AUGMENTED FOAM: TOUCHABLE AND GRASPABLE AUGMENTED REALITY FOR PRODUCT DESIGN SIMULATION

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Abstract: Computer Aided Design (CAD) applications have become designers' inevitable tools for expressing and simulating innovative ideas and concepts. However, replacing traditional materials and mock-ups with 3D CAD systems, designers are faced with the intangibility problem. As a touchable and graspable interface based on 3D CAD data, we proposed Augmented Foam, which combined Augmented Reality technologies and physical blue foam with little additional effort. Using Augmented Foam, blue foam mock-up is overlaid by a 3D virtual object, which is rendered with same CAD model used for mock-up production. In order to solve the visibility problem between the reviewer's hand and the virtual object, we implemented a hand detection and separation. Augmented Foam was tested for a cleaning robot design. Twenty participants were asked to evaluate the perceived visual reality of product appearances for 6 design simulation techniques including Augmented Foam. We found that the participants perceive the shape, size, and color of product appearance more accurately than renderings on CRT, traditional Augmented Reality, and a foam mock-up.

Key words: 3D CAD System, Design Simulation, Augmented Reality, Physical Interaction, Skin Detection

1. Introduction

With advances in Computer Graphics and Geometric Modeling technologies, CAD tools have been rapidly distributed since 1990's to become designers' inevitable means for expressing and simulating innovative ideas and concepts. As a consequence, traditional processes are being replaced by 3D CAD systems in making thumbnail sketches, soft study models, control drawings, hard mock-ups, etc. As information unit of design tools has been transformed from atom to bit, performance of designers has been greatly improved; most design tasks are now impossible without CAD tools. However, as the environment transforms from physical world to virtual world, designers are faced with emerging intangibility problems. To address these issues, we investigate the possibility of new product design simulation technique based on augmented reality (AR).

1.1. Intangibility Problem in Traditional 3D CAD Systems

In the early ages of product design, designers used to sketch ideas in 2D or 3D forms with various wieldy materials such as paper, pencils, markers, plaster, clay, wood, and polymer foams. Now, replaced by computer-based CAD systems, designers are faced with the intangibility problem. As realistic as it can be, the rendering results on monitors cannot provide realistic tactile feelings of design models as can foam models or other physical prototypes. Furthermore, unlike 2-dimesional scale renderings and 3-diensional physical mock-ups, 2.5-dimensional perspective drawings have lost a cue for the perception of absolute size (Fig. 1). For these reasons, inexperienced designers often incorrectly estimate the results of 3D CAD design, repeating mistakes.

To solve the intangibility problem, Rapid Prototyping (RP) technologies such as SL (Stereo Lithography), SLS (Selective Laser Sintering), LOM (Laminated Object Manufacturing), 3D printing, and FDM (Fused Deposition...
Modeling) have been developed to be used with 3D CAD systems[1]. However, rapid prototyping has some limitations to be used in early stages of industrial design process. Firstly, due to requirements of expense and labor, designers cannot easily test and develop ideas through iterative design-evaluation process. Secondly, because hard materials are used for rapid prototyping, design products are not easily modifiable as are form mock-ups (e.g., polystyrene foam, polyurethane foam). Thirdly, rapid prototypes are difficult to represent material properties such as colors and textures. For these reasons, most designers experience trial and errors during the product development processes with 3D CAD systems.

1.2. Augmented Foam: Incorporating Tangible Interaction with 3D CAD Model

Human tends to explore the surface of an object and comprehend realistic feelings of the size, volume, and roughness of the object through active touch [2]. At the design alternative evaluation stage, designers investigate objects by meticulously touching and sensing them, because visual information itself is insufficient. To provide sufficient information to the designers, an improved design tool should allow for tactile (tangible) information, while maintaining the strengths of convenient 3D CAD systems.

We propose the application of Augmented Reality technologies, which can be used to synthesize the real and the virtual objects. With blue foam, which is a designer’s favorite material for soft mock-up, AR may provide tangibility to a 3D CAD model. Blue foam made of polyurethane is inexpensive, easy to cut, and can be produced by CNC (Computer Numerical Control) in a short amount of time. In many design studios, CNC-produced blue foams are used to test design results of 3D CAD models. In this paper, we introduce touchable and graspable interface, where blue foam mock-up is overlaid by 3D virtual models using AR technologies. We call this interface Augmented Foam.

