# Stencil Marker: Designing Partially Transparent Markers for Stacking Augmented Reality Objects

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## ABSTRACT

We propose a transparent colored AR marker that allows 3D objects to be stacked in space. Conventional AR markers make it difficult to display multiple objects in the same position in space, or to manipulate the order or rotation of objects. The proposed transparent colored markers are designed to detect the order and rotation direction of each marker in the stack from the observed image, based on mathematical constraints. We describe these constraints to design markers, the implementation to detect its stacking order and rotation of each marker, and a proof-of-concept application *Totem Poles*. We also discuss the limitations of the current prototype and possible research directions.

**Index Terms:** Human-centered computing—Visualization—Visualization techniques—Treemaps; Human-centered computing—Visualization—Visualization design and evaluation methods

## 1 INTRODUCTION AND RELATED WORK

In augmented reality (AR) applications, the fundamental functional requirement is to register AR contents into the real world. An AR system estimates the 6 Degree-of-Freedom (DoF) pose of the camera to the real space by registering a coordinate (*e.g.*, by detecting fiducial markers or feature points). Although markerless tracking has become more popular due to technological advances, marker-based tracking is still widely used thanks to its simplicity in setting coordinates for simple AR use cases [1, 3].

The performance of marker-based tracking depends on the design of the AR marker pattern. AR Toolkit is one of the most famous square markers— [4]. Many variations of square markers followed after AR Toolkit. These frame-type markers embed a pattern within the are of the frame pattern [6].

AR Tag is another variant for AR Toolkit. It replaces the partial line fitting algorithm with a quadrilateral heuristic search algorithm and allows for interruptions that define lines at the edge of the marker, which improves the system's accuracy in detecting markers when marker's edges are obscured and in extreme environments [2].

There are many other types of AR markers. Random Dot Marker is such an example that consists of scattered dots in a plane and can be designed in a variety of shapes [7].

Markers can be designed not only in black-and-white but also in color. Colored markers can increase the information contained in a certain marker size. Langlotz combined red, green, and blue markers and made unsynchronized 4D barcodes to transfer data between public displays and mobile devices. [5]

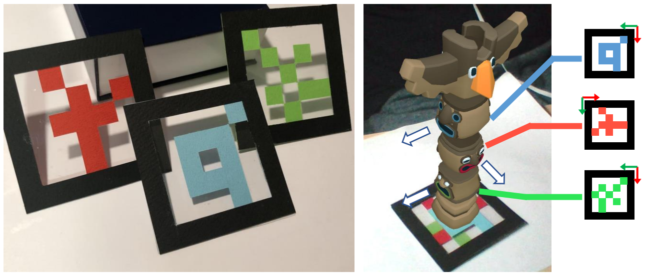

Figure 1: Stencil Markers. Left: 5x5-coded markers. Right: Demonstrating the stencil markers in a Totem-Pole application. The model reflects the order and the orientation of the three stacked markers.

Overlaying multiple virtual objects on the same location can be widely applied to various AR applications, such as entertainment and communication. Customizing the order and orientations of multiple objects provides rich information and promotes intuitive user operation. Existing black-and-white AR markers are, however, mainly intended to display a single object, and it is not possible to display multiple virtual objects in the same position and change the order and orientation of each object.

We propose a transparent color markers that allows 3D objects to be stacked in space. Our transparent marker has a central part for position detection, a peripheral part for orientation detection, and a color for order detection. Thus, our marker can manipulate the order and orientation of virtual objects. We provides mathematical formulation of our marker, implementation and marker detection process, and proof-of-concept application *Totem Poles*. Although some research has been proposed to extend the capabilities of a single black-and-white marker, to the best of our knowledge, our marker design is the first attempt to manipulate multiple virtual objects in the same position by marker-based AR approach.

## 2 MATHEMATICAL FORMULATION

Our approach to design markers is divided into two steps: identifying the order, and identifying the direction. After explaining the mathematical notation, we describe the mathematical constraints for each step.

### 2.1 Notations

Our common notations and variables are as follows:

- $\mathbf{c} = \{c_k\}$ denotes a set of all $K$ non-transparent colors such as red, green, and blue. Also, $\tau$ denotes transparent color.
- $\mathbf{M} = \{m_{ij}\}$ denotes a marker with $N \times N$ cells. Each cell $m_{ij}$ represents either one of the colors $\mathbf{c}$ or a transparent cell $\tau$.
- $\mathfrak{M} = \{\mathbf{M}_k\}$ denotes a set of all $K$ markers. Also, we denote each cell of the indexed marker as $\mathbf{M}_k = \{m^k_{ij}\}$. We now assume that each marker is composed of a single color that is different from the other markers. (*i.e.*, $m^k_{ij} = c_k \vee \tau$).

