Human-Centered Design Tools for Smart Toys

Anna Priscilla de Albuquerque[1](✉), Judith Kelner[1], and Patrick C. K. Hung[2]

[1] Federal University of Pernambuco, Recife, PE 50740-560, Brazil
{apa,jk}@cin.ufpe.br
[2] Ontario Tech University, Oshawa, ON L1G 0C5, Canada
patrick.hung@uoit.ca

Abstract. The smart toy industry faces challenges to achieve Hardware and Software (H&S) integration since numerous products are not generating enduring value propositions to the consumers. It is possible to achieve better H&S integration by following suitable design practices. Here, we propose four Human-Centered Design (HCD) tools for the development of smart toys solutions. The four HCD tools intervene on idea generation, data collection planning, and both low and high-fidelity prototyping of the solutions. The aim is to assist designers, developers, and engineers in producing better H&S integrated solutions by offering tools that meet HCD principles. The primary usage of the HCD tools with 27 graduate students assisted these multidisciplinary teams in creating five prototypes that were positively evaluated by end-users. Technical evaluation checks for the integrity of the prototypes after testing and results show comparative data on battery consumption and list potential privacy and security vulnerabilities. Improvements include adapting ideation tool to incorporate marketing-oriented strategies, authentication and data encryption for the toolkit, and assessing the tools with professional teams of the industry.

Keywords: Smart toys · Rapid prototyping · Human-centered design

1 Introduction

Toys are products designed for leisure and social play activities. Today, toys increasingly incorporate *Hardware and Software* (H&S) computation. Often, toys connect with online services and other computing devices like smartphones and game consoles, thus referred to as "smart toys". Smart toys solutions may appear in various shapes, such as a plush toy, a doll, a ball, a companion robot or a wearable gadget, and can use different computing technologies to obtain real-time data from their users (e.g., geolocation, relative positioning, bio-information, among the tracking of other physical activities) [1]. Computing technologies for smart toys vary since *Augmented Reality* (AR) applications to advances in

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robotics, wireless connectivity, *Artificial Intelligence* (AI), speech recognition, and location-based applications. Smart toys are a recent design trend, and toy companies still struggle on how to understand the integration of their H&S components. As a result, many solutions are not generating significant new benefits for the consumers (i.e., children and parents) [8]. Toy companies are holding onto the novelty factor of these smart toys, while these products need to create enduring *Unique Selling Propositions* (USP) for the consumers. USP must offer a better user experience than the user can get by using each of the H&S components individually. Meanwhile, toy companies continue looking for best design practices to deliver better H&S integrated solutions [24].

Technical teams usually apply design practices of other general-purpose toys to design smart toys. In general, those teams have none or little expertise in *Information Technology* (IT), such as information security [21]. Thus, they may not fully understand potential security risks and other IT aspects to address them throughout the product's life cycle. As a consequence, several toy companies are relying on third-party licensing technologies to develop their H&S integrated solutions. For instance, the French company *Volumique* supports technology licenses for several smart toys in the industry. In May 2019, the startup *PullString*, which was acquired by *Apple Inc.*, has announced the discontinuity of their speech processing license services for *Mattel* smart toys. It will lead to the deletion of the smart toys' connected application, including all collected and stored user data on their servers. Sensitive cases like this one may suggest that neither the toy companies have enough specialized technical teams or knowledge to design their H&S integrated solutions. Companies can benefit from investing in in-office multidisciplinary technical teams to produce better H&S integrated solutions. Researchers must supply these technical teams with appropriate tools, specifically intended for the design of smart toys. It is likely that such tools to consider the H&S integration aspects since the product's early stages.

Aiming to meet those needs, we propose four tools for the design of smart toys, which relies on *Human-Centered Design* (HCD) approach [10]. These HCD tools suit for planning and implementing of new H&S integrated solutions by intervening on ideation, data collection, and both low and high-fidelity prototyping of the smart toys. A group composed of 27 graduate students experienced the four HCD tools in a 16-week class assessment. Students had a multidisciplinary background in Computer Science, Design, and Engineering. As a result, they successfully generated, selected, planned, and implemented five smart toy solutions that were positively evaluated by end-users in playtesting sessions. We conducted a technical assessment to check for battery consumption and the physical integrity of the toolkit components after play-testing. Besides, we carried a vulnerability analysis for data security and privacy [21] by simulating attacks on the *Bluetooth Low Energy* (BLE) and *Near-Field Communication* (NFC) modules. Security strategies from the literature may solve the identified vulnerabilities [6]. Future evaluation of the tools will incorporate a list of improvements to assist professionals from the smart toy industry.

