultimately realise that form. This lack of materialism limits the value of the design tool and the exploration of the design space where material behaviour can provide important feedback. This work examines the modes and value of material feedback in design using systems engineering principles, illustrates the challenge with current tools and explores a prototype simulative interface. It approaches the problem from a new perspective of simulating physical manipulation and experiment rather than existing CAD paradigms.

Keywords. Interactive design tools; material simulation.

1. Introduction
1.1. BACKGROUND

In the modern era, architecting and building have become two separate endeavours, separated by a chasm between an architect’s vision and the practicality of building within resource constraints. This chasm is an artificial separation that requires time and effort to bridge and introduces risk, error and waste. Despite some historical opposition of this separation by critics like Ruskin and others, the movement has distanced designers from the material used to realise designs.

Digital tools are slowly bridging this chasm with technology, changing the nature and business of designing and building. This is not simply an evolution in the efficiency of building, but a change in the way designs are realised. The changes ripple all the way back to how designers work in the design tools and how those tools can inform design. To understand this change, we
must examine the nature of the chasm and the relationship of the tools to the designer.

1.2. PROBLEM DEFINITION

For this work, I am concerned about the nature of the feedback of material behaviour to the designer. There is a primitive direct saliency when designing directly with the material as an artist or craftsperson would. The material behaviour has a direct channel of feedback to the designer and the moves and gestures that are made are intimate with the material. As we look at designing within the currently available digital toolset, there is a lack of this informative intimacy with the material that limits the design space that can be explored, even with digital rapid prototyping tools. The distance from the material often leads to arduous post design rationalisation.

1.3. OBJECTIVES AND METHOD

This work investigates the use of feedback of material behaviour to designers during the design process by decomposing the structure of these feedback channels and evaluating the value of this communication. Methods of data flow diagrams and systems engineering principles, I approach this by examining prior research, applying analysis techniques, extrapolating historical developments in this framework and exploring a prototype interface for material responsive extension to current tools.

2. Background

2.1. FEEDBACK IN THE DESIGN PROCESS

Design involves a cycle of generation of possible solutions to a problem, perhaps ill-defined, through pursuit, testing and refinement of solutions. Feedback from possible solutions provides validation of the explored space at many levels and may redefine the problem itself. In this pursuit the designer has many tools available to them including their own experience, physical analogy, imagination, prototyping and, increasingly, digital tools. What is common among all of these tools is the feedback the tool provides to the designer that they can use to refine the solution or spark new design paths.

Feedback loops are well supported by studies of designers through observation (Fricke, 1993; Cross and Dorst, 1998) and through theoretical models of designing (Oxman, 2006). These studies have found a common set of activities in the design process which involve a feedback loop of analysis, synthesis and evaluation. Often the way these paths of feedback have been realised is in
separate processes with separate tools supporting them.

2.2. MATERIAL KNOWLEDGE IN FEEDBACK LOOPS

While material knowledge is needed for the rationalisation of designs, some target material performance may be considered early in the design stage. Cross (Cross and Dorst, 1994) and Akin (Akin and Lin, 1996) have observed, in controlled design cognition studies, that the quality of design may be correlated to the frequency of non-exclusive modal shifts between drawing, examining and thinking (analogous to synthesis, evaluation and analysis) during exploration of conceptual design. This suggests that tools engaged during this time of creative rapid shifting of strategies have a large effect on the quality of the design solution. Information flow in this phase includes internal knowledge and external feedback from the design tool including material behaviour. Friction to information flow between the designer and tools will negatively impact the design solution or increase the effort to refine the design.

While not every design process may be informed or dependent on material behaviour, there is evidence that material feedback loops have an important value to designers for both rationalisation and design exploration. This includes design in which material behaviour is used only as an analogy for the final form. In the analysis I examine why reducing the material feedback loop has value and look for clues as to the next logical steps in the development of the tools.

3. Exploration: material feedback loops

3.1. CLOSING THE LOOP

By examining actual feedback loops in the designing process, we can understand the nature and value of the information passed back to the designer. If we ignore, for the moment, the implicit knowledge of the material by the designer, which functions as a short cut in the design process, we can diagram the feedback loop of the naïve designer in a simple mode of designing with a separate builder without prototyping (figure 1).

