Stackable Music: A Marker-Based Augmented Reality Music Synthesis Game

Max Chen
mjchen@wpi.edu
Worcester Polytechnic Institute
Worcester, Massachusetts, USA

Shano Liang
sliang1@wpi.edu
Worcester Polytechnic Institute
Worcester, Massachusetts, USA

Gillian Smith
gmsmith@wpi.edu
Worcester Polytechnic Institute
Worcester, Massachusetts, USA

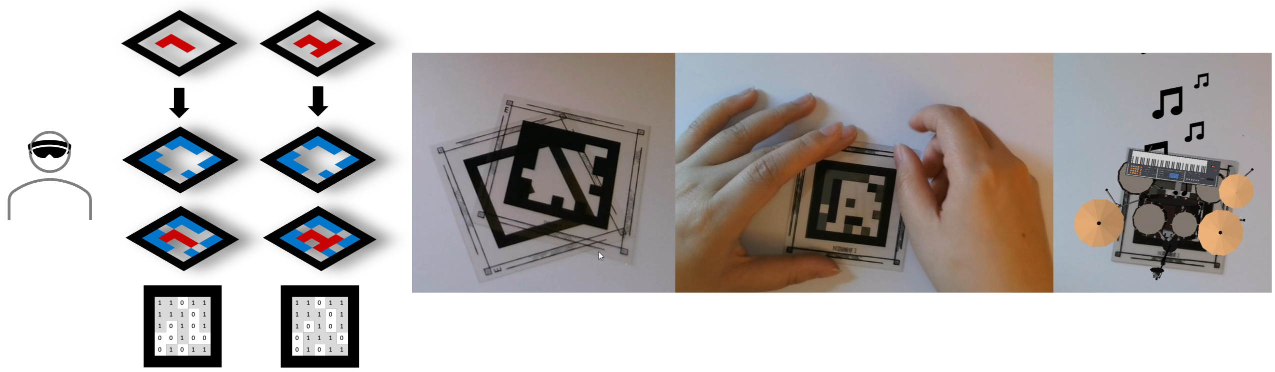

Figure 1: An illustration of stacking transparent AR markers and photos of the Stackable Music application. When multiple transparent AR markers are stacked and recognized by the camera, the application takes them as input and generates a variation of jazz.

ABSTRACT

Augmented reality (AR) allows the rendering of digital content on top of the physical space, which is a promising medium for tangible interaction. Marker-based AR is widely used thanks to its low cost and ease of integration, but the gameful aspect of manipulating the physical AR markers remains understudied. In this paper, we explore the stacking mechanics of transparent AR markers and create an AR music game called Stackable Music. Stackable Music can be developed, assembled, and set up at the home or office with a printer using several sheets of transparent film and a PC or mobile device with a camera.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; *Human computer interaction (HCI)*; Interface design prototyping.

KEYWORDS

Marker-based AR, AR Game, Tangible Interaction, Transparent AR Markers

CHI PLAY '23 Companion, October 10–13, 2023, Stratford, ON, Canada

ACM ISBN 979-8-4007-0029-3/23/10…$15.00
https://doi.org/10.1145/3573382.3616071

ACM Reference Format:
Max Chen, Shano Liang, and Gillian Smith. 2023. Stackable Music: A Marker-Based Augmented Reality Music Synthesis Game. In *Companion Proceedings of the Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '23 Companion), October 10–13, 2023, Stratford, ON, Canada.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3573382.3616071

1 INTRODUCTION

Augmented Reality (AR) technology merges digital content with the physical environment [1], which is an emerging field of study in human-computer interaction (HCI). Based on the method of mapping digital objects to physical surroundings, AR can be divided into two categories: markerless and marker-based [30]. AR markers function as reference points in the physical environment, helping to place virtual objects and content in the user's field of view. Markerless AR identifies anchor objects, like flat surfaces (such as walls, ceilings, and tabletops), or human body parts such as limbs and hands, as reference points in the physical environment. Despite significant progress in head-mounted AR devices and marker-less AR interactions, marker-based AR maintains extensive usage due to its affordability and simplicity of integration. This approach enables tangible interaction and serves as a liaison between physical and digital spaces [4], thereby asserting its importance in the post-screen era [16]. The tangible characteristic of printed markers has gained justifiable popularity in fostering creative activities [39], storytelling [7, 13, 24, 38], games[21], learning[6, 11], physical prototyping [20], and enhancing social interaction [35].

Using marker-based AR in card games is an intuitive design decision, as cards are physical media for printing images or QR

Figure 2: Renowned existing fiducial marker systems including ARToolkit, ArUco, ARTag, InterSense, and ReacTIVision.

codes. AR can add dynamics and graphical elements by overlaying animated characters, visual effects, and 3D models onto the physical card, which is helpful in reminding players of the rules and spells in the game [3]. AR can be used to recognize card and player actions to help calculate the damage and result of a battle[22]. AR card games are also widely used in educational settings, such as allowing users to mimic physical actions such as shaking and pouring in chemistry experiments using card-based or box-based marker design[23].

