# Industrial motivation for interactive shape modeling: a case study in conceptual automotive design

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## Abstract

As Computer Graphics makes rapid strides in various aspects of digital shape modeling it is easy to lose perspective of the larger motivations for digital shape modeling in design and animation. This chapter provides a high level view of shape modeling illustrated within the space of conceptual automotive design. Automotive design provides a unique perspective on digital shape modeling, where digital models are critical to downstream production processes but automotive designers almost exclusively work with sketches, clay and other traditional media. Design iterations that transition between physical and digital representations of a prototype are thus a big bottleneck in the industrial design lifecycle. In this chapter we propose a top-down approach, starting with the design desirables and suggesting modeling paradigms that harness skills and creativity of designers.

**CR Categories:** I.3.3 [Computer Graphics]: Geometric modeling, User Interaction

**Keywords:** Shape modeling, User Interaction

## 1 Introduction

We shall not cease from exploring, and the end of all our exploring,
will be to arrive where we started, and know the place for the first time. -*T.S.Eliot*.

Computer Graphics continues to battle the challenging question: **How quickly and effectively can a designer transform a mental concept into a digital object, that is easy to refine and reuse?** If hearing, speech and sight are analogous to the audio IN, audio OUT and video IN of an electronic device, the essence of our problem is that humans do not have an explicit video OUT.

This is a problem of great industrial importance today. Designers almost exclusively prefer traditional design techniques of sculpting and sketching, instead of computer aided digital styling tools that operate on mathematical representations of geometry. Most manufacturing processes, however, use digital models making design iterations a big bottleneck in an industrial design lifecycle. The majority of industry-based surface modeling research is, therefore, focused on incrementally making existing digital styling tools more designer friendly, while the root of the problem lies deeper.

The fundamental pitfall is that current digital tools are unable to decouple the creative process from the underlying mathematical attributes of the surface representation. As an example, when modeling an object using a network of bi-cubic or higher order polynomial spline surface patches, concepts like patch resolution, topological connectivity and continuity across surface patches constrain the creativity of the designer. The solution is to start from scratch with a designers perspective and develop computer interaction paradigms that harness their skills and creativity. These interaction techniques will in turn define the requirements of the underlying mathematical representations of geometry. Studies have shown that designers and people in general abstract shape as aggregations of complex surface attributes, that we will collectively call *surface-features* that are independent of any geometric model representation.

Conceptual modeling should, therefore, focus among other things on the development of new mathematical representations or adapting existing ones, to capture the essence of shape as perceived by designers. To be able to make tangible progress towards such a goal we must first mathematically quantify this *essence of shape* in terms of geometric surface-features. Design methodologies in industry are both complex and diverse and it is important to have a well-defined process to study and within which to evaluate proposed solutions. This chapter will focus on the early stages of conceptual automotive design, which has been slow in adapting to the use of digital styling tools, despite being a trendsetter in digital modeling for the engineering phase of its design lifecycle. Design iterations and revisions that transition between physical and digital representations of a prototype are currently one of the big bottlenecks in the design lifecycle of an automobile.

The remainder of this chapter is organized as follows: Section 2 discusses the generally desirable properties of systems for conceptual design. Section 3 illustrates these properties within the automotive design space. Section 4 then proposes a framework for conceptual automotive design based on commonalities observed from the current workflows in practice at various automotive design centers. Current trends in geometric shape representation and interactive shape modeling are then discussed in the context of their applicability to the automotive design framework. Section 6 provides concluding remarks.

## 2 Conceptual modeling desirables

Newer generations of industrial designers are increasingly savvy with digital modeling techniques. Their design education, however, continues to be grounded in traditional sketching and sculpting techniques, which embody a number of desirable properties that any digital modeling system should embrace.

