billiARds: Augmented Reality System with wearable Force-Feedback device[1]

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Abstract

In this paper, we propose billiARds which is an Augmented Reality (AR) system that, in addition to visual and aural augmentation, provides force-feedback. We develop a vision-based tangible AR interface to support intuitive interaction with billiARds system. In order to enhance user's experience, we go a step further by adding force-feedback to the tangible interface. Our primary contribution is incorporating force-feedback into AR without restraining mobility of the user. To achieve this, we design a wearable device for force-feedback using body-worn motors. This device is based on wire-tension mechanism. The user can easily operate the proposed system while playing billiARds game around a table. Furthermore, we also consider ways to effectively use various modalities, side by side, in an AR environment. In this regard, we perform experiments to evaluate whether visual and aural cues can enhance haptic perception of the user.

1 Introduction

Augmented Reality (AR) supplements user's perception of real world by stimulating one or more senses (Azuma, 1997). Various modalities are being exploited in this regard. Most of the systems only augment visual objects to user's view. AR-Bowling is an application that enables users to play an augmented bowling game using hand gestures, and provides appropriate visual cues (Matysczok, 2004). However, visual cues alone are not sufficient to provide intuitive interaction to users. Some AR systems also deliver tactile feedback to enhance user's experience. Tactile feedback can be provided synthetically through tactile actuators (Kajimoto, Kawakami, Tachi & Inami, 2004) or naturally through tangible AR interfaces (Billinghurst, 2001). However, these systems still fall short of providing realistic interaction when dynamics is involved. In such situations, force-feedback is required to ensure user's sense of realism.

While tactile feedback is readily employed in wearable AR systems, providing force feedback is much more complex. It brings more challenges to the realm of AR, mobility being the greatest. One such application, developed for planning human skull surgeries, provides force-feedback when the user interacts with augmented skull models (Scharver, Evenhouse, Johnson & Leigh, 2004). The system uses PHANTOM, which is fixed on a desktop, for force-feedback (Massie & Salisbury, 1994). Another system employed a vision-based approach to overcome the problem of constant contact with haptic device (Ye, Corso, Hager & Okamura, 2003). A stereo camera tracks user's hand, and the haptic device is moved as a robot to come in contact with user's hand only when needed. However, current AR systems providing force-feedback use devices which are fixed, e.g. PHANTOM. The problem with these systems is that they support a limited working area and thus constrain mobility of the user.

Humans have a remarkable ability to fuse multi-modal sensory stimuli for building inferences about their environment. Especially, when dynamics is involved, information about motion imparted, on an object, by an applied force can provide cues about the object's properties (Massie & Salisbury, 1994). Various experiments have been done to study effects of multi-modal stimuli on human perception. Miner, Gillespie and Caudell (1996) conducted a tri-modal study to examine how visual and auditory stimuli enhance the effectiveness of haptic interface in a virtual environment. They also presented a summary of earlier works done to study cross-modal stimuli. However, we did not find any effort that employs cross-modal effects to supplement haptic perception in an AR environment. It is, thus, evident from the above discussion that current AR systems employ desktop based force-

[1] This work was supported by GIST.

feedback devices which restrict user's mobility. Moreover, these systems fail to exploit human ability of perceiving multi-modal stimuli.

To overcome the problem of limited mobility and to employ multi-modal effects for reinforcing haptic sensation in AR environment, we propose billiARds system. billiARds is an Augmented Reality system that provides force-feedback without confining working space of the user. In order to ensure mobility of user, we develop a force-feedback device using body-worn motors. This device is based on wire-tension mechanism (Hirose et al., 2001; Bonivento, Eusebi, Melchiorri, Montanari & Vassura, 1997). The user can easily carry the system while interacting with virtual balls through tangible AR interface. We develop a tangible AR interface that is a step ahead of existing ones in a sense that it provides both natural tactile sense and synthetic force-feedback. Our primary contribution is incorporating force-feedback into AR without restraining mobility of the user. Our second contribution is to evaluate if visual and aural feedback can reinforce user's haptic perception in an AR environment.

This paper is organized as follows. Chapter 2 explains the design and implementation of billiARds system. In chapter 3, we discuss experimental results. Finally, conclusions and future work are presented in chapter 4.

2 billiARds System

billiARds system enables a user to interact with virtual objects using a tangible stick. The system set-up for billiARds is illustrated in Figure 1. In this chapter, we explain in detail the working of billiARds system.

