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MARIO: Mid-air Augmented Reality Interaction with Objects ☆

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ABSTRACT

A seamless connection between a game space and the real world is a long-sought goal of the entertainment computing field. Recent games have intuitive interactions through gestures and motion-based control. However, their images are still confined to the displays. In this paper, we propose a novel interaction experience in which mid-air images interact with physical objects. Our "Mid-air Augmented Reality Interaction with Objects" (MARIO) system enables images to be displayed in 3D spaces beyond screens. By creating a spatial link between images appearing in mid-air and physical objects, we extend video games into the real world. For entertainment purposes, a game character appears in mid-air and jumps over real blocks that users have arranged with their hands. A user study was conducted at public exhibitions, and the results showed the popularity and effectiveness of the system as an entertainment application.

1. Introduction

What if a game player could make Mario [1] run a course of his or her own design made by arranging wooden blocks in the real world and what if they could control Mario's movements through means other than game pads? If such features could be realized, game players could immerse themselves in the game space and thus enjoy interactions with game characters in more intuitive ways.

Aiming at an attractive game experience, we have imagined a scenario where users can play with physical objects and characters moving through the air. A user comes to our system with no preparation. This is very similar to a situation in which people play with game machines in game arcades. Blocks are placed on the game table, instead a controller. On this table, the user freely arranges the blocks and makes a 3D structure as he/she likes. Since the blocks are completely ordinary ones, the user does not have any difficulty in handling them. The shape, position, and orientation of the blocks, which the user has arranged, are detected by a sensor and reflected in the game world. A game character appears in mid-air and jumps on the blocks. The character will bounce off the surface of the block and the orientation of the blocks's surface controls the direction of the bounce.

On the basis of this scenario, we propose a novel augmented reality (AR) interface called "Mid-air Augmented Reality Interaction with Objects (MARIO)." MARIO realizes a direct user interaction between visual images and physical objects beyond the confines of a physical display (Fig. 1). An image is displayed and moves in 3D (*xyz*) space. Users of MARIO are freed of the need for physical displays during their interaction with mid-air images. Moreover, MARIO does not require users to wear additional devices, making it very easy to use. As in most AR systems, it also maintains high levels of temporal, spatial, and optical consistency between images and physical objects, and users can experience a strong sense of reality and immersion from the game.

The contributions in this paper are as follows:

(1) A new mid-air imaging display shows images that freely move in a mid-air in a 3D space measuring 350 (W) × 300 (D) × 250 (H) mm. Viewers can see the images without special glasses.
(2) An intuitive AR application enables users to control mid-air images with everyday objects or their hands. Shadows are cast by the images to give viewers the sense of reality.
(3) The popularity and effectiveness of MARIO as an entertainment system was proven during a six-month public exhibition.

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2. Related work

2.1. Augmented and mixed reality interfaces

Augmented and mixed reality (AR/MR) studies aim at making a seamless connection between a virtual space and the real world by superimposing visual images on the real world [2,3]. AR/MR interfaces have attracted a great attention in the entertainment field since they can augment real-world spaces with visual effects.

For example, AR quake [4] could transform real-world spaces into game spaces by overlaying game characters and visual effects on the real-world background through a head-mounted display (HMD). Players could move around in the real world and fight with enemies in the game space. By eliminating the border between the game space and the physical world, players could experience a game conveying a sense of reality.

The recent advent of portable and versatile devices such as smartphones and tablet computers has broadened the use of AR applications. Since smart devices are usually equipped with cameras, sensors, and displays, video see-through AR applications can be easily implemented on them. Second surface [5] provides a means of superimposing images on 3D space. With the aid of GPS, images can be linked to positions in the real world. By using tablet devices as a virtual window, users can leave a memo or scribbles as direct annotations on a mid-air space.

Moreover, the use of AR markers together with portable devices has enabled novel gaming experiences. Sony's AR play [6] merges the game space with the real world through PlayStation Vita, a portable gaming device. Game characters and special visual effects are overlaid on a player's desk or table, for example, and shown from displays. Such AR applications provide players with new gaming experiences by augmenting physical objects with images.

Although these video see-through AR applications can merge images and the real world in a simple way, they place limitations on the imaging position. In video see-through applications, images are only placed inside the display. The physical world can be augmented only inside the display area, not in 3D space. Thus, the spatial consistency between the superimposed images and the 3D space is not complete. In addition, users need to wear or carry displays to see the overlaid images.