- **Abstraction from underlying surface math**
  Most mathematical surface manifolds are represented at some point by a discrete set of points (control points for parametric or subdivision surfaces, vertices for polygon meshes) that often become handles for shape manipulation. This not only exposes the designer to the understanding of the mathematics and topology of the shape representation but also forces the learning and usage of tools that may not have been considered intuitive when decoupled from the geometric representation. Designer interaction paradigms should thus be defined

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such that the user is oblivious of the underlying mathematical surface representation. [Singh 1999] provides an example of such design, where the user interacts with sweeps just like in the physical world (see Figure 11) but the underlying curve manipulation is accomplished through splicing and fitting cubic spline curve segments.

- **Invite interactive creative exploration**
  Often digital modeling tools are made easy to use by narrowing their scope to a specific design space. As examples, two successful sketching systems Teddy [Igarashi et al. 1999] and SKETCH [Zeleznik et al. 1996] simplify the inference of a 3D model from sketched curves by making assumptions of the user design space. While SKETCH is tuned to create simple analytic shapes, Teddy is focussed on the creation of smooth organic forms. Design innovations are often the result of serendipitous exploration. Design tools should thus be interactive and easy to use without compromising their power of creative expression, as far as possible. A major advantage of interactive digital modeling tools is the ability to undo an operation allowing users to experiment without fear of making mistakes. It is thus important that increased complexity and sophistication of a modeling tool does not come at the expense of its interactivity.

- **Allow for precision and constraints**
  Industrial design models typically need to adhere to various engineering constraints before they can be manufactured downstream. Integrating such constraints early into the conceptual design process eliminates costly iterations in the design lifecycle, where models need to be redesigned because they violate some insurmountable constraint.

- **Workflow mimics traditional design media**
  Sketching and sculpting with physical media are both easy to use and creatively unfettered approaches to visual communication. Digital modeling techniques could do well to capture the modalities that make these approaches successful. Systems such as [Igarashi et al. 1999],[Tsang et al. 2004], for example, strive towards the modeless fluidity of sketching and exploit traditionally used gestures to invoke various commands as part of the sketching process

- **Leverages domain expertise**
  Designers often have skills in using specialized physical devices for conceptual design that digital modeling approaches should attempt to benefit from. Many automotive designers, for instance are proficient tape artists [Balakrishnan et al. 1999], a skill that allows them to lay out designs on large surfaces using tape of varying thickness and tension (see Figure 4).

## 3 Automotive design process

The current automotive design lifecycle is 3-4 years, of which as much as half is spent in the early stages of conceptual design. Automotive designers largely work in traditional media and hand their designs off to modellers. Modellers are technically skilled people that create digital models with surfacing software, using the physical designs as a visual reference. These designs are then evaluated both digitally and physically using rapid prototyping technology and the entire process iterates towards a converging design. In addition to the general desirables of a conceptual modeller there are many aspects of shape modeling that make the automotive design space unique.

Figure 1: Curvature continuous surfaces

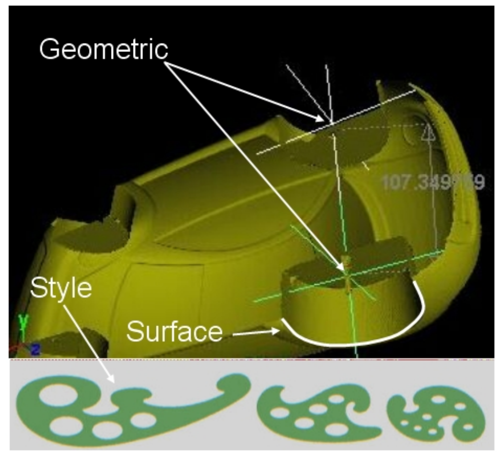


Figure 2: Automotive design constraints

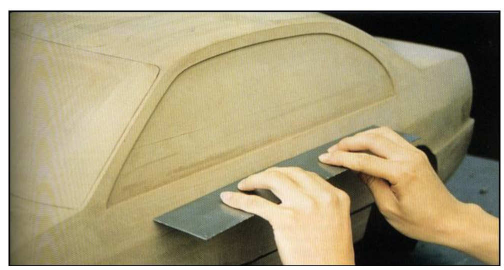

Figure 3: Editing a physical model prototype

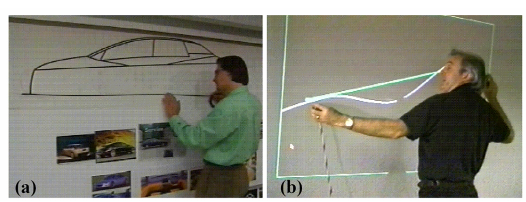


Figure 4: Digital Tape Drawing [Balakrishnan et al. 1999]

