Development of a flexible augmented prototyping system

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ABSTRACT

In designing physical objects, tangible models play an important part. Recent advances in augmented reality displays show new directions to support this field of prototyping. This paper focuses on the combination of rapid prototyping of physical objects and luminous tangible interfaces: digital imagery is projected on physical models. This yields a number of issues, including the design of the mixed-reality dialogue and the perceived quality of the augmented prototype. A system, called WARP (Workbench for Augmented Rapid Prototyping) is under development; the first implementation employs a turntable supports movement of the object, while a variety of materials and lighting conditions can be applied. Its evaluation yields a number of future issues, including hybrid modeling and optics and location tracking.

Keywords

Augmented Reality, Rapid Prototyping, design process.

1. INTRODUCTION

Tangible Prototypes and scale models play an important role in the design process, e.g. in the field of Industrial Design, in which ergonomic, aesthetic, mechanic, and manufacturing aspects all need consideration. In [Sta99], three common visualization techniques are mentioned for the early stages of design: sketching, modeling, and collage-making. In particular, modeling is said to "probe three-dimensional relations and proportions of certain design solutions". The act of creating such visualizations is as important as its result; often new solutions emerge during this process. In the literature, a number of models are described, including sight models, cardboard mockups, working prototypes, and so on.

Main function of these prototypes is to gain insight in a design and to communicate important aspects of an artifact. A significant advantage of the employment of prototypes is that these are accessible by all stakeholders in the design process –it forces the designer to concretize his or her more or less abstract thoughts and ideas to a concrete representation. Furthermore, prototypes have an integrative character [Smy00]–combining spatial structure with the aspects mentioned above.

A multitude of prototyping methods exist. The traditional method of manual model making can be found in almost all design realms. This strongly depends on the domain, individual approaches, craftsmanship of design teams, and available resources. Two new prototyping approaches have been introduced in the past decades, rapid prototyping and virtual prototyping.

Rapid Prototyping refers to the automatic manufacturing of physical shapes based on a digital model. These techniques have developed rapidly in the last decade. Rapid prototyping can be divided in incremental, decremental and hybrid technologies. In the case of incremental prototyping, the object is being build by adding material in a controlled manner so that a desired shape is formed. Examples are Stereolithography and Selective Laser Sintering. Decremental prototyping starts from a stock of raw material from which material is removed so that the desired object is left. The best know example is automated CNC milling. Hybrid technologies like Laminated Object Manufacturing use a combination, as the layers are cut out of solid material and are then stacked together. These methods enable fast and

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relatively cheap manufacturing of models in a broad range of materials [Cam02]. Its results are hands-on prototypes, which can be used for all kinds of evaluation, including ergonomic and aesthetic. Rapid Prototyping extends the advantages of traditional physical prototyping by ensuring an accurate correspondence between the artifact specification (in a CAD model) and its "hardcopy", and allows (semi) automatic manufacturing of the prototypes.

In recent years, powerful computer aided design engineering tools have been introduced that allow so-called Virtual Prototypes: digital displays of the product in a simulated environment, offering various evaluation and modification means. A vast range of activities can be performed with the model, enabling improved analysis, and communication. Furthermore, it establishes a tight relationship between modeling and simulating, as the prototyping results are easily propagated into product changes.

2. PROBLEM STATEMENT

Artifact Prototyping

Both methods described above have a number of limitations. The first is expensive (both in time and/or cost) and typically requires a lot of manual finishing after manufacturing. Furthermore, it results in a static, monochrome shape made in a single material, that typically does not allow modification. Furthermore, it cannot simulate interactive behavior – which is quite eminent in consumer products. The second, Virtual Prototyping, deprives the sense of tangibility and human scale, an aspect that plays an important role in product design. Through the lack of a physical existence, it also makes it very difficult to experience the product's scale and its relationship to its physical context.

In the literature, rapid prototyping methods are usually compared by cost, production time, and quality. As a designer's tool, quality cannot be directly translated to the sense of realism or physical accuracy. The prototypes are considered to act as a tool in the reflective dialogue between designer and artifact [Sch94]. This subjective, context-dependent aspect is difficult to assess. The sense of engagement [Lau89] seems to play an important role in creation and evaluation of prototypes [Smy00].

