

Flying LEGO Bricks

Observations of Children Constructing and Playing with Programmable Matter

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ABSTRACT

In this paper, we present a case study that explores how children could learn to interact with programmable matter. Flying drone swarms enable physical visualizations of complex data and simulation of physical objects and processes, e.g., planetary movements. The swarms can be digitally controlled as an ensemble as a form of (sparse) “programmable matter.” We worked with the toy company LEGO®, to design and evaluate a “build and fly” experience with 240 children in a public exhibition. The children decorated a bendable handheld controller with LEGO® bricks and then used this controller to animate the flight of a 10-drone swarm. Results indicate that children enjoyed the constructive play and performance aspects of the system. Four main patterns of player behavior emerged, which we discuss in relation to possible improvements to the system. We provide implications for design of programmable matter systems for supporting child play experiences.

CCS CONCEPTS

- Hardware~Emerging interfaces
- Human-centered computing~Mixed / augmented reality
- Human-centered computing~Empirical studies in ubiquitous and mobile computing

KEYWORDS: Organic User Interfaces; Claytronics; Radical Atoms; Programmable Matter; Swarm User Interfaces

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Figure 1. Child moving and bending the butterfly-shaped controller to control a drone swarm.

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1 INTRODUCTION

Programmable matter involves the control of dynamic physical nano-structures to form 3D objects, or even materials [53]. In its purest form, it entails billions of atomic actuators that connect and form physical objects on demand, through some programming language or interaction technique [20]. Although this form of programmable matter is still science fiction, new technologies such as 4D printing [52] and self-assembling robots [43,44] provide first steps in that direction. One of the issues in self-assembly of three-dimensional structures is structural integrity, i.e., intermediate states of construction may lead to unstable structures that collapse under their own weight. To address this, flying modular robotic systems [11,19] have been developed, which utilize flying voxels capable of self-assembly in mid-air. Since the atomic structures are made out of nano-quadcopters, self-assembly does not require intermediate states or support materials. This makes it relatively straightforward to create physical animations with flying physical voxels. In this paper, we present a case study that explores how children could learn to interact with this type of programmable matter.

1.1 Constructionist Learning

When we were invited by LEGO® to develop and evaluate a flying bricks experience for children aged 5-12 at the LEGO® World Expo, we were inspired by Constructionist theory as a framework for investigating a new way of learning interactions with computers: by playing with programmable matter (see Figure 1). According to constructionist theory [40], and its constructivist roots [4,41], learning is most effective for children when they are making tangible objects in the real world. Playing with LEGO® bricks provides a good example of this style of learning, where a child constructs a mental model of the world by literally trying out the connection between physical objects in the real world. In software too, constructionist learning theory has been highly influential, and led to the first Object-Oriented Programming languages: Kay's Smalltalk [25]. Papert's LOGO language [1,40] spawned a way to control LEGO® Bricks via the Mindstorms robotic kit and programming language. One important aspect of learning to program or control programmable matter then, is the notion of assembly or construction: Children should be allowed to construct their own physical object using their own hands, just as they do with LEGO® bricks.

1.2 Embodied Cognition and Interaction

We were inspired by the idea that embodied interactions should involve and support bodily activity, with movement that is mapped directly to the task. Embodied cognition focuses on how sensorimotor activity influences human learning, understanding, and reasoning—it is the notion that cognition occurs in and with the body, not just the brain [2,33,34]. Not only is the mind not separate from the body, but the subject is not separate from the object [24]. According to Merleau-Ponty, our body develops “an understanding with regards to the world” [37]. Piaget's schemas, or “habits” according to Merleau-Ponty, bear direct relation to the dialog between the subject and the object: the physical environment [13]. Fishkin [17] used the theory of Embodied Cognition [50] as a framework to develop an understanding for interactions with Tangibles through Embodied Interaction metaphors: Where the body and bodily movement is more or less coupled with the movement of the physical objects representing software objects in the real world. Dourish emphasizes skill and experience of the human and natural practice over detached rational logic when interacting with software systems [14].

According to [16], embodied interactions can be categorized from fully, nearby, environmental, to distant.