We believe that images should be placed in the physical world beyond the confines of displays. A close spatial link between images and physical objects will enable intuitive interactions between game characters and players. Users should not need to wear additional displays in such interactions, and this would enable them to have a walk-up-and-use AR experience. With the MARIO system, we aim to place images at precise locations in 3D space together with physical objects.

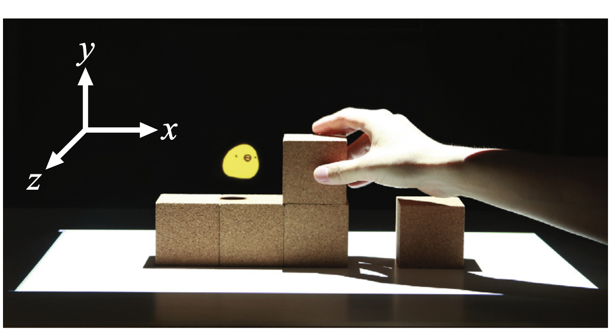

Fig. 1. The MARIO system. Users can directly interact with physical objects and mid-air images. A virtual character (Hiyoko, a chick) is displayed in mid-air on wooden blocks. A coordinate system is defined as *x* for width, *y* for height, and *z* for depth.

2.2. Mid-air imaging optics

Seeking to go beyond the confinement of images to physical screens, researchers have developed various imaging optics to present images in mid-air of a 3D space.

Half-silvered mirrors (HSMs) have been often used to present visual images in mid-air. HSMs have the advantage of distortion-free imaging. Like ordinary mirrors, they form mid-air images by reflecting incident light. The resulting images have no distortion on the image plane. Since the imaging position has a linear relationship with the distance between the HSM and the display, it can be easily and precisely calculated before the implementation. In addition, the imaging position can be changed without distortion. Such advantages mean that HSMs provide a simple way to superimpose mid-air images on physical objects in AR applications [7,8].

Despite such advantages, HSMs place stringent limitations on the imaging position: they cannot form mid-air images in front of their surface since the images are virtual ones and can only be placed behind the HSM. However, we would like to place mid-air images on physical objects in front of the imaging optics in order to enable a direct user interaction between the mid-air images and physical objects. Therefore, we sought an alternate way to form mid-air images in front of the imaging optics.

Convex mirrors (CVMs) and concave lenses (CCLs) suggest a way to overcome the limitations of HSMs: by using converging incident light, these optics form real images in front of them. Thus, viewers can view mid-air images without seeing them through imaging optics [9,10]. Moreover, the images can be precisely superimposed on physical objects set in front of the imaging optics [11].

However, unlike HSMs, CVMs and CCLs cause intrinsic distortion in the resulting images due to their curved surfaces. In addition, because of the nonlinearity of the thin lens equation, it is very complicated to calculate the position and size of the image.

Novel real imaging optics (RIO) have been devised that enjoy the merits of HSMs and CVM-CCLs. This real imaging optics contains an array of reflectors, so that a mid-air image can be formed by reflecting and converging incident lights, as in the case of CVMs and CCLs. The imaging mechanism is based on reflection on pairs of orthogonal micro-mirrors, so the resulting images are located in plane symmetric position of lighting source about the optics plane, similar to plane mirrors, and have no distortion, like HSMs [12]. Since the imaging position and size are also expressed with a linear mirror equation, the design of the optical system becomes much easier than with a CVM or CCL. Because of these advanced features, mid-air images can be formed and freely move in 3D space using Dihedral Corner Reflector Array (DCRA) [13,14].

Table 1 summarizes the optical properties of HSMs, CVM-CCLs, and RIO. In MARIO system, we have aimed to present mid-air images in 3D (*xyz*) space. Thus, distortion-free imaging is an essential requirement to present mid-air images viewable from various positions. Moreover, in order to realize direct user interactions between the mid-air images and physical objects, the imaging position should be in front of imaging optics. For these reasons,

Table 1
Properties of mid-air imaging optics.

Imaging optics	Distortion-free	Mid-air imaging in front of optics
Half-silvered mirror	✓	
Convex mirror, Concave lens		✓
Real imaging optics (DCRA, AIP)	✓	✓