Exploring Visuo-Haptic Mixed Reality

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Abstract In recent years, systems that allow users to see and touch virtual objects in the same space are being investigated. We refer to these systems as visuo-haptic mixed reality (VHMR) systems. Most research projects are employing a half-mirror, while few use a video see-through, head-mounted display (HMD). We have developed an HMD-based, VHMR painting application, which introduces new interaction techniques that could not be implemented with a half-mirror display. We present a user study to discuss its benefits and limitations. While we could not solve all technical problems, our work can serve as an important fundament for future research.
Keywords Haptics, Mixed Reality, Augmented Reality, User Interfaces, Interaction Techniques, Color Selection

1 Introduction

Human perception is multi-modal: the senses of touch and vision do not operate in isolation, but rather closely coupled. This observation has inspired systems that allow users to see and touch virtual objects at the same location in space (VHMR systems). Most VHMR systems have been implemented using a half-mirror to display computer graphics in the haptic workspace [8, 14, 18]. This approach achieves a better integration of vision and touch than a conventional, screen-based display; thus, user interactions are more natural. Few research projects (for example, [3]) use a video see-through, HMD instead of a half-mirror. An obvious advantage of the HMD is that the user's view of the real world and the computer graphics are not dimmed. While this is definitely increasing the realism of the virtual objects, it is hard to present to the user a consistent scene: real-world, computer graphics, and haptic forces have to be aligned very precisely.

In this paper, we want to show that the HMD-based approach has significant advantages, as novel interaction techniques can be implemented. Figure 1 shows a user who paints with a virtual brush on a virtual teacup. He can see and feel the brush, as it is superimposed over a PHANTOM [17]. The user can feel that he is holding a cylindric object in his right hand. Combined with the visual sensation, he experiences a believable illusion of a real brush. To achieve this effect, two ingredients are necessary: fully opaque occlusion of real-world objects by computer graphics, and handmasking. Handmasking [12] refers to the correct occlusions between the user's hands and virtual objects. These effects could hardly be implemented with a half-mirror display.

Our contributions in this paper are: First, a novel, simple registration method for VHMR systems. Second, we have created a VHMR painting application that enables users to paint more intuitively on 3D objects than in other approaches. Third, the interaction techniques for this painting application contain novel elements: bi-manual interaction in a VHMR system, and the transformation of a haptic device into an actuated, tangible object.

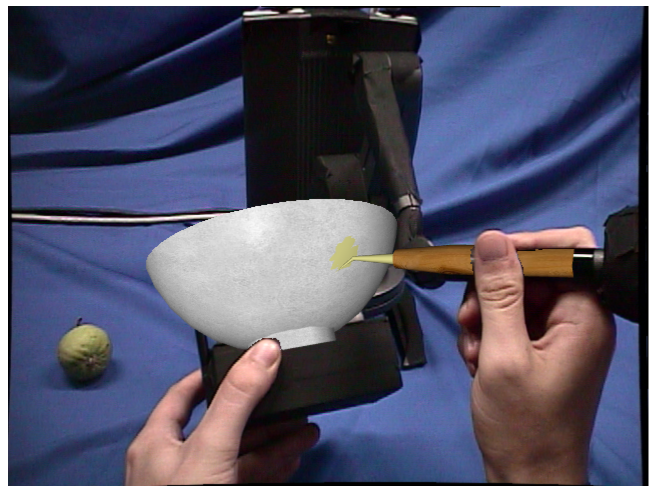


Figure 1: View through an HMD in our VHMR painting application.

2 Related Work

For precise alignment of MR graphics and haptics, a good solution seem to be the methods proposed by Bianchi et. al. [3]. Our approach is not as precise and robust. However, it is much easier to implement.