This case requires the designer to hand off indirect design documents to a separate maker who implements the design into a physical instance and returns the information about constraints to the maker indirectly. This is a costly and long process which reduces the quality of information back to the designer and ultimately limits the material sensitivity of the designer to observation of full scale implementation. It is evident why the “expert” designer’s material knowledge is valuable in producing feasible / adept designs rather than rely on indirect feedback in a longer loop.
The tradition of prototyping has reduced this loop for visual, mechanical and material feedback. The history and pedagogy of prototyping in design is well documented. The effect of prototyping is to reduced the total length of the loop and bring the feedback closer to the designer. If the act of prototyping is used as a design tool directly by the designer, the activity is approaching the immediate modal shifting feedback that has been shown to have high value to the design process. This direct manipulation of the material in ‘playing’ with the prototype changes the mode of design thinking.

Rapid prototyping directly from digital designs such as laser cutting, CNC-machining or 3D-printing further reduce the time to gain feedback and increase the iterations that a designer can achieve with the same amount of effort. The value of the prototype depends on the accuracy of modeling the actual scale behavior.

This indicates a historical trend of cost reduction (or ease of iteration) and increasing accuracy and value of the feedback (figure 2).

Other information flow diagrams were used to understand various modes of designing, prototyping and materialisation including novel approaches of design in the physical realm with digitisation in the manner of Geary (Shelden, 2002). The scope of this research did not allow further quantitative measures of loop length in resource cost or time and this is left for a future area of investigation.

3.2. DIGITAL MATERIAL FEEDBACK

The next logical progression in closing the feedback loop is to allow digital simulation of the material behavior. This reduces the feedback loop to near direct manipulation of the material, albeit without tangibility. If we examine

![Figure 1. Design feedback loop, separate builder, no prototyping.](image-url)
the flow of information (see figure 1), the flow from the intermediate tool back to the designer (figure 1 dashed line) is the most immediate and powerful. This step has already been incorporated into digital design tools for visualisation with the increasing fidelity of rendering engines expanding the space of visual exploration. Just as visualisation has become more advanced as computing power has improved, simulation of basic homogeneous and mildly heterogeneous material behaviors is now possible.

3.3. DESIGN TOOLS PARADIGMS

Design tools have been developed, regardless of the underlying geometry representation, for providing manipulation of abstract primitive shapes without regard for material at the time of design. This has lead to the paradigm of basic build up of geometric operations that only have an indirect analogy to the physical action of manipulating real material (see example above). This disconnection between design tool operations and the physical operations to materialise the design pushes the implementation and knowledge of material specific behaviors to other tools and experts away from the designer. This is just a new manifestation of the design loop shown above.

Other explorations into projecting material behavior into a digital simulative tool (Oxman and Rosenberg, 2007) have explored problem with non-interactive scripted simulation of complex behaviors. The simulative and generative solutions are largely purpose-scripted. Based on historical progression in other software user interface maturations this does not represent a sustainable and flexible design tool solution.
How could digital design tools evolve to allow manipulation of simulative material?

4. Exploration: tools solution

4.1. ILLUSTRATING THE PROBLEM: THE “SIMPLE” RIBBON

As an illustration into the limitations of the current toolsets for designers, a “simple” ribbon shape was chosen. This shape is very simple to calculate physically. It is a simple band folded and joined at right angles and the material defines the shape (figure 3). Attempts and failure to reproduce this shape in representative digital tools (Bentley Generative Components, AutoCAD, Digital Project and Rhino) illustrates the lack of tools to deal with even simple material behaviours.

The conclusion of this exploration was that the tools available for digital design were poor in exploring even a simple physically defined figure without geometric derivation and scripting to reproduce the physical behavior.

A tool was developed in the Processing environment to simulate the material behavior rather than rely on the built in primitives of existing tools. This tool was developed from the general physics of elastic material behavior, calibration against physical material and simulating both the twisting and gluing used to make the ribbon physically. The simulated ribbon recreated the geometry found in the paper ribbon as well as other similar designs and was able to illustrate simple limits to material elasticity. This tool, however, still lacks an interactive design experience.

4.2. EXTANT MATERIALLY RESPONSIVE TOOLS

Tools that offer simulative interactive environments are emerging, but are not...
yet used in the architectural design field. Blender (www.blender.org) is one of the best examples; it used to build virtual objects with behavioural attributes for the entertainment industry. A sculpture mode allows the designer to sculpt in gestures very similar to physical manipulation. This tool is aimed at virtual production but using it as a design tool for physical artefacts is intriguing.

Other tools simulate more macro physics behaviour, typical of this class of software is Crayon Physics (www.crayonphysics.com). Of note with this tool is the design interface which behaves like traditional sketch pad. Tools in this class are just beginning to be commercialised. Autodesk Inventor is focused on mechanical design through simulation.

Commercial design tools are still largely manipulating abstract geometric and post design simulation and not material simulations at design time. These are largely object based rather than process or assembly.

