# RFIBricks: Interactive Building Blocks Based on RFID

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## ABSTRACT
We present *RFIBricks*, an interactive building block system based on ultrahigh frequency radio-frequency identification (RFID) sensing. The system enables geometry resolution based on a simple yet highly generalizable mechanism: an RFID contact switch, which is made by cutting each RFID tag into two parts, namely antenna and chip. A magnetic connector is then coupled with each part. When the antenna and chip connect, an interaction event with an ID is transmitted to the reader. On the basis of our design of RFID contact switch patterns, we present a system of interactive physical building blocks that resolves the stacking order and orientation when one block is stacked upon another, determines a three-dimensional (3D) geometry built on a two-dimensional base plate, and detects user inputs by incorporating electromechanical sensors. Because it is calibration-free and does not require batteries in each block, it facilitates straightforward maintenance when deployed at scale. Compared with other approaches, this RFID-based system resolves several critical challenges in humancomputer interaction, such as 1) determining the identity and the built 3D geometry of passive building blocks, 2) enabling stackable token+constraint interaction on a tabletop, and 3) tracking in-hand assembly.

## Author Keywords
RFID; Tangible User Interface; Building Blocks; Constructive Assembly.

## ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

## INTRODUCTION
Physical building block systems have been demonstrated as promising tangible user interfaces (TUIs) [12, 28] for interactive construction. The physical affordances and tactile feedback allow users to intuitively assemble the blocks into the desired physical form. The versatile and seemingly endless possibilities allow users to develop their manual function, spatial recognition, and creativity [14].


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Developing a reliable and easy-to-maintain building block system remains an open challenge. Regarding reliability, studies have proposed the use of building blocks with embedded electronic circuits and sensors to detect the assembly [1, 9, 20]. Although the physical connections are reliable, the embedded active components require additional maintenance efforts, such as charging or battery replacement, which may limit the scalability and sustainability of the solution. Regarding ease of maintenance, studies have proposed passive building block systems based on computer vision tracking [4, 10], capacitive tracking [6] and magnetic tracking [18]. However, these solutions do not satisfy applications requiring full three-dimensional (3D) model construction.

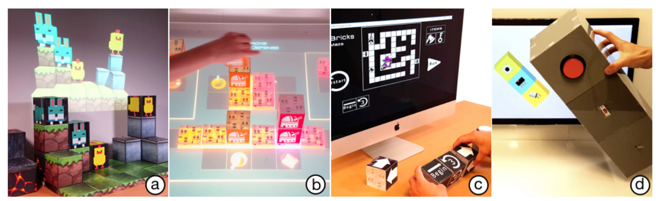


**Figure 1. RFIBricks is a reliable and easy-to-maintain interactive building block system based on UHF RFID sensing. (a) Interactive physical modeling. (b) Tabletop tangible gaming. (c) Tangible programming. (d) Modular input device.**

In this paper, we present *RFIBricks* (Figure 1) an interactive building block system based on passive ultrahigh frequency (UHF) radio-frequency identification (RFID) sensing. The system is mainly realized through a simple yet effective hardware solution: modifying UHF RFID tags as *rich-ID contact switches* (Figure 2a) to realize a lightweight, calibration-free building block system based on UHF RFID sensing. Each UHF RFID tag is first disassembled into a pair of components, namely a *chip* and an *antenna*, using a vinyl cutter. Subsequently, we attach a magnet to each terminal as a low-ohmic magnetic connector that forces alignment. When the two parts snap to each other, the copresence of a pair of IDs is considered a unique interaction *event*.

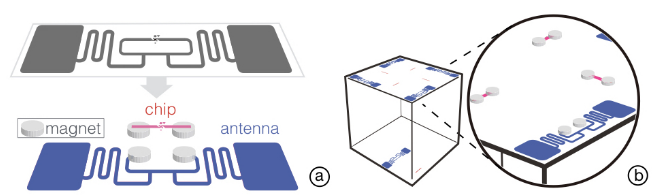


**Figure 2. (a) Modifying a UHF RFID tag as an *RFID contact switch*. (b) Spatial RFID contact switch pattern is applied to a basic 1×1 block.**

A spatial RFID contact switch pattern is applied on the top and bottom of each building block (Figure 2b); also, four

RFID contact switches are formed as a base plate, which is then deployed as a two-dimensional (2D) grid (Figure 3a). Each RFID switch on each block is registered once with the corresponding spatial properties. Thereafter, the spatial design allows the system to not only recognize these blocks but also determine the position and orientation of a building block placed on the sensor grid by using Cartesian coordinates. For instance, the one chip placed on the bottom of block #47 represented the block's identity, and the four chips on the base plate are registered with their actual spatial location (x,y,z=0) and the represented orientation $\theta = \{0, \pi/2, \pi, -\pi/2\}$. When the block is placed the plate, the registered information pertaining to the pair of IDs indicates that a block is stacked upon the plate in the stacked orientation. For instance, the *event* of block #47 stacked at $(x, y, z = 1, \theta = \pi/2)$ is used to update the detected geometry. Moreover, it allows the system to resolve the stacking order of the building blocks (Figure 3b), irrespective of whether the blocks are stacked in the users hands or on a plate. By combining these features, we realized a lightweight, reliable, and interactive 3D building block system based on UHF RFID.