In their taxonomy, Fishkin et al. ask the question “How closely tied is the input focus to the output focus? To what extent does the user think of the states of the system as being ‘inside’ the object they are manipulating?” On the one end of the extreme, the output device is the input device. Here, the state of the device is fully embodied. The analogy proposed is that of sculpting clay. This is similar to the principle of Input=Output in Organic User Interfaces [23], where the action (e.g., bending) of the display itself provides the input to the system. The second case is where the output takes place near the device. The original Graspables system [18] is an example of this. In the Environmental category, the output immediately surrounds the user's body, for example, as sound. In the Distant category, the output is somewhere else, removed from the user. The analogy here is of the traditional remote control, but with the distinction that there may be embodiment in the action of the controller that represents some aspect of the remote object. Skulmowski et al. proposed a more simplified model that describes embodied cognition as degrees of bodily engagement (low vs. high, e.g., seated vs. active), and task integration (e.g., incidental vs. tasks that integrate with bodily movements) [51].

1.3 Contributions

Informed by the above, we designed a study observing the creation and control of flying programmable matter systems by children, using a constructionist perspective. To our knowledge, this is the first study of its kind. How do children experience and play with voxel swarms, and what insights can be gained to inform the design of such systems? Our main contribution is the results from interviewing a group of 240 children, who were asked to construct a tangible controller, then control a swarm of 10 drones. We identified four common play styles: Mesmerized, Exploring, Controlling and Performing. We also contribute implications for design of programmable matter systems to support play experiences.

2 RELATED WORK

First, we will discuss work on related topics of study.

2.1 Programmable Matter and Swarm Interfaces

According to Goldstein et al. [20], Claytronics are a form of implementation of programmable matter in which each atomic element consists of a self-propelled robot, called a Catom. One issue with a large collection of Catomic robots is how to control them. One promising approach is that of a swarm interface, defined by Le Goc et al. [29] as “an interface made of independent self-propelled elements

that move collectively and react to user input”. The Kilobot system by Rubenstein et al. was one of the first to demonstrate forming complex structures out of a large number of robots [43]. It served as the basis for a dynamic programmable display consisting of a swarm of one thousand robots [44]. Although Kilobots showed flocking behavior as a means of controlling shape, it moved very slowly and was not interactive. Alonso-Mora et al. [5] suggested a display in which each pixel is a robot with an addressable color. Their system is interactive, and allows users to sketch and perform mid-air gestures [5,6]. Zooids [29] extended this approach with the direct manipulation of a tangible robot swarm. All these systems operate in only two dimensions. While there are systems that are able to self-assemble in three dimensions [49,57], these do not mimic the movement of 3D voxels. That requires self-propelled Catoms that are able to not just move autonomously, but that also overcome gravity through self-levitation.

2.2 Self-Levitating Tangible User Interfaces

A natural extension to swarm interfaces is that of self-levitating tangibles. Here, self-propelled robots that are able to fly can arrange themselves to assemble more complex structures. Examples include Flight Assembled Architecture [8] and Termite Inspired Construction [55]. These systems are, however, not interactive. Researchers have explored the concept of levitating displays via flying robots equipped with projectors [39,48] and high-resolution displays [21,49]. These explorations were typically limited to a single drone that primarily acted as a visualization agent. Drone 100 [57], however, is a platform comprising 100 quadcopters that act in parallel to display images in mid-air. Another example of quadcopters representing 3D structures is BitDrones [21]. This system investigated how small quadcopters that serve as self-levitating building blocks can facilitate human-drone interaction via means of direct touch, bimanual input techniques and gestural interactions. It served as an inspiration for the current work.

2.3 Children Playing with Tangible User Interfaces

There are, to our knowledge, no studies of children interacting with programmable matter or self-levitating tangibles. However, there is a lot of prior work regarding the methods of study of children playing and learning with traditional tangibles [7,31]. These works inspired us during the design and evaluation with children. Ensuring the environment is conducive to the child play activity requires thought about spatial arrangements [22] and play supporting artifacts should embody creative or

constructive capabilities [56]. When children ‘walk up and use’ a new technology or are in the process of learning, the child must feel in control [36] and the technology must be rugged in order to maintain confidence and to ensure that breakdowns do not cause anxiety or frustration.

3 DESIGN RATIONALE

We worked together with LEGO® to design a programmable matter experience for children to showcase at their annual LEGO® World Expo. It was important for us to balance the aims of the company with our research interests in designing for children. We used the following design principles in designing the experience:

Constructive play. Based on the theory developed by Papert, and in line with the LEGO® build experience, it was important to have an element of construction to the exhibit: Children should be able to customize some parts of the drone experience.

The metaphor of the brick. To allow children to imagine that the drones were in fact flying LEGO® bricks, LEGO®’s main product, we wanted to include the use of the original bricks in the construction experience.