In short, the current threshold to create prototypes that provide a rich sense of engagement is high. These limitations severely influence the act of design, as concrete, integrated representations of the artifact play an important role in communication and conceptualization.

Related Research

In combining the potential of both Rapid Prototyping and Virtual Prototyping, research on tangible computing and mixed reality requires consideration. William Buxton and George Fritzmaurice denote a detailed analysis of the limitations of traditional interaction devices and the possibility to extend the dialogue with tangible interfaces [Fri95][Bux99]. Key technologies of tangible systems have been summarized in Table 1. At least four related projects are worth mentioning in our context: URP, Illuminating Clay, Dynamic Shader Lamps and Projection-based Augmented Engineering.

URP [Und99] is an urban planning system, in which skyscrapers are represented by physical wireframe

System	Tracking	Projection	Objects
Programmable bricks Toronto [Fri95]	Wacom tablets	Top projection	Generic (programmable) bricks, special tools
Graspable Real Reality User Interface [Bru96]	Glove	Traditional display	Specialized
Zowie's garden [Ver99]	Radio frequency (up to 60 objects)	Traditional display	Special objects (action figures)
SenseTable [Pat01]	Wacom Tablets (extended)	Top and side projection	Pucks with dials
Dynamic Shader Lamps [Ban02]	Polhemus 3D trackers	Two projections on object.	House (as painting canvas) and paint brush stylus
Illuminating Clay [Pip02]	3D laser scanner	Top projection	Reinforced Clay slab

Table 1. Existing techniques for Tangible Computing

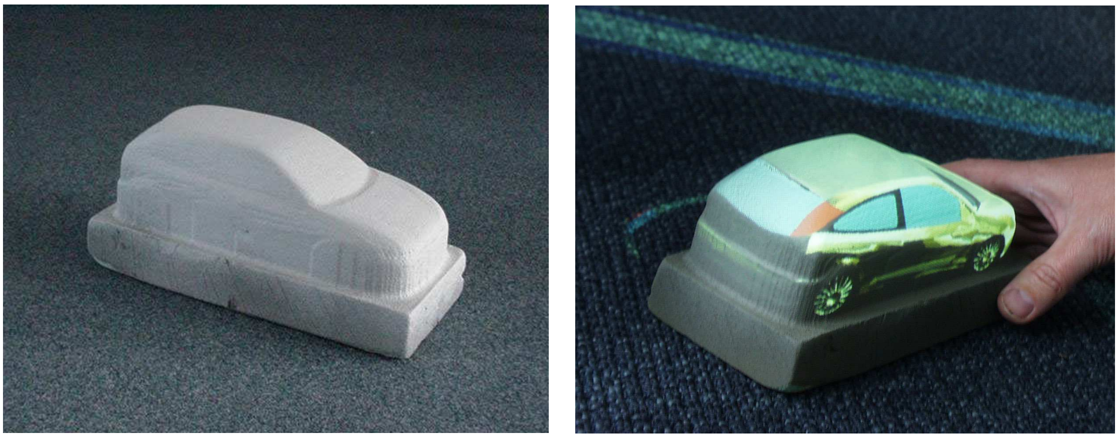


Figure 1. Typical foam model of a car (left) augmented by projection (right)

models, which can be moved freely on a table. A camera-based position tracking system reads the position/orientation of the models to a simulation module, which calculates a number of aspects of importance to city planning (wind turbulence, shadow/sun reflection).

Illuminating Clay [Pip02] describes a system that continuously monitors a slab of clay with a 3D laser scanner (scan rate: approx 1.0 Hz). A beamer projects various images on the clay surface and its surroundings, allowing a number of landscape analyses.

Shader Lamps [Ras01a] in the dissertation of Raskar and consecutive publications, systems are presented that project directly on physical models. As a part of "spatially augmented reality", the basic light model and illumination issues when multiple beamers are employed are presented in Raskar and Low [Ras01b]. An important observation is that the casting of an image on a physical object is complementary to constructing a perspective image from a virtual object by a pinhole camera. As such, no special algorithms are required to pre- distort the computer image, a simple transformation matrix is sufficient. Bandyopadhyay et al. [Ban01] extend the concept of shader lamps with dynamic tracking and interactive painting.