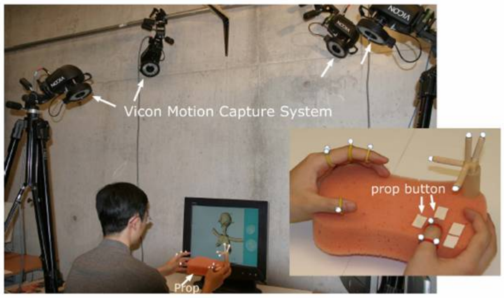


Figure 5: Sculpting with motion capture [Sheng 2004]

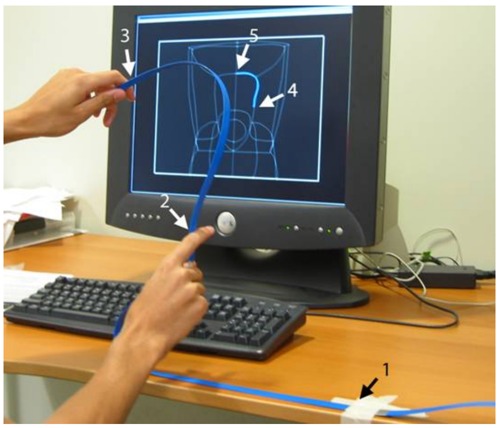


Figure 6: Manipulating curves with ShapeTape [Grossman et al. 2003]

- **Curvature continuous shapes**
  Automobile surfaces display a high degree of continuity, barring a few sharp features that run along the character lines of the design. Many automotive designers think in terms of the shape, size and location of specular highlights on the design and for these highlights to be smooth and unbroken, the surfaces needs to be at least $C^2$ continuous (see Figure 1).

- **Character or flow lines captured intrinsically**
  Character and flow lines that define the principal curvatures along surfaces are an important characteristic of automotive design.

- **Embodies geometric, surface and style constraints**
  While automobile design can be far more free-form than say marine or airplane design (due to fluid and aerodynamic constraints), the designs must adhere to certain constraints. These constraints can be geometric, such as hard points or dimensions on the engineered design, surface constraints, such as the circular shape of wheel arches, or stylistic, such as a signature look and feel for an entire family of automobiles (see Figure 2).

- **Flexible re-use of legacy data**
  Automotive designs do not change radically over short periods of time. It is thus important for design tools to facilitate the evolution of models and support the re-use of parts of designs that have already been engineered. Operations such as cut and paste play an important role is data re-use (see Figure 7).

- **Interfaces digital and physical modeling**
  Given the production lifecycle and costs that go into automotive design it is unlikely that a design will ever be approved without the creation of physical prototypes. Design updates are often made on these prototypes making it important to build better bridges between physical and digital modeling techniques (see Figure 3).

- **Large scale displays and novel interaction devices**
  Equally important to the automotive design process are design visualizations at the true scale of the models. This implies the need for large scale display devices [W. Buxton 2000] that are capable of displaying an automobile to scale. A number of high degree of freedom input devices today such as a flock of birds [T. Grossman 2002],[Llamas et al. 2003], motion capture systems [Sheng 2004] (see Figure 5) and ShapeTape [Grossman et al. 2003] (see Figure 6) show potential at emulating current large scale modeling techniques in practice in automotive design (see Figure 4).