Safety and control through tangible controller. Although [8] was originally tangible, in that children would be able to control the drones by touching them, safety guidelines associated with the exhibition space required the drones to fly in a closed-off area. Thus, the shape and movement of the controller utilizes a noun and verb metaphor using direct mapping such that the butterfly-shaped controller corresponds to the swarm shape (noun) and bending the wings, tilt, and rotation of the controller corresponds to similar movement of the swarm (verb). To avoid drones crashing into each other, we limited the speed of all interactions. While this made the system less responsive, this also conserved battery power.

Easy to learn. To allow as many children as possible to go through the experience, we needed a very clear mapping between the controller and the drone swarm, such that children could learn to control the swarm after a brief instruction and 45 seconds of operation.

Fun and inspirational. In accordance with LEGO® design guidelines for playful experiences, we designed the controller and swarm shape to be very playful, and chose the embodiment of a butterfly as we believed this to appeal universally to children of all ages.

4 IMPLEMENTATION

Next, we will describe the system, including the physical layout of components and the design choices of the 10-

drone swarm behavior. For technical details of the drone flight control we refer to [11,12]. We extended the Griddrones system to fit within the constraints of the space provided. We adapted control to support distant interactions with the drone swarm using a tangible controller. Here, we focus on describing the tangible controller, the computer vision system, and the unique flight behavior developed to support the experience.

4.1. Task Overview

The purpose of the task was for each child to design and animate a flock of 10 drones. For this purpose, they had to first decorate a tangible controller with LEGO® bricks. These were then scanned by a computer vision system to position and colour individual drones in the flock. Finally, the child was allowed to move the controller to explore its mappings with the behavior of the drone flock.

4.2 Tangible Controller

The design of the controller balanced the desire for children to feel creative freedom during the build process, yet at the same time provide enough structure and simplicity to allow children to walk up and use the system without any prior experience with drones or 3D interaction techniques.

Figure 2 shows the tangible controller. It consisted of two pre-shaped pieces of LEGO® baseplate, each sized 12x12 cm. While different shapes were possible, we decided to focus on a playful design in which the tangible controller resembled the wings of a butterfly. The two baseplates were joined by a hinge made out of a flexible translucent plastic. At the bottom of each wing, a plastic case containing an IMU was placed that allowed measurement of 6 degrees of freedom: 3DOF wing acceleration and 3DOF orientation. The left IMU unit contained an Arduino Pro Micro with an ATMEGA 32u4 chip and an ESP-8266 Wifi module that sent controller parameters to the drone OS computer over WiFi via UDP. The right IMU unit contained a 3.7 V single-cell lithium-polymer 300 mAh battery that also powered the left IMU via a small wire. One LED in each IMU unit was powered to pulse white when responding to movement, and would turn red when the battery ran low. One magnet per IMU unit allowed the tangible controller to be affixed to a small desk unit providing computer vision.

While the tangible controller was capable of measuring 3DOF of acceleration, this data was not used to position the drone swarm. The reason for this was that we did not want the children to be able to move the drone swarm within the safety enclosure. Instead, only the 3 DOF orientation data from each wing was used to compute the

angle of the two-wing structure relative to each other, as well as roll, pitch and yaw of the entire controller. This allowed the controller to express 4 degrees of freedom.

4.3 COMPUTER VISION STATION

A scanning station was used to allow children to process their design. It consisted of a table instrumented with a camera, lights and computer. We developed a simple computer vision algorithm to sense the colors of bricks and assign placement of the colors to the swarm.

The baseplate accepted standard LEGO® bricks to be attached to it, allowing children to decorate the controller. Each LEGO® brick was one of 3 colours: Red, Green or Blue. By placing the LEGO® brick on the wing, the children could determine the relative location and colour of a drone in the swarm. Placement was measured using a computer vision unit. After decorating the controller, children would place the controller on this unit such that the magnets snapped to those inside the unit. The computer vision unit consisted of a laser-cut scanning station constructed out of MDF. This box featured a flat surface with two magnets to hold in place the controller. A protruding arm featured an RGB USB 2.0 camera unit as well as an LED illumination ring. The camera unit scanned the baseplates via a computer vision program running on an Intel NUC. This determined the relative position and colour of any LEGO® bricks on the controller. Touching a capacitive sensor on the scanner would start the scanning process. The NUC would send relative position data to the drone OS, upon which it would launch the drone swarm.

