GaussRFID: Reinventing Physical Toys Using Magnetic RFID Development Kits

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ABSTRACT
We present *GaussRFID*, a hybrid RFID and magnetic-field tag sensing system that supports interactivity when embedded in retrofitted or new physical objects. The system consists of two major components — *GaussTag*, a magnetic-RFID tag that is combined with a magnetic unit and an RFID tag, and *GaussStage*, which is a tag reader that is combined with an analog Hall-sensor grid and an RFID reader. A GaussStage recognizes the ID, 3D position, and partial 3D orientation of a GaussTag near the sensing platform, and provides simple interfaces for involving physical constraints, displays and actuators in tangible interaction designs. The results of a two-day toy-hacking workshop reveal that all six groups of 31 participants successfully modified physical toys to interact with computers using the GaussRFID system.

Author Keywords
RFID, magnetic tangibles, analog Hall-sensor grid.

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

INTRODUCTION
Physical toys provide a rich set of interactions; invite people to feel instantaneous haptic feedback, and to enjoy hedonic and immersive experiences. However, they are not as interactive as digital games, which also allow people to experience digital content beyond real-world physics. For decades, designers of physical toys, developers of digital games, and researchers into augmented reality (AR) and tangible user interfaces (TUI) [8] have sought to bridge physical and digital experiences. Simple but powerful toolkits for so doing would help to expedite such a development.

Passive RFID (Radio Frequency IDentification) technologies are useful for implementing tangible interfaces that involve multiple objects, because the tags are passive and maintenance-free. Most importantly, a tangible object can be easily made into a container of information [6] by embedding an RFID tag into an existing physical object to enable it to be reliably recognized, while keeping its original form and functions [14]. Numerous works have used passive RFID to detect user actions such as presence [2], touch [15], and rotation [5]. Advanced techniques for so doing use on/off keying to detect 1D interactions [16] embed additional sensors in a RFID tag as input widgets [13], or form multiple tags into compound widgets [1] to support interactivity. UHF RFID systems can further be used to detect multiple tagged objects simultaneously, and to resolve discrete or coarse-grain user activities [9]. However, since RFID systems still cannot immediately and precisely resolve the position and orientation of a tag, attaching an RFID tag does not turn a physical object into an effective tangible controller that can interact with a computer. This limitation motivates the combination of magnetic-field tracking with RFID sensing herein.

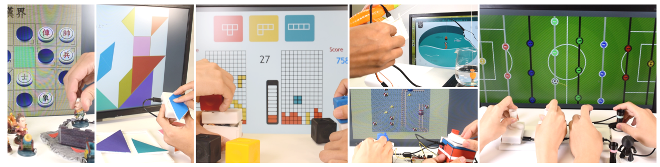

Figure 1. *GaussRFID* is a hybrid RFID and magnetic-field tag sensing system that supports interactivity when embedded in physical objects.

This work develops *GaussRFID* (Figure 1), a toolkit that fuses RFID sensing and GaussSense [11], which is a portable magnetic-field camera technology for resolving the occlusion issues that arise in optical sensing. Unlike a magnetometer for tracking objects [7], GaussSense tracks the movements, rotation, and tilt of passive magnetic tangibles in a 3D space close to a surface [10] with minimal required initial training. However, identifying passive magnetic tangibles is challenging. Although passive magnetic tangibles can be identified by analyzing distributions of magnetic fields [12], the method requires considerable training, and the training burden increases with the number of tangibles. Combining magnetic tangibles with RFID seems to be a more practical means of deploying interactive systems on a large scale, because do so completely eliminates the need for training.

DESIGNING MAGNETIC RFID TAG SENSING SYSTEMS
Like an RFID system, GaussRFID is a system of passive tags and readers. The passive tag, *GaussTag*, comprises an RFID tag with a permanent magnetic unit in its case. The portable tag reader, *GaussStage*, comprises a synchronized RFID reader and analog Hall-sensor grid pair: the RFID reader resolves the ID of a GaussTag while the analog Hall-sensor grid simultaneously obtains the 3D position and partial 3D orientation information, using the algorithm introduced in GaussBits [10]. The two sensing mechanisms can operate together in a complimentary fashion.