Fiducial markers, artificial patterns which balance fast and precise pose estimation with a straightforward and cost-effective deployment, play a critical role [10]. As illustrated in Fig.2, renowned fiducial marker systems include square-shaped marker systems such as ARToolkit[19], ArUco[12], and ARTag[9], and irregular-shaped marker systems such as InterSense[27] and ReacTIVision[18]. Using fiducial markers rather than image markers allows standardized production because it does not require individual training over each image tracker.

However, the use of printed fiducial markers in HCI introduces several limitations. For instance, they are permanent; once printed, few modifications can be made. In addition, most AR applications only use AR markers as reference points. The physical affordances of materials and the interaction of AR markers are less studied and utilized in playable media. One unique inter-marker mechanic that can bring creative potential to AR interaction is stacking. When AR markers are printed on transparent film and stacked, the formation of new markers can be captured and recognized by the camera, thus becoming a new input modality to the interactive system.

In this paper, we describe using transparent film as a physical material for AR markers and experiment with stacking transparent AR markers. As a proof-of-concept, we developed Stackable Music, a card game that leverages stacking transparent AR markers to enhance tangible interaction in music synthesis. Further, we discuss the affordances and limitations of the transparent AR markers and propose future research directions.

2 BACKGROUND

2.1 Dynamic Fiducial Markers

Previous studies in dynamic characteristics of fiducial markers proved the potential of multimodal physical-digital experiences. Some works investigated the physical shape of the media to hold the AR marker, for example, by putting the markers on the surfaces of a cube[17] or on everyday objects[8]. Other works looked into materials that allow dynamic changes. For example, HueCode uses a physical bandpass filter so that the robot camera can capture both ArUco and QR codes printed in different colors on plain paper [28, 34]. Peiris et al. used thermochromic inks to create dynamic AR markers so that the pattern can morph into a new one for each temperature range[29].

More recently, scholars started to investigate intra- and inter-marker interactions. Intra-marker interaction uses physical deformation and paper crafting to influence the presence and absence of a marker. Zheng et al. explored tangible experiences by combining paper mechanics with printed fiducial markers [37]. An interesting aspect is that the markers are not directly presented in the front scene for interaction but rather positioned in the background for the camera to capture. Building upon this research, Tinycade, an introductory platform for alternate controller design, employs rotation and the presence or absence of AR markers in the background to detect and represent "joystick" behaviors [14, 15]. Inspired by [37], Scheirer and Harrison presented DynaTags, a comprehensive library of 23 mechanisms that enhance the content payload of individual markers [31]. One significant distinction is that DynaTags works with a standard and unmodified smartphone, providing a versatile solution for marker-based interactions. DynaTags introduced stacking mechanics by cutting windows into the markers and letting information through from a lower layer. When the structure is purposefully designed, the physical ordering of the stacked elements can be conveyed and deciphered [2].

Inter-marker interaction uses a combination of relationships (e.g., distance, presence, and absence) to serve as input variables for the interactive system [26, 32]. This technique has been widely applied towards using a camera to detect the physical distance between locations.

All of the aforementioned works are designed and intended for fiducial markers to be printed on plain paper, while our work explores the possibilities of transparent film.

2.2 Transparent Film Paper and AR Markers

Transparent film papers are thin sheets with coatings that allow light to pass through without significant distortion. They are commonly used in crafting projects for various creative purposes. There have been works studying transparent markers from a technical perspective. Teixeira et al. presented a study titled "Towards Transparent Marker," which showcased the marker's unique capabilities of being visible from both sides and the marker interference involved in stacking[33]. Zhang et al. proposed a method of stacking multiple transparent colored AR markers in space to display and manipulate multiple objects' order and rotation, proposing the mathematical constraints involved in marker design and the implementation of detecting the stacking order [36].

Our work delves into the HCI aspect and outlines the design of the stacking mechanism for AR interactions.

2.3 AR in Musical Expression

Researchers and practitioners are enthusiastic about applying AR in artistic and musical expressions. Zünd et al. proposed the concept of Augmented Creativity and illustrated 6 prototyped applications to enhance real-world creative activities, one of which is a music arrangement application that uses image-based markers for a mobile application to detect and render 3D models of the instruments and audio[39]. Lucas reported the design of AuSynthAR, an affordable AR musical instrument that requires only a mobile device, a set of tokens, a sound output device, and, optionally, a MIDI controller [25]. Kelly et al. presented ARcadic with an implementation of a "disc jockey (DJ)" table interface for music performance using fiducial markers and cardboard [20]. DynaTags introduced a music synthesizer with modular blocks that can be connected to create looping sounds, where a sequence of three blocks displays two markers detected by an overhead phone, allowing the creation of songs by assembling multiple sequences [31].

Our work uncovers the creative potential of the stacking mechanic and transparent AR markers by experimenting with prototyping and analyzing them in a music arrangement activity.