A similar line of research has been proposed by Bimber et al. [Bim01] at the Fraunhofer institute in Germany. In their Projection-based Augmented Engineering concept, a RP made model is tracked and a digital image is projected on a half-silvered mirror plate that is fixed between the viewer and model. This plate can be tilted and also used as a whiteboard (allowing sketching in the 3D scene).

Although these projects clearly indicate a promising avenue in computer aided design, the augmentation of physical prototyping hasn't been explored in the context of design. Furthermore, the systems are proprietary and are difficult in testing several interaction techniques and models.

3. Augmented Prototyping

In this paper, we introduce the concept of augmented prototyping (AP); by using the principle of Shader Lamps, digital images are projected on objects, which have been manufactured by rapid prototyping techniques. As Figure 1 illustrates, this type of augmentation offers a dynamic display for materials, local features, and other information. In contrast to [Bim01], the employment of direct projections offers a tangible and social interface [Dou01] Our aim is to develop an augmented prototyping method that allows a tradeoff in geometric accuracy between physical and virtual models, enables to express material properties and local features, and to place it in a context for evaluation. This platform should offer an accessible test bed for both research and education, focused on the early phase of design in which the speed of creating an impression of the product is important. For identification purposes, we call the system WARP (Workbench for Augmented Rapid Prototyping).

Of course, this production method will have limited use. First, it is depending on existing rapid prototyping methods (introducing constraints in maximum volume and manufacturing speed). Second, occlusion and shadows that are cast on the surface by the user or other parts of the system. Theoretically, the problem to illuminate all visible surfaces is treated in [Stu99]. Convex objects are can be easily illuminated, others strongly depend on granularity.

WARP Architecture

The WARP architecture considers the "prototyping pipeline", i.e. the production flow of the prototype. It encompasses both software and hardware, the basic workflow is presented in Figure 2. Here, we can distinguish the original (digital) model, a generation