Our VHMR painting application was strongly inspired by the dAb system [2]. A PHANTOM is used in a desktop setup to imitate the techniques used in real painting. Sophisticated paint-transfer functions and brush simulations are used in this system. While we can't compete with these, we offer the possibility to draw on 3D objects. More importantly, we take the painted objects out of the screen and next to the haptic device. By removing the separation of display space and interaction space, we believe to achieve a much more intuitive user interface. Our brush closely resembles a *fude* brush (commonly used in Japanese calligraphy). Two previous projects have already been conducted on performing calligraphy with a PHANTOM [24, 20]. Again, they are only desktop systems. Our brush paints directly on the texture of a 3D object. For 2D input devices, this has been done very early by Hanrahan and Haeberli [5]. Recently, commercial products, such as ZBrush [13] offer this functionality. Painting on 3D objects with a haptic device has already been presented by Johnson and colleagues [9]. The commercial Freeform system [16] offers even more manipulation methods for 3D objects.

Regarding the interaction techniques for the painting application, we have picked up an interesting idea from Inami and colleagues [7]. They used a projection-based system to hide their haptic device. We camouflage our haptic device by overlays in an HMD. Our interaction technique of picking colors from the real world is in parts similar to Ryokai and colleagues' I/O Brush [15]. We discuss the relation to our work in detail in Section 6. In contrast to most other research in VHMR we enable users to perform direct interaction with both hands. Walairacht et. al. [23] allow bi-manual interaction of virtual objects in MR. However, their registration results are not as precise as in our system.

3 CHALLENGES FOR VHMR APPLICATIONS

Figure 2 gives an overview of the processes within a human user and the VHMR system she is using. The human's sensori-motor loop receives signals through the visual and haptic channel and turns these into actions, e.g., into hand movements. A similar loop can be found in the technological components that implement a VHMR system. Sensors and trackers provide information about the real world. These signals are interpreted by a controller and turned into visual and haptic output. A unique feature in haptic systems is the mechanical coupling of these two loops. The haptic device is controlled by both sensori-motor loops: the human's and the computer's.

The upper half of Figure 2 describes a stand-alone visual MR system, whereas the lower half describes a stand-alone haptic system. In a VHMR system, the interaction space and the space for visual augmentations are merged. Thus, the user can observe her own hands performing interactions (arrow 1 in Figure 2). This seems to be a benefit for many interactions. However, this benefit also comes with a new problem: the core challenge in VHMR is to combine the haptic and the visual system consistently and maintain this consistency at all times (arrow 2 in Figure 2). Based on this observation, we can identify several challenges:

Registration In spatial applications, registration refers to the precise alignment of various coordinate systems. For conventional MR the alignment of real world and computer graphics is still being investigated. For VHMR a new challenge occurs: the spatial locations of haptic and visual output must match perfectly. A discontinuity between these two channels destroys the illusion that VHMR tries to create. Thus, precise tracking of the haptic device (arrow 3 in Figure 2) is crucial.

Performance The haptic and visual channel impose different constraints on the system's performance. For a stable visual impression, 25Hz are sufficient. However, for the haptic channel a much higher update rate is needed. Typically, the actuation of a haptic device (called servo loop in haptic literature) should happen at at least 1000Hz, to avoid perceivable force discontinuities.

Stable force rendering To achieve stable force rendering in a haptic system is already difficult [4]. However, in a VHMR system, this challenge is even harder. The spatial relation between the haptic device and the virtual objects are determined by sensors. These sensors have limitations regarding robustness, update rate and accuracy. These limitations are propagated to the force rendering. For example, a jitter of 0.5 millimeters will hardly be perceived on the visual channel. On the haptic channel, this jitter leads to force discontinuities as will be discussed in Section 5.

Human-computer interaction In [10, 11], systems have been presented that focus on a similar vision like we do: they combine MR with 3D prints to enable users to feel the augmented objects. Users of those systems have liked this combination very much. However, they are clearly limited in flexibility, since 3D prints take a long time and can't be modified easily. These problems could be overcome by VHMR. VHMR primarily concerned with merging the haptic and visual world. The immersiveness of the user experience can be further enhanced by merging the virtual objects better with the real world. A variety of techniques have already been proposed to for this purpose: shadows [19] and occlusions [12].