3 DESIGN

3.1 Music Arrangement

Music arrangement is an activity in music synthesis that involves creating and arranging music through computer software or a synthesizer. We explore tangible AR interaction in a trading card game in which individuals with varying degrees of musical knowledge can work together to create music. We classify musical expressions into three categories: drums (like claps, kicks, hats, cymbals, and rims), instruments (such as bass, guitar, keyboard, and orchestral), and vocals. When creating a mix, the guideline is to use no more than one selection from each category. In this work, music samples are collected from free sources online. The selection is purposeful to encompass a variety of styles.

3.2 The Design of Transparent AR Markers

The design of the transparent AR marker uses Custom Marker Creator[1], a design tool to create a customized ArUco dictionary. An ArUco marker is a square marker composed of a black border and an inner content that determines its identifier through a binary matrix. Predefined ArUco dictionaries are useful for ease of integration and robust camera pose estimation. Designing a customized ArUco dictionary is necessary because combining multiple markers was not considered when the standard ArUco dictionaries were created. For example, as illustrated in Figure 3, stacking ID = 1 and ID = 2 from the standard ArUco dictionary creates a pattern that is not included in the same dictionary.

Customizing an ArUco dictionary starts with indicating the number of bits in the marker content by determining the dimensions of the square matrix. Typical matrix dimensions include 5x5, 6x6, and 7x7. The size of the matrix influences the number of identifiable markers in the dictionary and the expressive space for individual marker content.

Another restriction in designing stackable transparent AR markers is marker interference. To ensure the stacked pile of markers is recognizable, the maximum number of markers and their orientation are significant factors, as they are related to the interference

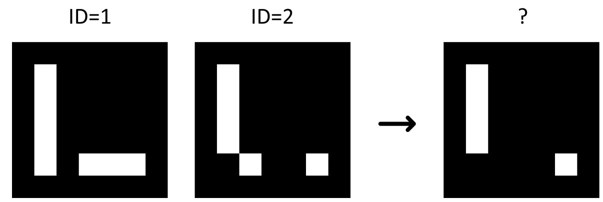

Figure 3: An example of stacking two markers from the standard ArUco dictionary generates a pattern that is not included in the dictionary.

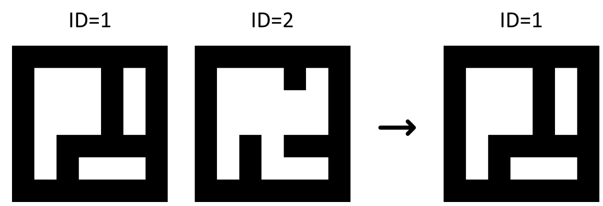

Figure 4: An example of marker interference. In this example, two markers have overlapping patterns, causing the stacked deck indistinguishable.

each marker causes on the others. Figure 4 shows an example in which two markers have overlapping patterns, causing the stacked marker cannot be distinguished. To bypass the complexity of overlapping patterns, a simple solution is to create a set of markers in which each two of the markers have no interference. Inspired by "orthogonal" markers [33], here we introduce the concepts of "group" and "ring". A group is a set of markers; only markers from different groups can be stacked together. When groups are allocated distinct territories that do not overlap, stacking markers from different groups will not result in any interference among markers. One way to allocate distinct territories is to divide the marker content into concentric squares, where each square locates at a different "radius". As a matter of convenience, we refer to these segments as "rings". When the marker's width is an odd number, the central bit stands alone. While a single bit might convey minimal information, it can serve as a toggle button. This functionality proves valuable in the context of stackable marker mechanics.

In Stackable Music, we utilized a 7x7 marker template, consisting of 3 rings and a central square. As illustrated in Figure 6, Each category (Drum, Instrument, and Vocal) is assigned a unique layer and corresponding ring. The central square functions as a Stop-and-Play control; audio can only be played when this square is present as shown in Figure 7. The area outside the marker is left open for graphic design. In thisd instance, as seen in Figure 8, we opted for a simple hand-drawn frame with the letter "E" positioned in the top left corner to indicate the marker's front/back side and orientation.

3.3 Unity Implementation

We developed Stackable Music AR using Unity. *OpenCV for Unity*[2] is a paid Unity plug-in that allows developers to use OpenCV[5],

[1] https://jingruchenmax.github.io/StackAR/

[2] https://enoxsoftware.com/opencvforunity/

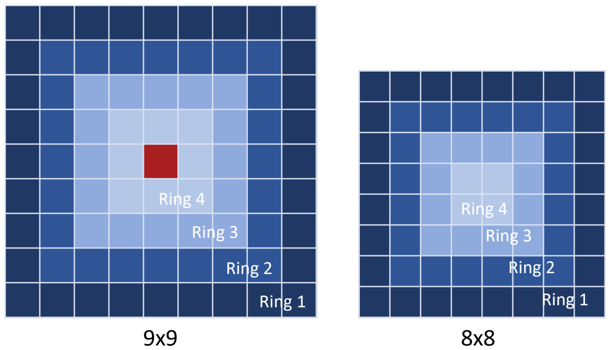

Figure 5: An illustration of dividing the marker content into rings.