2 Related Work

Standard design practices for smart toys are mostly marketing-oriented, such as gender-oriented practices and the licensing of transmedia contents from franchises like *Star Wars* and *Marvel*. A common practice is to price the H&S components separately since most of the smart toys offer digital contents for purchase in their connected applications [8]. UK-based marketing group, *Juniper Research*, issued a report which estimates that the purchase of in-app contents will reach 25% of the total revenue of this sector (17.7 billion USD) by 2023 [18]. Usually, these marketing-oriented practices guide the technical teams through the entire design process, which may suggest that H&S components are often planned to support independent play experiences. For instance, the smart toy *Hasbro's Furby Connect* and its mobile application allow parallel playtime using only one of the H&S components. There is little information about the use of specific design tools by toy companies that support H&S integration [24]. While, in related literature, researchers are addressing specific design tools for H&S integrated solutions and the *Internet of Things* (IoT) related applications. Design tools cover everything since ideation tools to interaction models, including low and high-fidelity prototyping tools.

Ideation tools facilitate group discussion, supports the fast development of new ideas, and facilitates collaboration in the brainstorming sessions. Note that card set is a recurrent approach used by related literature. Hornecker proposes card sets to stimulate group discussion during brainstorming sessions [11]. Each card set represents one aspect of her *Tangible User Interface* (TUI) framework, namely: tangible manipulation, spatial interaction, embodied facilitation, and expressive representation. She experimented the card sets with professionals and students during ten workshops. Inspired by her work, the *Internet of Tangible Things* (IoTT) card set consists of 16 cards; 8 cards represent TUI properties and another 8, the IoT properties [3]. The card set was used by 21 participants to help them in the planning of interactivity properties of both low and high fidelity prototypes, the last using the prototyping board *Kniwwelino*. Another study, which was based on related work [16], used card sets and gamification to assist engineers in assembling IoT properties [22]. The authors also conducted workshops with master's students in Electrical and Computer Engineering and other related areas to evaluate their ideation tool.

Schneider advocates that prototypes support the extraction of valuable information for the product's implementing cycles [20]. Either low or high fidelity prototypes can present explorative, experimental, or evolutionary purposes, and all of them enable to elicit general and specific requirements for the desired solution. Rapid prototyping tools can make high-fidelity prototyping of smart toys faster and easier for creators than using custom hardware solutions for each design. They offer more freedom on the editing and testing of play and interface features during both planning and implementing design cycles. We can classify existing rapid prototyping tools for smart toys into smart devices, AR-based platforms, mobile-based platforms, and hardware toolkits. Each prototyping tool approach has its advantages and disadvantages. First, smart devices can be considered smart toys themselves [14,15,23]. They are ready to use and play, and usually promotes inter-device connection and embodied interplays. However, they present fixed interface features, which limit creators to only editing the play features. For instance, *Sifteo Cubes* are modular cubic displays. They can transfer data from one to another and allow touchscreen and natural gesture interactions (e.g., shaking and flipping the cubes) that enable prototyping of closed rules solutions [15].

Second, AR-based platforms use cameras to detect objects (e.g., tokens, cards, and toys) by using either marker-based and markerless recognition techniques (i.e., recognition of shape, color, lighting, saturation, texture, and other image descriptors) [9,13]. In addition to cameras, AR-based approach often requires complex setup to support detection and displaying virtual contents, such as mobile devices, *Head-Mounted Displays* (HMD), and *Infrared* (IR) tabletops. Note that AR-based platforms may expose the user's privacy due to the collection of personal data such as facial pictures or videos of the players manipulating the toys. Mobile-based platforms explore multi-touch, conductive materials, or contactless technology to detect objects using smartphones or tablets [4,19]. This approach reduces setup complexity and privacy issues when compared with the AR-based one. However, these platforms are also limited to promote token-tabletop interaction (e.g., placing tokens on the touchscreen). Finally, hardware toolkits, usually modular pieces, consist of a collection of sensors, actuators, communicators, and other electronic circuits that are reprogrammable [12]. They offer more freedom to the editing of both play and interface features since they permit creators to select components that best fit their projects. Still, the level of programmability, size, and distribution of hardware components can limit its adaptability features. Thus, adequate H&S integration is essential when implementing a hardware toolkit. Achieve better H&S integration, we propose three planning tools to guide the technical teams from the initial concepts until the high-fidelity smart toy solutions. In the next section, we detail how the four tools meet HCD principles and the context of use for H&S integration.