4.3.1 Algorithm

First, the computer vision algorithm processed the camera image by firstly, filtering for contrast, colour and brightness. A sharpening filter was applied, after which square detection was performed. This consisted of the following steps: An edge detector found the edges of the bricks. The algorithm then determined the intersection of edges to find vertices. It then compared the angles of the edges from the vertices to determine right angles. From this it compiled a list of square candidates. Square candidates were then filtered by finding the area such that it matched the size of a brick. The center of each area was recorded as a drone position. Finally, each area was sampled for colour. Although children were told to limit the number of bricks to 10, we truncated the list of position and colour data to the first 10 bricks recognized by the algorithm.

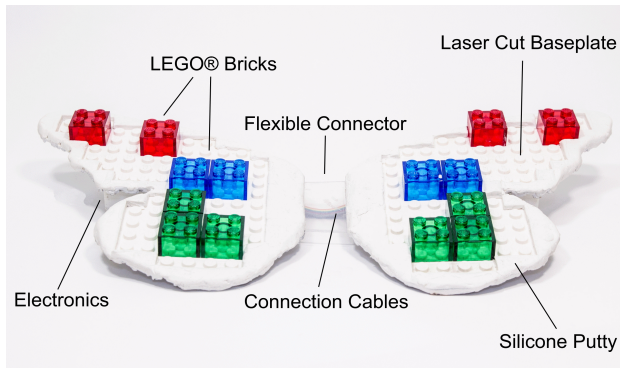


Figure 2. Butterfly Tangible Controller.

4.4 SWARM ANIMATION

Each drone swarm animation lasted for 45 seconds. This provided the opportunity for the child to learn the function of the controller, while maintaining the ability to run 4 children per battery swap. After the LEGO® brick pattern was scanned, the software assigned each of the 10 drones a position and color according to the layout of the controller. After establishing a WiFi connection to the controller, the operating system launched each drone in sequence from front to back. This was done to ensure there were no mid-air collisions. Drones were then continuously directed to their appropriate locations by processing the data from the tangible controller in real time. The Arduino in the controller calculated a unit quaternion for each wing that was relayed to the operating system. From these quaternions, the operating system calculated the appropriate x,y,z offset and orientation for each drone from its location on the original plane. This information was sent to the software drone object, which relayed it over WiFi to the flight controller of the drone. Data was filtered such that the maximum velocity of the drones would never exceed 1 m/s. This resulted in a drone swarm animation that directly mimicked the 3DOF orientation and angle of the two wings of the tangible controller.

5 STUDY

In order to study how children respond to programmable matter, we recruited 240 participants, over 4 days, at the LEGO® World Expo. We were interested to learn how children would express themselves through the system. How would the children build the wing patterns? How would the children control the swarm? How expressive would the control movements be? How do children make sense of the experience, and what improvements would they suggest?

5.1 Participants

While the system was designed for children between 7-11 years, we allowed all interested children to participate. We recruited 240 children between 4-16 years of age with an average age of 9.39 years, 57 female and 183 males. The Flying Bricks experience was visible to visitors in the main expo area, however, parents were required to sign consent forms to reserve a place in line and accompany their child to take part in the study.

5.2 Procedure

Parents were asked to fill out demographic information and give permission to use photographic and video documentation during the study. Parents then accompanied the children to the waiting area. Due to the need to replace batteries after approximately 6 minutes of flight, a batch of 3-4 children were queued up to wait their turn, while others were invited to play test other experimental prototype toys.

Each child was asked to decorate the baseplate in the shape of butterfly wings with a total of 10 bricks. They were instructed that they should place 5 bricks on both the left and right wing using any color of available bricks (see Figure 2). The child was asked to place their creation on the scanning platform so that the system could analyze their design and transfer the colors to the drone swarm. After the scanning process was completed, the drones in the adjacent area took flight and the controller was handed to the child. They were asked to stand at a point located in the center of the glass wall. The child was then told to move and bend the controller as they desire. After 45 seconds, the drones changed their LEDs to blink red and moved to the sides to land. The facilitator explained that the drones needed to rest and invited the child to answer some questions about their experience with a separate interviewer. The children answered questions in a contextual interview regarding their experience, including positive and negative aspects and ways in which we could improve the system. The interviewer had a duplicate controller on the table so that the child could refer to it when needed.