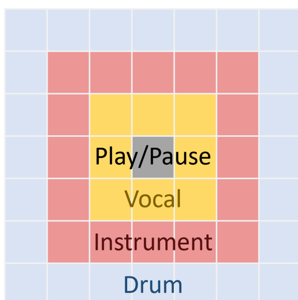

Figure 6: Each music category occupies a layer and is assigned a ring area and a central square as an on/off button.

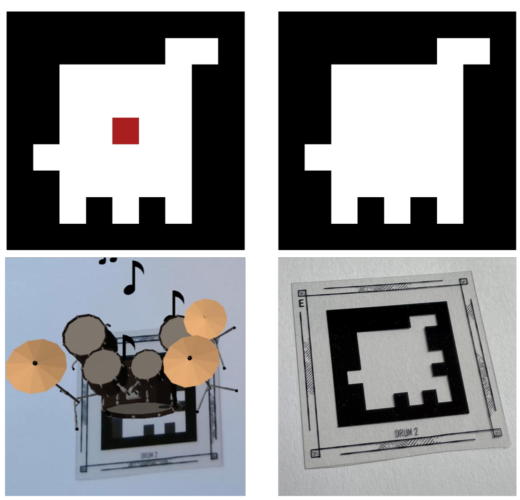

Figure 7: The audio player and animation will only be triggered when the central square is occupied.

an open-source computer vision and machine learning software library, in Unity. *OpenCV for Unity* was used to detect custom ArUco code. We implemented audio, 3D model, and particle effects. Once a marker is detected, the corresponding audio, model, and animation are presented. The concept of decoding a combined marker is shown

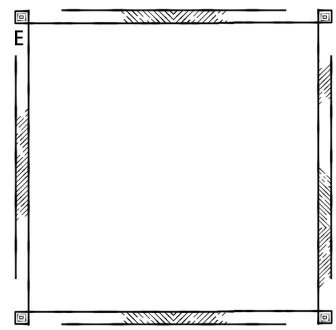

Figure 8: A decorative frame surrounds the marker on the outside.

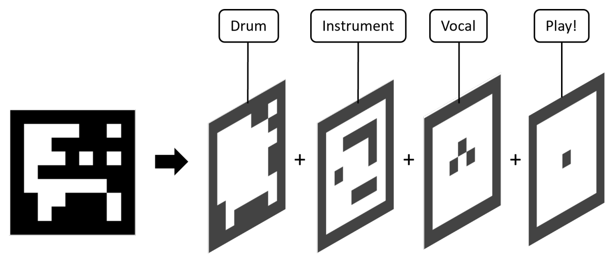

Figure 9: An example of a combined marker that consists of four groups, including drum, instrument, vocal, and play.

in Fig. 9. All combinations of markers from different groups are calculated and added to the marker dictionary for detection. The combined markers consist of multiple basic markers, meaning that the audio, model, and particle effects are also derived from the basic markers.

3.4 System Setup

Stackable Music requires transparent AR markers, a computer, and a camera, shown in Fig. 10. It is recommended to use a top-down camera with a desktop for an optimal experience. The choice of transparent film product depends on the type of printer. In our case, we used a low-cost inkjet printer and compatible transparent paper for creating the prototype. After that, the transparent AR markers are ready to be cut.

3.5 Gameplay

The gameplay of Stackable Music involves stacking a subset of provided transparent markers to create a musical composition, employing pre-recorded music clips. The primary objective of the game is to acquaint players with the distinct features of each music clip and facilitate the generation of harmonious compositions. When the Stop-and-Play marker is included in the stack which is captured by the camera, the corresponding music clip will be played and looped. The order in which the markers are stacked does not affect the outcome. Additionally, if multiple stacked decks of AR markers are observed by the camera, they will be played simultaneously.

Stackable Music is a solvable game, because the number of markers is countable, resulting in finite potential marker combinations.

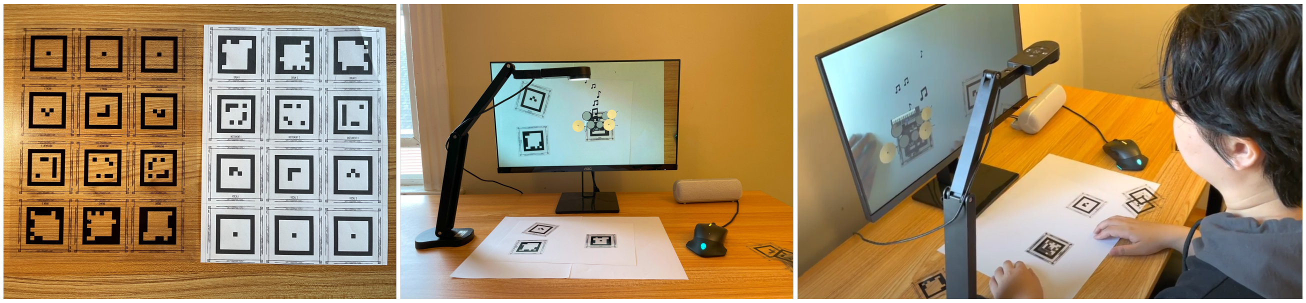

Figure 10: An example system setup with printed transparent markers and a desktop computer with a top-down camera.