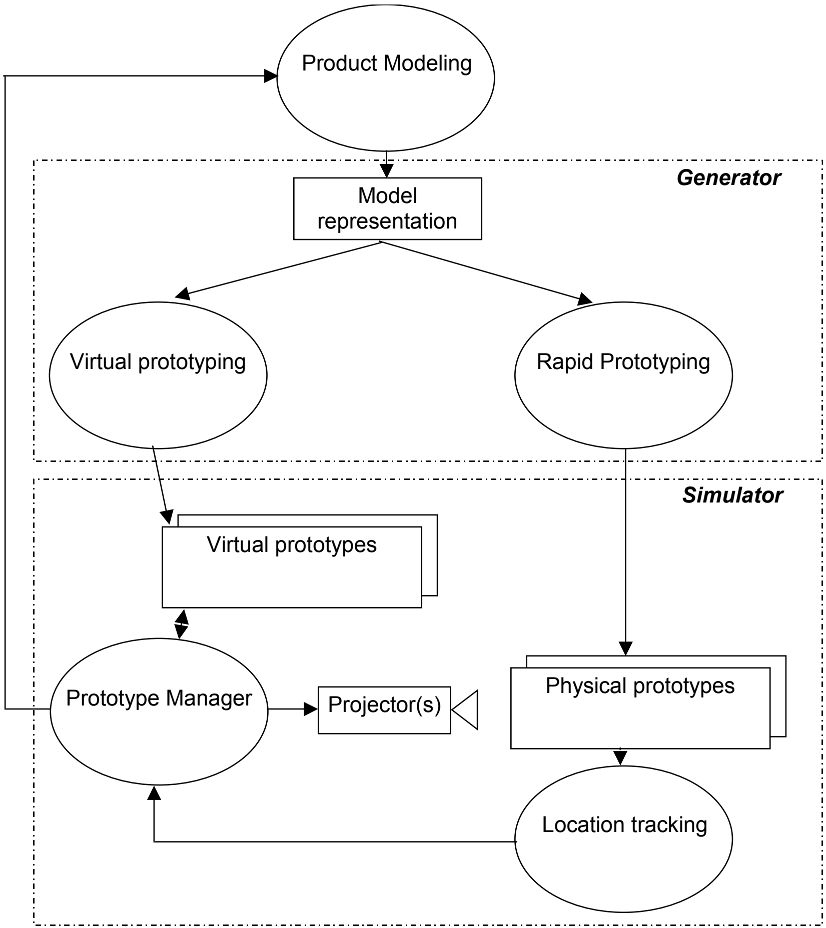


Figure 2. Proposed workflow of the WARP system

phase that takes care of conversions and manufacturing of physical components, and a simulation phase, in which the augmented prototype is actually put in use.

In the generation phase, rapid (physical) prototyping includes the provisions for selecting shape orientation and model segmentation. Most existing techniques support standard geometry formats (e.g. the STL file format). For the virtual counterpart, processing might be required to identify local features, to map colors and materials, and to add dynamic properties to the model for simulations.

Main focus of this paper will be the simulator phase. As already mentioned in Table 1, a large number of possibilities exist to track the position of the physical prototype. The WARP system should be able to support a multitude of those. Other interaction techniques, such as a stylus, a 3D mouse pointer, and speech-based interfaces should also be considered.

In the simulator module, the Prototype Manager plays an important role. A first concept is depicted in Figure 3. The AP Dialogue Management System represents the core of the software system, which has the responsibility to initiate/calibrate the hardware, to process the input and control modifications in simulation/modeling environments. Depending on domain and possibly on a particular design, a collection of simulation applications might be applicable. A standard interface has yet to be developed to enable communication between these and the dialogue management system, and to propagate the changes of the model representation. For the latter, a separate module maintains the product specification, expanded by meta information on the design process, communication and

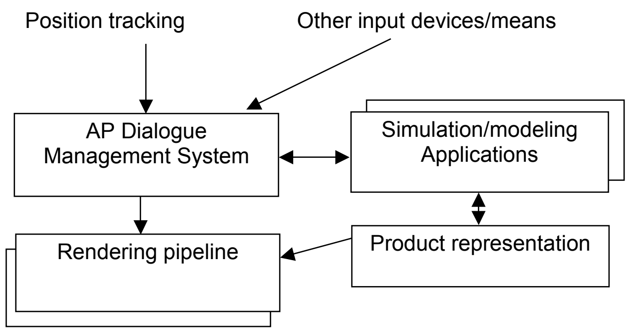


Figure 3. The Prototype Manager architecture.

interaction steps. It also controls conversion algorithms necessary to produce the physical parts. The rendering pipeline combines the 3D view with other elements of the dialogue, possibly displaying state, progress, and review comments. As a single projection cannot illuminate the whole model (unless semi-transparent or specialized display means are used), a collection of beamers could be employed, all with a separate rendering pipeline but sharing the same dialogue management system.

The WARP architecture should also support the iterative character of design: propagating decisions and alterations of the augmented prototype to the product model.

4. Pilot

As a first generation of the WARP system, we decided to focus on supporting a design review context. In this setting, the effect of exploring material and color properties of a fixed global shape seemed most appealing to start with. A turntable is used to orient the physical model (1 degree of freedom), while the traditional computer mouse is used to alter the virtual model.

As an example, we selected a model of a ford focus. The physical scale model was manufactured made by a 3-axis milling machine from Polyurethane foam (dimensions approximately 10x22x10 cm). This physical model was manufactured in about one hour. In the virtual model, 3 components can be selected to alter material properties (car body, wheels, wheel frames).