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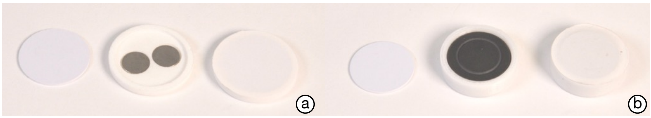

Figure 2. (a) Rollable GaussTag. (b) Tiltable GaussTag.

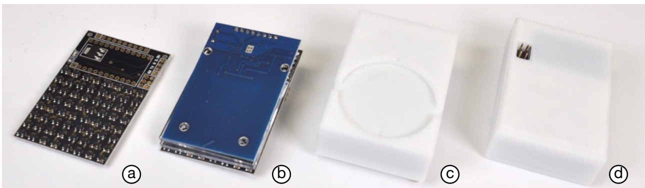

Figure 3. GaussStage. (a) Analog Hall-sensor grid. (b) Assembled module comprises an RFID reader, an analog Hall-sensor grid and a microcontroller. (c) Cavity on top of case. (b) Connecters on bottom of case.

Designing GaussTags as Passive and Attachable Tokens

The major benefits of the RFID tag, such as supporting *unpowered*, *lightweight* and *attachable* uses, must be preserved in the new tag design. Following GaussBits [10], which demonstrated several passive magnetic units that support rotation or tilt, the following design is chosen to realize the features while making the magnetic units as light as possible. For rotation, two flat-disc magnets are attracted to each other; for tilt, an flat-disc magnet with a larger radius is used. The chosen design of magnetic units enables a GaussTag to be shaped as a coin-like token for attachment. The GaussTag is implemented using a 12.5mm (radius)×1mm (height) round NXP S50 Mifare RFID tag, which can be passively powered by a 13.56MHz reader that is placed a couple inches away. Two 5mm (radius)×1mm (thickness) cylindrical neodymium magnets are embedded in each Rollable GaussTag (Figure 2a), and a 12.5mm (radius)×3mm (thickness) ferromagnet is embedded in each Tiltable GaussTag (Figure 2b). Components are encapsulated in a 3D-printed case.

Designing GaussStages as TUI Design Platforms

As a TUI design platform, the tag reader should not only the have the main advantages of magnetic-field and RFID tracking — *portability* and *responsiveness* — but also be *easily configurable* and *extensible*. With respect to portability, an 8x8 Winson WSH136 analog-Hall sensor grid with a 4(W)×4(H) cm^2 sensing area (Figure 3a), an ATMega32U4 microcontroller, and an NXP MFRC522 RFID reader are integrated in a compact 62mm×40mm×8mm module (Figure 3b). The RFID reader senses one tag at a time with a reliable anti-collision mechanism. Based on experimental results, the horizontal gap between the analog-Hall sensor grid and the RFID reader is set to at least 4mm, to prevent electrical magnetic interference between them. The density of the Hall-sensor grid is the same as that in GaussSense [11], so the positioning accuracies are similar (<1mm error). With respect to responsiveness, the firmware that is installed in the microcontroller synchronizes the two sensors, yielding a 60fps refresh rate. The sensing module is encapsulated in a 3D printed case on top of which is a round cavity with a radius of 19mm. The cavity constrains the movement of the token within the area of reliable tracking.

Several plug-and-play components are provided to make the GaussStage easily configurable and extensible. To extend or modify its input capability, a user can simply plug additional analog or digital sensors into the connectors under the GaussStage, or use caps to the round cavity of the case to eliminate one or two degrees of freedom (DOF) of the movement of the token (Figure 4a-c). To extend the output capability, additional LEDs, piezo speakers, or actuators can be plugged into the bottom of the GaussStage, in which is installed a vibrator and servo motor, as shown in Figure 4d. To expand the sensing area, an USB hub is used to connect easily multiple GaussStages to a computer if needed. Once the GaussStages are plugged into a computer, the users can easily program software applications with the GaussSense SDK[1].