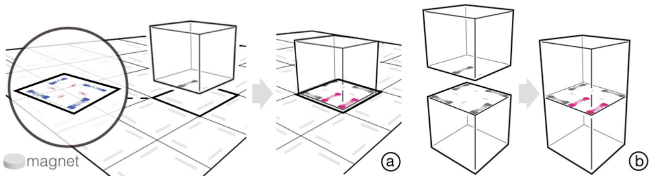


**Figure 3. Principle of geometry resolution. (a) A grid of RFID contact switches used as a base plate for localization. Unconnected blocks activate no tags. Connected blocks activate two unique ID simultaneously; thus, the ID and the orientation of the stack can be determined. (d) The stacking order of the building blocks is resolved in the same method.**

In addition to supporting the resolution of discrete stacking location and the resulting geometry, we generalize the RFID contact switch design to sense interactivity in the 3D physical model. We demonstrate the generalization by interfacing with conventional electromechanical sensing elements, such as a push button and a switch. Moreover, to demonstrate the uses and design implications of this system, we present several example applications, including interactive physical modeling, tabletop tangible gaming, tangible programming, and modular input device creation. Furthermore, we detail the system implementation. Finally, the empirical study results are presented to validate the performance of this system and to provide directions for future optimization.

The proposed RFID-based interactive building block system overcomes several critical challenges in established problem spaces in humancomputer interaction, such as 1) resolving 3D building block geometry and the ID of each block in a constructive TUI, 2) enabling stackable token+constraint interaction [28] on a tabletop computer, 3) tracking in-hand assembly and 4) realizing a wireless and battery-free modular/stackable input device. The major advantage of the proposed approach is that it is simple and does not require batteries in each block, facilitating straightforward maintenance when deployed at scale.

This remainder of this paper is organized as follows. Related work is discussed first. Subsequently, we explain the physical design of RFIBricks and real-time sensing schemes and provide several examples to highlight the basic features of this building block system. Later, we detail its implementation and evaluate the system performance. Finally, conclusions are presented with directions for future research.

## RELATED WORK

In this section, related work is discussed under the following heads: 1) active building blocks that embed electronics, 2) passive building blocks that track the assembly using computer vision, capacitive, or magnetic tracking techniques, and 3) techniques that utilize UHF RFID to detect tangible interactions on passive objects.

### Active Building Blocks

Building block systems that embed microprocessors and sensor modules into blocks can reliably detect the interaction events and therefore resolve the assembled geometries. Several studies have proposed using electronic connectors in blocks for information topography [9], tangible programming [20], and interpreting virtual structures [1]. Regarding flexible stacking, StackBlock [2] augments arrays of infrared emitters and receivers for precise block localization, Construkts[1] enables geometric solutions for 3D assembly, and A-Blocks [11] infers block manipulations by using motion sensors. The advantage of these approaches is that block stacking can reliably be detected. Additionally, the local power source of blocks can be utilized to drive sensors and actuators in order to enable rich tangible interactions, such as multimodal building block interactions [31, 8], kinetic tangible input and output [25], and distributed display block manipulation [21]. Although these electronic building block systems exhibit favorable reliability and versatile capabilities for tangible interaction, they require additional maintenance costs, such as battery charging and replacement, which limits the scalability and sustainability of construction. By contrast, the RFIBricks system is based on passive RFID, which is battery-free as the energy is harvested wirelessly from the reader; hence, the maintenance efforts do not increase with the scale of 3D modeling.

### Passive Building Blocks

Computer vision, capacitive, and magnetic tracking techniques have been utilized to infer the 3D structure of passive building blocks. For example, DuploTrack [10] resolves 3D geometries that are built using conventional Duplo building blocks by using the images captured with a red-green-blue depth camera, which can monitor the spatial manipulations of constructed physical models in real time. Lumino [4] resolves 3D constructions of fiber-optic bundles on a diffused-illumination optical tabletop platform by using specific marker designs, which allows the fiber-optic bundle to pass the visual markers of the block in each layer of the stack down to the optical tabletop surface through fiber optics. CapStones [6] resolves a stack of tangible blocks by utilizing similar pass-down mechanisms to transmit the conductive footprints of the building blocks in each layer of the stack

[1] http://www.construkts.com/

down to a conventional capacitive multitouch display. GaussBricks [18] resolves the 3D construction of magnetic building blocks in the near-surface of a thin LCD panel by using the magnetic-field images extracted with an analog Hall-sensor grid attached to the back of the display device.

A common advantage of the aforementioned solutions is that they keep the blocks *passive* and thus ensure that they are straightforward to maintain for 3D construction at scale. However, these solutions become unreliable when their applications require interactivity. The performance of camera-based approaches is limited by the occlusions introduced by the users and the 3D physical structures and the resolutions and perspectives of the cameras; therefore, they often require extensive calibration, sophisticated algorithms, or customized installations. The capacitive solution is limited by the electrical interference introduced by environmental factors or human hands as well as the sensitivity of the sensing hardware. The magnetic tracking solution is limited by inverse quadratic decay in magnetic strength as sensing distance increases; thus, it cannot effectively support full 3D physical constructions beyond the near-surface volume. By contrast, the RFIBricks system utilizes UHF RFID signals to identify and localize the building blocks. The RF signals of the tag propagate wirelessly without being affected by the line-of-sight problem, robustly tracking the ID of each tag in a sensing volume that is comparably larger than that of magnetic and capacitive tracking. Moreover, the lightweight deployment only requires users to appropriately install the RFID readers and the antenna. Hence, the RFID-based solution appears an ideal candidate for providing lightweight, reliable 3D physical modeling using building blocks.