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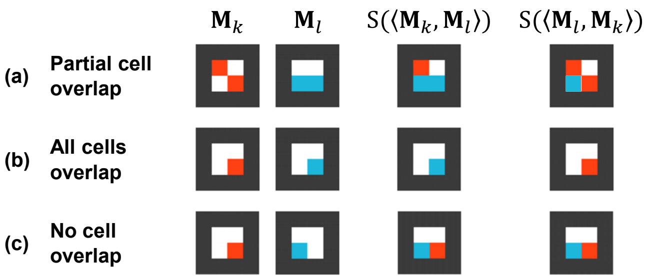


Figure 2: A minimal example demonstrating the concept of transparent colored markers based on Equation (1) and (2). Each column shows $\mathbf{M}_k, \mathbf{M}_l$, and the stacked image $\mathbf{S}(\Gamma)$ on $\Gamma = \langle\mathbf{M}_k,\mathbf{M}_l\rangle$ and $\Gamma = \langle\mathbf{M}_l,\mathbf{M}_k\rangle$, respectively. (a) If one or more cells overlap and there is one or more cells where the color of the marker is visible, it is possible to uniquely identify the order of the markers from the observed markers $\mathbf{S}(\Gamma)$ for all possible stacks $\forall\Gamma\in\Gamma_{\mathfrak{M}} = \{\langle\mathbf{M}_k\rangle, \langle\mathbf{M}_l\rangle, \langle\mathbf{M}_k,\mathbf{M}_l\rangle, \langle\mathbf{M}_l,\mathbf{M}_k\rangle\}$. (b) If there are no cells where the color of each marker is visible, it is not possible to determine whether the stack is $\Gamma = \langle\mathbf{M}_l\rangle$ or $\langle\mathbf{M}_k,\mathbf{M}_l\rangle$. (c) If there is no overlap cell, it is impossible to determine whether the marker order is $\Gamma = \langle\mathbf{M}_k,\mathbf{M}_l\rangle$ or $\langle\mathbf{M}_l,\mathbf{M}_k\rangle$.

- $\Gamma$ denotes a stack of marker, *i.e.*, the tuple of $\mathbf{M}$ without redundancy. The order of the tuple represents the order of its real marker stack starting from the bottom to the top. Also, a set $\Gamma_{\mathfrak{M}}$ represents all possible stack combinations given a marker set $\mathfrak{M}$. *E.g.*, $\Gamma_{\mathfrak{M}} = \{\langle\mathbf{M}_1\rangle, \langle\mathbf{M}_2\rangle, \langle\mathbf{M}_1,\mathbf{M}_2\rangle, \langle\mathbf{M}_2,\mathbf{M}_1\rangle\}$ when $K = 2$.
- $\mathbf{S}(\Gamma) = \{s_{ij}\}$ denotes an observed marker corresponds to $\Gamma$, viewed from the top. Thus, $\mathbf{S}(\Gamma)$ consists $N\times N$ cells (*i.e.*, $s_{ij}\in\mathbf{c}\vee s_{ij}=\tau$). We will design the markers so that $\mathbf{S}(\Gamma)$ is unique for all possible stack $\Gamma_{\mathfrak{M}}$.
- We define an *overlapping* condition between cells as follows. Given two markers $\mathbf{M}_k$ and $\mathbf{M}_l$ in a stack $\Gamma$, cell $(i,j)$ is overlapping when the cell on two markers are both non-transparent (*i.e.*, $m^k_{ij}\neq\tau\wedge m^l_{ij}\neq\tau$).

### 2.2 Marker Design for Order Detection

First, we reveal the constraints of the marker design to make the order of markers in a stack detectable.

An observed image $\mathbf{S}(\Gamma)$ must creates a pattern that can identify the order of the stack $\Gamma$. To achieve this, for any stack $\forall\Gamma\in\Gamma_{\mathfrak{M}}$, it should be possible to distinguish from the image $\mathbf{S}(\Gamma)$ which of the two markers in the stack is on top.

To simplify the problem, we consider a stack that only consists from $\mathbf{M}_k$ and $\mathbf{M}_l$, $\Gamma = \langle\mathbf{M}_k,\mathbf{M}_l\rangle$. To be able to identify the order of $\mathbf{M}_k$ and $\mathbf{M}_l$, these markers must satisfy the following constraints:

A. There must be one or more overlapping cell in $\mathbf{M}_k$ and $\mathbf{M}_l$, *i.e.*, $\exists(i,j)\in\mathbb{R}\times\mathbb{R}, m^k_{ij}\neq\tau\wedge m^l_{ij}\neq\tau$.

