Lightweight Capacitance-based Block System for 3D Space Interaction

Koshi Ikegawa
University of Tsukuba
1-1-1 Tennodai, Tsukuba,
Ibaraki, 305-8573 Japan
ikegawa@iplab.cs.tsukuba.ac.jp

Arika Yoshida
University of Tsukuba
1-1-1 Tennodai, Tsukuba,
Ibaraki, 305-8573 Japan
yoshida@iplab.cs.tsukuba.ac.jp

Masaya Tsuruta
University of Tsukuba
1-1-1 Tennodai, Tsukuba,
Ibaraki, 305-8573 Japan
tsuruta@iplab.cs.tsukuba.ac.jp

Buntarou Shizuki
University of Tsukuba
1-1-1 Tennodai, Tsukuba,
Ibaraki, 305-8573 Japan
shizuki@cs.tsukuba.ac.jp

Tetsuya Abe
University of Tsukuba
1-1-1 Tennodai, Tsukuba,
Ibaraki, 305-8573 Japan
abe@iplab.cs.tsukuba.ac.jp

Shin Takahashi
University of Tsukuba
1-1-1 Tennodai, Tsukuba,
Ibaraki, 305-8573 Japan
shin@cs.tsukuba.ac.jp

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Abstract
Capacitive Blocks is a block-shaped tangible user interface that connects the physical space to the virtual space, allowing users to build 3D models in the virtual space by handling tangible blocks. The system counts the number of stacked blocks by measuring the capacitance with a capacitance meter; the system recognizes the structure of stacked blocks arranged in a grid using the capacitance meter and generates 3D models. In this study, we improved the stability of Capacitive Blocks, presented by Yoshida et al. at UIST '15, by revising the block design: each block of the new system has a built-in capacitor. To evaluate the improvement, we conducted an experiment. The result showed a counting accuracy of 96.5%.

Author Keywords
Tangible; building block; stacking; 3D modeling; computational devices; interactive devices.

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation (e.g. HCI)]: User Interfaces - Input devices and strategies, Prototyping

Introduction
A tangible user interface (TUI) (e.g., [5, 8, 11]) allows users to operate intangible materials in the virtual space

by operating tangible objects in the physical space. Especially, a block-shaped TUI (e.g., [1, 13, 15]) allows users to build 3D models in the virtual space by handling tangible blocks such as LEGO[1] in the physical space. This can be done even without expert knowledge, which makes the block-shaped TUI a suitable 3D modeling method for beginners and children.

Block-shaped TUIs have mechanisms to recognize the position of the placed blocks and the connections among the blocks. The mechanisms can be classified into two approaches. The first approach embeds a microcontroller and a complex circuit into the blocks (e.g., [1, 13]). The second approach uses cameras around the blocks (e.g., [3, 9]); however, its setup occupies space and the camera image suffers from occlusion by the user's hand.

To explore an alternative approach, Yoshida et al. [14, 15] developed a capacitance-based block-shaped TUI called Capacitive Blocks. Their block is 3D-printed only with filaments (i.e., conductive and nonconductive ones), which forms a capacitor. Their system counts the number of stacked blocks by measuring the capacitance of the stacked blocks. However, Yoshida et al. stated that the system sometimes fails to count the number accurately when blocks are stacked over three layers because the blocks' capacitances differ from each other owing to the inaccuracy of 3D-printing and abrasion of blocks.

In this study, we improved the stability of Capacitive Blocks by revising the block design: each block of the new system has a built-in capacitor (i.e., laminated ceramic chip capacitor). This results in all the blocks having the same capacitance with high accuracy. To evaluate the improvement, we conducted an experiment. The result revealed that our system allows the blocks to be stacked up to 17 layers. In addition, we implemented a 3D modeling application that allows users to change the viewpoint and zooming level in the virtual 3D space so that they can examine the structure of stacked blocks.