5.3 Data Collection

We gathered both objective recorded data as well as self-reported data from interviews. Objective data included video and photographic images of the build and fly activity and images of the scanned patterns of each child's decorated butterfly wing controller. Self-reported data was gathered from contextual interviews after the play session. This was intended to provide insights into the thoughts and experiences of the children and ideas for how the

system and overall experience could be improved. The study interviewer had extensive experience in working with children and aimed to cover all aspects of the experience. The interviewer ensured to ask the following questions:

1. “How did you figure out how to fly the swarm of bricks?” This was intended to prompt the children to explain, in their own words, how they understood the system and to give initial impressions for what appealed to them about the interaction.
2. “If you could make anything, a game, a person, anything, what would be fun to make with ‘Flying Bricks’?”
3. “What would you change to make ‘Flying Bricks’ more fun?”
4. “Tell us about any problems you had.” These could include Critical, Significant or Minor problems.
5. “Tell us about the good experiences you had. Positive experience, super experience?”

These questions served as a general guide; however, it was up to the interviewer to engage with the questions in the depth that was appropriate. If a child was especially shy or did not want to provide lengthy answers, the interviewer would move on and spend more time on the questions that seemed to be of interest to the child. The interviewer reviewed their notes after the first day of the study and compiled a list of unique topics that were brought up for each question. This was discussed in a debriefing meeting with the authors of this paper and through discussion we reviewed the notes and agreed to consolidate some of the codes that were similar. The interviewer kept a summarized list of codes and topics that they used when taking notes on the remaining three days. At the end of each of the remaining three days, a debriefing took place with the authors to identify and discuss the codes and unique, highly detailed, or surprising responses.

6 RESULTS

All of the participants claimed to enjoy the experience and were able to control the drone swarm with the controller they built. Preliminary analysis of the feedback suggests that most children wished the flying activity lasted longer. Various uses for drone swarms were imagined as well as suggestions for improvement. The interview notes were transcribed and translated to English by two additional researchers and input into a simple database and analyzed for frequency of topics.

6.1 How did you figure out how to fly the bricks?

Children were asked how they learned to control the drone swarm. We did not expect children to be able to

articulate their learning process to the level of a pedagogue, however, we posed this question to encourage the child to think about the activity as a challenge they completed and to celebrate their play session. We expected that the child might compare the activity to other experiences. The responses mainly focused on their experiences with game consoles, RC cars/planes/drones games, and toys. There were also some interesting outliers.

54.6% (131 children) mentioned experience with either game consoles, remote control vehicles, or past drone experience as being helpful. 34.2% (82 children) did not know or have a specific answer. 7.1% (17 children) claimed that the experience was like nothing they had ever experienced before and did not know how they learned to control the swarm. They were still very excited after the flight experience. 4.2% (10 children) had other explanations for how they figured out how to control the drone. Of these, four mentioned the instructions given by the facilitator, three mentioned that they had experiences with virtual reality, one mentioned past experiences with a sibling, another claimed that they figured it out by moving very slowly, and one child claimed that it was like controlling an animal.

6.2 If you could make anything?

Children were excited to explain what they would make with the flying brick system and many of the children gave more than one idea. Only 11.7% (28 children) did not answer or claimed they would just play with the system. The answers touched on recurring topics that we grouped to provide an overview.

34.2% (82 children) mentioned they would fly around. Colorful answers included flying to school, flying around the house, and flying to McDonald’s.

26.7% (64 children) mentioned ways they would play with the swarm together with other toys. In most cases they named specific toys they play with including building with LEGO bricks on the drones themselves, other flying stuffed dolls, and pets.

25.4% (61 children) mentioned new forms and shapes for the swarm.

22.1% (53 children) claimed that they would use the swarm to move things. This included moving toys by carrying them, to carrying messages, and tidying up.

15.8% (38 children) wanted to use the swarm to take video or photographs. Most made this statement generally, yet some mentioned more playful uses of the photography including spying and capturing a play session.

14.2% (34 children) mentioned games that they would like to make with the drone swarm. Specific game examples included: hide-and-seek, obstacle racing, drone soccer, tag, puzzles, chess, cops and robbers. One especially enthusiastic child explained that he would like to make “Grand Theft Auto but a special version for drones.” – *participant#127, m, 11yrs*

11.7% (28 children) explicitly mentioned social interactions with the swarm and their friends or family.

5.8% (14 children) mentioned new ways they could control the drones or specific changes to the controller.