3 Human-Centered Design Tools

HCD practices for interactive systems are defined by the international standard ISO 9241-210:2019 [10]. ISO provides recommendations to employ HCD principles throughout the life cycle of computer-based interactive systems. It is concerned with ways integrated H&S components can enhance human-system interaction. This article proposes to employ HCD practices as a strategy to develop better H&S integrated smart toys. Note that once employing HCD practices does not dismiss the usage of traditional marketing-oriented practices (e.g., gender-oriented and transmedia contents). The goal here is to provide a set of practical tools that can assist the technical teams in developing better H&S integrated solutions. Is expected that the HCD approach can lead to a positive impact on the product's USP. According to ISO, H&S integrated systems designed by HCD practices offer a set of qualities. It increases productivity and operational efficiency, are easier to understand and use, reduce training and support costs, enhance usability to a broader audience and can promote accessibility, improve user experience, reduce discomfort and distress, provide competitive advantages, and contribute towards sustainability objectives. The HCD approach should meet the following principles. First, the design must rely on a clear understanding of the context of use, which covers the user's needs, the interaction environment, and all involved stakeholders. Users must take part in the design and development steps, which must be iterative and driven by user-centered evaluations. The design process must account the whole user experience, and a multidisciplinary team with complementary skills and perspectives must convey it.

In the present article, we propose four design tools that aim to improve H&S integration of smart toys. To adequately relate the HCD principles with the context of use of smart toys, we performed a content analysis of 297 smart toys from the systematic mapping of literature and industry [1]. The content analysis consisted of observing the following aspects: (a) what are the H&S components and how do they interact and connect? (b) what types of data are gathered and exchanged among these H&S components? (c) how do the play rules and dynamics regulate the data sharing, storage, and individual behaviors of each H&S component? (d) how does the user experience occurs with these H&S components during play, and which approaches are adequate to evaluate such experience? Hence, the content analysis supported us to summarize the context of use for smart toys into the following principles.

1. Smart toy solutions must combine physical and social play experiences.
2. User interface setup must be ready to play and reduce complexity.
3. Data collection must prioritize the user's privacy.
4. Play activities must be suitable for both indoors and outdoors.
5. User experience must integrate a multi-target audience.

The five principles above, helped us to propose the four HCD tools. Moreover, content analysis also permitted us to establish *Data Collection Patterns* (DCP) and a list of *Prototyping Requirements* (PR) that support the data planning tool and both low and high-fidelity prototyping tools. First, DCP items classify how data are gathered and exchanged among the H&S components and how play rules regulate data sharing, behavior, and storage [2]. Second, the PR items define what type of data should be collected by the smart toys and how occurs the data processing in the interface components. The DCP and PR items are listed below.

- *DCP1.* Data sharing modalities should regulate all play behaviors: Sharing patterns are namely, "replicate," "extend," and "replace" (e.g., the smart toy extends its motion tracking data to a virtual prefab in the connected application).
- *DCP2.* Individual data behaviors should respect the play rules: Behaviors patterns classifies into "create," "destroy," and "transform" (e.g., the smart toy transforms the color of the virtual prefab from green to red when shaken in the Z-axis).

- *DCP3.* Data storage should support selected data behaviors: Storage patterns comprise "update," "activate," and "augment" (e.g., the smart toy updates its state from green to red when shaken in the Z-axis).
- *PR1.* Prototyping should support adaptability: H&S components should be selected according to the needs of each design, and these components should be fitting for toys of different physical shape, materials, and size.
- *PR2.* Prototyping should support distributed data collection and processing: Smart toys should support connectivity and interoperability of communication protocols for transferring data between the H&S integrated components.
- *PR3.* Prototyping should support multimodal user feedback: Adequate multimodal user feedback can mix visual, auditory, and tactile modalities.
- *PR4.* Prototyping should support different play features: Smart toys can fully or partially regulate the play rules. Open-ended rules permit the players to add or edit new dynamics through play while closed rules are pre-set and can follow progressive challenges through structured level design.
- *PR5.* Prototyping should limit personal data collection: Smart toys should only collect non-personal data [2] from the users while personal information must be retrieved and processed by the secure connected devices.

Furthermore, to fully meet the HCD principles, the four tools must support an iterative and user-centered evaluation design process. According to content analysis and related works, adequate user-evaluation tools for smart toys must meet a set of practices. First, it must combine qualitative and quantitative approaches, and the evaluation instruments must meet the target-audience needs (i.e., children and adults). Evaluation protocols must pass through a pilot assessment, which includes specialists, and it must assess the usability and enjoyment of user experiences. Finally, the HCD tools aim at multidisciplinary. The teams must have complementary backgrounds of at least two of these subjects: Design or Arts, Computer or Electronic Engineering, and Computer Science (i.e., computer programmers). Also, specialists' backgrounds may include relevant fields in Education, Health, Science, and Sports. The following sub-sections describe the proposed HCD tools.