B. For each marker, there must be one or more cells where the marker color is visible, *i.e.*, $\forall c\in\{c_k,c_l\},\exists(i,j)\in\mathbb{R}\times\mathbb{R}, s_{ij}=c$.

Figure 2 shows examples where the order of two $2\times2$ markers can and cannot be identified.

Next, we consider an arbitrary stack $\Gamma$ that includes $\mathbf{M}_k$ and $\mathbf{M}_l$. Since all markers are assumed to have different colors, the above constraints A, B must hold for all possible marker pairs.

To extend the constraint A to any stack, all possible marker pairs must first have one or more duplicate cells. Also, cells above the overlapping cells must be transparent so that the overlapping cells can be observed. These constraints can be denoted as follows:

$$\forall(\mathbf{M}_k,\mathbf{M}_l)\in\mathfrak{M}\times\mathfrak{M}(k\neq l),\exists(i,j)\in\mathbb{R}\times\mathbb{R},$$
$$(m^k_{ij}\neq\tau\wedge m^l_{ij}\neq\tau)\vee(\forall\mathbf{M}\in\mathfrak{M}\backslash\{\mathbf{M}_k,\mathbf{M}_l\},m_{ij}=\tau). \tag{1}$$

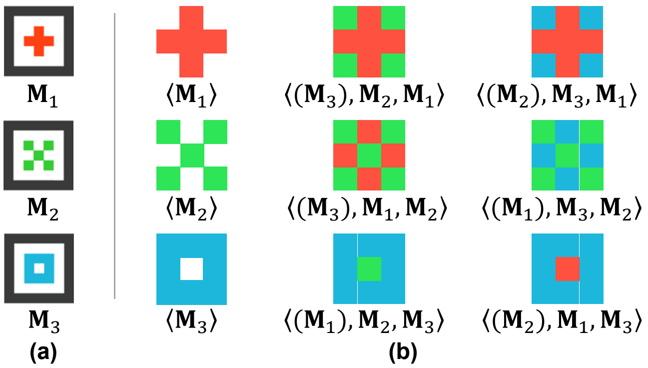


Figure 3: (a) The central part of the markers we designed with $5\times5$ cells satisfying the constraints of order detection. (b) Observed markers for all possible stack combination. The presence of the markers denoted in the brackets $(\cdot)$ cannot be determined in the central part of the marker itself yet can be confirmed at the periphery parts used to detect marker rotation.

To extend the constraint B to any stack in the same way, for each marker, no matter how the markers are stacked, there will be one or more cells where the marker color is visible in the observed image. This can be denoted as follows:

$$\forall\Gamma\in\Gamma_{\mathfrak{M}},\forall c\in\Gamma,\exists(i,j)\in\mathbb{R}\times\mathbb{R},s_{ij}=c. \tag{2}$$

From the above discussion, it can be seen that we can specify an order for any stack by designing markers that satisfy Equation (1) and (2).

Note that our marker further takes rotations into account. Hence, to satisfy Equation (1) even in the rotated state, the cells for order detection must be placed in a rotational invariant position on the marker.

Figure 3 (a) shows the central part of the markers we designed with $5\times5$ cells satisfying the constraints of order detection (Equation (1) and (2)), and Figure 3 (b) shows the observed markers $\mathbf{S}\Gamma$ for all possible stack combination.

### 2.3 Marker Design for Rotation Detection

For rotation detection, we need to place colors on the marker to satisfy Eq. 2, taking care not to create rotationally symmetric cells.

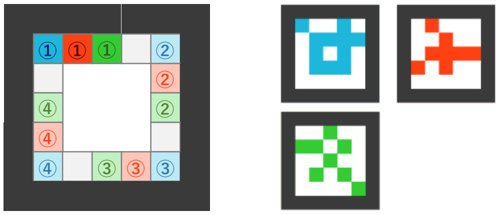
The smallest design to detect the rotation of each marker for any possible stack is a design that has a different color at a different position on one side of the perimeter when all the markers are stacked (Figure 4 (a)). To improve marker detection stability, we increased the number of non-transparent cells so that the colors of all markers in the stack appear for any possible stack and avoid symmetry (Figure 4 (b)).