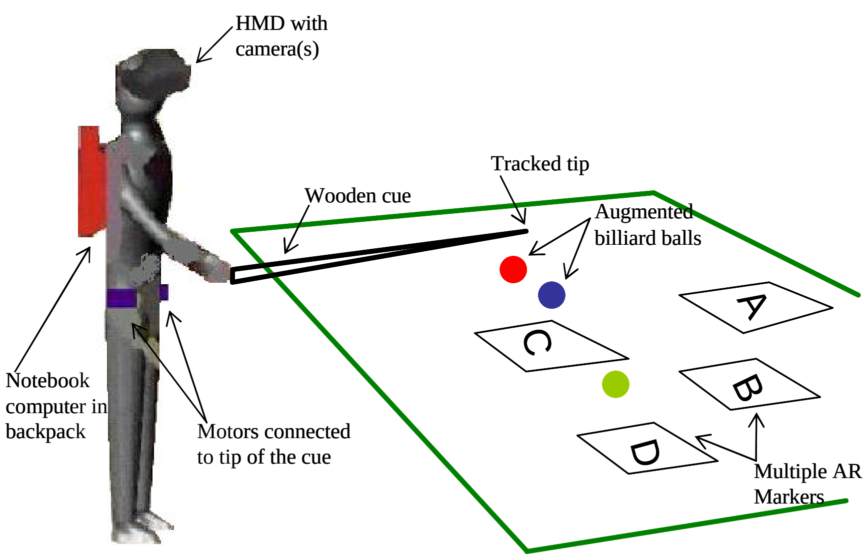

Figure 1. System set-up for billiards

A user can play billiARds by striking augmented balls with a wooden stick. Force-feedback is provided on the cue when a virtual ball is hit. Simultaneously, collision sound is augmented to instigate user's cognition of billiard dynamics. Visual animation and audio feedback significantly supplement user's haptic perception. The control flow of the system is described in Figure 2.

2.1 Tangible AR Interface

We develop a vision-based Tangible AR Interface for intuitive 3D interaction. We use head-mounted camera(s) for 3D tracking of billiard cue so that user's workspace is not confined. User can operate the system while moving around in indoor environment. We carried out various experiments on the proposed system with two different set-ups. These set-ups differ only in the number of cameras (one or two) used for tracking wooden cue. This, obviously, has subsequent effects on usability of the system. The results of these experiments are summarized in chapter 3. In the following, we explain the vision-based tracking method used for each set-up.

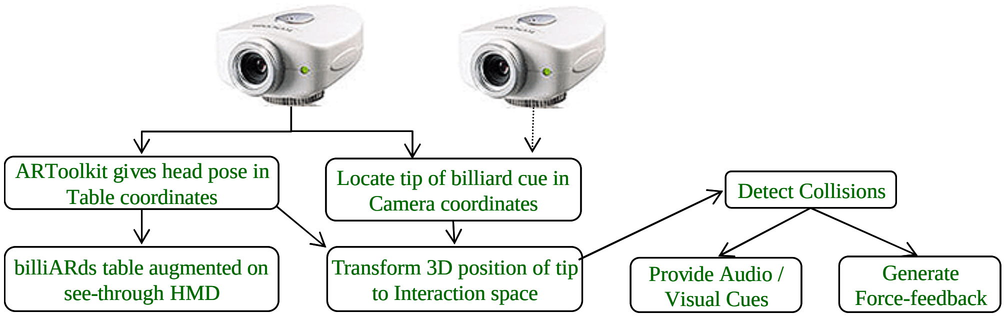

Figure 2. Control flow of billiARds system

2.1.1 *Tracking*

In the first arrangement, we use two head-mounted cameras for 3D tracking of billiard cue (relative to user's head). For this, we wrap two magenta-colored markers near the tip of the cue. Tracking is done by triangulation between the two cameras (Hartley & Zisserman, 2000). Offline calibration provides us intrinsic and extrinsic camera parameters. The extrinsic parameters are such that the origin lies at an external point visible to both cameras. Taking right camera as reference, we transform the origin to right camera and obtain the two camera matrices using equation (1) and (2).

$$P_r = K_r[I \mid 0] = K_r[R_r \mid T_r]\begin{bmatrix} R_r^{\mathbf{T}} & -R_r^{\mathbf{T}}T_r \\ 0 & 1 \end{bmatrix} \tag{1}$$

$$P_l = K_l[R \mid T] = K_l[R_l \mid T_l]\begin{bmatrix} R_r^{\mathbf{T}} & -R_r^{\mathbf{T}}T_r \\ 0 & 1 \end{bmatrix} \tag{2}$$

where P_r and P_l denote camera matrices for right and left camera, respectively; K_r and K_l are intrinsic parameters for right and left cameras, respectively; and $[R_r|T_r]$ and $[R_l|T_l]$ represent extrinsic parameters for right and left cameras, respectively. K and R are 3×3 matrices, while T is a 3×1 vector.