### Interaction Techniques Based on UHF RFID Sensing

RFID sensing techniques have been widely used for detecting the location and movements of passive tagged objects [22, 23, 26, 29, 32], gesture-based inputs [3, 30], daily activities [5], or people [7]. However, these applications usually require multiple RFID readers to be deployed. To enable lightweight deployment, recent studies have introduced a series of interactive systems that use only one RFID reader, with additional cameras being used to enable object-localization applications. ID-Match [17] was used to distinguish individuals in the crowd by combining a depth camera with a UHF RFID reader. PapierMache [13] identified objects by using RFID tags but localized them using an occlusion sensitive camera. RFID-only solutions, such as IDSense [16], recognized the physical movements and touch events of everyday objects using real-time classification of the received signal strength indication (RSSI) and phase angles; however, it requires training and calibration and is insufficiently precise and responsive for interactive building block applications.

For interaction, PaperID [15] supports real-time signal classification to sense the near-surface gestures and finger touch input on paper-made artifacts. RapID [27] further increased the speed of RFID tag state recognition by applying probabilistic filtering to process the RFID signals, reducing the input response time to $<$200 ms. Another method for achieving responsive user interaction is to modify the RFID tags and integrate electromechanical sensors (e.g. switches) into the circuitry connections between the RFID chip and antennas, which has been proposed by Philipose *et al.* [24], Marquardt *et al.* [19], and PaperID [15], so that the clear presence of or signal change in ID information can be utilized to indicate an interaction event. However, they have not extended the techniques to interactive building block applications. To the best of our knowledge, RFIBricks is the first interactive building block system based on UHF RFID sensing. RFIBricks achieves robust and responsive 3D geometry resolution using only a single RFID reader, without the need for prior learning and calibration. Hence, it is straightforward for end users to deploy.

## DESIGN AND IMPLEMENTATION

### Design Principles

To realize a lightweight, reliable interactive building block system to support assembly at scale, the system should satisfy four design principles: *P1) ease of maintenance, P2) lightweight deployment, P3) reliability and responsiveness, and P4) scalability.* Users should be able to play with numerous easy-to-maintain building blocks, and charging or replacing the battery in each building block should be effortless. Moreover, connecting building blocks should be easy, and the physical structures should be simple and durable. In other words, users should be able to easily reconfigure the assemblies without damaging the building blocks. Furthermore, the system should be easily deployed with minimal effort for installation and calibration. In other words, users should be able to easily activate the system for portable use. The geometry of 3D construction should be correctly resolved without noticeable delays, and accuracy should not decrease when users interact with the system. Therefore, users can comfortably use the system and immediately receive correct feedback. The system should be able to track numerous blocks simultaneously, and the computational complexity of geometry resolution should be bounded. Therefore, the system can support physical modeling at scale without significant degradations in performance.

UHF RFID is a suitable sensing techniques for realizing a system that satisfies the aforementioned design principles. To ensure *ease-of-maintenance* (*P1*), a passive UHF RFID tag wirelessly harvests energy from the reader and therefore requires no charging or battery replacement. The sensing system can be easily activated (*P2*) by simply activating the RFID readers, and the ID of a passive tag can be read without calibration. RFID sensing is reliable (*P3*), because of the error-correction mechanism; additionally, the fast transaction time makes the system highly responsive. The UHF RFID reader can track numerous passive tags simultaneously (*P4*).

### Design Challenges

Several major design challenges, however, still undermine the realization of a UHF RFID sensingbased physical building block system. First, UHF RFID sensing systems support limited localization capabilities. Using RSSI and phase angle can achieve localization to some extent but may violate *P2* because of the need for calibration and dependence on environment factors (e.g., metallic materials). Only the use of the ID information of tags may meet the requirement for lightweight deployment. Second, RFID systems cannot determine the orientation of a passive RFID tag. The geometry of construction involving building blocks in various orientations may not be correctly resolved, thus violating *P3*. Third, RFID systems support limited interactivity. The signal of an RFID tag is activated when a tag is in detection range of a reader. However, user interaction events, such as the physical contact made during construction, require additional shielding mechanisms or active circuitry (which violates *P1*); otherwise, the interaction events cannot be reliably resolved, thus violating *P3*. These critical design challenges are addressed by the solutions that we present in the following sections.

### Modifying RFID tags as Rich-ID Contact Switches

To achieve reliable contact sensing of the building blocks and to keep the system deployment as light as possible, we choose the most robust and independent feature — the ID information of a tag — as the design signal resource. Depending on whether the antenna is elicited, the ID information has two states: *presence* and *absence*. Therefore, for the present application, a robust mechanism to trigger state transition during physical contact is required.

Our idea is to modify RFID tags as *RFID contact switches*. Figure 2 shows a modified UHF RFID tag, which is disassembled into a pair of two components: *chip* and *antenna*. Each component has two terminals formed by silver conductive ink; thus, the two parts can connect to each other. When the terminals of a chip and an antenna connect at the proper alignment, the pair functions as a normal RFID tag that can be elicited within the sensing range of a reader; otherwise, the ID of a chip cannot be sensed without an antenna. To assure the proper alignment of the two parts, we add a neodymium magnet to the terminals of each part so that a valid connection is easily formed when snapping them together. The strong attraction force between the two magnets creates a low-resistance link for robust electrical connection [33]. The physical design of this electromechanical sensing mechanism, therefore, enables reliable contact sensing of the building blocks while keeping the system deployment lightweight.