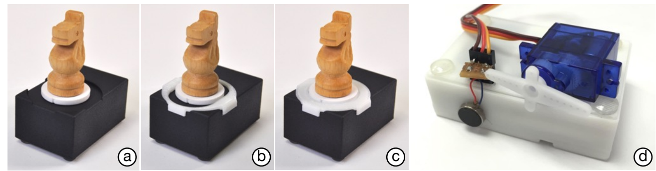

Figure 4. GaussStages with (a) a cap applied, (b) a *slider* cap that eliminates one DOF, and (c) a *holder* cap that eliminates two DOF. (d) A vibrator and a servo motor that are connected to a GaussStage provide physical movement as output.

WORKSHOP

A two-day toy-hacking workshop is conducted to study the applications and the experiences of users.

Participants and Apparatus. Thirty-one undergraduate and graduate students from engineering (22) and design (9) departments participated in the whole workshop. The participants (21 males, 10 females) aged 20-37 (mean age, 22.95; STD, 3.85) were separated into six groups of at least five-participants, each group with at least one designer and three engineers. Participants participated in a physical toy-hacking workshop with no preliminary knowledge of the GaussRFID system. They were asked to bring their own laptops and physical toys to the workshop. In the workshop, a basic toolkit, including tens of GaussStages, hundreds of Rollable GaussTags, and hundreds of RFID tags, magnets, servo motors and vibrator modules, were provided. Brainstorming and prototyping tools (e.g. post-it memos, paper clay, foam boards, Arduino, 3D printers) were provided on demand.

Procedures. On day one, the organizers provided a brief overview of the capabilities and limitations of the RFID and magnetic-tracking technology, and then introduced the developed GaussRFID to the participants in several simple exercises (Figure 5a). Then, the participants brainstormed during two 20-minute sessions to discuss their toys (Figure 5b) or to elaborate ideas about new ways to play with those old toys. After some simple ideas had been gathered, the participants were asked to produce several lo-fi prototypes using foam boards, paper clay, and readily available everyday objects, and then to present their concepts using tangible products [3] to all participants (Figure 5c). The feedback gathered included areas in which the presented game design and tangible interaction design could be improved, and the possible ways of implementation. On the second day, each group refined the ideas that were offered on the first day, and built

[1] http://developers.gausstoys.com/

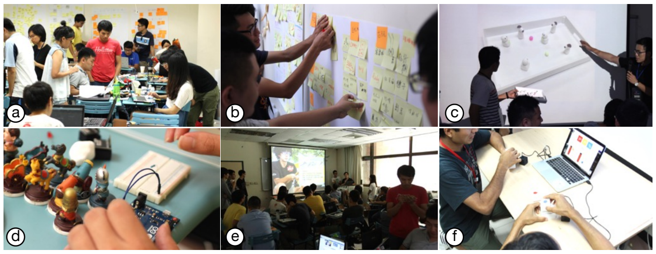

Figure 5. Two-day toy-hacking workshop.

Figure 6. *Tangram Reader* allows the reader to read the story book by assembling Tangram pieces. The reader can assemble the pieces of the tangram by (a) placing, moving and rotating a piece into the desired position. (b) When a player becomes stuck, the system provides a color as a hint. (c) When the shape has been completed, the hidden character appears and the story continues.

hi-fi prototypes using 3D printing or by toy hacking (Figure 5d). After six hours of implementation, each group presented its interactive prototypes to some invited external experts in the field of tangible interaction design and research (Figure 5e), and demonstrated the interactive prototypes to all attendees (Figure 5f). Finally, the participants were asked to respond to a questionnaire to provide feedback. After the workshop, ongoing collaboration with at least one member of each group was carried out for an additional 3-12 hours/person to finalize the products. Based on the comments that were gathered during the workshop, the form of physical toys was fabricated using 3D printing, the graphics of the game were redesigned, and the games and interactions were fine-tuned without changing the original theme of each project.

Results and Discussions

This section presents and discusses the six physical toys (Figure 1) reinvented by the workshop participants.

Designing Spatial Interactions of Tokens with a Constraint

The *Tangram reader* (Figure 6) turns the traditional tangram game into a feature for reading an electronic book. A GaussTag is attached to the center of each piece of the tangram, and a vibrator is attached to the GaussStage. A reader assembles the on-screen tangram by placing, moving and rotating a physical piece into the desired position. When the moved piece is close to the desired position, it snaps to the position with the orientation and the GaussStage slightly vibrates; the player can thus assemble the presented patterns on the display. When a user becomes stuck, the system displays a color of the tangram to provide a hint as to which piece should be used. When the user has completed the shape, the hidden character appears, and the story continues. This application shows that an appropriately shaped token can represent spatial information. The physical cavity of the GaussStage confines the movement of token, allowing 3-DOF spatial operations to be mapped.