Color subtraction is used to detect two colored markers on the cue. Detected regions with areas smaller than a threshold are ignored. Centers of circles bounding the detected regions are taken as points for triangulation. We get two points from each image and assume that the cue is oriented from bottom to top in each image. So, correspondence between points can be found by their relative positions along height of the image. As the cameras matrices are known, we use linear triangulation to extract 3D position of the tip as shown in equation (3).

$$\begin{bmatrix} x_r P_r^{3\mathbf{T}} - P_r^{1\mathbf{T}} \\ y_r P_r^{3\mathbf{T}} - P_r^{2\mathbf{T}} \\ x_l P_l^{3\mathbf{T}} - P_l^{1\mathbf{T}} \\ y_l P_l^{3\mathbf{T}} - P_l^{2\mathbf{T}} \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = 0 \tag{3}$$

where $P^{i\mathbf{T}}$ is *ith* row of camera matrix P; (x_r,y_r) and (x_l,y_l) are coordinates of 2D points in right and left image, respectively; and $[X,Y,Z,1]^{\mathbf{T}}$ is 3D location of the tip. The 3D location is expressed with respect to reference camera. Once we know the 3D position of both markers, we get orientation of billiard cue from the vector joining the two 3D points.

In the second arrangement, we use single head-mounted camera for tracking billiard cue. For this, we attach an AR marker near the tip of the cue. ARToolkit is used to recover 6DOF pose of the billiard cue (Kato & Billinghurst, 1999). This gives a 3×4 transformation T_{Cue} (illustrated in Figure 3) representing cue's position and orientation in camera coordinates.

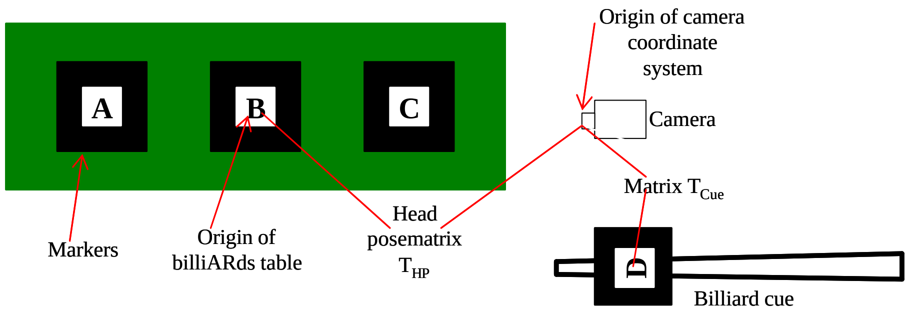

Figure 3. Various coordinate systems

3D position of the tip is transformed from cue coordinates to camera coordinates using equation (4).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{cam}} = T_{\text{Cue}} \times \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{cue}} \tag{4}$$

where $[X\ Y\ Z]^{\mathbf{T}}_{cue}$ and $[X\ Y\ Z]^{\mathbf{T}}_{cam}$ denote position of the tip in cue coordinates and camera coordinates, respectively.

2.1.2 Interaction

We augment virtual table surface and billiard balls on a real table which bears multiple markers. The user wears a see-through HMD to view augmented objects. User's head pose (relative to the table) is required for precise augmentation and registration. This is determined by tracking multiple AR markers, placed on the table, through head-mounted camera. ARToolkit is used for this purpose. It gives us the transformation matrix T_{HP} (illustrated in Figure 3). The billiards table is augmented such that the virtual world coincides with marker coordinate system.