### Designing Lego-like Interactive Building Blocks

Because only ID information is used in our system, the spatial structures, such as a sensor grid, should be considered for localization. We deploy a grid of contact switches to function as a sensing plate. Because of the large ID space, we bound a Cartesian coordinate system to the ID of each switch. Therefore, the sensing plate can localize a brick in two dimensions in the presence of the ID.

A blocks orientation can be resolved by deploying multiple tags on the surface. For a cubic block, its four directions must ideally be resolved. Therefore, we place four RFID contact switches in a rotational, symmetrical manner with respect to the center of the surface (Figure 3). Each placement method triggered a unique ID for reliably resolving a blocks orientation. Figure 4 shows the implementation of a basic block.

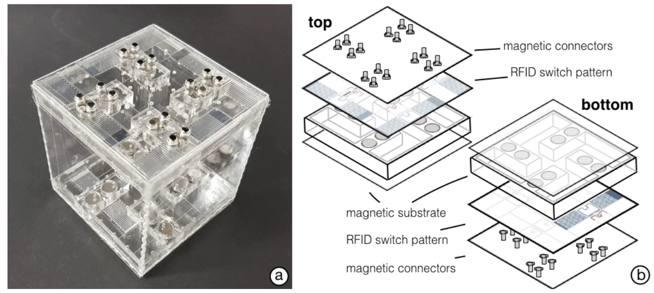


**Figure 4. (a) Basic block. (b) Component overview.**

Stacking can be sensed by extending localization from 2D to 3D. Therefore, we deploy a switch on both the top and bottom sides of the blocks. When a block is stacked on another, a pair of IDs are activated simultaneously. The copresence of the two IDs determines the stacking order of the blocks, and the system accordingly updates the geometric construction.

In this system, stacking need not be performed only on the base plate. Because the RFID sensing can recognize tag activation in a 3D volume, users can stack bricks either in their hands or on the base plate, akin to how children play with Lego bricks.

Compound blocks, such as the $1\times2$ and $1\times3$ blocks shown in Figure 5, are provided to build the models that comprise overhanging parts, which cannot be realized by stacking the basic $1\times1$ building blocks. A compound block is made by simply combining several basic $1\times1$ blocks in the same direction. When a block is stacked on the units, a unique combination of tags is activated. By computing the centroids of all the activated tags and their orientation, the position and orientation of the blocks can be resolved.

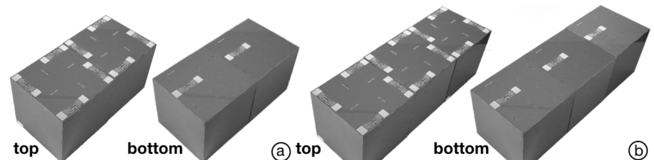


**Figure 5. Compound blocks. (a) $1\times2$ block. (b)$1\times3$ block.**

Similarly to the contact switch, the electromechanical design can be generalized to increase the input capability of the building blocks and physical construction. Inspired by earlier studies [19, 24], we designed and developed a widget block system (Figure 6) in which an electromechanical sensor is attached to each widget block to detect user inputs, such as pressing or rotating a widget on the block or tilting the block. The ground and signal terminals of each electromechanical sensor are connected to a tag and antenna so that the presence of an ID could be resolved as the interaction events of a specific element.

### System Implementation

#### *Hardware*

The system is implemented using an Impinj Speedway Revolution R420 UHF RFID reader for sensing. The reader can connect to a maximum of four 445 (W)×445 (H)×40 (T)$mm^3$ AANT925SMA circular polarized antenna, which operate with a signal bandwidth of 902 MHz to 928 MHz and

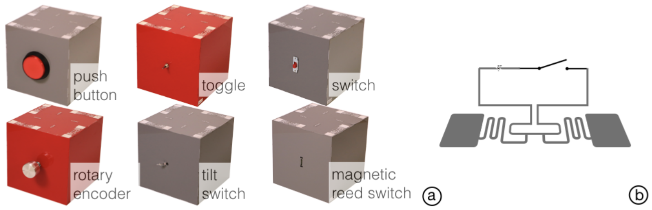


**Figure 6. (a) Widget blocks. (b) Schematics.**

a signal amplitude of 12dBi; the signal coverage area is approximately 6 (W)×6 (H)$m^2$. AZ-9662 UHF RFID tags were used for prototyping because the conductive circuits are exposed on the surface of the thin plastic substrate, allowing for easy circuit modification. The tags and antenna of each 70 (W)×17 (H)$mm^2$ UHF RFID tag was precisely dissembled into two components by using a Stika SV-8 8" Vinyl cutter (Figure 7), which allowed us to feed a roll of tags into the feeder for batch manufacturing.

For each sensing plate, the tag components were manually placed on a laser-cut 148 (W)×148 (H)×1 (T)$mm^3$ acrylic plate (Figure 7c). Two 4 mm-radius, 5 mm-thick neodymium magnets were affixed to the terminals of each component as the magnetic connectors. All magnets had the same polarity facing upward to prevent upside-down stacking. The manual installation of components was guided by the outlines engraved on the surface. Each unit could be fabricated in 3-5 minutes, and each 1×1 block could be assembled in 6-10 minutes per worker.