1.3. Visibility Problem in Augmented Foam

The biggest challenge of implementing Augmented Foam is the visibility problem: the visibility between the real environment and the virtual models are difficult to be correctly displayed. For example, when a designer touches a blue foam mock-up, virtual object that overlays the blue foam also overlays the designer’s hand, and hence the designer’s hand on the foam becomes occluded. In this case, the conflict between the visual and tactile information debases the designer’s feeling of immersion. Because the interaction is carried out with designer’s hands and foam mock-up, we focused on the occlusion problem between the virtual object and user’s hand in Augmented Environments.

In this paper, we proposed a new product design simulation technique using AR technologies to overlay

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Fig. 1 Change of product design process by introducing 3D CAD system
virtual models on a widely used material, blue foam. The visibility problem between the virtual model and the user's hand is solved by robust detection of the hand regions. With correct visibility, the proposed Augmented Foam provides integrated interface of visibility and tangibility.

2. Related Work

AR, providing magical feeling of immersion, has been one of the most attractive research topics in the human computer interaction and computer graphics field since early 1990's [18]. Thanks to advances in hardware devices, tracking technologies, and display technologies, AR implementations are available on commercial off-the-shelf desktop and notebook computer systems. AR has been employed in various application areas, one of which is design for new product development.

2.1. Augmented Reality Applications of Design Work

AR, as an interaction tool between users and the computer systems, has been used for collaborative design applications [3-6]. Ahlers et al. [3] and Schumann et al. [4] proposed the use of AR technologies to support remote collaboration in performing tasks such as equipment placement. AR technologies have also been used for collaborative design tasks in collocated situations [5, 6]: MagicMeeting system [5] was developed to evaluate design results of automobiles; BUILT-IT system [6] was used for cooperative urban planning. In Fata Morgana project [7], designers were able to walk around a newly designed virtual car for inspection and comparisons with others.

AR application examples of design work developed up to present are limited to large-scale objects that the designers were not able to grasp and move. In these examples, the information provided was limited to visual information, lacking physical interactions between the observer and the object. In many product design processes, physical interaction and tactile information are advantageous, even critical.

2.2. Virtual Overlay Techniques on Physical Prototype

In some previous researches, virtual models were overlaid on physical objects in order to provide realistic material experience. Shader Lamps were used to project inherent material properties (colors, textures, etc.) in order to reproduce realistic appearance of the original object [8]. Projectors were used to illuminate on white-colored neutral objects.

Hinckley et al. utilized physical props as a passive-haptic interface in Virtual Environments [20]. However, there were spatial discrepancy between visual interface and haptic interface. Low et al. also allowed for passive-haptic interface for projector-based dioramas [21]. Projectors illuminated on the display surfaces of a synthetic room created using Styrofoam blocks.

Augmented Prototyping used the RP and AR technologies to improve product development process by combining physical and virtual prototyping [9]. Using AR, the colors and textures were overlaid on the parts produced by RP. Designers used HMD's to review the 3D CAD products provided with visual reality and tactile feedback.

Among the previous work, Augmented Prototyping is similar to Augmented Foam in concepts and employed technologies. However, Augmented Foam uses CNC-produced foam mock-up, which is available in the early design stages as well as for reviews. Augmented Foam also resolved the visibility problem of the user's hand with the virtual products to allow for active haptic interactions between the designer and the object with corrected visibility.

2.3. Hand Occlusion Problems in Virtual/Augmented Environments

Hand and/or finger detection contributed to interaction with 3D Virtual or Augmented Environments. Wu et al. implemented user’s finger tracking using a single camera for a virtual 3D blackboard application. Skin region was detected using color predicate, which is a histogram-like structure [13]. However, the detected skin region seemed to be coarse, which might be enough for finger position determination. In our application, the goal was to correctly display skin region, and hence elaborate detection was required. Malik et al. proposed a method for detecting a hand over top of the pattern to render the hand over the top of the virtual object in an AR implementation [12]. They used a simple image subtraction method, fixing the camera pose. Their method is not applicable to Augmented Foam where the camera, the foam mock-up, and user’s hand may change their poses in real-time.

![Fig.2 The Concept of Augmented Foam](image-url)
3. Key Concepts of Augmented Foam

3.1. Physical Interaction with Virtual 3D CAD Model

Augmented Foam allows for physical interactions between the designer and the virtual 3D CAD models. A blue foam mock-up can be produced by CNC based on a 3D CAD model. Using AR technologies, the same CAD model can be overlaid on the mock-up, resulting in Augmented Foam (Fig. 2). The Augmented Foam is now a touchable and graspable AR instance. Augmented Foam is differentiated from other AR implementations in that it allows for haptic presence to the users through physical interactions (Fig. 3a). Augmented Foam also support for natural visual presence through shadows and reflectance in the real environment (Fig. 3b).