For interaction between colored tip and virtual balls, both must be placed in same coordinate system. Tracking gives us location of the tip in camera coordinates. 3D location of the tip is transformed from camera coordinates to coordinates of augmented table using equation (5).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{vt}} = T^{-1}_{\text{HP}} \times \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{cam}} \tag{5}$$

where $[X\ Y\ Z]^{\mathbf{T}}_{vt}$ and $[X\ Y\ Z]^{\mathbf{T}}_{cam}$ denote position of the tip in virtual table coordinates and camera coordinates, respectively. In order to support interaction through wooden cue, we must detect collisions between tracked tip of the cue and virtual balls. For this, we consider radii and positions of the cue tip and the balls. billiARds user can only strike the balls with the tip.

2.2 Audio-Visual Feedback

When a collision between stick and a ball is detected, appropriate visual and aural cues are provided to instigate user's haptic perception. We provide four distinct auditory cues which vary in pitch and loudness according to the force of collision. The pitch and loudness of audio-feedback is directly proportional to the force applied by user on virtual object. In order to change the perceived pitch of the sound, we vary the sampling frequency between 45 kHz (minimum) and 65 kHz (maximum). Loudness perceived by the user is varied by changing intensity level of the sound. Generally, a 10 dB increase in intensity is perceived by most listeners as a doubling in loudness. We vary the intensity between the maximum (supported by the computer) to 20 dB less than the maximum. Table 1 shows the cues provided along with their triggering events.

Table 1. Audio Cues

Event	Duration (sec)
When cue strikes a virtual ball.	0.15
Collision between balls.	0.15
When a ball is pocketed.	0.37
When a ball rebounds off a table rail.	0.07

2.2.1 billiARds Dynamics

The direction and magnitude of the push exerted by the cue on virtual ball determines the game dynamics. The magnitude of this force is proportional to how fast the cue is moved just before the strike. This is calculated from tracking history of the cue. We assume that the push exerted on the virtual ball is always directed along orientation of the cue at the time of collision. This is rational in billiards game scenario because when user hits a ball, the cue is only moved along its length. When the cue strikes a ball, we consider various variables to drive dynamics of the billiards table. These include mass and radius of balls, co-efficient of sliding friction, and velocities of colliding and deflecting balls. For balls in collision, velocities are updated using law of conservation of momentum. We observed that vision-based tracking is not accurate enough to determine the precise point on ball surface where the cue strikes. So, we make another assumption that the stick always strikes at center of the ball (center of mass). This simplifies the simulation because, as shown in equation (6), the torque becomes zero when radius and force are parallel, i.e. q=0. Thus, we ignore the angular motion of the ball and only consider translational motion.

$$t = r \times F = |r|\,|F| \sin q = 0 \tag{6}$$

where t denotes torque; and r and F are radius and force vectors, respectively.

2.2.2 Occlusion

Virtual table hides part of the real scene because it is rendered over captured image of the scene. This also removes the wooden billiards cue from user's view. In order to enhance user's gaming experience, the system must deliver appropriate occlusion between real and virtual objects. Since we do not have depth map of the environment, we rely on a simpler model-based approach to handle occlusion. It works well because the only real object we deal with (i.e. billiard cue) has simple shape without any minute details. After tracking position and orientation of the real cue, we render a tapered cylinder (truncated cone) in a stencil buffer. This model is precisely rendered so that its dimensions and pose coincide with those of the real cue. When we overlay the virtual table through this stencil buffer, it covers other parts of the scene while leaving the wooden cue visible. The result is shown in Figure 4.