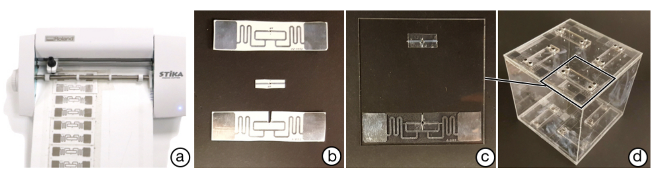


**Figure 7. Fabrication process of a basic block. (a) Separating the antenna and chip of each RFID tag by using a vinyl cutter. (b) Results. (c) Mounting the parts on the corresponding positions of contact surfaces. (d) Mounting the surfaces on a block with magnetic connectors.**

### *Sensing Algorithm*

A simple yet effective sensing algorithm is implemented to handle the state transitions. A lookup table $T$ is established to maintain the *presence* and *absence* of each tag registered on our system, and the total number of *presence* tags is recorded $|T|$. For each sample $S$ of RFID readings, the system obtains a list of *presence* tags, and the total number of *presence* tags is recorded as $|S|$. Sampling is performed in at fixed frequency $f = 1/t$, where $t$ is the interval between two samplings. In each sampling, the system obtains a list of differences of *presence* $D$ between $T$ and $S$ as well as the length of the list $|D|$. When 1) the $|D|$ is even and 2) both $|T|$ and $|S|$ remains consistent after $K$ samples, the system updates the new geometry by resolving the stacking events in $D$, and renews the lookup table $T$ with the sample $S$ for the next updates. Nonetheless, if either or both conditions are not satisfied, the update is regarded as an invalid one and is ignored.

The 3D geometry is computed by two sets of tags: grounded ($G$) and ungrounded ($U$) tags. All tags on the base plate are initially assigned to the set $G$ with a Cartesian coordinate $C = (x, y, z = 0, \theta = \{0, \pi/2, \pi, -\pi/2\})$. In each valid update, the system determines whether a tag belongs to the set $G$ or the set $U$. Take the $|D| = 2$ cases as an example: if one of the tag $T_b = T_{bottom}$ belongs to the set $G$, it means a user is stacking a block directly on the plate; thus, we add the tag $T_t = T_{top}$ to the set $G$ with a newly assigned Cartesian coordinate $C_t = (x_b, y_b, z_b + 1, \theta_b + \theta_t)$. Otherwise, if both tags do not belong to the set $G$, it means the user is stacking a block outside the base plate; thus, we maintain the stack in the set $U$ by assigning the tentative coordinate $C_t$ to $T_t$. When $T_b$ is stacked on the top of another tag in the set $G$, both $C_t$ and $C_b$ are updated, and both $T_t$ and $T_b$ are added to the set $G$.

The $|D| > 2$ cases are caused by either stacking compound blocks on more than one units or by stacking multiple same-type units at the same time. Stacking a compound block on more than one units can be resolved without ambiguity because the system knows that the ID belongs to a compound block (*R1*), and the orientation of a compound block is known as the orientation of tags (*R2*). Stacking a 1×1 block and a compound block (e.g. a 1×3 block) at the same time is ambiguity free because of *R1*. However, stacking multiple same-type units at the same time could be ambiguous because *R1* is invalid in this case. Although this case seldom occurs in single-user interactions, it may frequently occur in multiuser scenarios when the sampling frequency $f$ is sufficiently high. We elucidate this limitation and the possible disambiguation solutions in the Discussion section.

## APPLICATION EXAMPLES

Four application examples are proposed to demonstrate the uses of this system.

### Physical Modeling & Tangible Interaction

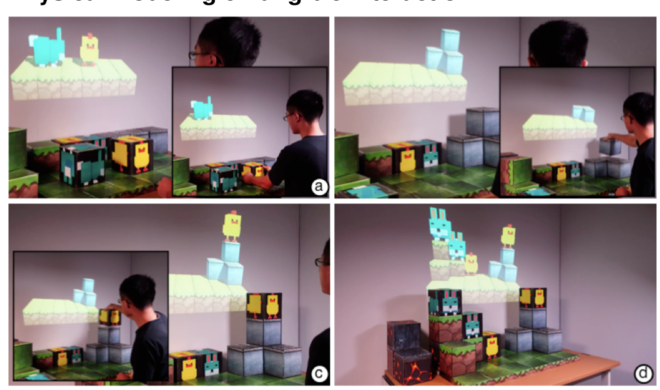


**Figure 8. Tangible Minecraft. A user (a) stages the characters by placing them on the plate, (b) builds the environment by stacking the blocks, and (c) places a character on top of the built mountain. (d) Results.**

The building block system tracks the ID and orientation location of each block; thus, it is suitable not only for physical modeling but also for tangible interaction. Figure 8 shows a tangible version of the Minecraft game[2]. A 3×6 grid of tiles was deployed as a playground. Several blocks representing characters and construction materials were provided to construct an environment that allows users to play with the characters. In the game, a user prepares the characters by placing them on the plate, creates the environment by stacking

[2]https://minecraft.net/

the building material blocks at desired locations in desired forms, such as by building a rocky mountain or a mountain covered by a forest, and subsequently freely places characters by stacking the character blocks on top of the built terrain.