## 4 A proposed framework for automotive design

We now distil these observations and a study of various automotive design pipelines in practice into a proposed framework for conceptual automotive design illustrated in Figure 7. We broadly structure current and projected modeling technology and techniques into three stages of rough model generation, model refinement and model presentation.

### 4.1 Rough Model Creation

Sketches (on paper or using a pen and tablet), physical sculpture, character lines and basic parameterized shapes typically form the creative input to this earliest phase of digital model creation.

A big challenge in this stage is the ability to take such varied input and transform it appropriately to consistently represent parts of the model in a common 3D space. The side view sketch in Figure 8, for example, needs to be scaled to be consistent in space with top and front view sketches. Early design sketches and sculpts may also have inconsistent or missing information in parts of the design that are resolved with model refinement. Determination of the intended fidelity of different parts of the models in the different pieces of input is thus a non-trivial problem. Precise engineering criteria are left out of the initial design input to leave the designer unencumbered creatively, but they are part of the input to the technique that constructs the rough model from the design input. As an example, while a designers sketch may only adhere roughly to engine block dimensions, the rough model created should make precise allowances for the engineering constraints. The rough model should also have the ability to determine a set of surface-features on the model that can be edited at this stage to make larger stylistic changes to the model.

Physical 3D prototypes can be scanned [Curless ] and the data structured using reverse engineering techniques [V. Krishnamurthy 1996]. Creating 3D models from 2D sketches is far a trickier problem [Eggli et al. 1997],[Lowe 1991] but sketches do tend to have surface-features and character lines explicitly depicted. In the final analysis there is likely to be an element of user interaction in the creation of a rough digital model from the given design input [Tsang et al. 2004]. The success of a technique is likely to be in its