Figure 7. *Chinese chess* allows for moving multiple chess in the same-class chess (e.g. two guards) at the same time. A user makes a move by (a) placing a character on the commander platform, (b) rotating it to target direction, and (c) stamping it to defeat the enemies.

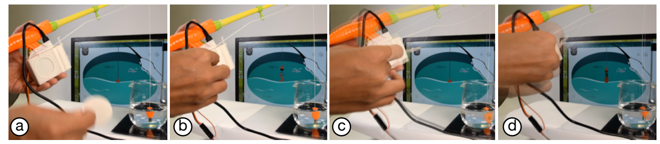

Figure 8. *Fishing game* renders real haptics for virtual fishing. A user (a) holds the fishing rod and (b) attachs the tagged handle to start. (c) When a fish gets on hook, the rod vibrates and changes its shape to inform the user to (b) pull the fish up from the water by rotating the handle.

Designing Tokens in Rich Representation

The *Chinese Chess* game (Figure 7) comprises 14 tagged figurines, which represents both their identity and the orientation through their appearances. A GaussStage with a mounted vibrator is used as a commander platform. A user can easily select the desired character by placing the figurine on the platform, set the target direction by rotating it, and make the move by stamping it to the platform. The vibration of the platform immediately informs whether the attack has been effective.

Designing GaussStages as Shape-Changing Interfaces

The *Fishing game* (Figure 8) shows that the portable GaussStage allows to be embedded in physical toys. In the game, a GaussStage is mounted on a fishing rod as a reel. The GaussStage controls a servo motor, and the shaft of the servo motor is connected to the tip of the fishing rod using a fishing line, so it can bend the fishing rod. The GaussStage applies a *holder* cap (Figure 4c), which allows a handle that is attached to the top of a GaussTag to rotate on it. When a fish takes the bait, the rod slightly vibrates; when a fish is hooked, the fishing rod changes shape to the user to rotate the handle to bring the fish up out of the water.

Track the Train (Figure 9) is a multi-player game that exploits the shape-changing capabilities. A user directs a train by bridging the track using a specific token. To the bottom of each GaussStage is attached a servo motor, which can vibrate the platform at various frequencies and amplitudes, causing the platform to move and sound as if it is traveling along the rail. The haptic feedback of velocity thus helps users to focus on the main task, which is tracking the train.

Competing Graspables and Disabling Inputs of Opponents

Snatch Tetris (Figure 10) shows that a game can feature a limited number of instances of a physical Tetris game. The game provides three colored tagged cubes as controllers and two black tagged cubes as attackers. The size of the controller cubes allows users to grasp only one at a time, so they must release the current cube to grab another one, which may belong to another player. This out-of-band interaction [17], which is not in the sensing range, is the most interesting part of the game. Another interesting aspect of the game is that

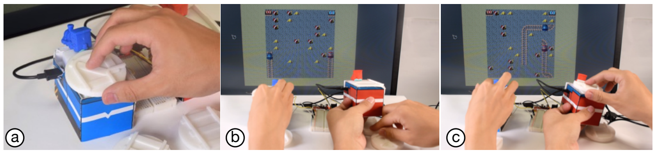

Figure 9. ***Track the Train*** **renders the speed of a train via the vibrations of the platform. A user (a) directs the train using a specific token, (b) competes against another user by briging the rail faster and (c) wins the game by arriving the platform first.**

