Computational Design and Fabrication of Customized Gamepads

Chinmay Rajguru
University of Sussex
Brighton, East Sussex, U.K.
c.rajguru@sussex.ac.uk

Christos Mousas
Purdue University
West Lafayette, IN, U.S.A.
cmousas@purdue.edu

Lap-Fai Yu
George Mason University
Fairfax, VA, U.S.A.
craigyu@gmu.edu

Figure 1: Example of an in-game sword and a sword gamepad created by our approach and used during the gameplay

ABSTRACT

CCS CONCEPTS

• **Computing methodologies** → **Computer graphics**; • **Applied computing** → *Computer games*; • **Human-centered computing** → *User interface design*; *User studies*.

KEYWORDS

computational design, fabrication, 3D printing, optimization, gamepad

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1 INTRODUCTION

Thanks to 3D printers' increasingly affordable cost, much research on fabricating and 3D printing functional objects has been conducted in the past few years [Jacobson et al. 2014; Mueller et al. 2014; Savage et al. 2015]. Besides their use in engineering, designers that need prototypes have also used them to quickly and affordably evaluate the desired manufactured object. In this paper, by taking advantage of 3D printing and intelligent fabrication through computers, we present a solution for fabricating and printing functional gamepads. We believe that our approach can help manufacturers create gamepad prototypes customized for specific games. Thus, such prototypes can be 3D-printed for testing before being used for mass factory production.

We got inspired from prior work on prototyping interactive objects [Lee et al. 2004] as well as by noting that in video games the gamepads have an important role in improving users' gaming experience [Cairns et al. 2014; Thompson et al. 2012]. We then hypothesize that fabricating and 3D printing gamepad related to a specific game could serve as a valuable contribution to users and the gaming industry. Here we note that the use of customized gamepads is targeting casual and mid-core game players. We assume that these types of players would appreciate enjoying the gaming experience by using multiple gamepads related to the game they play.

In this paper, we propose to create game-centered gamepads. From our perspective, a game-centered gamepad should be closely associated with the gameplay and the game itself. For example, it might resemble the shape of an in-game sword. In this case, the gamepad has a sword-like appearance, and the sword gamepad can use, for example, an accelerometer to capture the user' s motions, which would then be reflected in the virtual character's motions within the virtual world. Moreover, the hand-held sword's appearance should be identical to the virtual character's sword (see Figure 1).

To develop these gamepads, we introduce a novel approach for fabricating 3D objects into functional gamepads in this paper. Our method allows users inexperienced in 3D modeling-related software

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to easily and automatically generate gamepads using a variety of 3D models that can be found in online databases. To begin, a template gamepad is first used as a reference, and a user-defined target 3D model is chosen as the object to which the gamepad's button layout should be retargeted. Then, the template gamepad and the 3D model are pre-processed to ensure efficient handling. The button layout of a chosen gamepad is used as a template, and an optimization process is employed to retarget the layout of the buttons to the 3D object. Finally, the designer inserts the electronics into the print object, and the gamepad is ready to be used in a gaming scenario.

We conducted a user study to validate the fabricated gamepads' functionality. Specifically, the user study investigates the relationship between their use in video games and players' experience with them, thus extending several previous user studies on gamepads and control mechanisms [Cairns et al. 2014; McGloin et al. 2013; Skalski et al. 2011; Williams 2013]. The first objective of the study was investigating whether the fabricated gamepad can be characterized as a stable and valid physical object. Secondly, through the user study, we aimed to understand the possibility of enhancing player's gaming experience. We report five conditions of the experiments that examine users' experience with the different gamepads during trials. Based on the results of these trials, we can assert that the fabricated gamepads 3D-printed for the purposes of this paper are efficient, function as designed, and enhance the gaming experience.

1.1 Contributions

Our proposed approach can help manufacturers create gamepad prototypes customized for specific games, which can be 3D-printed for testing before mass production. To achieve this, several important steps are proposed. The main contributions of this paper are:

- Proposing a novel computational approach for designing and fabricating customized gamepads.
- Proposing an optimization process for transferring a gamepad's button layout to a target 3D model.
- Conducting a user study that investigates whether the fabricated gamepads could enhance users' gaming experience.

2 RELATED WORK

In this section, we review relevant works related to computational design, as well as fabrication and evaluation of customized gamepads.

2.1 Computational Design Tools

The use of 3D printers would not be popular without the development of methods and tools for helping people design and fabricate functional objects. Computational design methods aim to solve problems related to a variety of issues that a designed 3D object may have. For example, computational design methods have been devised to deal with an object's elasticity [Lu et al. 2014], balancing [Zhang et al. 2016], stability [Prévost et al. 2013], and functionality, for example, whether an 3D furniture object can be folded [Li et al. 2015]. Such methods provide designers with the necessary tools for creating a variety of customized objects.