3.1 Brainstorming Toy

Inspiration to create new concepts for H&S integrated smart toys can derive from observing children playing with traditional toys and digital games [13]. Here, we propose the *Brainstorming Toy* as the first HCD tool. It uses various traditional toys along with a set of play rules cards to help creators in generating concepts for smart toys. The goal is to stimulate them to create ideas by assembling the interface features (of the toys) with digital or traditional play features (of the games). Traditional toys set includes everything since balls, Frisbee, hula hoop, toy cars, dexterity toys, sword, figurines of animals (e.g., sea animals, mammals, and insects), dominos, chessboard, and so on. Play rules cards include short descriptions for closed rules (e.g., runner and tower defense) and open-ended rules (e.g., hide and seek, tag, and hotchpotch). Besides, this HCD tool aims to mediate the communication between the multidisciplinary teams, which still is challenging. It supports group discussion by involving all participants since the early concepts – by not separating designers and programmers and by providing means so that they can express themselves better. Its structure is based on *Discussion 66* technique [7]. The original technique consists of distributing participants into small groups so that they can discuss ideas following a sequence of statements or questions. It proposes shifting the participants in the groups to stimulate an exchange of views and to avoid creators to fixate on a single idea.

The *Brainstorming Toy* is performed in groups of 3–5 participants and by exchanging both creators and toy resources within the groups. Short sessions include a 15 min opening session, three or more exchanging sessions (5 min), and a 10 min closing session (that reunites the initial group). After the timing, one or two participants, along with one or two toy resources, are exchanged. Exchanges in the groups must follow simple rules (e.g., professional background, age, or gender). In the short sessions, the entire group discusses one toy at each time, by following a structured paper sheet. The paper sheet contains sections to detail both play and physical aspects of the toy (e.g., "how does one play with this toy?" "what are the toy's materials?"). After describing the toy sample, the group should sort one or more play rules cards to generate ideas. One creator, assigned as the "reporter," has to write down all requested contents in a legible form on the backside of the sheet.

After the closing session, all paper sheets must be collected and grouped by assembling sheets of the same toys. At that moment, the groups receive these sheets to the recycling ideas session. The goal of this session is to improve the quality of ideas by applying creative constraints to them. Creative constraints consist of ten items based on the context of use defined in the previous section. Items include "the idea uses two different physical interactions," "it promotes tangential learning," "it includes two age groups of end-users," "it collects only two types of data," "it has two toy components in the interface," "promotes therapy or rehabilitation," "it supports at least two social interaction modalities," "offers accessibility," "it has a toy component with attachable parts," and "it is gender-neutral." Recycling occurs by adding to the ideas at least one or two constraints. In a marketing-oriented context, the list of creative constraints can add or replace specific items related to transmedia characters, themes, educational topics, among other marketing indicators.

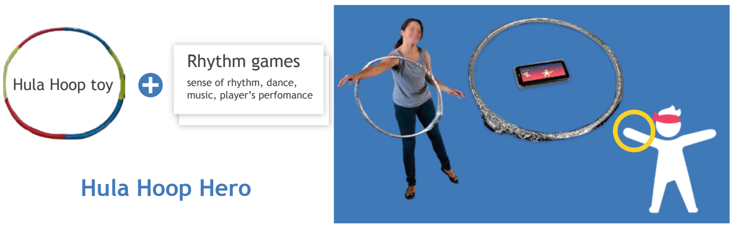

Fig. 1. Hula Hoop Hero concept generated by the students in brainstorming.

All original and recycled ideas serve for the final selection. Each creator selects one up to three preferred ideas to detail them using a slide presentation template. The detailing consists of defining the expected H&S components for the interface and setting the core play rules. Note that if creators pick an original idea, they have to apply the constraints to improve it before detailing. The final idea selection takes part in the *Data Collection Planning* tool. Figure 1 illustrates an example of the *Brainstorming Toy* results. The *Hula Hoop Hero* concept, produced by the students, combines a traditional hula hoop toy with the "rhythm games" card. This H&S integrated solution uses the smart toy to measure the physical movements, and the BLE connected the application to keep the score of the player's performance, display the next movements, and play the songs.