4 VHMR PAINTING APPLICATION

In our visionary painting application, users should be able to paint with a virtual brush on a virtual, earthenware teacup (our teacup is a traditional Japanese teacup, called *chawan*). Our goal was to make this interaction as easy as possible. We decided to let the users control the virtual teacup with a graspable object. Additionally, we have invented a new interaction technique to make color selection from real objects very easy. Typically, our users were drawing the appearance of real-world objects onto the teacup.

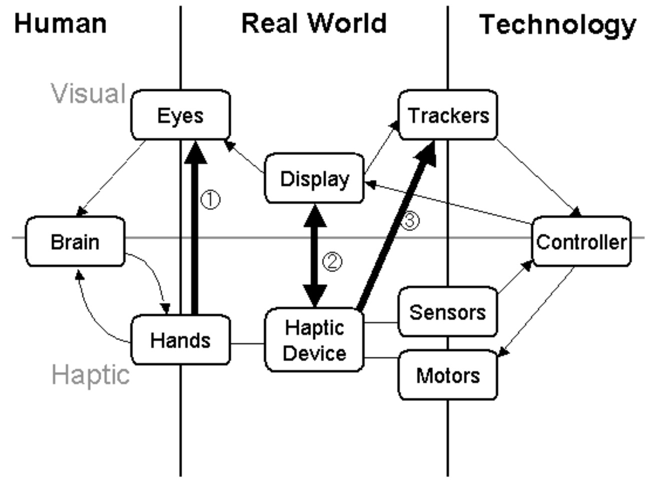


Figure 2: Schematic overview of a VHMR system. Arrows represent data-flow. The haptic device is mechanically coupled with sensors, motors and the user's hands. The implications of the numbered, bold arrows are discussed in Section 3.

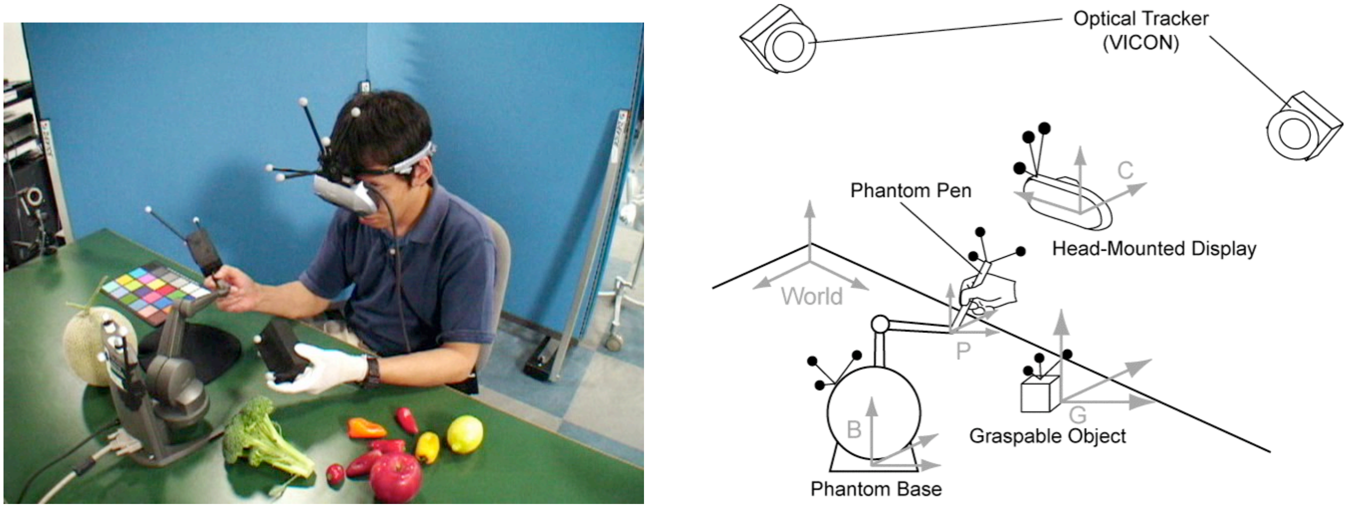
Next, we explain the hardware (Section 4.1) and software (Section 4.2) that we have used in our prototype. Then, we describe our registration method (Section 4.3) and the implementation of color selection (Section 4.4).