6.3 What would you change to make it more fun?

Children reported various ways that the system could be improved. For the expo, our collaborator wanted to ensure that as many children as possible could experience programmable matter thus we adjusted the flight time. The most common request for changing the system focused on the length of flight time—the children wanted to fly the swarm for as long as possible and would ask if they could try the system again. We also limited the angular motion and slowed the drone movement to increase the robustness and stability across the many play sessions and to contain the swarm to the 3m x 3m enclosure. Many children suggested that the swarm could move faster and move in various ways. There were many wild ideas children had for making the system more fun including carrying people, making animal shapes with arms, creating fireworks and canons, shooting water, fire breathing dragon, shooting candy, drawing emoticons, or playing weird sounds, among others. It was also common for the children to name other LEGO toys they have and to suggest that they could play with them and the drones.

6.4 What problems were encountered?

Children were asked if they encountered any problems during the play session. The facilitator would ask the child to explain, for each listed problem, whether it was critical, significant, or just a minor problem in their mind. Results suggest again that the limited flight time was seen as the most important problem children faced.

Secondary to this, children complained that learning to control the swarm was a problem. This was mostly due to the limited time allotted to this process, which was due to the limited battery life. In the future, we would like to conduct longer play sessions to give more time for children to enjoy the experience – all were able to walk up

and use the system, but the short flight sessions led to children longing for more.

6.5 What was enjoyable about the activity?

Children reported various aspects of the experience that they enjoyed that can be grouped broadly into 5 main categories including controlling the swarm, flying/moving the swarm, building the controller, moving and bending the physical controller, appreciation of the colors/lights of the drones, and appreciation of technical novelty.

6.5.1 Controlling the Swarm

46.7% (112 children) remarked about controlling the swarm.

“controlling them. They can do more than regular drones!” – participant#233, f, 10yrs

“controlling multiple drones at once was fun!” – participant#216, f, 8yrs

“It is fun that you are allowed to build and control it yourself!” – participant#201, m, 7yrs

“...it did exactly what you wanted it to do!” – participant#200, m, 12yrs

“...that you don't need buttons!” – part#188, m, 8yrs

6.5.2 Flying/Moving the Swarm

34.2% (82 children) claimed that flying or moving the swarm was enjoyable. These comments would often be very direct, but some provided more detail.

“When they take off. The tickling sensation in the stomach.” – participant#121, f, 9yrs

“The drones do not fly alike, and can move differently from each other.” – participant#197, m, 9yrs

“It is cozy that it looks like a butterfly and it can fly!” – participant#235, f, 10yrs

6.5.3 Building the Controller

14.6% (35 children) remarked about the build experience of placing the bricks on the controller as being enjoyable. Most of these children simply mentioned ‘building the controller’ was fun, however there were unique ways children described this.

“...making the formation yourself” – part#107, m, 12yrs

“...fun to build on the controller” – part#119, f, 8yrs

“...putting LEGO on it was fun” – part#102, m, 7yrs



Figure 3. Variations in wing pattern decoration including one, two, and three-color designs.

6.5.4 Moving and Bending Controller

25.9% (62 children) described the Moving or bending of the physical controller as among the enjoyable aspects.

“...bending the butterfly so the drones would follow.”

– participant#35, m, 8yrs

“...bending the wings so the drones would do the same.”

– participant#37, f, 7yrs

“Bending it was fun!” – part#103, m, 7yrs

“...it followed my movements.” – part#96, m, 11yrs

“...it moved like I did!” – part#115, m, 10yrs

6.5.5 Colors and Lights

22.9% (55 children) children made remarks about the colors and lights, whereas many would mention that they liked the “matching pattern”, a few comments provide deeper insights.

“there were good colors, red, green, and blue!”

– participant#196, m, 12yrs

“the best thing was that you could pick the color yourself!” – participant#134, m, 11yrs

“deciding on the lights!” – participant#98, m, 12yrs *“the colors matching the bricks!”* – part#18, f, 9yrs

6.5.6 Technical Novelty

16.7% (40 children) commented on the overall technical novelty, making claims such as how it was surprising how

it worked, or more generally that it is fun, or that the number of drones made it fun.

6.6 How did the children decorate the controller?

Children spent between 30 seconds and 4 minutes placing the 10 bricks on the controller to be scanned. Each pattern was saved for later review. When we designed the controller, we wanted to give the sense of creative freedom and choice and thus we instructed the children to place the bricks in any pattern or color they wished, just so that each wing has 5 bricks to correspond to the 2 columns of flying voxels. As shown in Figure 3, there were beautiful and inspiring creations to appreciate. We highlight some of the recurring decoration patterns, taking inspiration from [45] by providing visual highlights along the design dimensions of color, symmetry and form.

One-color - There were only 4 children who built with one color and these are shown in Figure 3. Most involved symmetry of form. Row d shows the one-color result of white when a child wanted to place no bricks.