4.3. DESIGN TOOL DEVELOPMENT

Current traditional design tools such as AutoCAD, Bentley, Rhino, Digital Project and others support primitives operations but lack operations for simulating material behaviour such as bending or stretching. The ribbon exploration above illustrates whole class of design alternatives which involve bending or twisting that are unavailable to a designer using one of these tools.

We can show how these features would be added to traditional tools, although the feasibility of retrofitting current software with a whole new type of object behaviour and simulation may not be possible. We illustrate the simulative design environment with mock ups of additional features in the Rhino environment.

This is not proposing to replace other more accurate simulation of material or other attributes by more specialised software but to provide feedback to the designer similar to the strong material feedback of physical modelling in as an extension of the tools in use today by designers.

We can illustrate this by following a scenario with well understood sheet material to show simulated manipulation. The material could be wood or paper or other material manipulated in the elastic zone of deformation. In an expanded tool, malleability, nonlinear and asymmetric elasticity curves could also be modelled.

4.4. DESIGN TOOLS FEATURES TO SUPPORT MATERIAL BEHAVIOR

Creating the object involves specifying the material properties using extensions of the existing object attributes. Objects can be manipulated with traditional tools for cutting, splitting, Boolean solid operations and mesh editing
that affects the physical boundaries of the object without regard for materiality. This is standard functionality of existing tools.

An object can be ‘relaxed’ into the default state and ‘glued’ to a plane (figure 4). The concept of ‘gluing’ is adopted from the physical world and closely follows the actual operations that you would use to construct the object. The relaxed state of an object might be one of curvature or even an intermediate state of construction and a malleable object may have the relaxed state change with the application of forces.

The act of gluing the object fixes these points in relation to some other object, in this case the world UCS. In this mock-up, the yellow 2D arrows indicate the ‘glued’ fixed patch that is attached. This patch of gluing could be any shape, but here it is rectangular. In more sophisticated environments gluing could have yield strength.

Springs can be assigned to points on the surface, edges or to whole planes and the object responds the same way a physical material would behave. Springs have force and direction. The direction could be normal to the plane.
or pointing at some other point, either fixed or on another object. The designer should be able to attach a spring to a dynamic point and experiment with the material behaviour in real time (a spring anchored in a dynamic point).

The failure mode of real material is very complex, but the object should indicate the limits of elastic deformation. It should be clear to the designers that they are approaching or past the limits of deformation. The object can be redefined with different material and the object will respond to that change given the force and gluing that had occurred.

Objects should allow interference with other objects and they should be able to exert pressure just as solid objects should be expected to behave. Chains of operations should be supported, so gluing one plank to another, should behave properly (figure 5). Note that the end of the first plank is twisted in relation to the other end, truly simulating the torque placed via the force of the second plank.

Note that the assembly sequence and the operations involved mirror the actual assembly process although perhaps not always linearly.

While there is more that could be implemented, the three features described here: Interference, Bending and Gluing could create a robust environment for materially responsive design.

5. Conclusion

5.1. SUMMARY

With the increasing fidelity of simulative environments, the capability is emerging from purely technical assembly and engineering digital environments into environments that mimic physical manipulation of material. This advance will provide the designer with an environment that allows form finding and / or early materialisation of abstract form through feedback that has been shown in this paper to have value to the entire macro process.

5.2. FUTURE DEVELOPMENTS

I believe that we are on the cusp of design tools transitioning from the purely abstract basic object manipulation to more immersive simulation environments where the designer can explore the mechanics, material behaviour, fabrication constraints, assembly and visualisation directly in the design tool in near real-time. Many trends point to this future including the progress in understanding design as a process, the advancement of digital rationalisation and the availability of enabling computing power. Change in the business of architecting has also increased the designer’s interest and responsibility in rationalisation and delivery of designs. Pressure from firms leveraging (and
struggling with) these technologies is driving development of more advanced
simulative integrated software. These tools will expand the designer’s ability
to explore the design space while producing designs that are more easily
rationalised and responsive to the material properties.

5.3. CONCLUSIONS

This research has produced several conclusions: Material feedback in design
tools has strong theoretical support including that early rationalisation / materi-
alisation has implicit value to the downstream process after conceptual design,
both in design quality and project economy. There is a historical progression
of tighter material feedback loops driven by value to the design process which
would indicate that simulative tools continue that trend. Most commercial
design tools only weakly support material simulation and it is possible to build
tools that effectively simulate the behaviour of material within constraints.
Having digital simulative environments opens new areas for design explora-
tion and material use.

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