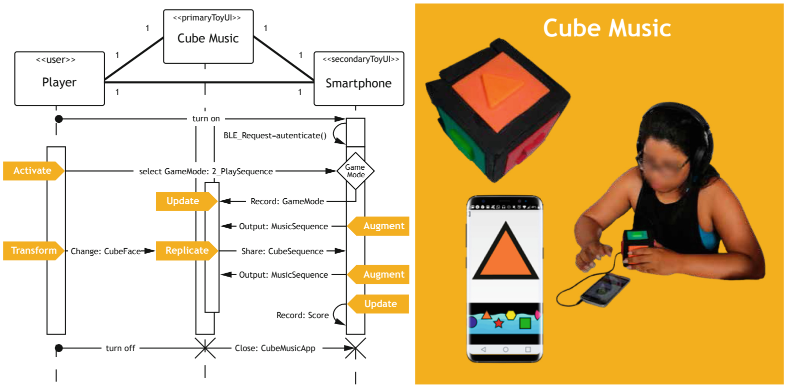

Fig. 2. Cube Music's data collection plan diagram

3.2 Data Collection Planning

UNICEF issued the *Memorandum on Artificial Intelligence and Child Rights* in 2019. It includes the topic named *Children's Rights at Play*, which aims to guarantee the right of privacy by international frameworks for children through the development and marketing of smart toys solutions [25]. The *Data Collection Planning tool* aims to minimize selecting ideas that can potentially introduce threats to children's privacy in the implementing phase. It comprises of two parts. The first part consists of each creator to choose one or two ideas from the *Brainstorming Toy* to pick what type of data they expect that the idea will collect. A paper sheet organizes these types of data into three groups. (A) Non-personal data collection includes non-personal identification, unidentifiable positioning systems, and motion tracking information [2]. (B) Personal-data collection covers data like voice, facial pictures, and other user profile information (e.g., full name, e-mail address, and billing information). (C) Sensitive data collection includes multimedia files related to objects (e.g., pictures or videos of markerless or marked objects with fiducial markers or QR codes).

Often, smart toys, especially those with connected applications, tend to gather unnecessary personal information that may not be relevant for playing time [6,21]. If any personal or sensitive data type is selected; the creator has to pick an alternative for non-personal data to use it instead. In that way, they can reflect if collecting personal information is essential or not to their concepts. Only similar concepts pass for the second part of the planning (i.e., same idea or different ideas related to the same toy component). Participants can exchange ideas if they wish to do so. They can pick-up other concepts to work, only if the idea not expects to collect any personal data. The second part of the *Data Collection Planning* tool consists of the diagram sheet—the diagram uses UML-like notations inspired by the class, sequence, and activity UML diagrams [2]. In the diagram, the creators can plan the data collection exchanges and processing among the H&S components. The diagram relates three entities based on the *Toy User Interface* (ToyUI) interaction model [1]; these are the user, the primary ToyUI (i.e., the smart toy), and the secondary ToyUI (i.e., the connected components). It uses the data collection patterns described in the previous section (i.e., replicate, create, update) along with other UML-like notations. The goal of this diagram is to plan, according to the defined play rules, how will occur the data sharing among each component, including the individual behaviors and appropriate data storage.

After completing the diagram, all planned ideas are assembled and listed for 3-choice voting. After choosing the best-rated ideas, the multidisciplinary teams are set based on the profile of the creators and their preferences. Teams use the planning diagrams as a guide to building both the low and high-fidelity prototypes. Figure 2 shows another of student's projects. The *Cube Music* uses the BLE module to connect to a music application. The data collection diagram uses the "replicate" data sharing pattern to governs all behaviors. The app plays a sequence of music notes which are associated with geometric shapes and colors. Then, the player memorizes the sequence and replay it by flipping the cube. It uses the "transform" pattern to describe the cube's behaviors. The upper face is selected by the application to validate the sequence at each time. All storage patterns are necessary due to the defined play rules (i.e., activate, update, and augment).

3.3 I/O Stickers

The low-fidelity prototyping practice combines traditional toys with office and crafting materials like papers, colored pens, scissors, tapes, and cardboard. To facilitate the practice, the *I/O Stickers* represent different sensors, communication protocols, types of inputs and outputs, displays, and data storage behaviors. The goal of this HCD tool is to simplify technological and interactive aspects to help the teams in first prototyping the interface setup. In that way, by attaching one sticker to a toy component, it may help them to plan and test the concepts.