While there isn't a traditional win-or-lose condition, players will eventually realize they have solved the game by iterating through all possible combinations.

To add replayability and uncertainty, Stackable Music is recommended to be played by multiple players (2-4) in a group. Players can share the music they create with others and seek feedback.

4 DISCUSSION, LIMITATIONS, AND FUTURE WORK

Through the design of the technology and prototyping the experience of the game Stackable Music, we explore what new expressive potentials are enabled by this technology, and also identify some potential future directions for research. The discussion is fueled by reflecting on the transparent AR marker system through the design process, rather than a conducted user study.

4.1 Low-cost "Do it yourself" (DIY) and tangible AR

This work explored the novel stacking mechanics of AR markers using affordable materials - transparent film sheets. Being tangible and touchable are important features for an AR starter DIY project. The unique interaction of stacking markers is fun and intuitive, which also leads the creators to think about the design affordances and limitations of objects. In particular, the marker design aspect explicitly requires the designers to think about the size of the marker and the restrictions of marker interference.

The prototype requires a certain amount of effort in crafting and hands-on practice. Aligning the markers when stacking requires the edge of each marker to be precisely cut. Currently, the stacked markers need to be precisely aligned, with an acceptable error tolerance of 1-2 mm.

Additionally, the transparent film itself is a great medium for artistic expression. The blank space outside of the marker content can be designed with decoration or with meaningful information like themes and marker annotations. Besides graphics, one can think of all kinds of physical shapes, for example, triangles, circles, or other metaphors that work well with AR content.

4.2 Occlusion, lighting, and reflection

Occlusion poses a significant challenge for all fiducial marker systems, as it raises questions about their resilience in detecting partially-covered markers. Currently, the customized ArUco dictionary with OpenCV demonstrates reasonable performance in this regard. However, the accuracy of detection also relies on the design of the markers themselves. Traditionally, researchers have computed and tested various patterns to determine the optimal set for fiducial marker systems. However, in the context of supporting stacking mechanics, custom AR markers are created that may not be fully optimized for accuracy. To address this, future efforts can be directed toward simulating and predicting the quality of markers within the custom marker design system. Such simulations would allow designers to determine the expected accuracy of their marker designs.

Another significant challenge is lighting. While ample lighting is preferred for camera detection, the transparent film used often has reflective properties. This becomes problematic for detection when the light source is either point-like or directional, as it can create unwanted reflection circles. One potential avenue for future exploration involves experimenting with alternative transparent materials that minimize or eliminate these reflection issues. Additionally, integrating the system with controlled and even lighting sources, such as light boxes, could offer a promising direction for mitigating the challenges posed by lighting conditions.

4.3 Customization and creative coding

An interesting direction is to integrate creative coding functions with the AR marker so that the music piece or art can be customized. To support the creative coding aspect, an implementation of a code-sharing server could be highly beneficial for the community. This server would provide a platform for artists to share their code snippets, techniques, and innovative ideas. This exchange of knowledge and expertise would not only enhance the quality of individual creations but also contribute to the evolution and growth of the entire Stackable Music ecosystem.

4.4 Social and community building

The gameplay in Stackable Music is similar to a trading card game. Trading card games encompass a card-based gameplay format that combines strategic deck-building elements with card trading mechanics among players, both during and outside of gameplay. This type of game emphasizes social interaction as a significant aspect of the overall gaming experience, alongside the card battles themselves. AR implementation typically involves showcasing 3D models, animations, and audio effects to enhance the visual appeal and immersive nature of the user experience. In addition, our research takes a distinct approach by placing an emphasis on facilitating tangible interactions and social engagement between players, addressing different aspects of the AR game experience. In future studies, a user study and research in the wild can help us gain valuable insights into the design elements and social aspects that hold the highest significance for players.

4.5 Sharing physical product

The introduction of stacked markers in the gameplay of Stackable Music has brought about a unique advantage in terms of selection and arrangement. Unlike plain paper markers, where it can be challenging to convey the distance between markers and the overall layout, stacked markers provide a clear visual representation of the music composition. This makes it easier for players to share their creations and communicate their intended arrangements to others.

To enhance the accessibility and portability of the stacked markers, an intriguing option for storage and transport would be the use of an acrylic photo frame keychain. This compact and versatile accessory could serve as an ideal container for the markers. The acrylic frame would provide protection from wear and tear, ensuring that the markers remain intact and legible. Additionally, the transparency of the frame would allow users to easily view and identify the stacked markers without needing to remove them from the keychain.