### Stackable Token+Constraint Interaction on Tabletop

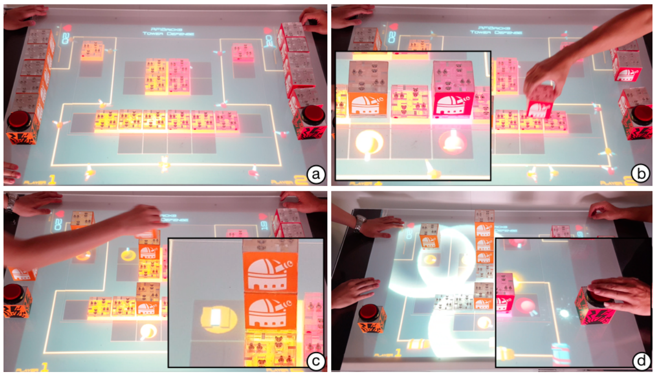

**Figure 9. Tower Defense. (a) Transparent tiles were fixed at the desired location on the tabletop. Weapon blocks were distributed to the players. A player (b) sets a weapon by placing a block, (c) upgrades a weapon by stacking, and (d) ignites a bomb by pressing the button.**

The base plates (tiles) can be placed anywhere on a surface (e.g. a tabletop display) for distributed localization and stack sensing. Figure 9 shows a tower-defense game in a tabletop setting. A table with bottom-up projection was deployed as the playground. Tiles were fixed at the desired location on the tabletop depending on the projection graphics. Several basic blocks and one button widget block representing the weapons were distributed to two players. In the game, enemies periodically attack the player; thus, the player must consider the effective deployment of weapons to defeat them. A player attacks enemies by placing a weapon block on the tile at the desired location, upgrades a weapon by stacking a weapon block on another one, or ignites a bomb by pressing the button at the appropriate time. Notably, in addition to the rich, high-resolution visual feedback shown on the display, a user can see through the tile and perceive low-resolution visual feedback, such as a flash of light when firing a bullet. Users can also perceive this from the top of a tile or even a stack of blocks because the top and the bottom sides of both blocks and tiles are transparent.

### Tangible Programming

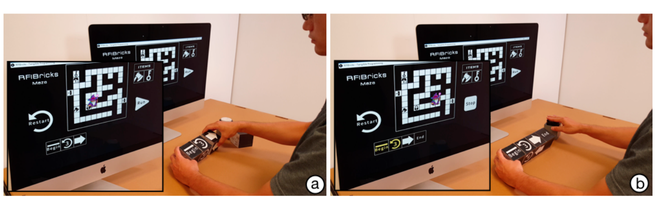

**Figure 10. Tangible programming. A user (a) selects a desired functional block, rotates it to the orientation of the proper parameter, attaches the block, and (b) triggers the action by pressing the button**

The blocks can be stacked horizontally to represent sequential, logical information. A tangible educational programming application was developed as shown in Figure 10. Several basic blocks and one button widget were distributed to the student. Different blocks represent different functionalities, such as begin, end, loop, step, and direction, with different parameters in each direction. To guide a character to escape from a maze, a user selects the desired functional blocks, rotates them to the orientation of the proper parameter, and sequentially snaps them to the stack with a begin block at its end. After the action sequence is completely edited, the user triggers the action by pressing the button. Notably, the wireless, occlusion-free RFID technology allows the user to freely hold the stack and the blocks in their hand and have the input operations correctly detected.

### Modular Remote Controller

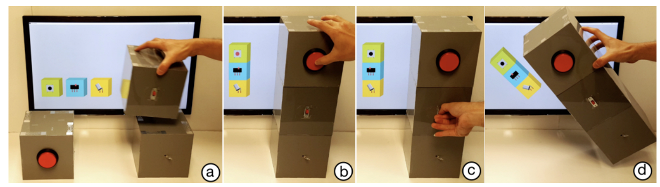

**Figure 11. Modular input device. (a) A user combines the desired input modality by stacking the widget block together. Subsequently, the actions of (b) pressing a push button, (c) turning a switch on or off, and (d) tilting the entire stack are detected correctly.**

Widget blocks are stackable. A user can combine the functionalities of multiple widget blocks into a single, multifunctional remote controller for wireless and batteryless uses. Figure 11 shows a modular kit for building an on-demand remote controller. The kit comprises a push-button block, a switch block, and a tilt-switch block. A user combines the desired input modality by stacking the widget block together. Afterward, the actions of pressing a push button, turning a switch on or off, and tilting the entire controller can be detected correctly. The block can be made smaller so that more functionality can be integrated into a graspable form factor.

## PERFORMANCE EVALUATION

Measurements were conducted to understand the responsiveness and scalability of our system.

### Pilot Session: Responsiveness vs. Tag Amount

The response time of the RFID reader was tested in a pilot session. We placed unmodified AZ-9662 UHF RFID tags on the supporting platform in the one antenna condition, collected 60 s of samples, and obtained the mean refresh rate of RFID sensing, where fps was computed as the total records received divided by 60 s. The results (Figure 12d) suggest that even when 100 blocks, which is equivalent to 200 tags, are activated simultaneously, the system can achieve a comparable response time to RapID (>5fps) [27]. Therefore, we constructed 100 blocks for the formal sessions.

### Session 1: Stack Sensing Capability vs Location

The first study aims at understanding the capability of 1D stacking versus different locations and angles corresponding to the center of the antenna.