For example, the motion tracking sensor sticker attached to a toy can mean that the toy component can collect 3D positioning and orientation. Figure 3 shows the *Zombie Tag* low and high-fidelity prototypes. Students defined three interface components for setup: the smart toy is a zombie glove, and two secondary components are the bracelets and game cards. The selected stickers for the smart glove are short-range communication, audio output, single input, and user profile and data. The *I/O stickers* chosen for the bracelets are the single input and user profile and data; the game cards use the multimedia output sticker to represent the play contents. Note that the teams successfully represented all planned behaviors using the *I/O stickers*, and they used it as a reference to develop the Zombie-tag's high-fidelity prototype.

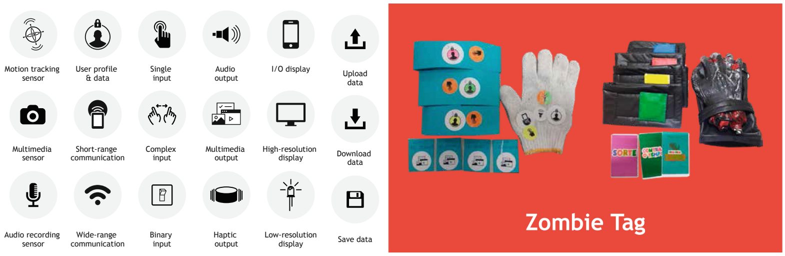

Fig. 3. I/O stickers and the Zombie Tag's low and high-fidelity prototypes.

3.4 IoT4Fun Toolkit

The fourth HCD tool is *IoT4Fun Toolkit*; it allows wireless connectivity via BLE and NFC to support distributed data collection and processing. It collects only non-personal data of both objects and users using a motion-tracking sensor and supports the design of visual, auditory, and tactile feedback. The toolkit uses the *Arduino IDE* to supports the programming of either open-ended or closed play rules and behaviors. Finally, it was manufactured using a modular *Printed Circuit Board* (PCB) approach to improve adaptability. Modularity makes the toolkit fitting for the design of smart toys of different shapes and sizes. The toolkit consists of eight modular PCBs attached to individual hardware components. All modules are attachable to a hub module using plug-and-play flat flex ribbon cables. The hub module contains a central unit, which is an *Arduino Mini-pro* with 16 MHz crystal oscillator, and a 10 DOF IMU motion tracking sensor. The BLE module is a 2.4-GHz BLE, and the NFC module operates at 13.56 MHZ. The visual output module consists of 3 RGB LEDs, the auditory module is a 2 1 W 8OHMS speaker, and the tactile module is a vibrator motor. A polymer li-ion battery module powers the hub module and all connected modules. The toolkit includes a USB recording module that permits ease updating of programmed behaviors of all connected modules. In Fig. 4, we show how the modular toolkit offers adaptability for different "toy-shells." First, the students distributed the components through the *Cobi's* body. They placed the NFC module in the bottom of a cardboard ramp to read the cookie disks. Then, the visual feedback module locates at the top of the body to simulate the eyes, and milk acrylic amplifies the LEDs intensity. Diversely, the *Magic Potato* team assembled most of the toolkit components inside a plastic ball. Except for the visual feedback module, which passes through a leash of the plush toy to simulate the bomb's wick.

Fig. 4. IoT4Fun Toolkit adapted by the Cobi and Magic Potato teams.

4 HCD Tools Results

The four HCD tools assessment occurred during coursework of the graduate program in Computer Science in the *Federal University of Pernambuco* (UFPE), in Brazil. The coursework lasted for 16 weeks between August to December 2018. A group of 27 creators participated in this assessment, among 15 master students and 12 doctorate students with multidisciplinary backgrounds on Computer Science, Engineering, Design, and related areas. The smart toy solutions were named: *Hula-hoop Hero, Cube Music, Zombie-tag, Cobi,* and *Magic Potato*. First, both *Hula Hoop Hero* and *Cube Music* explore the classic H&S integration setup. The two smart toys use the BLE module to connect with their respective mobile applications. Diversely, both *Cobi* and *Zombie-tag* use the NFC module to connect with secondary toy components (i.e., cookie disks and bracelets, respectively). Only the *Magic Potato* prototype did not explore connectivity – it uses the motion tracking sensor to collect positioning information to adapt its behavior through play. Thus, the last three projects do not fully meet the expected setup for H&S integration since they do not present mobile apps. Additional features could justify the need for this classic H&S integration. For example, apps are suitable to keep track of the player's performance and scores, and they allow the editing features, such as selecting play modes or customizing the rules. However, in all three projects, they were not essential.