The keychain aspect of the storage solution adds a practical element to the design. By attaching the acrylic photo frame to a keychain, players can conveniently carry their stacked markers with them wherever they go. This promotes spontaneous music creation and sharing opportunities, as players can readily showcase their compositions and engage in collaborative experiences with others.

Furthermore, the acrylic photo frame keychain offers an aesthetic appeal. It allows players to showcase their creativity and personalized markers, turning them into portable works of art. The transparent nature of the frame also provides a visually pleasing way to display the stacked markers when not in use.

5 CONCLUSION

Marker-based AR offers a unique and engaging experience by incorporating the tangible manipulation of trackable objects as an input to interactive systems. The interaction between and within markers adds an extra layer of fun to tangible interactions. In this paper, we presented the design of transparent AR markers and demonstrated their integration into a captivating card game called Stackable Music. Additionally, we examined the potential that stacking transparent markers brings and highlighted certain limitations. Based on our findings, we put forth future directions in the interactive and creative domains that can benefit from the use of transparent AR markers. By further exploring these possibilities, we can unlock new realms of interactive experiences and foster innovation in various fields.

ACKNOWLEDGMENTS

We thank Karen Royer and Albert Ruixiang Han for contributing to the brainstorming phase of this research, as well as Shawn Gilles for proofreading the manuscript. We also thank the reviewers for their insightful comments.

REFERENCES

[1] Ronald T. Azuma. 1997. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments* 6, 4 (Aug. 1997), 355–385. https://doi.org/10.1162/pres.1997.6.4.355

[2] Tom Bartindale and Chris Harrison. 2009. Stacks on the surface: resolving physical order using fiducial markers with structured transparency. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*. ACM, Banff Alberta Canada, 57–60. https://doi.org/10.1145/1731903.1731916

[3] Santiago Bedoya-Rodriguez, Cristian Gomez-Urbano, Alvaro Uribe-Quevedoy, and Christian Quintero. 2014. Augmented reality RPG card-based game. In *2014 IEEE Games Media Entertainment*. IEEE, Toronto, ON, Canada, 1–4. https://doi.org/10.1109/GEM.2014.7118433

[4] Mark Billinghurst, Hirokazu Kato, and Ivan Poupyrev. 2008. Tangible augmented reality. In *ACM SIGGRAPH ASIA 2008 courses on - SIGGRAPH Asia '08*. ACM Press, Singapore, 1–10. https://doi.org/10.1145/1508044.1508051

[5] G. Bradski. 2000. The OpenCV Library. *Dr. Dobb's Journal of Software Tools* (2000).

[6] Sandra Camara, Valentina Nisi, and Teresa Romão. 2021. Enhancing Children Spatial Skills with Augmented Reality Serious Games. In *Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '21)*. Association for Computing Machinery, New York, NY, USA, 94–100. https://doi.org/10.1145/3450337.3483470

[7] Gabriel De Ioannes Becker and Eva Hornecker. 2021. Sally&Molly: A Children's Book with Real-Time Multiplayer Mobile Augmented Reality. In *Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '21)*. Association for Computing Machinery, New York, NY, USA, 80–86. https://doi.org/10.1145/3450337.3483498

[8] Adam Drogemuller, James Walsh, Ross T. Smith, Matt Adcock, and Bruce H Thomas. 2021. Turning everyday objects into passive tangible controllers. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '21)*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3430524.3442460

[9] Mark Fiala. 2004. Artag, an improved marker system based on artoolkit. *National Research Council Canada, Publication Number: NRC* 47419 (2004), 2004.

[10] Mark Fiala. 2010. Designing Highly Reliable Fiducial Markers. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 32, 7 (July 2010), 1317–1324. https://doi.org/10.1109/TPAMI.2009.146 Conference Name: IEEE Transactions on Pattern Analysis and Machine Intelligence.

[11] Anna Fuste and Chris Schmandt. 2019. HyperCubes: A Playful Introduction to Computational Thinking in Augmented Reality. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts (CHI PLAY '19 Extended Abstracts)*. Association for Computing Machinery, New York, NY, USA, 379–387. https://doi.org/10.1145/3341215.3356264

[12] S. Garrido-Jurado, R. Muñoz-Salinas, F. J. Madrid-Cuevas, and M. J. Marín-Jiménez. 2014. Automatic generation and detection of highly reliable fiducial markers under occlusion. *Pattern Recognition* 47, 6 (June 2014), 2280–2292. https://doi.org/10.1016/j.patcog.2014.01.005

[13] Terrell Glenn, Ananya Ipsita, Caleb Carithers, Kylie Peppler, and Karthik Ramani. 2020. StoryMakAR: Bringing Stories to Life With An Augmented Reality & Physical Prototyping Toolkit for Youth. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376790