4.1 Hardware

The haptic device in our experiment is a PHANTOM Desktop [17]. We used Canon's COASTAR (Co-Optical Axis See-Through for Augmented Reality)-type HMD [21] for visual augmentations. It is lightweight (327 grams) and provides a wide field of view (51 degrees in horizontal direction). It is stereoscopic with a resolution of 640x480 for each eye. A special feature of this HMD is that the axes of its two video cameras and displays are aligned. For accurate position measurements, we have used a Vicon tracker [22]. This is a high-precision optical tracker, typically used in motion capturing applications. It delivers up to 150 Hz update rate and high absolute accuracy (0.5 mm precision). All software was deployed on one PC with 1GB RAM, Dual 3.6GHz Intel Xeon CPUs, GeForce 6600GT, and two Bt878 framegrabbers. The operating system was Gentoo Linux with 2. 4. 31. Kernel.

4.2 Software

For rendering the computer graphics, we used plain OpenGL with an additional model loader. Furthermore, we have employed two frameworks: OpenHaptics (Version 2.0; included with the PHANTOM) and MR Platform [21] (Internal version). MR Platform provides a set of functions for implementing MR applications; for example, calibration, tracking, and handmasking. Our implementation of handmasking does color-based detection of the user's hands in the video images obtained from the HMD's cameras. This information can be used to mask this part of the computer graphics scene via OpenGL's stencil buffer. As a result, the user's hands are always visible (see Figure 1).



(a) Photo.

(b) Schematic drawing including named coordinate systems.

Figure 3: Setup for our VHMR painting application.

4.3 Registration Procedure

From a calibration perspective, we have three relevant objects (see Figure 3): the user's HMD, the base of the PHANTOM and the PHANTOM pen. The relation between the attached markers and theses physical objects can be calibrated using MR Platform's calibration tools. For rendering of the computer graphics, we just use the Vicon's tracking data. Its update rate is high enough, whereas the jitter is almost not visually perceivable by a user. The graphical framerate was constantly 30 Hz. For the haptic rendering, we had to chose a different approach, since OpenHaptic's HLAPI bases its force rendering on the values of the PHANTOM's encoders. However, the absolute position accuracy is bad (we measured up to 20mm error). Essentially, the PHANTOM's measurements are nonlinearly distorted. To keep the haptic and MR world consistent, we determine the offset between the PHANTOM's measurements and the real pen position (as determined by the Vicon) in every haptic rendering pass. The inverse of this offset is applied to the geometry that is passed to HLAPI. Thus, the haptic experience matches the visual experience, although they happen internally in two different locations. This approach results in haptic rendering that jitters with the same amplitude as the Vicon's data.

4.4 Cross-Reality Color Picking

We allow users to select colors from real world objects (see Figure 5). We use a slightly different setup to explain the mathematics behind this interaction technique: a tracked pen is used to pick a color from a real teapot (see Figure 4). The known parameters are the 6DOF values of C and P (see Figure 3b). During camera calibration we have determined: the focal length of the camera f (unit: pixel) and the 2D coordinates of principal point of the camera (p_x, p_y) (unit: pixel). The unknown parameters are: the 6DOF of the pen's tip in camera coordinates M and its translation component $((T_x, T_y, T_z))$. To obtain the 2D coordinates of the pen's projection point (u, v) (unit: pixel), we proceed:

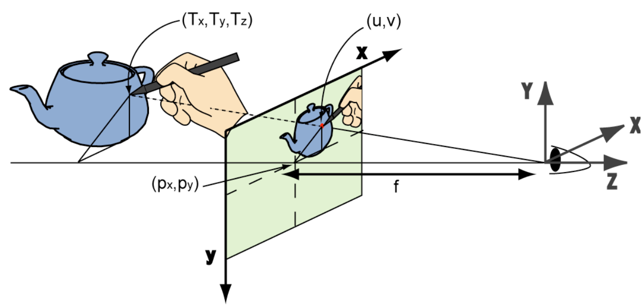


Figure 4: Mathematical description of cross-reality color picking.

$$M = C^{-1} P \tag{1}$$

$$u = -f \frac{T_x}{T_z} + p_x, \; v = f \frac{T_y}{T_z} + p_y \tag{2}$$

Since u and v refer to the pixel coordinates of the ideal image, we must transform them to the pixel coordinates of the actual, distorted, camera image. MR Platform's lens distortion model is a quintic radial distortion model. The distortion parameters for it were gathered during camera calibration. MR Platforms utility classes allow us to determine the corresponding pixel in the real image. We read the (R,G,B) value of that pixel and are done.