3.2 Interactive Simulation of Product Appearance Attributes

Because the surfaces of traditional foam mock-ups are rough and difficult to represent material properties, they were mainly used for evaluating size and volume of design alternatives. In Augmented Foam, the colors and textures of the object can be easily modified, and detailed shapes can be expressed through programs. In addition, designers may change the size and position of detail design such as decorative textures and buttons to find optimal parameters interactively.

3.3. Making Rapid & High-fidelity Interactive Prototype for User Testing

Recently, the appearances and user interfaces are designed concurrently in product development. The appearance and user interface are mutually dependent, and hence require thorough user test during design process. Currently, designers generally use quick & dirty prototypes such as paper mock-up or virtual prototype in the early design stages to evaluate the results [10]. The results of product appearance design are hardly reflected to user interface design due to limited project schedule. Augmented Foam can be easily integrated with user interface design prototype to make a rapid & high-fidelity interactive prototype allowing for realistic and practical user tests (Fig. 4).

4. Solution for Hand Occlusion Problem

To detect user’s hand from a real environment image, the skin regions need to be identified from the background. To be less affected by illumination conditions, HSV color space is often used instead of RGB color space. However, color space transformation doesn’t seem to make noticeable difference in skin color detection [16]. Comparisons of RGB value combinations have demonstrated no worse results than other methods in skin region detection [15]. Wark et al. exploited that simple thresholding method with R/G ratio detected skin-like colors effectively [17]. We have tested several previous methods of skin color detection to empirically find a method with desired performance. In our implementation, we employed a method similar to that of Peer et al. [14]. Our skin region detection algorithm is summarized in the following.

\[ R > 95 \text{ and } G > 40 \text{ and } B > 20 \text{ and } \\
R > G + 15 \text{ and } R > B + 15 \]

In many situations, detected skin region boundaries were rough, causing negative visual effects. To smooth boundary regions, we performed edge-detection convolutions (horizontal / vertical / diagonal) to detect boundary regions and applied a smoothing filter along the boundary.

5. Implementation of Augmented Foam

5.1. Making Foam Mock-up from 3D CAD Data

Augmented Foam was designed to construct a physical foam mock-up from a 3D CAD data and overlay the 3D
model of the same data on the mock-up. In our implementation, object models were constructed using Rhinoceros 3.0 (Fig. 5 left), then converted to STL format. Foam mock-ups were produced by CNC from blue polyurethane foam (Fig. 5 middle). CNC-produced foam mock-ups were painted in dark blue to simplify skin-color detection. Lastly, an artificial marker was installed on the mock-up for visual tracking (Fig. 5 right).

5.2. System Configuration for Augmented Foam

An artificial visual marker was used to register virtual objects on the foam mock-up. For visual marker tracking, which is required for virtual object overlay, we used ARToolKit2.65 library [11]. For video capture and display, a Firewire web camera (iBOT) delivering 640x480 pixels at 30 Hz and a video see-through HMD of SVGA-resolution (DH-4400VPD) were used respectively. A desktop PC with a GeForce™ graphic card was used to capture real video images and to compose AR images (Fig. 6). We measured the graphics performance by rendering an object with more than 70,000 triangles. The frame rate was about 14.5 frames per second in the case of Augmented Foam with skin detection algorithm.

5.3. Integration of Physical Foam and Virtual Overlay

CAD data of STL format (same format that was used for CNC production) was also used for virtual overlay. Due to visibility problem, general-purpose AR technologies cannot be used for physical interactions with real/virtual objects. In our research, the hand regions were separated from the background using skin-detection algorithm. As a result, designers were able to touch and grasp the virtually overlaid object without visual interferences.

The difference of general-purpose AR and Augmented Foam is demonstrated in product design simulation processes (Fig. 7). In most AR implementations, such as ARToolKit examples, plane markers are used without a mock-up, and hence the virtual objects (mug and its grasp) are not touchable (Fig. 7 a1–a3). As can be seen in Fig. 7-a3, the virtual object has floating effect, isolated from the real environment, for lacking shadow effect, etc. As a contrast, Augmented Foam enhances visual presence by providing shadows and reflections (Fig. 7-b3).

Augmented Foam with hand visibility correction
Fig. 7 General-purpose AR (a1–a3) and Augmented Foam (b1–b6): (a1) Plane marker (a2) Virtual overlay on a plane marker (a3) Virtual overlay on a table, (b1) Augmented Foam without virtual overlay, (b2) Augmented Foam with virtual overlay (visibility problem), (b3) Augmented Foam on a table, (b4–b6) Augmented Foam with corrected hand visibility (various color cups)

demonstrates noticeable enhancement in visual presence. In Fig. 7-b2, the reviewer’s hand is occluded by the virtual overlay of the mug object, while in Fig. 7-b5, the hand and the virtual object are seamlessly synthesized. With corrected hand visibility, the designers are provided with enhanced visual presence while exploring, touching, and grasping the product. As in Fig. 7 b4 and b6, various aesthetic perceptions can be simulated by changing product properties and grasping postures.