[14] Peter Gyory. 2022. Creating Platforms to Support Craft and Creativity in Game Controller Design. In *Creativity and Cognition (C&C '22)*. Association for Computing Machinery, New York, NY, USA, 708–710. https://doi.org/10.1145/3527927.3533733

[15] Peter Gyory, Perry Owens, Matthew Bethancourt, Amy Banic, Clement Zheng, and Ellen Yi-Luen Do. 2022. Build Your Own Arcade Machine with Tinycade. In *Creativity and Cognition (C&C '22)*. Association for Computing Machinery, New York, NY, USA, 312–322. https://doi.org/10.1145/3527927.3533023

[16] Robert J.K. Jacob, Audrey Girouard, Leanne M. Hirshfield, Michael S. Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. 2008. Reality-based interaction: a framework for post-WIMP interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. Association for Computing Machinery, New York, NY, USA, 201–210. https://doi.org/10.1145/1357054.1357089

[17] Carmen M. Juan, Giacomo Toffetti, Francisco Abad, and Juan Cano. 2010. Tangible Cubes Used as the User Interface in an Augmented Reality Game for Edutainment. In *2010 10th IEEE International Conference on Advanced Learning Technologies*. IEEE, Sousse, Tunisia, 599–603. https://doi.org/10.1109/ICALT.2010.170 ISSN: 2161-377X.

[18] Martin Kaltenbrunner and Ross Bencina. 2007. reacTIVision: A Computer-Vision Framework for Table-Based Tangible Interaction. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana) *(TEI '07)*. Association for Computing Machinery, New York, NY, USA, 69–74. https://doi.org/10.1145/1226969.1226983

[19] Hirokazu Kato and Mark Billinghurst. 1999. Marker tracking and hmd calibration for a video-based augmented reality conferencing system. In *Proceedings 2nd IEEE and ACM International Workshop on Augmented Reality (IWAR'99)*. IEEE, San Francisco, CA, USA, 85–94. https://doi.org/10.1109/IWAR.1999.803809

[20] Annie Kelly, R. Benjamin Shapiro, Jonathan de Halleux, and Thomas Ball. 2018. ARcadia: A Rapid Prototyping Platform for Real-time Tangible Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/3173574.3173983

[21] Maren Klimm, Dominik Walczak, and Daniel Ayen. 2019. JumpAR – Augmented Reality Platformer. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts (CHI PLAY '19 Extended Abstracts)*. Association for Computing Machinery, New York, NY, USA, 261–266. https://doi.org/10.1145/3341215.3358249

[22] Albert H. T. Lam, Kevin C. H. Chow, Edward H. H. Yau, and Michael R. Lyu. 2006. ART: augmented reality table for interactive trading card game. In *Proceedings of the 2006 ACM international conference on Virtual reality continuum and its applications (VRCIA '06)*. Association for Computing Machinery, New York, NY, USA, 357–360. https://doi.org/10.1145/1128923.1128987

[23] Meng Chun Lam, Hwei Kei Tee, Siti Soleha Muhammad Nizam, Nurhazarifah Che Hashim, Nur Asylah Suwadi, Siok Yee Tan, Nazatul Aini Abd Majid, Haslina Arshad, and Sook Yee Liew. 2020. Interactive Augmented Reality with Natural Action for Chemistry Experiment Learning. *TEM Journal* 9, 1 (Feb. 2020), 351–360. https://doi.org/10.18421/TEM91-48 Num Pages: 351-360 Place: Novi Pazar, Serbia Publisher: UIKTEN - Association for Information Communication Technology Education and Science.

[24] Jingya Li, Erik D. van der Spek, Jun Hu, and Loe Feijs. 2019. Turning Your Book into a Game: Improving Motivation through Tangible Interaction and Diegetic Feedback in an AR Mathematics Game for Children. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '19)*. Association for Computing Machinery, New York, NY, USA, 73–85. https://doi.org/10.1145/3311350.3347174

[25] Pedro Pablo Lucas. 2019. AuSynthAR: A simple low-cost modular synthesizer based on Augmented Reality. Zenodo, Porto Alegre, Brazil. https://doi.org/10.5281/ZENODO.3673011

[26] Kyzyl Monteiro, Ritik Vatsal, Neil Chulpongsatorn, Aman Parnami, and Ryo Suzuki. 2023. Teachable Reality: Prototyping Tangible Augmented Reality with Everyday Objects by Leveraging Interactive Machine Teaching. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3581449

[27] Leonid Naimark and Eric Foxlin. 2002. Circular data matrix fiducial system and robust image processing for a wearable vision-inertial self-tracker. In *Proceedings. International Symposium on Mixed and Augmented Reality*. IEEE, Darmstadt, Germany, 27–36. https://doi.org/10.1109/ISMAR.2002.1115065

[28] Yoshito Okada, Daiki Fujikura, Yu Ozawa, Kenjiro Tadakuma, Kazunori Ohno, and Satoshi Tadokoro. 2021. HueCode: A Meta-marker Exposing Relative Pose and Additional Information in Different Colored Layers. In *2021 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, Xi'an, China, 5928–5934. https://doi.org/10.1109/ICRA48506.2021.9561783 ISSN: 2577-087X.