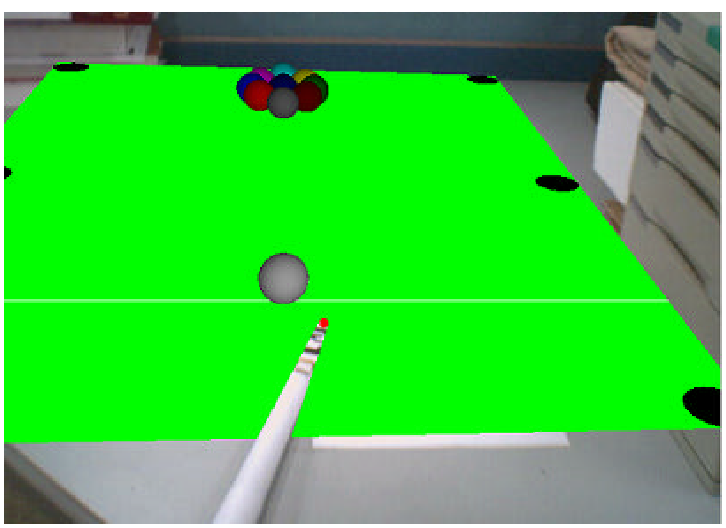

Figure 4. Occlusion between real cue and augmented table

2.3 Force-Feedback

Two AC servo motors are mounted around user's waist. Each motor is attached to the billiard cue using a separate string. Using encoder data of motors, we can obtain orientation of the cue and position of the tip. While the cue is moving, the direction of motion of the tip gives us the direction of force exerted by user on the billiard ball. When the wooden cue collides with a virtual ball, a torque control algorithm for motors is used to provide force feedback. The force feedback involves producing a calculated pull, directed exactly opposite to the force applied by user, at the strings. The magnitude of force-feedback is proportional to speed of the cue before the strike. The top view of motors arrangement is shown in Figure 5.

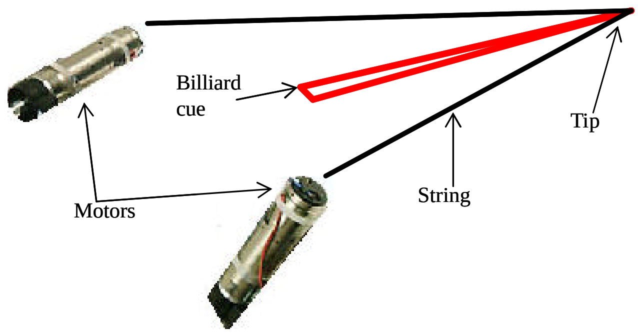

Figure 5. Arrangement of motors for force-feedback

With two motors, the system can only provide 2D haptic sense. We observed that when a user hits a ball, the cue is almost horizontally placed for most billiard games. In such cases, the angle between cue and the table is small and the component of force perpendicular to the surface of table is negligible. Exceptions to this fact are advanced strokes, such as masse` and pique`, which are played with upright cue to reverse-spin the cue-ball. These are strictly experts' shots and are rarely used by amateurs. So, we based our force reflection device on the assumption that force applied to a billiard ball is always horizontal. This assumption is rational within our game scenario, and thus, we can provide sufficient realism to the user.

In order to track the tip of the cue based on wire lengths, we solve forward kinematics. Considering reference frames *{0}* and *{1}* with their origins at wire-extraction points, wire lengths L_0, L_1 can be expressed by equation (7).

$$L_1 = \left\| T^0 - S_1^0 \right\| \qquad (7)$$
$$L_0 = \left\| T^0 \right\|$$

where $S_1^0 = [s_{1x}, s_{1y}]$ denotes coordinates of origin of *{1}* with respect to *{0}*, and $T^0 = [x,y]^{\mathbf{T}}$ represents cue-tip coordinates with respect to *{0}*.

Solving equation (7) gives us x and y coordinates of the cue-tip. Unit vectors, u_0 and u_1, along the strings can be expressed by equation (8).

$$u_0 = \frac{1}{\sqrt{x^2+y^2}}[x, y]^{\mathrm{T}} \qquad (8)$$
$$u_1 = \frac{1}{\sqrt{(x-s_{1x})^2+(y-s_{1y})^2}}\left[(x-s_{1x}),(y-s_{1y})\right]^{\mathrm{T}}$$

We use equation (9) to calculate the tension required in wires to exert force f on the cue tip.

$$f = p_0 u_0 + p_1 u_1 = J^{-T} p \qquad (9)$$
$$J = [u_0, u_1]^{-T}$$

where p is the vector of wire tensions, and J is Jacobian matrix of the haptic device. From equation (9), we can write:

$$p = J^T f \tag{10}$$

While the cue-tip moves freely in space, wire-tensions may become negative. This renders the wire-lengths indeterminable. Therefore, a small force is always applied at the cue-tip to ensure that the wire-tensions remain positive. To ensure transparency of haptic device, this force must be constant at all locations. Magnitude of this force depends on structure of device and user's feeling. Experimenting with different values, we found that 1N is the optimal value to keep wire-tensions always positive without compromising transparency of the haptic device. Figure 6 shows the resultant force on the cue-tip before, after and at the instant of collision. The figure shows that a force of 5N is exerted on the cue-tip at the instant of collision. The force is held constant before and after the collision.