*Apparatus.* Figure 12a shows the experimental apparatus. Measurement was conducted in an empty 75 $m^2$ room. A 5 mm-thick acrylic supporting surface was placed in the

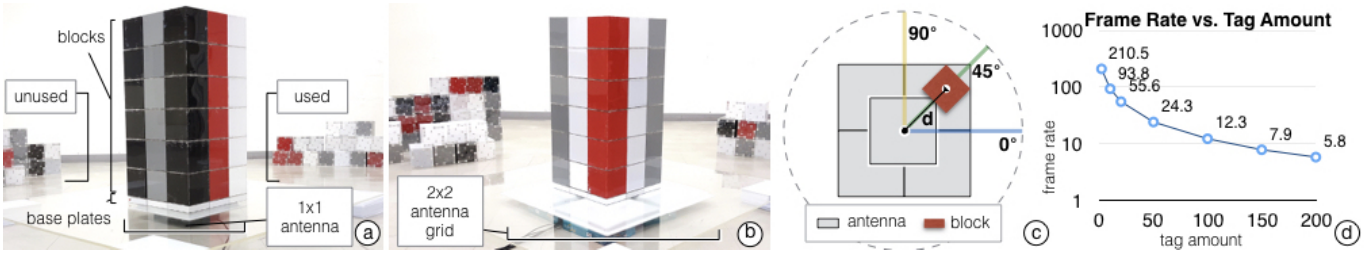


**Figure 12. Experimental apparatus and pilot session results. Six layers of blocks stacked on a 3×3 tile were measured on a 5 mmthick acrylic supporting surface by (a) 1 antenna or (b) a grid of 2×2 antennas. (c) Experiment parameters. (d) Pilot session results in frame rate vs. tag amount.**

center of the room as the supporting surface. An Impinj Speedway Revolution R420 UHF RFID reader was placed outside the room, connecting ANT925SMA circular polarized antennas with long wires. The antenna was placed on the floor in the center of the room, immediately under the center of the supporting platform. Two sizes of the blocks, *large* and *small*, were evaluated. Each large block ($150 \times 150 \times 150 mm^3$), which were mounted with five pairs of RFID switches (top: four; bottom: one), were fabricated using parts extracted from the 70 (W)×17 (H)$mm^2$ AZ-9662 UHF RFID tags; each small block ($65 \times 65 \times 65\ mm^3$), which was also mounted with five pairs of RFID switches (top: four; bottom: one), was fabricated using parts extracted from the 44.5(W)×10.3(H)$mm^2$ AZ-9610 UHF RFID tags. A total of 100 large blocks and 100 small blocks were prepared and used in the study. Additionally, 100 large ($150 \times 150 \times 3\ mm^3$) and 100 small ($65 \times 65 \times 3\ mm^3$) tiles, which were mounted with four pairs of the RFID switches extracted from the AZ-9662 UHF RFID tags, were used in the study.

*Procedures.* Figure 12c shows the experimental parameters used in measurement. Before each measurement iteration, all blocks were removed from the surface and placed at least 3 m vertical distance away from the center of the antenna. Measurement commenced at the center of the antenna (i.e., $d = 0$). In each iteration, a block was stacked. If the ID of both tags was read within 10 s, another block was stacked; otherwise, the last successful stack layer height was recorded. After 10 iterations, if a nonzero layer height was measured more than once, a larger $d$ was tested; otherwise, another angle was tested from $d = 0$. Three angles (0°, 45°, 90°) were measured in the session. Because the antenna that we used was circularly polarized, emitting and receiving signals in a circular symmetric manner, the three angles should be sufficient for describing the effect on the angle of the stack. In total, 30 rounds (10 iterations×3 angles) of measurements were conducted for each case.

During measurement, two pools of tiles and blocks were maintained: *Used* and *Unused* (Figure 12a). A block from the unused pool was randomly selected for measurement every time. After each iteration of measurement was completed, all measured blocks were removed from the surface to the used pool. The unused pool was refilled when it was empty. This ensured that no block was measured more than once in each cycle of 100 measurements. All the blocks used in the experiment were tested before the formal session. No defects were observed throughout the session.

*Results.* Figure 13a and Figure 13b show the results for the two sizes of blocks. Results of a repeated measure analysis of variance revealed an effect for *distance* and *stack height* ($p < 0.01$) but no effects for *angle* and the *stack height* ($p > 0.01$). The large blocks reached an average stack height of 7.43 layers (SD = 2.21) at $d = 0$, and the small blocks reached an average stack height of 8.2 layers (SD = 2.44) at $d = 0$. Regarding sensing area, the stack height of both the large and small blocks linearly decreased with $d$. The lower bound of the stack height's 95% confidence interval (CI) for the large blocks was >1 layer when $d$ was two blocks from the center, and that for the small blocks was >1 layer when $d$ was three blocks from the center. The results indicate that the small blocks support stacking at a higher resolution.

**Session 2: Stack Sensing Capability vs. Stacking Volume**

The second session investigated the capability of sensing 1D stacking versus base area sizes, which refers to stacking volume. The apparatus used was the same as that in Session 1.

*Procedures.* The results of Session 1, four dimensions of $n \times n$ base plate, where $n = \{1, 3, 5, 7\}$, were tested in this session. Only $d = 0$ and 0° were tested in this session. For each iteration, an entire layer of the blocks was stacked. If the IDs of all $N = 2n^2$ tags were read within 10 s, another layer was stacked; otherwise, the last successful stack layer height was recorded. After 10 iterations, if more than once a nonzero layer height was measured, a larger based area was tested; otherwise, the session was terminated.

*Results.* Figure 13c shows the results of the two block sizes. The large blocks achieved an average of 3.7 layers of the stack (SD = 0.67) on a 3×3 base area, and the small blocks achieved an average of four layers of the stack (SD = 1.05) on a 3×3 base area. Both the large and small blocks' 95% CI lower bound stack height was less than one layer when the base area was larger than 5×5. The results show a clear limitation for reliable 3D physical modeling

**Session 3: Stacking Sensing Capability vs. Antenna Grid**

This session investigated the relationships between performance and signal coverage.

*Apparatus.* In addition to the apparatus used in Session 1 and 2, four ANT925SMA circularly polarized antennas were used and deployed as a 2×2 antenna grid (Figure 12b). Grid deployment was tested because it retains ease of realization and provides a generalizable perspective for investigating signal coverage without affecting the direction of antennas.