5 USER TEST

We tested our painting application by conducting a user test. We asked 14 subjects to paint teacups with our system. The procedure was:

1. General training (about 1 minute): The users were employing the viewer application to touch a virtual object. This made them experience the force sensation in our system and familiarized them with the graspable object for controlling the virtual object.

(a) Initial state.

(b) Move the brush to a real-world object and press the button on the PHANTOM pen.

(c) Apply the selected color to the teacup.

Figure 5: Interactions for cross-reality color picking.

2. Training for painting application (about 2 minutes): We put several objects such as vegetables and fruit on the table. Then, the subjects could familiarize themselves with color picking from those objects and painting on the cup.
3. Painting: (about 5 minutes): Next, the subjects could paint whatever they felt like.
4. Questionnaire: (about 3 minutes): Finally, the subjects completed a feedback questionnaire.

The results of the test are shown in Figures 6 and 7. We can draw the following positive observations, based on the users' feedback:

Very intuitive system Even in the extreme short time-slots for our study, subjects had no problems to understand and use our system. This makes us very confident about the ease of use. It would be hardly possible to achieve similar results in this short time using a standard 3D modeling application.

Good overall system concept Color picking, overall visual appearance and force sensation received positive feedback from almost all users. A user commented: "I like the function of moving my viewpoint, the cup and the pen at the same time. Commercial painting tools allow the user to move these things only separately, but not in parallel."

Artistic expression possible As Figure 6 shows, it was possible to create interesting pieces of art with our system.

However, several points received criticism:

Jittery haptic experience There is a clear limit to the haptic experience in our system—it is quite unstable; thus, it is hard to draw straight lines. One subject was trying to write a Japanese character. As can be clearly seen in his drawing (see Figure 7), our system was too jittery to allow this kind of precise lines. Almost all users complained about this in the questionnaire.

Problems in depth perception The stereoscopic effect of our HMD is not working when the cup is too close to the eyes. Convergence can only happen at more than 30 cm distance. Some of our subjects held the cup closer than 30 cm in front of their eyes, so they did not have any stereoscopic effect. Thus, they complained that the distance between the pen and cup is not easy to understand.

Over-simplification of the brush The visual impression of the brush had two big problems that were not liked by users. First, the computer graphics of the brushes' bristles are not natural. Second, the area of color application does not match the bristles' position. When we apply color on the texture, we just render a circle on the surface. The circle's center is at the contact point and the radius scales with the length of the bent bristles.

Limitations of the PHANTOM Another problem in our system was that the working area was very small (160 mm x 120 mm x 120 mm). This made the brush interaction unnatural.

6 DISCUSSION

While we could not overcome all technical difficulties, our VHMR painting application has shown new directions for human-computer interaction. While other systems perform better on particular aspects of the painting interaction (e.g., better computer graphics [2], or better haptic rendering [20]), the overall concept of our system contains novel points. We foster the advantages of using an HMD by allowing users to naturally interact with real world objects, as exemplified by our new cross-reality color picking technique. Also, by fully occluding the tip of the PHANTOM with a computer graphics representation of a brush, we create a virtual, tangible device. Furthermore, we support bi-manual interaction in a VHMR system.

To wrap up, we would like to discuss the insights that we have gained about our painting application.

Color picking Our new interaction technique for cross-reality color picking was one of the features that our users liked a lot. It seems to go very well with the metaphor of MR. One part of the interaction is very similar to the I/O brush: acquiring colors from real world objects by touching them with a brush. However, actually using these colors is very different in our system. The I/O brush still needs a computer screen to paint on. In our system, we can paint directly on objects located in the real world, eliminating the unnatural interaction of using a computer screen as a canvas.