Two-color - Very few designs included only two colors and while they tended toward formal symmetry, surprisingly, most two-color patterns involved using separate colors on each wing.

The majority of the designs involved all three colors.

Three-color full symmetry - Some children spent much time placing the bricks symmetrically and with corresponding colors. This is perhaps not so surprising

considering that we instructed the children to place five bricks on each wing, thus the limited number of bricks may have led them to focus intently.

Three-color diagonal variations - It was fairly common for children to place the bricks in diagonal arrangements, with varying choices for color and formal symmetry.

Three-color linear asymmetry - Linear patterns were also popular, and again there were variations in symmetry of color choices.

Three-color sparse to clustered - Children decorated the wings placing the bricks in different spacings. In Figure 3 the column provides exemplars from a) sparsely decorated to e) tightly clustered.

6.7 Four play styles

We reviewed the videos and photos from each session to identify styles, strategies, and techniques used to control the swarm. Through video documentation and based on observation notes by the facilitators, we identified four patterns of play behavior during the sessions: mesmerized, explorers, controllers, and performers. While this generalizes across a diversity of unique play behaviors, it helps to gain a sense for recurring strategies children used to control the swarm and respond to the tangible controller.

Mesmerized - Some of the children were mesmerized when the drones took flight and seemed to be frozen in place. This was most common with the youngest children, and those who had little experience in remote control of toys or game systems. The accompanying parents would, in most cases, notice that their child was not responding and would prompt their child with either a simple verbal prompt or a slight nudge on the arm to encourage the child to move the controller. Many of these children would respond, but in some cases, parents would reach over and guide the hands of their child so that they would see the connection between moving the controller and the swarm movements. This was very interesting to witness as it reminded us that parents are often tuned into the emotional state of their children and try to provide assistance and scaffolding during learning as needed [32,46]. A screen capture from one of the videos as shown in Figure 4 depicts such an interaction between father and son.

Explorers - In contrast, many children were extremely active in manipulating the controller exploring the degrees of freedom and the limits of the control. A few children tried to turn the swarm over by flipping the controller over, yet when they reached the angular limit, they understood the constraint and would explore other



Figure 4. Child helped by his father, who guided movements and control of the drone swarm

movements. One of the most memorable sessions involved a child who took a very scientific approach and asked the facilitator what would happen if he didn't place any bricks. The facilitator explained that the white color would be scanned and the drones would be colored with white LED light. The child was adamant on trying this for his build. Just as claimed, the drones were all white and the child was happy that he knew how the system works.

Controllers - Controllers were those children who seemed to control the swarm with very small and careful movements as if the swarm behavior is something that should be managed with precision. These children would often focus intently on the swarm and watch to see the effects. Some of these children would also look down at the tangible controller and back again as if they were taking account of the placement of the bricks. In two cases, a brick popped off the controller and fell onto the floor. From the facilitator point of view, this did not affect the flight and should not matter, however, these children grabbed the loose brick and anchored it on the tangible controller again as if it was helpful to maintain the flight. The controller for these children could be described as a breakdown in Heideggerian terms [15,28], whereas their focus was not entirely on the task (flying) but divided by the tool. The controller became "present-at-hand" [15,28] with their focus very much on understanding the controller mappings and the sensitivity of the input.

Performers - These children engaged in the most outwardly noticeable and expressive movements with the controller. This is in contrast to the controllers who seemed apprehensive to move and bend the controller. The performers seemed to look beyond the controller—as if it was transparent, "ready-to-hand" [15,28], and was used by the children as part of the costume for

performance. These children seemed at ease with uncertainty and seemed engaged with making large sweeping movements and often moving the controller around as if the controller was flying.

7 DISCUSSION

Results suggest children enjoyed the build experience and our data provided insights as to how children learned to control programmable matter through physical experimentation, a prime example of Constructionism.