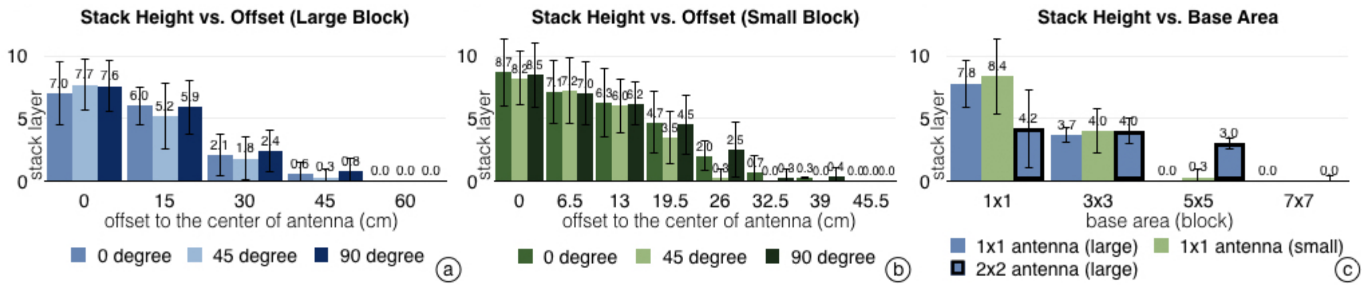


**Figure 13. Experimental results on the capability of sensing 1D stacking. (a) Results on Large blocks and (b) small blocks on different angles and offsets $d$. (c) Results on different base area sizes at $d = 0$, which refers to different stacking volume.**

*Procedures.* The measurement procedures are the same as those of Session 2. Four dimensions of $n \times n$ base plate, where $n = \{1, 3, 5, 7\}$, were tested in this session. Both large and small blocks were tested with the $1 \times 1$ antenna. Nonetheless, only large blocks were tested with the $2 \times 2$ antenna grid because a small block stacked at $d = 0$ of the $2 \times 2$ antenna grid could not be tracked because of the gap between the antennas.

*Results and Discussions.* Figure 13c shows the results for the two block sizes. The large blocks achieved an average stack height of three layers (SD = 0.67) on a $5 \times 5$ base area, which is an improvement over the results obtained in Session 2. Notably, the results of both the $1 \times 1$ and $3 \times 3$ base area suffer from a larger standard deviation that was not shown in the previous two sessions possibly because the initial position $d = 0$ is not in the center of an individual antenna, which corresponded to our findings from the previous two sessions. Nonetheless, the stacking volume increased with the antenna grid. The results initially indicate that adding an antenna is useful for extending the volume of the playground. We expect future optimization to improve this result.

## DISCUSSION

*Concurrent Stacking.* The current sensing algorithm may be incapable of resolving concurrent stacking of two 1x1 blocks because it may generate two ambiguous presence states in the lookup table. For instance, when a gray block and a red block are simultaneously stacked in position A and B, respectively, the lookup table may bind the gray one to either position A or B. The ambiguity can be resolved by applying switch patterns that activate a different number of tags for the different classes. For example, each red block has two switches on its bottom that simultaneously activate four RFID tags; the ambiguity of concurrent stacking can be solved on the basis of the amount of ID presented. This disambiguation method is useful for multiuser applications that require few token classes, such as Monopoly.

*Side-by-Side Connection.* Side-by-side connections can be realized easily by deploying the same contact switch pattern on every face of the block so that a more sophisticated 3D topology, such as a tree, can be realized without using a base plate and compound blocks. Nonetheless, side-by-side connections will introduce some ambiguities that our proposed 3D geometry detection algorithm cannot resolve. For instance, snapping a block on the base plate between two blocks forms a connection of six tags simultaneously. Additional RFID features are required for disambiguation. Because the side-by-side connection is not a mandatory feature for enabling Lego-like construction, we will pursue it in the future.

*Scalability and Responsiveness.* The most substantial limitation of the scalability and responsiveness of our system is the limited sensing bandwidth, which is inherited from current challenges concerning RFID sensing techniques. Because the bandwidth is limited, the system becomes slower and less reliable as the number of tags increases. A possible solution to improve this factor for large-scale physical construction is deploying multiple RFID readers at different operating frequencies to increase communication bandwidths. However, increasing the number of RFID readers is another deployment cost to consider.

*Incorporating Other RFID Sensing Techniques.* Because only ID information is utilized in our system, the system can incorporate other RFID-based interaction techniques to improve interactivity; for example, near-surface or touch gestures on the building block by classifying advanced RF signal features, such as RSSI and phase angles [15, 16]. Interaction responsiveness be further enhanced by the probabilistic filtering algorithms addressed in RapID [27].

## CONCLUSION

This paper presents RFIBricks, a lightweight and reliable interactive building block system based on UHF RFID sensing. This simple yet effective physical design transforms an RFID tag into an RFID contact switch and therefore enables the localization of the tag in 3D using a 2D grid of RFID contact switches. The proposed sensing algorithm effectively enables resolution of the 3D position and orientations of building blocks as well as the assembled geometry. The interactivity can be further enhanced by connecting the RFID contact switches with other electromechanical sensors to support more vibrant tangible and embodied interaction. The system evaluation addresses the limitations and design opportunities of our prototype system, which lays a foundation for further investigation of interactive tangible interaction platforms involving physical building blocks.

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