6. Application to Design Work and Evaluation

Augmented Foam has been used for appearance and user interface design test of a cleaning robot model. Simulations of design alternatives have been performed in order to identify problems and make updates. As a result, observations for 5 product designers (32.5 years of age in average, four males and one female) were made, which was focused on how the designers interacted with Augmented Foam. Firstly, Augmented Foam provided the basis for evaluating the positions and sizes of the control panels of the cleaning robots, which was not available in traditional CAD or general-purpose AR systems. Secondly, different from foam mock-ups, Augmented Foam allowed for rapidly replacing and comparing other design alternatives of control panel to find the strength and weakness of each alternative (the left two figures in Fig. 8). Interactive Augmented Foam, integrated with user interface design prototype, enhanced realities that virtual prototype could not provide by itself. More than anything else, Augmented Foam provided spatial interaction between the designers and the products: designers were able to thoroughly test user behaviors of touching and controlling the products (the right two figures in Fig. 8).

Including the above qualitative observation, we evaluated the utility of Augmented Foam with resolving hand occlusion problem (AFS, Figure7-b5) by comparing the user feedbacks from other design simulation techniques focusing on observing product appearance in a quantitative way. The techniques compared with AFS are CAD (renderings displayed on CRT), AR (traditional Augmented Reality, Figure7-a2), AF (Augmented Foam without resolving hand occlusion problem, Figure7-b2), and FM (foam mock-up). These 6 techniques are relatively much cheaper and less time-consuming than hard mock-up that many designers have made generally for design simulation and evaluation.

AR enables designers to observe the models of design results in the real world with ease but does not provide haptic interactions with them. AF can provide haptic interactions by adopting physical foam mock-up but provoke inter-sensory discrepancy on account of hand occlusion problem.
Fig. 8 A high-fidelity interactive prototype for designing a floor-cleaning robot: (left) Augmented Foam with virtual overlays on a foam mock-up, (right) Interactive Augmented Foam integrated with user interface design prototype: can be practically manipulated.

We recruited 20 participants aged between 23 and 29. All of them are industrial design graduate students and have sufficient experiences of using 3D CAD systems for design works. Half of them were males (mean 26.2yrs) and the others females (mean 25.1yrs). Each participant was asked to observe the appearance of the above-mentioned cleaning robot model presented through 6 different design simulation techniques within 5 minutes and evaluate the perceived visual reality of product appearance with several criteria, such as shape, size, and color. We conducted a within-subject experiment counterbalanced for order of presentation and asked the participants to rate the visual reality of product appearance on a 7-point scale. Table 1 demonstrates the mean ratings for each design simulation technique and evaluation criterion and figure 8 shows the overall differences between them. And, the participants were asked to complete a wrap-up questionnaire. The questionnaire consisted of 3 questions about advantages, weak points, and other potential applications of AFS.

For observing the shape of overall design, AR provided the visual reality of modeling objects worse than 5 other techniques. The t-tests between AR and CAD (t(19) = 4.41, p = 0.000), between AR and AF (t(19) = 3.48, p = 0.003), and between AR and AFS (t(19) = 4.17, p = 0.001) were significant at alpha=0.01. The t-test between AR and FM (t(19) = 2.76, p = 0.013) was significant at alpha=0.05.

In the case of the shape of detail design, CAD and AFS gave participants a better visual reality than 3 other techniques. Only two t-tests between CAD and AFS (t(19) = 0.46, p = 0.649) and between CAD and FM (t(19) = 1.89, p = 0.074) were not statistically significant.

Another set of t-tests was performed between the 6 simulation techniques for the size of overall design. There was significant difference in observed visual reality between CAD and the others and between FM and AFS (t(19)=2.52, p=0.021). FM provided the best visual reality of product appearance to the participants but CAD presented the worst reality.

For observing the size of detail design, only two t-tests between AR and AF (t(19) = 1.19, p = 0.248) and between AFS and FM (t(19)=0.00, p = 1.000) were not statistically significant. AFS and FM showed the best results and CAD was the worst technique for observing the size of detail design.

Lastly, in the case of observing the color of product appearance, there were significant differences in visual realities between FM and the other techniques. AFS was the best and CAD was the worst as a whole.