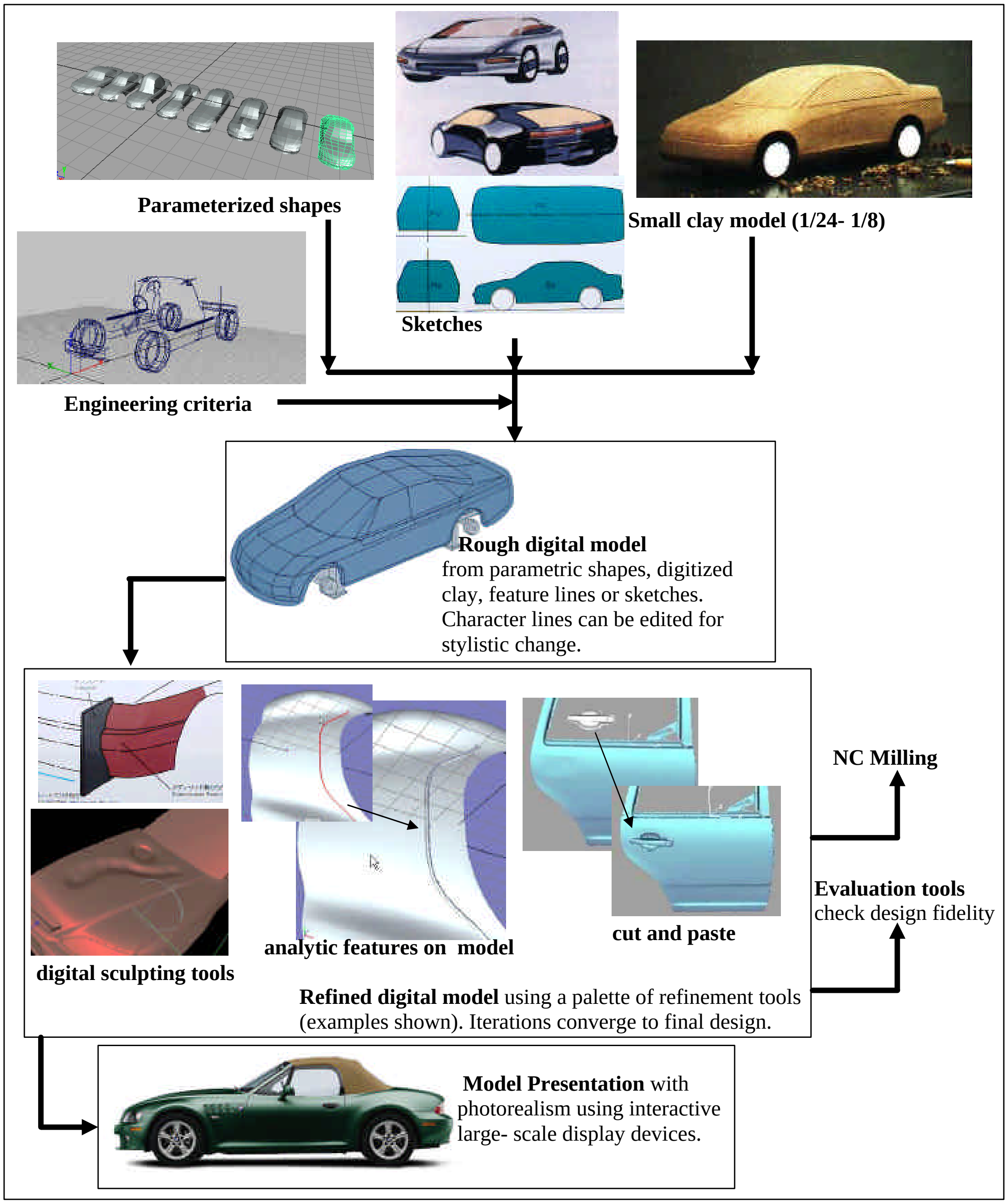


Figure 7: Proposed Automotive Design Workflow

judicious use of user input to help resolve ambiguities in the given input.

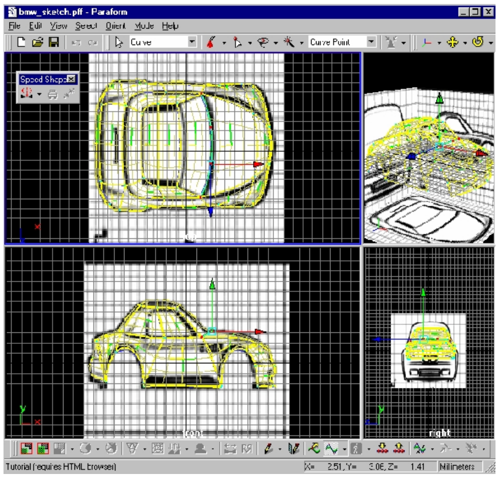

Figure 8: Aligning orthographic sketches into a common 3D space

### 4.2 Model Refinement

Once a rough digital model that has been structured and parameterized with respect to various surface-features and character lines, it is refined and embellished using tools that capture the design desirables of Section 2 and Section 3. A good suite of tools is one that would provide good coverage over the following functionality (see Figure 7):

- Constraint preserving global deformations [Llamas et al. 2003].
- Cut and paste [Biermann et al. 2002].
- Surface-Feature based editing [Sorkine et al. 2004].
- Local deformation and sculpting of object detail [Massie T. H. 1994].

### 4.3 Model Presentation

Design reviews on automobiles typically take place on life-sized displays or physical models built to scale with realistic materials and lighting. Indeed many designers conceptualize models based on the interplay between shape, shadows and highlights [P. Poulin and Frasson 1998]. The importance of this observation is twofold. First, digital modeling techniques should incorporate surface evaluation tools like curvature comb plots (see Figure 9), reflection and zebra maps, and high quality rendering early in the modeling process. Second, techniques that create lighting or edit shape based on the direct manipulation of shadows and highlights [P. Poulin 1997] are worthwhile additions to an automotive designers toolbox.

Once a version of a digital model is approved it is typically used to generate a physical prototype and is also subjected to a number of design and engineering fidelity checks that may result in further iterations of the design cycle.