Occlusions We have used two mechanisms to provide correct occlusions. First, we have used color-based hand-masking. Second, we have masked our tracked objects by rendering their geometries into OpenGL's depth buffer. Both methods were sufficient for our prototype, but both have inherent problems. For the tracked objects, we had to determine their geometries by hand. This was both cumbersome and not precise. For example, we did not measure the geometries of the attached Vicon markers. It seems to us that a 3D scanner would have been very useful. Even more useful would be a method that could deal with occlusions during runtime, for example a real-time computation of depth maps [6].

The hand-masking had even more problems. First of all, this approach does not yield a high performance. Second, the two hands can't be distinguished. This led to our decision to make user's wear a glove on their left hand. Third, this method is error-prone, especially when we used lots of colorful real world objects, some of those were masked, because their color is similar to the user's hand. The real-time depth maps that we proposed above, could also be applied to the occlusion problem of the user's hands.

Merging the haptic and visual world Essentially, we have adapted everything in our system to the real world. This included adapting the haptic world according to the measurements of the Vicon. The usage of such a highly accurate, but not very robust tracker led to problems for the haptic impression. Although the visual impression was correct at all times, the haptic world was perceived as unstable by users. As a result, our system was not well balanced. We plan to implement Bianchi et. al.'s method [3] to overcome this limitation.

Performance considerations Although our system performed well in the painting application, we could clearly see its limits. Objects with a polygon count over 200000 resulted in bad performance. We could use load-balancing of the different parts of our application to improve it. Either, by balancing better on our CPUs (better threading), or by using several PCs and networking our system. Also, we could move parts of the calculations on the GPU.

To optimize even more, we are considering to buy specialized hardware for physics simulation and collision detection (e.g., PhysX [1]). Since the heaviest task for huge models is the collision detection, we expect great benefits from this approach.

Future Work As one might remark, we could have implemented our painting application without using a haptic device, by using a real, tracked cup and brush. Only the applied color could be MR. When just thinking about the painting application, this is definitely true. However, our work is a first step towards a bigger vision. We would like to enable users to interact naturally with arbitrary virtual objects.

When using the PHANTOM device for VHMR, pen-shaped tools can be realized. In our example application, we have implemented a brush. Future work could be to build a variety of other tools with the PHANTOM: e.g., drills or hammers. Other haptic devices would enable us to build other kinds of tools.

Ultimately, we would like to use a general-purpose haptic device that can be used to simulate almost any real-world tool. For example, the SPIDAR haptic device [23], seems promising in this regard. With it, we could also get rid of our graspable object, but instead let the users touch the to-be-manipulated object directly. We are convinced that once we have implemented such a system, it will have major impact on the research fields of MR, haptics and human-computer interaction.

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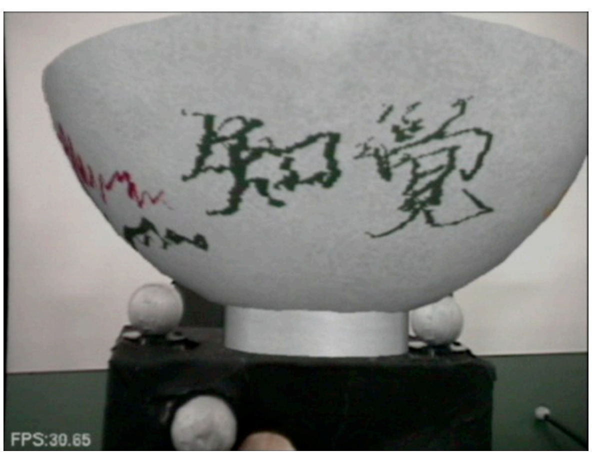
Figure 6: Drawings created with our painting application.



(a) One subject has drawn the character chihkaku (Japanese for: perception).

(b) Later, we asked the same subject to draw the character with a fude brush on a piece of paper.

Figure 7: Problem in our system: straight lines are hard to draw.