[1] `https://www.lego.com`

Related Work

Block-shaped TUIs have been intensively researched. Among them, there was much research that embedded microcontrollers in blocks. The systems by Anderson et al. [1] and Watanabe et al. [13] recognize the structures of blocks by using embedded microcontrollers that communicate with each other. StackBlock [2] uses blocks with an embedded array of infrared (IR) LEDs and photo transistors to recognize the connection. Glauser et al. [6] embedded microcontrollers in the joints of a structure, which synchronizes to 3D models in a computer. By contrast, our block has no microcontroller but only a capacitor, which is a passive component making our blocks and block system lightweight.

Some research studies used cameras to recognize the connections of blocks in a block-shaped TUI. Baudisch et al. [3] used a table's built-in camera to recognize the height of stacked blocks, each of which has a glass fiber bundle and markers. Miller et al. [9] and Gupta et al. [7] recognized the structure of stacked blocks using a depth camera and reproduced them in a computer as a 3D model. By contrast, our system counts the number of stacked blocks by measuring the capacitance instead of using cameras, thus solving the occlusion problem.

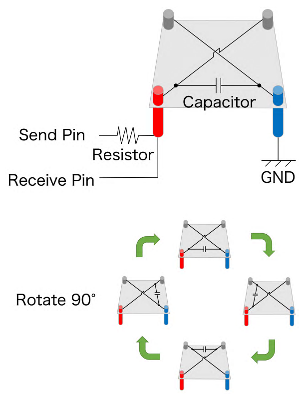

Figure 2: The wiring of our block. It can be detected even when rotated by 90°.

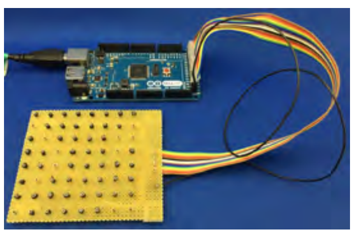

Figure 3: Construction of our sensing circuit consisting of a baseplate and a capacitance meter.

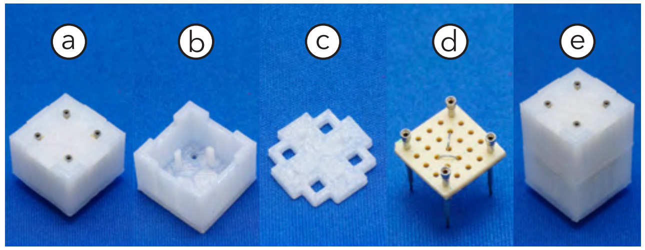

Figure 1: Construction of our blocks: a) block consisting of b-d, b) box, c) lid, d) core circuit, e) stacked blocks.

There are some research studies that detected placed objects on the basis of capacitive sensing. For example, Voelker et al. [12] realized a marker that generates touch events without power (i.e., passive) on capacitive touchscreens, which can be detected by unmodified capacitive touchscreens. On the other hand, we focused on applying capacitive sensing to count the number of stacked blocks. Chen et al. [4] developed a method that can detect coordinates and the number of stacked blocks on a touchscreen by touching blocks. However, the detection occurs only when the user touches the block because the system uses capacitance that is charged by touching. Moreover, because of the limited number of contacts and the threshold of capacitance that a touchscreen detects, the number of stacked blocks is limited. By contrast, our system can detect blocks without touching and extends the number of blocks that the user can stack.

Yoshida et al. [14, 15] developed a method for block detection without touching, using unique blocks that have capacitance themselves and capacitance meters arranged in a grid. In this paper, we reviced their blocks and found that the capacitance was accurate enough to extend the number of blocks that can be stacked.

Revised Capacitive Blocks

Block

Our blocks (Figure 1a) consist of a box (Figure 1b), lid (Figure 1c), and core circuit (Figure 1d). The circuit consists of a $10\,\mathrm{nF}$ chip capacitor (manufacturing error of 1% or less) and four pin-sockets that connect the blocks to each other (Figure 1e). We chose $10\,\mathrm{nF}$, which is much larger than the capacitance of the user's body (approximately $200\,\mathrm{pF}$ [10]), to eliminate the effect of the user's body. The wiring of the core circuit shown in Figure 2 enables two blocks to form a circuit even when they are rotated by 90°, although two pin-sockets are enough for measuring a block's capacitance (one connected to the sensing circuit and one connected to the ground). We 3D-printed the box and lid. Combining the three parts forms a $20 \times 20 \times 15\,\mathrm{mm}$ rectangular cuboid.