From these results, we came up with several important observations. First, AFS is a more efficient technique for perceiving the product appearance than CAD, FM, and other AR-based techniques. Second, AF is more useful for shape perception than AR. It is assumed that the result is due to the enhanced visual presence created by interaction.
Table.1 Mean ratings (S.D) of the perceived visual reality to 5 product appearance criteria

<table>
<thead>
<tr>
<th>Design simulation techniques</th>
<th>Mean ratings (S.D)</th>
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<tbody>
<tr>
<td></td>
<td>Shape of overall design</td>
</tr>
<tr>
<td>CAD (Renderings displayed on CRT)</td>
<td>5.7(1.3)</td>
</tr>
<tr>
<td>AR (Traditional Augmented Reality)</td>
<td>4.8(1.1)</td>
</tr>
<tr>
<td>AF (Augmented Foam without resolving hand occlusion problem)</td>
<td>6.0(1.1)</td>
</tr>
<tr>
<td>AFS (Augmented Foam with resolving hand occlusion problem)</td>
<td>6.2(1.1)</td>
</tr>
<tr>
<td>FM (Foam mock-up)</td>
<td>5.8(1.2)</td>
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</tbody>
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Evaluation criteria for the perceived visual reality of product appearance

Fig.9 Differences of mean ratings between 6 design simulation techniques

between a foam mock-up and environment.

AFS is superior to AR and AF in the aspect of perceiving shape and size of detail design. By contrast, there were no significant differences in overall design. For the shape and size of overall design, participants could get enough information standing back a short distance. However, the detail design could not be perceived accurately until the participants made a close investigation. When exploring the object surfaces by AFS, the participants seemed to experience both visual and haptic cues without inter-sensory discrepancy.

FM provides designers with physical interaction. As a consequence, the appearance of their design would be very easily assessed than other design simulation techniques. However, FM is inferior to AFS in terms of the shape of detail design (t(19) = 2.94, p = 0.008) and color (t(19) = 25.25, p = 0.000). Actually, FM is made from soft polyurethane foam which is cheaper and easy to handle. On the contrary, it is relatively difficult to provide precise details and colors of the physical design. The experiment result shows the possibility of overcoming the weak aspect of FM with AFS. AFS has a virtual overlaid function that was provided by a new rendering technology. The graphical augmentation could provide the participants in this experiment as for the detailed product appearance rather than FM.

The open-ended wrap-up questionnaire also gave several meaningful findings. Most of participants evaluated AFS as a better simulation technique because of its cost-effectiveness and ease of use. They expected that designers can realize their ideas thoroughly using AFS only with little effort. However, many participants also pointed out that wearing HMD using AFS might be still less convenient, preventing their realistic view with the real environment. Several participants also reported that AFS could be useful as a tangible user interface for interactive game contents.
In summary, AFS is much more useful in design simulation than other simulation techniques compared. The virtual overlay in AFS augments visual reality of a foam mock-up, and tactile force feedbacks from AFS enable inter-sensory disambiguation in shape perception.

7. Conclusions and Future Work

We proposed and implemented Augmented Foam, a touchable and graspable Augmented Reality, which can help designers make high-fidelity prototypes for their design ideas very rapidly and easily. The usefulness was tested through a cleaning robot design example. As expected, Augmented Foam provided visual reality and tactile feedback, elevating the feeling of immersion through multi-sense stimuli and spatial interaction between designers and design results. From the comparative experiment with traditional AR and Augmented Foam without resolving hand occlusion problem, we found that the enhanced visual reality provided by Augmented Foam comes from successful sensory-motor coordination.

This study also suggested further issues of this form of design. Firstly, the rendering speed (frame rate) of the system was not so sufficiently fast to consider the augmented scene via HMD as natural as the real world scene. To address this problem, we should adopt an enhanced computing system and optimize the skin detection algorithm for acceleration.

Second, many participants pointed out the problem of unwieldyness thanks to the HMD. While Shader Lamps[8] and Smart Projector[19] could be an good alternative display technique to HMD, they roughly require great efforts to implement and to calibrate. As a result, the investigation of display devices would also be inevitable in this line of studies.

Third, for virtual object rendering, the illumination conditions of the real environments were not considered in our current implementation. We plan to capture the illumination condition of the real environment in real-time to control the lighting of the virtual objects. The environment map can be also captured and used for rendering onto shiny virtual objects.

We observed situations when the marker-based object tracking failed by hand occlusion or became unstable in slanted views. We expect to improve object tracking by CAD-based natural feature tracking, which might be occlusion-tolerant and more stable. We also investigate to develop a skin detection algorithm that is less affected by illumination conditions.

References
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