Different group of users evaluated all prototypes during playtesting sessions. The teams used usability questionnaire adapted from the *System Usability Scale* (SUS) [5], 5-points *Likert* scale likeability questionnaire based on the work of [26], and additional qualitative instruments (i.e., semi-structured interviews, group discussion, observation, and video analysis). First, technical specialists tested all prototypes, which helped the teams to overcome technical and design issues and to make general improvements. Second, teams went on the field to test their prototypes with end-users, preferably with those from the intended target audience. Not all groups managed to assess the prototypes with children. For instance, the *Cobi* team tested their prototype with two children; the girl aged 2 and the boy 4. *Magic Potato* team tested the prototype with two girls (6 and 10 years old). *Cube Music* tested the toy with one boy aged 6 and *Zombie-tag* team tested with three children from 11 to 13 years old (two boys and one girl). All collected user data received written parental consent before testing.

Finally, during a playtesting event on UFPE campus, 40 students of the *Physical Education and Sports Department* were invited to play. They presented a high level of interest in physical activities and sports, which were an adequate fit for the intended target audience. User profile summary consisted of 23 males, and 17 females and age ranged from 18 to 23 years old, while one participant was aged 50. Teams collected data from 8 to 15 participants each, and they analyzed results separately – 26 participants played with at least two prototypes. All smart toys worked adequately and presented as robust enough to allow 90-120 min of playtesting sessions. The public positively evaluated them all, according to the user evaluation instruments used by the teams (i.e., SUS scores $\geq 71.7 \leq 87$, likeability average values $\geq 3.5 \leq 4.5$, purchase intent average values $\geq 3.5 \leq 4.3$, and positive qualitative information). All smart toy solutions presented adequate H&S integration and promoted enjoyable experiences to their users. As an outcome of this event, they applied a shortlist of improvements for their final solutions.

4.1 Technical Assessment

There were reports from the teams about malfunctions of the *IoT4Fun Toolkit* modules during the playtesting sessions. The technical assessment consisted of three types of testing: functional integrity, battery consumption, and data security and privacy vulnerabilities. First, functional integrity tests used the *Arduino IDE* to check core functionalities of each module, and when necessary, a multimeter checked for punctual malfunctions of the PCBs. All original hardware components are fully working after the playtesting sessions. However, some parts of the PCB modules attached to these components suffered damage after testing. It may happen due to collisions during playtime, or by the way that teams handled the modules during development. Damages in the PCBs appears in two visual feedback modules, one auditory module, and one BLE module. It may suggest that the PCB manufacture should be better performed to conquer adequate robustness. In that sense, the future versions of the toolkit cab benefit from professional manufacturing by a third party. Moreover, protective cases can help to secure the modules and other components. Cases can use hard-plastic, acrylic, or flexible materials to reduce external impact during collisions.

Second, the battery consumption tests look to estimate the battery autonomy of each solution to support further improvements in the toolkit.

The instantaneous current analysis was performed using the current shunt method [17]. It consists of measuring the current of consumption, second by second, and according to the working time of each solution. The sensor ACS 712 5 A was attached in series to the toolkit to measure its current circuit. Once knowing the average consumption, it is possible to estimate the battery autonomy of each solution in Table 1. Battery autonomy calculation consists of the relation between 80% of the total battery capacity and the average battery consumption. The 80% rate simulates the behavior of a lithium polymer battery since generally in this type of battery, the circuit stops running before the voltage is entirely over. The total capacity of the battery module is 350 mAh. It uses the battery LP702035 3.7 V. Results suggests that battery consumption relates to how the teams implemented the solutions. *Cobi* and *Magic Potato* use the visual and auditory modules; however, the second solution requires more battery consumption than the first one. To circumvent this issue, note that the *Magic Potato* uses an adapted battery module with six batteries working in parallel; thus, its estimated capacity is 2100 mAh. Hence, better programming practices must be employed to improve battery autonomy in future assessment.

Table 1. Battery autonomy results.

Smart toy	Battery consumption	Battery autonomy
Hula Hoop Hero	33.5 mA	501’
Cube Music	55 mA	305’27”
Zombie-tag	98 mA	171’25”
Cobi	80 mA	210’
Magic Potato	168 mA	600’