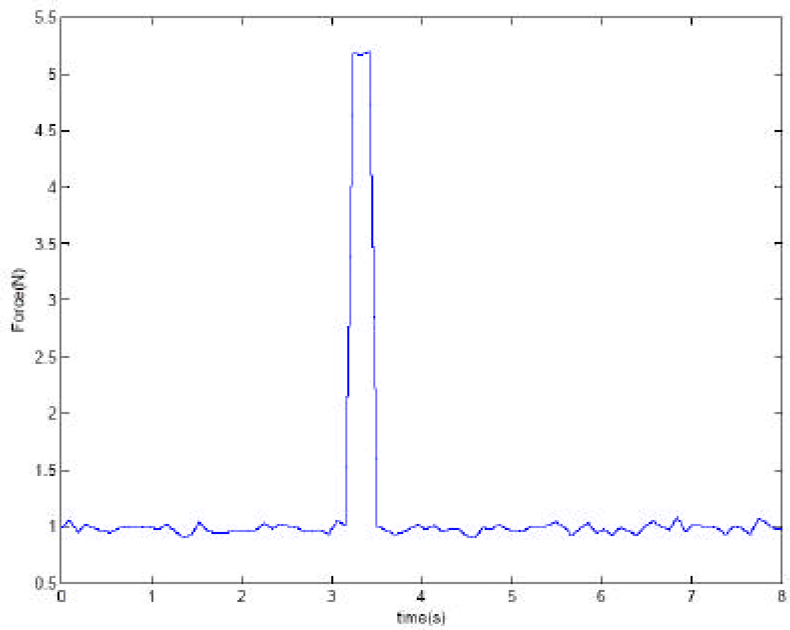

Figure 6. Force on the cue-tip

3 Experimental results

In order to test usability of billiARds system and determine factors which affect user's experience, we performed experiments with two different set-ups. In the first arrangement, two head-mounted cameras were used for vision-based tracking while the second set-up relied on monocular tracking. For both arrangements, we used a notebook computer (carried in user's backpack) with 1.5 GHz processor and NVIDIA GeForce FX5200 graphics accelerator (http://www.nvidia.com). The user put on i-glasses SVGA head-mounted display with 800×600 pixel resolution (http://www.i-glassesstore.com). A pair of earplugs was also provided for aural feedback. We used camera with video capture resolution of 640×480 pixels and shutter speed of 20 frames per second. A table (70 cm high) was set up with four AR Markers; each having dimensions of 16cm×16cm. For experiments, we augmented a virtual table over an area of 100 cm × 150 cm. The user carried a 60-cm long wooden cue for interaction. Force-feedback was provided with two brushless DC motors fixed to a belt around user's waist. The motors can provide an output torque of 120 mNm. The encoders operate at 540 pulses per revolution and the encoder data can track the tip with an accuracy of 2 mm. In the first configuration, we mounted two cameras on HMD. The cameras were placed 7 cm apart with their axes parallel to each other. We wrapped two magenta-colored markers (each 2 cm wide) close to the tip of wooden cue. The distance between markers was 3 cm. In the second configuration, we mounted only one camera on HMD. Instead of colored markers, we attached an AR Marker of size 5cm × 5cm near the tip of billiard cue.

We conducted an informal user study during which we observed that the system with monocular tracking was rated higher than the one with stereo-tracking. During the study, nine users (one at a time) put on our system and experienced the billiARds game by moving around the table. Afterwards, each user was given a questionnaire to grade four aspects of each configuration on a 7-scale (0-6). These include mobility, untethered interaction, effectiveness of force-feedback, and effectiveness of audio-visual cues in reinforcing haptic sensation. The results of this study are compiled in Table 2. During trials done to record user's response on effectiveness of force-feedback, sampling frequency and intensity of audio cues were kept constant. Also, parameters for visual cues remained unchanged. For trials done to evaluate effectiveness of audio-visual cues in enhancing haptic perception, a constant force-feedback was provided irrespective of the force applied by user.