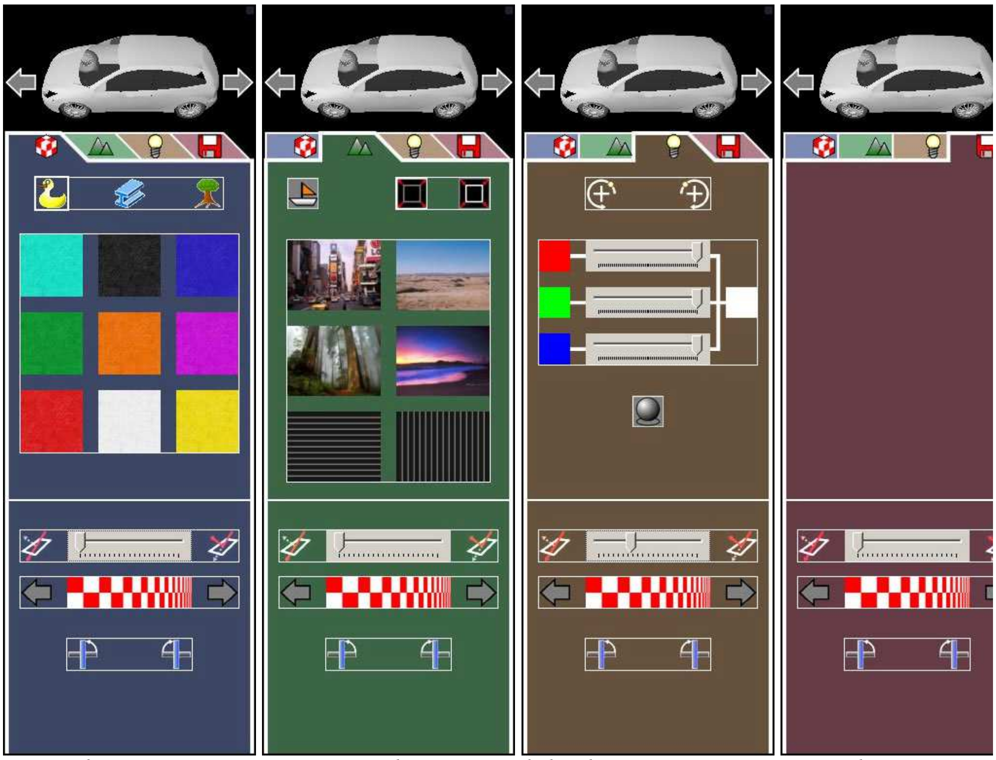
Dialogue

Developing a dialogue for setting such properties was not straightforward; the mixed-reality setup does allow direct access to the physical object, but its virtual counterpart requires interaction techniques that co-exist with this physical realm. Our first system supports simple tab-sheets, shown in Figure 4, the following functional areas have been identified:

Component selector: the object consists of a number of components, each can differ in material properties.

Material: palettes of materials are shown, grouped in three categories (plastics, metals, and woods). Each material corresponds to a bitmap for texture mapping and a reflectivity index.

Environment: a number of scenes are displayed as thumbnails, which can be selected to be used a reflection maps and/or backdrops. In addition to a number of standard environment bitmaps, white lines on a black background were included in 2 directions. These could be used as a Zebra Striping effect to inspect the continuity of the car surface.



texture-tab *environment-tab* *light-tab* *preset-tab*

Figure 4. Dialogue elements of WARP version 1.

Lighting: spotlight position and colors can be adapted. The user can activate a shadow drop (only visible when backdrops are used).

Presets: offers the possibility to store and retrieve material/lighting setting for exploring alternatives.

The employment of tab-sheets significantly simplified the AP dialogue management, as most simulation settings were directly mapped. However, this might not be optimal in use. Our implementation platform should cater for fast alterations of the dialogue.

Implementation

The first implementation of WARP was developed in Macromedia Director [Mac]. In its latest version, this multimedia authoring software also supports the visualization of and interaction with 3D models. As the behavior is defined by simple scripting and supports 2D overlaying on the 3D visualization, it serves as a powerful tool to explore a number of dialogue types for augmented prototyping.

For tracking the orientation, we built a wooden turntable. The angle is read by a simple encoder (a disassembled computer mouse). As two mice cannot be connected to a single computer, another PC is dedicated for capturing the orientation, which is sent to another PC that runs the prototype manager (see Figure 5).