Sensing Circuit

We created a sensing circuit to detect the stacked blocks (Figure 3). The sensing circuit consists of a baseplate and a capacitance meter. A set of four pin-sockets forms a capacitance meter. Among the four pin-sockets, one is connected to an Arduino MEGA microcontroller board and one is grounded. The remaining two are open: they are necessary for the connection of stacked blocks. We used the Capacitive Sensing Library[2] running on Arduino MEGA to measure the capacitance. This library realizes capacitance by measuring the charging time of the capacitor.

We describe a mechanism to count stacked blocks by measuring the capacitance. As shown in Figure 4, the capacitors in stacked blocks are connected in parallel. Generally, the total capacitance of capacitors connected in parallel is the sum of all the capacitors' capacitances.

[2]http://playground.arduino.cc/Main/CapacitiveSensor

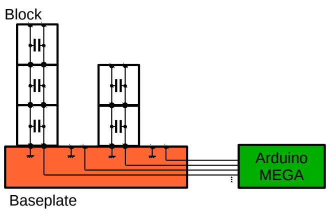

Figure 4: Schematic diagram of our circuit. The capacitors in the stacked blocks are connected in parallel.

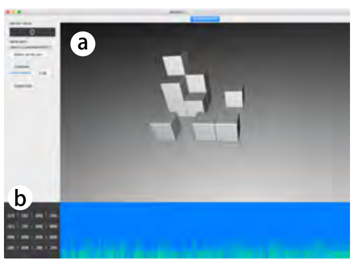

Figure 6: Screenshot of the 3D modeling application. a) A reconstructed 3D model of the blocks. b) The interface also displays the number of stacked blocks and the sensor values of each capacitance meter.

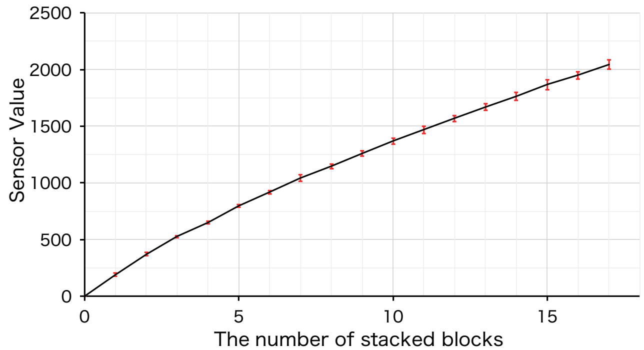

Figure 5: Sensor values of our sensing circuit for each number of stacked blocks.

Therefore, the total number of stacked blocks (n) can be calculated by $n = C/C_b$. Here, C is the measured capacitance of the stacked blocks and C_b is the capacitance of a block. However, our test result showed that the sensor value measured by the sensing circuit did not increase linearly, as shown in Figure 5 (this would be due to a characteristic of the Capacitive Sensing Library). Therefore, for the method of mapping between the sensor value and the number of stacked blocks, we adopted a quadratic function fitted to the sensor values.

3D Modeling Application

We implemented a 3D modeling application running on a PC (Figure 6) that shows the structure of stacked blocks in the virtual space and allows users to change the viewpoint and zooming level so that they can examine the model.

To reconstruct the 3D model in real time, the software reads the sensor values from the sensing circuit via a USB port, uses the quadratic function to count the stacked blocks on each grid position of the baseplate, and reconstructs a 3D model of the blocks. With this software, the user can now build a 3D model in the virtual space interactively by using blocks in the physical space. We show example 3D models that we created using the software shown in Figure 7.

Evaluation

We conducted an experiment using our 3D modeling application to examine whether the coordinates and number of stacked blocks were detected accurately.