[29] Roshan Lalintha Peiris, Owen Noel Newton Fernando, and Adrian David Cheok. 2011. A Dynamic AR Marker for a Paper Based Temperature Sensor. In *Ambient Intelligence (Lecture Notes in Computer Science)*, David V. Keyson, Mary Lou Maher, Norbert Streitz, Adrian Cheok, Juan Carlos Augusto, Reiner Wichert, Gwenn Englebienne, Hamid Aghajan, and Ben J. A. Kröse (Eds.). Springer, Berlin, Heidelberg, 195–199. https://doi.org/10.1007/978-3-642-25167-2_24

[30] Ihsan Rabbi and Sehat Ullah. 2013. A Survey on Augmented Reality Challenges and Tracking. *Acta graphica : znanstveni časopis za tiskarstvo i grafičke komunikacije* 24, 1-2 (Feb. 2013), 29–46. https://hrcak.srce.hr/102430 Publisher: Acta Graphica d.o.o..

[31] Cassandra Scheirer and Chris Harrison. 2022. DynaTags: Low-Cost Fiducial Marker Mechanisms. In *INTERNATIONAL CONFERENCE ON MULTIMODAL INTERACTION*. ACM, Bengaluru India, 432–443. https://doi.org/10.1145/3536221.3556591

[32] Anurag Kumar Singh and Jayesh S. Pillai. 2022. Exploration of inter-marker interactions in Tangible AR. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology (VRST '22)*. Association for Computing Machinery, New York, NY, USA, 1–2. https://doi.org/10.1145/3562939.3565642

[33] Joao Marcelo Xavier Natario Teixeira, Alexandre de Queiroz Burle, Arthur de Andrade Almeida, Thiago Buarque de Gusmao Lafayette, Vinicius Lima Ventura, Vitor Mendes Carvalho, and Veronica Teichrieb. 2022. Towards Transparent Markers. In *Symposium on Virtual and Augmented Reality (SVR'21)*. Association for Computing Machinery, New York, NY, USA, 74–83. https://doi.org/10.1145/3488162.3488212

[34] Yoshiki Yokota, Daiki Fujikura, Yoshito Okada, Kazunori Ohno, Kenjiro Tadakuma, and Satoshi Tadokoro. 2022. HueCode2: An Illumination-Robust Meta-Marker Overlaying Multiple Fiducial Markers using Optimal Color Scheme. In *2022 IEEE 18th International Conference on Automation Science and Engineering (CASE)*. IEEE, Mexico City, Mexico, 583–588. https://doi.org/10.1109/CASE49997.2022.9926583 ISSN: 2161-8089.

[35] Fabio Zambetta, William Raffe, Marco Tamassia, Florian 'Floyd, Mueller, Xiaodong Li, Niels Quinten, Rakesh Patibanda, Daniel Dang, and Jon Satterley. 2020. Reducing Perceived Waiting Time in Theme Park Queues via an Augmented Reality Game. *ACM Transactions on Computer-Human Interaction* 27, 1 (Jan 2020), 3:1–3:30. https://doi.org/10.1145/3361524

[36] Xuan Zhang, Jonathan Lundgren, Yoya Mesaki, Yuichi Hiroi, and Yuta Itoh. 2020. Stencil Marker: Designing Partially Transparent Markers for Stacking Augmented Reality Objects. In *2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. IEEE, Recife, Brazil, 255–257. https://doi.org/10.1109/ISMAR-Adjunct51615.2020.00073

[37] Clement Zheng, Peter Gyory, and Ellen Yi-Luen Do. 2020. Tangible Interfaces with Printed Paper Markers. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS '20)*. Association for Computing Machinery, New York, NY, USA, 909–923. https://doi.org/10.1145/3357236.3395578

[38] Zhiying Zhou, Adrian David Cheok, JiunHorng Pan, and Yu Li. 2004. Magic Story Cube: an interactive tangible interface for storytelling. In *Proceedings of the 2004 ACM SIGCHI International Conference on Advances in computer entertainment technology (ACE '04)*. Association for Computing Machinery, New York, NY, USA, 364–365. https://doi.org/10.1145/1067343.1067404

[39] Fabio Zünd, Mattia Ryffel, Stéphane Magnenat, Alessia Marra, Maurizio Nitti, Mubbasir Kapadia, Gioacchino Noris, Kenny Mitchell, Markus Gross, and Robert W. Sumner. 2015. Augmented creativity: bridging the real and virtual worlds to enhance creative play. In *SIGGRAPH Asia 2015 Mobile Graphics and Interactive Applications (SA '15)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/2818427.2818460

Received 2023-06-22; accepted 2023-08-03