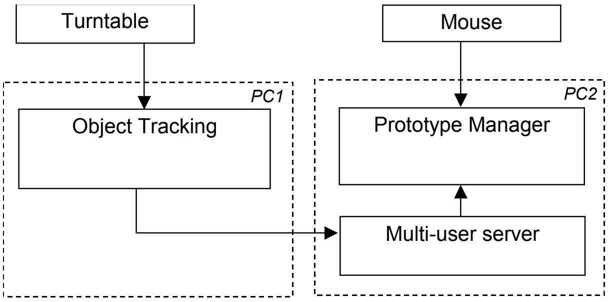


Figure 5. Network configuration.

Instead of using a top-projection, we mounted the beamer in a 45-degree angle off the vertical axis. From the point of view of a standing or sitting user, this allows illumination of a large area of the model. The material dialogue was projected on a wooden board, adjacent to the turntable (see Figure 6).

When there is a direct correspondence between virtual object and physical surface, the projector can be treated as the inverse of a pinhole camera [Ras01b]. This reduces the complexity of the required pre-distortion to a simple projection matrix, which is derived from the beamer parameters. In order to merge the virtual and physical models, a

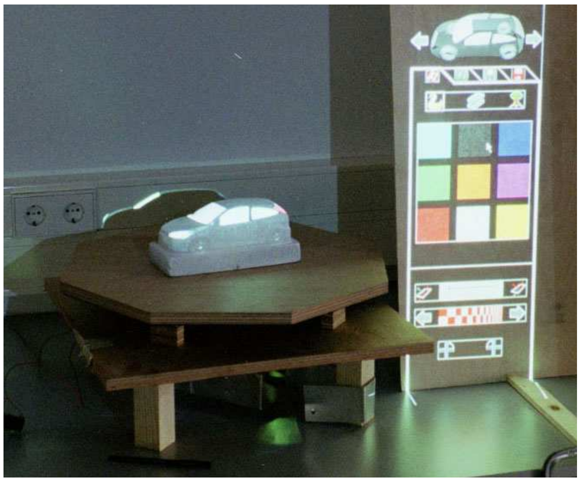


Figure 6. System setup, with turntable (left) and material dialogue (right)

calibration facility was developed that allows manual modification of the location of the projection viewport (x and y), camera distance (to the object's origin), camera-angle, field of view (perspective) and the rotation of the virtual model. Although this manual calibration required a considerable amount of time (especially the camera distance and its field of view), this has to be performed only once, as settings could be stored for later use.

Another important aspect of the calibration process was to place physical object correctly on the turntable, with its origin set on the center of rotation. An outline of the car was sketched on the table surface to assist this alignment.

In practice, the projection fitted almost perfectly; sometimes a 2-3 pixel displacement could be noticed behind the object. In terms of focus, the projection gave no difficulties. However, as the distance between projector and object was considerate, the resolution of the projection is small. Figure 7 shows a close-up of the projected model, in which the scan lines and pixels are clearly noticeable.

5. RESULTS

The implemented system was evaluated by a small subject group with a design background, 4 senior industrial design students and 2 staff members. Of the six, 3 have experience with 3D modeling software (Wavefront Maya, Solidworks), while none has used Rapid Prototyping techniques. After a short introduction, each was asked to reconstruct a 6 of pre-rendered images. These images were revealed in a handout ordered in increasing difficulty. These assignments involved setting material, reflection, and light properties as well as physical positioning of the prototype. Subjects had to verbally indicate when they were ready, a screenshot of their projection was

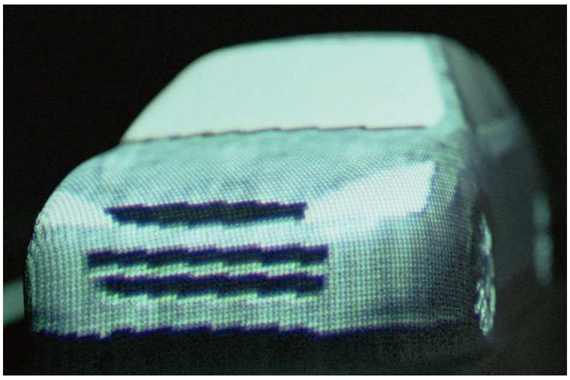


Figure 7. Close up of the projected model.

saved. This allowed the similarity of the assigned image and result to vary among the tests, which was judged afterwards by the observers. Furthermore, their behavior was monitored during the process and videotaped.