The four play styles remind us that children vary in how they play, explore, and interact with the world. The *mesmerized* children seemed to be overwhelmed with stimuli, which could have been from the novelty of the experience, the sounds of the swarm, or influence of the public setting. Kinch et al. propose a focus on setting the environment for young children and preparing them for a new experience [27]. The *explorers* quickly engaged and tried to find the limits of the system. The child who wanted to scan the butterfly controller without bricks was emphatic about knowing how the system works. While the tangible controller provided some physical constraints for bending, we saw that unrestricted movements were tried out as the children developed a model for how the swarm behaves. In future designs of the physical controller it could be useful to explore how the physical features, such as haptic force feedback, could help children understand the limits of the system. Another approach would be to introduce more complex physical build experiences that allow for reflection, crucial to learning embodied control [3]. The children we describe as *controllers* seemed to have learned from experiences with previous gaming consoles and remote-controlled toys that precise movements are useful. Whether appropriate or not, these metaphors were relied upon in the experience of controlling the drone swarm. This highlights the need for additional investigation with children to understand their originating schemata [10] and presents an interesting challenge of how we might encourage more expressive movements when these are appropriate. The *performers* category used very expressive movements and seemed to animate the ‘butterfly’ controller as they imagined a butterfly to fly. These children experienced some limitations to the movement as they would exceed the angular limits of the swarm and a mismatch between the orientation of the controller. This led them to reduce their movements, evidence that they understood how to control the swarm. Important future work should investigate how to maintain expressivity within the limits

of the system while encouraging more expressive behaviors in other children.

The results suggest that the children understood the causal connection between the choices in the build activity, the manipulation of the controller, and the behavior of the swarm.

7.1 Implications for Design

We share insights from the design and evaluation in the form of implications for design when staging play experiences with programmable matter for children. This intermediate-level knowledge [30] is strengthened by providing both our empirically grounded results in relation to the relevant theory and related examples [47]. The implications are in line with existing research on play and while these may not be entirely new, it is encouraging to see further evidence of the theory and guidelines proposed in recent research on play and physical interaction [9,38].

Accommodate differences in player behaviors. Some children may be overwhelmed by the experience and may need more time or assistance to engage with such a system. Other players eagerly explore the limits of the system and may respond well to additional complexity. Wyeth [56] proposed ‘transformability, flexibility and portability’ of play artifacts to fit the child’s learning through play. Flexible technologies should provide supporting features to the individual needs of the child, but not dictate how the child should play specifically-this is an ongoing challenge in the community, to develop platforms that celebrate and support the different needs and aspirations of each child. We designed the Flying LEGO system to invite creative expression of the children and limited the speed and movements of the swarm to provide a low barrier of entry.

Physical play elements can strengthen the narrative and guide player actions. The simple story behind the experience, although fanciful in many ways, provides coherence and lays out a simple narrative that young children could follow, e.g. decorate and scan the wings then fly their butterfly. I/O Brush, which is essentially a web camera attached to a computer, takes the physical form of a brush [45]. This along with the canvas and named activity of “painting”, guides the child’s understanding of the experience and directs explorative play. The child is invited to “dip the brush” to acquire colors and patterns, then drawing with the brush on the “canvas” which is just a screen, but these elements are

presented to the child as a painting system. The schema for painting guides the child to explore the environment acquiring new colors and shapes then painting, by dabbing and stroking the brush on the screen surface. Flying LEGO was designed around a simple butterfly narrative, which provides accessible mental framing for the experience. The child decorates a baseplate in the shape of wings with colored bricks. They scan the wings to transfer the colors to the swarm and then the child could bend and move the wings to bring the butterfly to life in the drone swarm. The naming of the swarm as a butterfly and wing-shaped controller support the central narrative and encourages explorative play. Exploring the physical design of tangibles has been proposed previously in order to support interactions with children and fostering an understanding of more complex digital systems [42]. Manipulation of the controller in our system resulted in the swarm mimicking the shape and movements and simplified the interaction. This direct mapping has been utilized in shape-changing interfaces [35] and in our case worked well to support the aim of the walk up and use system.

Consider opportunities for parents to participate. Our system stages a guided play situation [54], in which the child is invited to explore a prepared environment for the purpose of exploration and free play. While the parents encouraged more exploration of the play artifacts through verbal suggestions and in some cases physically guiding the children to move the controller, we are reminded that balancing intergenerational play can be designed into the play experience explicitly to provide a mutually rewarding experience [26].

8 CONCLUSION

We presented empirical findings from the Flying LEGO Bricks experience involving a build experience of a tangible controller, which is used to control a swarm of 10 drones. We used the platform to gain insights into how children respond to programmable matter. An evaluation of the system was conducted in a public venue with 240 children. Gathered data showed the richness of the children's creativity in the resulting build patterns as well as their observable behaviors and experiences of controlling the swarm. Four play styles when interacting with programmable matter were identified and implications for design are provided for facilitating play experiences with programmable matter for children. In future work we intend to explore larger and more dense programmable matter and will conduct additional studies with experiences of longer play duration.

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