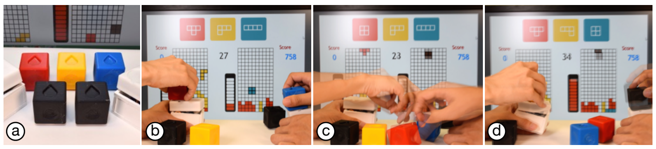

Figure 10. ***Snatch Tetris*** **allows players to compete the limited number of game pieces, and physically disable their opponents. (a) Three colored controller cubes and two black attacker cubes are provided. A user (b) grabs and places a colored cube on the stage to grab the desired on-screen piece, which is manipulated by moving and rotating the cube. (c) For the next move, the user must release the currently held cube to grab another one, which may belong to another player, so the user must snatch to grab it. (d) Attacker cubes can be used to cause the opponents stage to rotate wildly, preventing the opponent from playing at that time.**

a player can physically disable inputs of the opponent. The GaussStage is attached to an actuator-mounted graspable case via the shaft of a servo motor. When a user places the black attacker cube on the stage, the opponents stage rotates wildly for two seconds, so the opponent cannot play at that time.

Remote Multi-User Bi-manual Interactions

The *Table Football* game provides tangible handles, allowing remote, multi-user, and bimanual interactions. The game provides eight tagged handles and four stages with a *slider* cap (Figure 4b), on which users can slide and rotate tokens. Fixing multiple GaussStages on a platform eliminates the need for users to use their non-dominant hand to hold the GaussStages, allowing them to rotate the handles using both hands. The physical handles share similar visual elements (such as color, and associated icons), allowing users to grasp easily the desired handle using peripheral vision; the direction of the handle is also represented by the physical form its physical form. The GaussStages vibrate when the ball is kicked or when possession is gained, providing haptic cues to offload the players visual attention. Hence, the remote players can pass a ball between two hands, as in real table football.

USER FEEDBACK AND DISCUSSIONS

The responses to the questionnaire show that the participants enjoyed the process of toy hacking. On a five-point Likert scale, the participants agreed that GaussRFID is, overall, an easy-to-learn development kit (mean, 4.06; STD, 0.68) that enablesthem to concentrate on content development (mean, 3.93; STD, 0.63) and create desirable input and output effects (mean, 3.90; STD, 0.65). The participants primarily enjoyed the freedom of designing the appearance of the tagged objects. They also enjoyed the hedonic experience of active haptic feedback and the movements that were provided by the added vibrators and servo motors.

During the workshop, several technical limitations that influenced the designs were observed. The major limitation was

Figure 11. ***Table Football*** **allows remote users to play together. (a) Four tagged handles and two stages with a slider cap are provided to each team. The players (b) play the game by placing the desired handles on the stage, and then they try to take possession of the ball by moving the handle along the slider. (c) Once possession is gained, the player sets the target direction by turning the handle, and kicks the ball by stamping the handle on the stage.**

that the relatively small interaction area could sense only one token at a time. Making smaller GaussTags or using a UHF RFID reader with a larger RFID antenna and a larger analog Hall-sensor grid could have mitigated this design constraint. Participants also reported that the sensing range of the original Rollable GaussTag was limited (<5mm in z-axis), and they hacked the tags by attaching additional magnets or stacking them to increase the sensing range. Participants further reported that the RFID could not be recognized behind an LED display such as GaussBits [10], so most of the inputs were combinations of direct bindings and indirect manipulations.

Several input/output modalities were not tested. Using conductive sensing and/or flexible materials to the surface of a GaussStage can enable touch or pressing inputs. Adding a robotic arm, a small vehicle, or pneumatic actuators to a GaussStage can enable a wider range of movements as new outputs. Embedding LEDs and speakers into a GaussStage or incorporating a relay into a GaussStage to control electronic appliances (such as smart things) represent promising directions toward higher level of embodiment [4] in tangible interaction design.

CONCLUSION AND FUTURE WORK

This work develops *GaussRFID*, a magnetic RFID sensing system and development kit, that can be used for retrofitting or producing physical objects. The combination of a robust ID mechanism with magnetic tangibles greatly addresses the difficulty of representing the noun and verb properties of physical objects, effectively supporting applications that involve many tangible objects, and so seamlessly extending the physical affordance thereof into digital domain [8]. The applications that were created as interactive prototypes during a two-day workshop and the overall positive user feedback reveal that the toolkit is easy-to-use, easily configurable and extensible, and useful indesigning tangible interactions and content with rich form and function. Future work should consider increasing the scale of the applications, for boardgaming for example, and performing longitudinal evaluations to identify issues that may arise when this TUI development kit is deployed in everyday life.

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