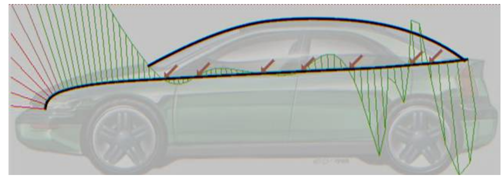

Figure 9: Curvature comb plot showing curvature discontinuities

## 5 Current modeling trends

It is clear that conceptual design in the future will require the co-existence of both physical and digital representations of objects. Physical models are converted to digital models using scanning devices [Curless ] and other data acquisition technology. Manufacturing processes such as milling, injection molding and rapid prototyping machines give physical form to digital models, in materials as varied as metal, synthetic foam and clay. The data acquisition technology and modeling paradigms used, the manufacturing techniques employed and last but not least the industrial application, all critically affect the choice of geometric representation.

### 5.1 Geometric surface representations

There are a number of ways of representing the surface of an object that are in active use in computer graphics today. The important ones are: Point clouds, Polygon meshes, Parametric curve and surface patches, Subdivision surfaces, Analytic shape primitives (cubes, spheres, cylinders for example) with CSG operations and Implicit surfaces (see Figure 10).

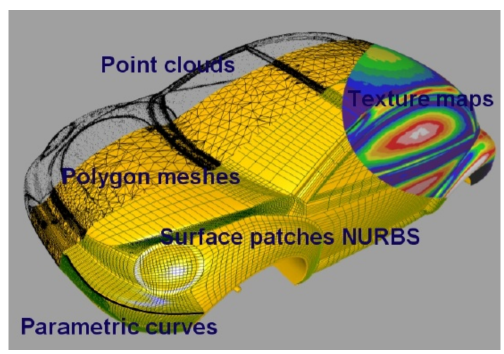


Figure 10: Various geometric representations used in automotive design

Historically, continuous parametric curve and surface patches constructed from piecewise polynomial splines, have been used to represent industrial design objects [Farin 2001]. There were many reasons for this. Cubic and higher order polynomials allow surfaces to be controlled with $C^2$ continuity. The curves and surfaces have an inherent parametric structure and the control point data structure with patch topology is fairly compact. As a result, Non-Uniform Rational B-Splines (NURBS) are an industrial standard today.

A point-cloud [S. Rusinkiewicz 2000], in contrast is a dense point sampling of a surface without any explicit surface elements. A point-cloud where the points are connected by polygon elements to form a surface manifold is called a polygon mesh. Polygon meshes provide a faceted linear approximation to continuous object surfaces. Properties such as surface continuity and a structured parameterization are not inherent but can be imposed externally if the mesh resolution is high enough. The lack of computing power to handle high-resolution polygon meshes made them unsuitable for industrial design applications in the past. Subdivision curves and surfaces have existed since the early 70s [Chaikin ] but have only recently drawn great interest in the computer graphics community as a way of bridging the complementary properties of parametric surfaces and polygon meshes. Subdivision surfaces have $C^2$ discontinuities at extraordinary vertices (vertices with a valence other than 4), making them far more popular in film and gaming applications than as a framework to represent surfaces for industrial design. While analytic shapes like spheres and cylinders are commonly found in various industrial objects, they are too restrictive by themselves as a general framework to represent complex shapes accurately.

Finally, implicit surface is a term that encompasses all objects that are represented mathematically as the solution to an implicit equation of points in a Cartesian space [Bloomenthal 1997]. Implicit surfaces are often built as an algebraic combination of analytic primitives. Implicit surfaces are a very compact, continuous representation and are a popular choice for interactive shape sculpting techniques since they deal automatically with changes in genus and topology of objects. Implicit functions such as radial basis functions (RBF), have also been successful in approximating and fitting a continuous surface model to sparse or irregularly sampled data [J.C. Carr 2001]. The problem with implicit surfaces historically has been the sampling search required to render the surface represented by the implicit function. This lack of an explicit parameterization also makes local morphological operations hard to define computationally. It should be evident from this last paragraph, that no one existing surface representation technique can be considered to be a comprehensive superset of the others in terms of desirable properties for the design of objects.