Although this test does not directly contribute to the main hypothesis of this research (i.e. the added value of augmented prototyping in design), we consider the familiarity of the interface and the illuminated physical model as an important aspect of the sense of engagement.

All participants could immediately operate the turntable. Although situations occurred in which subjects themselves cast shadows on the model, the hardware configuration did not create difficulties in use. However, the material dialogue required some guidance, not all subjects could predict which parameters could be set in a particular tab sheet. The selection of the product part (by using the arrow buttons above the tab sheets) had to be introduced and demonstrated before the users felt familiar with the interface.

A striking aspect was that the subjects with no 3D modeling experience took much longer to finish the tests (average 37 minutes compared to 18 minutes for those with experience). We hypothesize that this occurred due to the fact that operationalising the assignments requires basic conceptual knowledge on computer graphics and rendering, e.g. the interaction between spotlight colors and material settings, reflection maps, and texture scaling.

A questionnaire was used to capture some subjective aspects of the experience. All indicated that they understood and appreciated the augmented prototyping system. Students with 3D modeling experience indicated that they could not foresee working with this technology in practice – they preferred conventional modeling and visualization techniques. This opinion might be based on the lack of experience with Rapid Prototyping. Another explanation might be that the displayed functionality - modification of materials and colors – is often a minor aspect of the design process. They indicated that the system did not offer all kinematical degrees of freedom as a traditional modeling system. Others indicate that they would like to alter the artifact's geometry while using this system.

Some had critical views on the dialogue, especially on the employment of a traditional computer mouse and of icons used to indicate the tab sheets. A lot of improvements were suggested, for example to use 3D trackers and to include textual labels near the icons in the dialogue.

6. CONCLUSIONS AND FUTURE RESEARCH

In a relatively short time, an augmented prototyping system has been built. It uses a 3-axis milling facility that produces polyurethane models; these are put on a turntable to track orientation, a projector beams a 3D virtual model on the physical object. The employed technologies support rapid changes in the dialogue and visualization capabilities. This results in a platform that can be used to test a broad range of interface techniques and simulations.

Although the present interface is quite limited – only a single degree of freedom turntable and a traditional computer mouse are used as input means - it is our impression that it already offers a large sense of engagement at a low cost. Future versions of the WARP platform will support better tracking technologies and more (virtual) simulation means, providing an embedded interaction [Dou01]

In considering the prototyping constraints mentioned in Chapter 3, the design of many consumer products would be supported by this prototyping method. At present, it will be used by Industrial Design students in their curriculum as well as in research.

Future issues

Although we assume augmented prototyping has a large potential within the field of industrial design, a number of issues remain uncovered. Main concern is the determination of the added value of such prototyping means. We assume that the sense of engagement is a strong indicator, yet it is not entirely clear how this can be measured objectively. Bochenek et al. [Boc01] provide interesting assessment of prototyping means during design reviews, using metrics as the number of design errors found, the time to track errors down, and the time to create solutions for these.

Hybrid modeling

As Augmented prototyping combines a physical object with a projected image, new techniques have to be developed to generate those from an initial representation. Furthermore, by employing this hybrid modeling technique, tradeoffs can be made between the level of detail of the physical prototype and the projection. Apart from theories from geometric modeling and prototyping, this also needs consideration of human perception theory.

Optics and location tracking

In successfully merging the digital projection with the real object, a number of technologies have to be employed and extended. Much in line of the Shader Lamps theory developed by Raskar, the following issues need consideration: scene graph representation, rendering pipeline, projector optics, (multiple) object tracking. Special care has to be given to the calibration of real-world coordinate system and the virtual, in combination with the projector parameters. Furthermore, the alignment of the physical objects with the tracking technology is requires attention. Special features (e.g. holes) could be inserted in the physical model to assure this. In explorative experiments, the lag time (delay) is found to be a crucial factor in its use; slow update rates of position changes seem easily break the illusion. Furthermore, viewer-independent solutions are preferred, as these allow a group of people to unobtrusively experience and interact with the prototype.

7. ACKNOWLEDGMENTS

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