Table 2. User Feedback

Evaluated aspect	**Mean**		**Std. Dev.**	
	2-camera set-up	**1-camera set-up**	**2-camera set-up**	**1-camera set-up**
Mobility (0-6)	5.4	5.4	0.5	0.5
Untethered interaction (0-6)	4.6	4.6	0.88	0.88
Effectiveness of force-feedback (0-6)	2.4	5.2	0.88	0.67
Effectiveness of audio-visual cues in enhancing haptic perception (0-6)	2.2	4.4	0.66	0.88

During the trials, we observed that the users could freely move around the billiard table and had no difficulty interacting with augmented balls. This observation was reinforced by the user-feedback data (Table 2) which exhibited that the system provided untethered interaction to users. Moreover, the results also showed that both the configurations offered great mobility. This confirmed our first claim that billiARds system provides force-feedback in AR environment without restraining mobility of the user. However, we got conflicting results for effectiveness of the force-feedback provided by billiARds system. Users found that force-feedback was not much effective in case of two-camera set-up. But, the same aspect was rated high in case of one-camera configuration. Another contribution of this paper is to evaluate whether audio-visual cues reinforce haptic sense of users. In this respect also, the users' feedback showed ambiguous data. Audio-visual cues almost failed to enhance haptic perception of the user in two-camera configuration. However, these were sufficiently effective in case of one-camera set-up.

In order to disambiguate the findings of user-feedback with regard to the last two aspects (Table 2), we carried out three experiments to compare both set-ups. While aiming for a shot, a billiards player leans towards the table. In our set-up, we observed that the head-mounted camera of a player making a shot is about 40 cm above the rail. Moreover, the camera makes an angle of around 25 degrees with the table top. It has been observed that accuracy of ARToolkit varies with distance and angle between marker and camera (Abawi, Bienwald & Dörner, 2004). Therefore, all the experiments were done with camera configuration similar to this one. That is, the inclination angle of camera varied between 20 and 30 degrees and the height was set between 30 and 50 cm. For the experiments, we fixed the camera on a tripod and moved it between trials. The results of these experiments are shown in Table 3.

User receives a 2D view of the augmented environment. Ideally, a ball must be set in motion when 2D projection of the wooden cue approaches it in the augmented view. At the instant of collision, visual error was calculated as the distance (in number of pixels) between 2D projections of the real tip and the virtual ball in augmented view. 2D projection of the real tip was manually selected by the user, while that for the virtual ball is obtained by projecting its 3D position to 2D window.

We used response time to measure interactivity of our system. So, in the second experiment, we observed Lag_{av} before audio-visual feedback was provided. This is defined by equation (11).

$$Lag_{av} = t_{av} - t_{img} \tag{11}$$

where t_{av} is the time when audio visual cues were provided, and t_{img} is the time of image capture. In the third experiment, we observed Lag_{ff} before force-feedback was provided. This is expressed in equation (12).

$$Lag_{ff} = t_{ff} - t_{img} \tag{12}$$

where t_{ff} is the time when force-feedback was provided. For second and third experiments, we ignored the lag between user's action and image capture. However, our observations were reliable to compare the two configurations because both set-ups use same cameras.

Table 3: Observed Results

Observation	**No of Trials**	**Mean**		**Std. Dev.**	
		2-camera set-up	**1-camera set-up**	**2-camera set-up**	**1-camera set-up**
Visual Error (for tip) (in pixels)	50	6.6	1.8	0.97	1.06
Lag before audio/visual feedback (msec)	50	482	48	9.8	8.3
Lag before force-feedback (msec)	50	511	65	11.3	7.3

These results showed that visual error in two-camera set-up was much larger than one-camera configuration. Moreover, in two-camera set-up, significant lag was observed before audio-visual or force-feedback was provided. This gives an explanation for the ambiguous results we found in Table 2. Based on table 3, we can say that force-feedback was not much effective in two-camera set-up because of lag. Similarly, audio-visual cues failed to enhance force-feedback due to visual error and lag. Thus, we deduce that audio-visual cues, only if efficiently provided, can reinforce haptic perception in AR environment. This was duly achieved by the one-camera set-up.

4 Conclusions and Future work

In this paper, we summarize our experiences developing an AR-based system. The proposed system guarantees users' mobility while they freely move around billiard table and experience force-feedback in AR environment. Our main contribution is incorporating force-feedback into AR without restraining mobility of the user. In addition, we also assess how visual and aural feedback can affect user's haptic perception in an AR environment. Experiments showed that the audio-visual cues, only if effectively used, can enhance haptic sensation. In the future, we plan to develop more realistic physics model for generating audio-visual cues. In addition, we will study in detail the human factors involved in perception of multi-modal stimuli. Furthermore, multiplayer collaborative billiARds will be an interesting extension of the current system.

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