## 3 IMPLEMENTATION & APPLICATION: TOTEM POLES

To demonstrate our concept, we implemented the marker design and the simple application for three markers with $5\times5$ cells. In this section, we describe how to detect the order and rotation of markers from the captured images. After the order and rotation detection, we rendered the stacked *totem pole* pieces by using the detected marker order and rotations. Our application is implemented by Processing 3.5.4 and OpenCV 2.4.10. The application ran on a standard PC with a video rate. Please consult our supplementary demo video for more detail.

### 3.1 Marker Color Detection

Before detection, the color of each marker must be defined. We used three colors (red, green, and blue), a frame color (black), and a



(a) (b)

Figure 4: (a) Minimum marker configuration for detecting rotation. The numbers 1-4 correspond to the position of the cell when each marker is rotated at 0°, 90°, 180°, and 270°. (b) The final design of our markers, which can detect both rotation and order of the markers.

transparent color as the marker colors, as shown in Figure 5. Each color is given an individual ID.

Since color detection is sensitive to the lighting conditions, we designed a white balancing routine to adjust the colors. We first find a reference white color in the image. To find the reference white color, we designed the marker so that one of the four corner cells must be transparent. If we use this marker on a white background, the transparent cell will appear in white. For these four corner cells, we found the white cell with the highest value given by $r+g+b$ and determined the reference white color.

After determining the reference white color, the color of each cell is corrected according to the following equation:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 255/R_w & 0 & 0 \\ 0 & 255/G_w & 0 \\ 0 & 0 & 255/B_w \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \tag{3}$$

where $(R', G', B')$ is the original color and $(R_w, G_w, B_w)$ is the reference white color.

After we got the $(R, G, B)$ data of the cell, we can compare the color to all five pre-defined marker colors and measuring their distance using the L2 norm. The color ID of the closest color to the pre-defined color is considered to be the color ID of the cell.

### 3.2 Marker Order and Rotation Detection

After determining the color ID for each cell, we can get an observed marker $\mathbf{S}(\Gamma)$. This $\mathbf{S}(\Gamma)$ is used to determine the current marker stack $\Gamma$.

To detect the order of the markers, it is confirmed which markers are in the stack by checking the color IDs of the observed markers. Then, the order of each marker is determined by checking how the cells overlap. In the current setup, to determine the stack $\Gamma$, the stack in the $3 \times 3$ central region of the observed image is compared with the image in the central region that appears in the combination of all possible stacks $\Gamma_{\mathfrak{M}}$ (Figure. 3).

After determining the order, we need to determine the rotation of each layer. To determine the rotation, we consider all possible rotations of each marker in the given stack $\Gamma$, then compare to the observations $\mathbf{S}(\Gamma)$.

## 4 DISCUSSION

We investigate the remaining issues, and we prospect on the research of our markers in the future.

**Evaluation of detection error.** Although we are currently demonstrating our idea with an application using 5×5 markers, there is a trade-off between marker length and detection error, and a trade-off between the number of markers that can be stacked and detection error. We will proceed with a quantitative evaluation of these trade-offs.

**Color change depending on the environment.** Our current marker detection method is susceptible to lighting changes and can only be applied on a white background. This problem could be solved by improving white-balance correction.

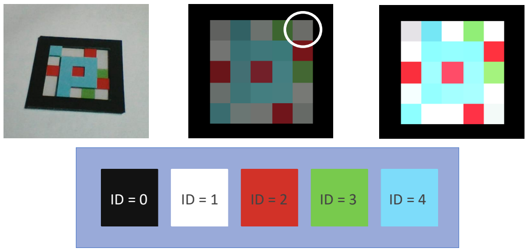


Figure 5: Example of the detection result. From the original picture to correct color blocks. (Top) from left to right: a photo captured by a camera, a 7x7-pixel marker image extracted and warped from the captured image, and a refined image by the color-normalized method described in Sec. 3.1. The cell circled in the middle image is used as the base color in white balance. (Bottom) The ID of each color.

**Automatic Marker Design Generation.** Currently, we design the markers manually based on the constraints. We believe that a detailed formulation of the constraints (Equation (1), (2)) will allow more color markers to be generated automatically by using satisfiability (SAT) solvers, etc.

**Fast search for order and rotation detection.** Our implementation uses a brute-force search to determine the order and rotation. A more efficient way to perform a fast search is appreciated.

## 5 CONCLUSION

In this paper, we have introduced a stacked transparent color marker that can be used to control the order and rotation of stacked virtual objects. We have described the mathematical constraints to design markers, the way to detect its stacking order and rotate angle, and a demo application *Totem Poles*. We hope to other researchers to extend the possibility for various human-computer interaction applications using these stackable AR markers.

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