Recent advances in graphics hardware and computing power have made it possible to render millions of points and triangles in real-time [S. Rusinkiewicz 2000]. As mentioned earlier, many industrial designers prefer to build physical prototypes in a real workshop to quickly resolve shape and form in 3D. These prototypes are transformed to digital models by 3D shape acquisition technology, typically as point clouds of widely varying sampling patterns and densities. These are usually converted into dense polygon meshes [Curless ]. Most continuous surface representations, parametric or implicit are also tessellated to a polygon mesh prior to rendering. Meshes, however, are often unstructured and irregularly sampled and display artifacts such as degenerate, flipped or sliver faces, undesirable holes and widely varying polygon sizes. Further, mesh models often need to be parameterized, segmented and built in parts as an assembly of complex shapes. The chief reason for this is that point clouds and polygon meshes do not directly incorporate the notion of surface-features.

In summary, there is a current trend towards preserving hybrid or multiple representations of shape so as to benefit from the complementary properties of different geometric representation schemes.

### 5.2 Devices for display and interaction

It is evident that the standard keyboard and mouse metaphor falls short in the design domain. Automotive design is a prime example, where design prototypes are close to the actual size of an automobile. Large format displays enable a designer to create, manipulate, and view the design of an automobile at full size. They are currently in active use in automotive design centers, strictly as an interface for design presentation but show promise for collaboration and real-time editing of the design by a team, during design reviews.

For novel displays to be used successfully in the design domain they must work well with input technology that conveys human design intent. Haptic input technology, such as the Phantom (Sensable Tech Inc.) allows us to investigate more effective digital sculpting systems [Massie T. H. 1994]. Consequently, our surface representations need to be able to easily handle rapid changes in curvature and even genus of the sculpted object, as well as represent the internal volume of the object. High degree of freedom input devices such as ShapeTape [Grossman et al. 2003] and a motion capture system [Sheng 2004] can be used to instrument the types of curve and surface physical tools that designers use in the traditional design industry (like the steels car designers use to shape clay) (see Figure 11). Motion-capture and 3D scanning systems can also be used to interactively create and animate digital models of physical objects [Liu 2003].

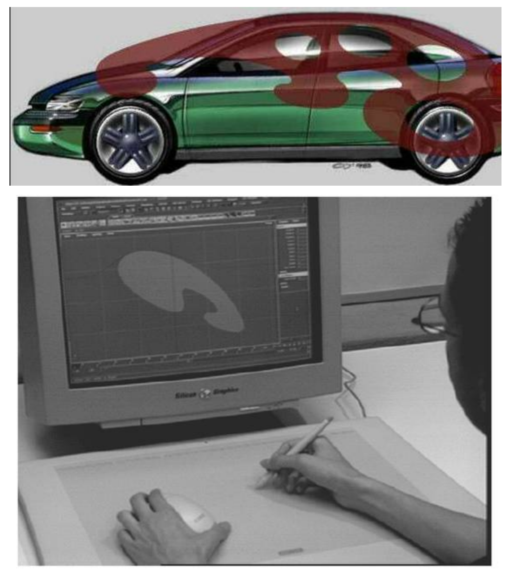

Figure 11: Curve modeling with sweeps [Singh 1999]

In general trends in conceptual shape modeling are moving in the positive direction of decoupling the interaction techniques from the underlying surface representation. Research on surface representation similarly is working towards structures which have the topological flexibility of unstructured data but also capture high level shape concepts of character lines and other surface features.

## 6 Conclusion

In this chapter we have presented industrial motivation for digital conceptual modeling tools. We have illustrated various desirable properties of a conceptual modeller within the automotive design space. We have defined a framework to structure the generally practiced automotive design workflow and touched upon current modeling representations and interfaces within this context. Various chapters in this tutorial further address these issues and propose detailed solutions to the questions raised in this chapter.

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