Three participants including the authors took part in this experiment. For the task, a participant stacked blocks one by one from 0 to 17 on a specified grid position of the baseplate. After that, the participant performed this task on another grid and repeated this for all 16 grid positions. We define these 16 tasks as a session. The participants repeated the session three times. Through the experiment, we recorded the results of the detection.

The accuracy in detecting the stacked coordinates (grid positions) was 100% on average. On the other hand, the accuracy in detecting the number of stacked blocks, shown in Figure 8, was 96.5% on average up to 17 layers.

Discussion and Future Work

The experiment result showed that the accuracy in detecting the number of stacked blocks was generally high but not 100%, which was 96.5% on average up to 17 layers. This would be because the standard deviation of sensor values increases when the number of stacked blocks increases, as shown in Figure 5. Therefore, we plan to implement a capacitance meter that senses the capacitance more accurately. Specifically, we will change

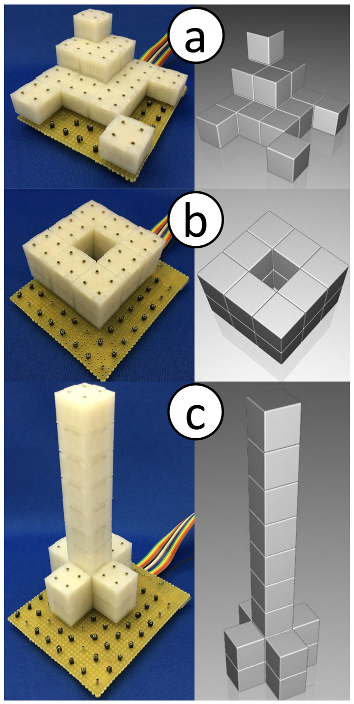

Figure 7: 3D modeling examples: a) steps, b) doughnut, c) rocket.

the capacitive meter from a software implementation using Capacitive Sensing Library to a hardware implementation.

Moreover, in our current implementation, because the pin-sockets we used were too thin and made of metal, their tips were bent frequently. As a future work, we plan to implement our blocks using thicker and robust connectors to stabilize the connection.

For the above improvement, we plan to re-evaluate the accuracy of the revised Capacitive Blocks and conduct a user study to explore how users would actually go about using these blocks.

In addition, as a step to support more realistic 3D modeling, we plan to adopt a sculpt modeling function to our system. In sculpt modeling, users first make a rough model and then smarten up the detailed parts. Because our system could be useful for making such rough models, we plan to explore such possibility by combining our system to a commercial software with a sculpt modeling function.

Conclusions

In this paper, we presented Capacitive Blocks, a block-shaped TUI that allows users to build 3D models in the virtual space by handling tangible blocks. We made Capacitive Blocks count stacked blocks by measuring the capacitance with a capacitance meter; the system recognizes the structure of stacked blocks arranged in a grid using the capacitance meter and generates 3D models. In this paper, we improved the stability of Capacitive Blocks by revising the block design over our previous work: each block of the new system has a built-in capacitor, which is a passive component. The result of an experiment to evaluate the improvement showed that the accuracy in detecting the number of stacked blocks was 96.5% up to 17 layers.

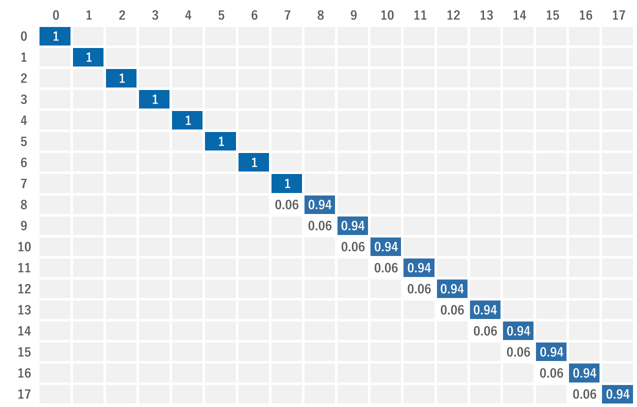

Figure 8: Accuracy of the number of stacked blocks. Vertical axis: actual count. Horizontal axis: detected count.

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