Finally, vulnerability analysis points out the main risks for data security and privacy of each solution. A vulnerability taxonomy for smart toys connected to mobile applications classifies threats into physical, nearby, and remote access types [21]. According to it, the toolkit is sensitive to *Unauthorized-config-physical* threats since it offers a USB recorder to update the hub module. It is intended to make the programming and updating of contents faster and easier, but it can be used for malicious configuration since it does not require authentication. The other types of threats are dependent on the toolkit implementation. For example, the toolkit can be sensitive to the *Unauthorized-config-nearby* threat, but both implemented mobile applications do not support configuring their smart toys through them. However, none of the solutions employ security standards to support *local data protection*, and the two connected applications permit both *tampering* of information and *denial of service* threats. Vulnerability items do not cover scenarios that use NFC communication, in which the exchange of data among two toy components (e.g., *Cobi* and the cookie’s disks) occurs. Thus, the present article adds a new item named *Insecure-NFC-practice* to the taxonomy, which is alike to the *Insecure-Bluetooth-practice*. The *Unencrypted-comm-channels* item was also adapted to cover NFC communication. Hence, to make the vulnerability analysis comprehensive, it includes testing the security of both BLE and NFC modules. First, the *Android* app, named *BLE Console*, was used to examine the security of the BLE connection. Parameters for a secure BLE connection consider if it requires user authentication and if the MAC address dynamically changes. As a result, both *Cube Music* and *Hula-hoop Hero* pairs without authentication and present fixed MAC addresses. The *BLE Console* app allows accessing of smart toy information. Information includes all data sent by the serial port, among manufacturer's information such as model, serial number, and firmware revision. Likewise, the *NFC Tools* app supports to examine the security of the NFC connection. Although NFC is a safer technology than other protocols for authentication, it still opens the potential for breaches for data disclosure. Neither *Cobi* nor *Zombie-tag* projects encrypted the NFC communications. It allows the attacker to get information from the tags or the reader. Using the *NFC Tools* app, one can access all recorded data on the NFC tags, including rewriting the tag information to limit further readings.

To improve reliability and circumvent the identified vulnerabilities, we select the following data *Security Requirements* (SR) for smart toys, which were proposed by [6]. First, communication between physical toy and mobile device must use a protocol that allows authentication and authorization mechanisms (SR5). Configuration file integrity must be maintained and verified in every mobile app play session (SR7). Every communication in toy computing environment must use cryptography mechanisms (SR8). The mobile app must monitor and limit database growth (SR15). The DNS must provide security mechanisms against external modification of stored data (SR10). Finally, the smart toy should avoid exposing unnecessary information once implemented (SR21). Note that once again, those requirements apply for smart toys connected to mobile applications. Thus, we adapted the SR5 item to cover NFC communication. It may suggest that a taxonomy of vulnerabilities and its security requirements must be expanded to cover a broader range of smart toy solutions. In future assessment of the toolkit is essential to ensure security standards for data encryption and build access control mechanisms, including parental control and management of privacy policies.

5 Conclusion

Toy companies are struggling with H&S integration to deliver products that offer better USP for the consumers. Here, we proposed four HCD tools to assist the companies' multidisciplinary technical teams in creating adequate H&S integrated solutions. All combined, the HCD tools assisted 27 graduate students in ideation, planning, and prototyping of five smart toy solutions. All HCD tools adequately meet the context of use for H&S integration, which was defined based on the content analysis of smart toy solutions from literature and industry. First, the *Brainstorming Toy* tool assisted the teams in creating solutions that combine physical activities with social play modalities, which include direct or parallel competition. Second, the *I/O Stickers* helped them to define interface setups that are simple to use and ready to play. As a direct result of the *Data Collection* tool and the *IoT4Fun Toolkit*, all developed solutions prioritized the user's privacy by limiting the data collection to non-personal information (i.e., motion tracking information). Besides, all solutions are suitable for play in both indoors and outdoors, and playtesting results suggest that they are enjoyable for multi-target audience groups.

More user feedback is needed to improve the HCD tools. Preferably, the next assessment of the HCD tools will occur in a cross-cultural scenario since personal experience may influence the results. Ideation may depend on the personal knowledge of the creators about the toys and how people can play with them. Is expected that by assessing these tools with creators from different cultures can turn results more suitable for a worldwide audience. Ideation can benefit from incorporating marketing-oriented strategies to increase its acceptance by the toy companies. Furthermore, the technical assessment results suggest the need for improvements in the *IoT4Fun Toolkit* on robustness, access control, data encryption, and other reliability aspects. Therefore, it is essential to build a reliable development framework to assist the creators in delivering the *IoT4Fun Toolkit* best potential. Until now, we cannot state conclusive findings for how the perceived H&S integration can impact the USP of the solutions. Research evidence resumes to the positive user evaluation results and cannot infer acceptance of the created solutions by this market niche. Although the HCD tools presented satisfactory results, the benefits of employing these HCD tools with the toy companies are unclear since the assessment happened with 27 graduate students. Future opportunities include reaching out for toy companies and professionals who are active in the industry for more comprehensive assessment of the tools.

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