Among other tools, Makers' Marks [Savage et al. 2015] facilitates the design and fabrication of functional mechanical and electronic assemblies, and CopyCAD [Follmer et al. 2010] and KidCAD [Follmer and Ishii 2012] allow users to estimate the parameters of physical objects that can be later used as input for designs. faBrickation [Mueller et al. 2014] provides the ability to print detailed areas around low-resolution LEGO blocks in 3D by using a mechanism for accelerating the printing process. ModelCraft [Song et al. 2006] models of its sensing elements to support enclosure development. Scratch [Resnick et al. 2009] is an easy-to-use language that helps novice users create functional electronics capable of being placed in 3D-printed objects. Moreover, .NET Gadgeteer [Villar et al. 2012] fabricates CAD extensions to develop enclosures for .NET Gadgeteer sensors and actuators. By using a mixed-reality environment, MixFab [Weichel et al. 2014] spatially aligns CAD models around the geometry of existing physical objects. Meshmixer [Schmidt and Singh 2010] solves shape reuse and composition problems in 3D mesh modeling. A smart measurement tool called SPATA [Weichel et al. 2015] allows designers to transfer real-world measurements to the dimensions of digital models. Finally, a component-centric interface called Enclosed proposed in [Weichel et al. 2013] facilitates the creation of prototype enclosures of fabricated 3D objects.

Fabricating functional objects is a complex process requiring a variety of computational design tools. Moreover, depending on the specific design requirements, different computational design and fabrication tools should be used. While the previous tools aimed to address specific issues within the fabrication process, our approach seeks to extend the existing list of such tools by proposing a novel tool for designing and fabricating functional gamepads.

2.2 Fabricating and Customizing Gamepads

Recently, many tangible and physical interfaces have served as prototypes that allow users to easily interact with computers [Jacobson et al. 2014; Savage et al. 2015]. Furthermore, several toolkits that support developing such interfaces have been introduced [Greenberg and Fitchett 2001; Lee et al. 2004]. These tools' main purpose is providing designers with the necessary components for customizing the construction of an interface. It should be noted here that according to [Salen and Zimmerman 2004], gamepads are an important part of the gaming experience. It is how players control gameplay, allowing them to engage in the action-feedback-action loop that constitutes playing the game.

Previously, a few attempts have been made by the research community to customize existing gamepads. For example, the prototype Trackball controller [Natapov and MacKenzie 2010] was developed to extend the widely-used Xbox gamepad for more efficient handling of point-select tasks. In this prototype, the right analog stick was replaced with a trackball. In the VoodooIO Gaming Kit [Villar et al. 2007], the authors introduced the concept of a reconfigurable gaming device which provides players with the ability to reconfigure the gaming space, making it suitable for their preferences and needs.

It should be noted that there are three basic categories of gamepad customization and fabrication. The first is related to customizing the gamepad's appearance. Among others, Controller Shop[1] provides appearance customization by changing the color of the gamepad and buttons according to user's preferences. The second relates to customizing functionality, and the Controller Project[2] provides customizations for existing gamepads by placing add-on complements that help the player handle and play the game more efficiently. The third category relates to the complete fabrication and customization of gamepads. The aforementioned Controller Project also fabricates gamepads based on user-specified geometry. The latter is similar to our solution. However, instead of manually designing the gamepads, in this paper, a computational approach that addresses this issue and automates gamepad design and fabrication is introduced.

2.3 Evaluating Gamepads

We also review some gamepad-related user experience studies that motivate our approach for designing customized gamepads.

There is abundant research indicating how various aspects of games influence a user's experience, such as the type of gaming device being used [Thompson et al. 2012]. A study conducted by Skalski et al. [Skalski et al. 2011] investigated the efficiency of gamepads designed for a specific game. They found that these specific gamepads (e.g., a steering wheel controller for a driving simulation game, a Wiimote controller for playing a golf game) enhance the player's user experience. Cairns et al. [Cairns et al. 2014] evaluated whether game controllers' naturalness (natural interaction) influences how the game is experienced. The results indicated that a prior natural mapping process leads to an improvement in immersion. Other previous studies have investigated how players become immersed in and are influenced by boxing-related games. Specifically, players using the Wii boxing gloves displayed an increase in hostility according to Williams et al. [Williams 2013] and an increase in cognitive aggression according to McGloin et al. [McGloin et al. 2013]. Based on the reported previous work, it can be stated that the type of gamepad used by players potentially influences their behavior and the gameplay. These findings are quite important since they motivated us to devise a computational approach for designing customized gamepads as well as to further investigate the influence of gamepad-type on players' gaming experience.

As mentioned, the present study examined two important factors: the first related to fabricated gamepads from the perspective of physical objects and the second related to user experience. There are different criteria and methods for evaluating user experience [Calleja 2011] and immersion [Jennett et al. 2008]. In our study, we were particularly interested in investigating whether game-centered gamepads change the way users experience a game. It should be noted that the term "user experience" is quite general, which has been examined in a variety of ways in the past [Bernhaupt 2010; Korhonen et al. 2009]. Bernhaupt [Bernhaupt 2010] discussed the meaning of the term from different perspectives. Refer to Vermeeren et al. [Vermeeren et al. 2010] for in-depth discussion of user experiences related to computer games.

The conducted user study attempted to investigate whether the use of multiple fabricated gamepads directly related to the game (e.g., the game objects with which a virtual character is equipped) enhance the user experience. This is important for understanding the influence a gamepad's appearance might have on users' gaming experience. In addition, switching between gamepads during the gameplay is another aspect that needs to be investigated, so as to understand how the use of multiple gamepads influences the gaming experience of the user. To the best of our knowledge, such a concept (switching between multiple gamepads associated with the game during the gameplay) and user study have not been investigated previously.

3 APPROACH AND PRELIMINARIES

In this section, we describe the proposed approach for converting a given 3D model to a functional gamepad, as well as the preliminaries regarding the fabrication of gamepads.

3.1 Overview

Figure 2 presents an overview of the proposed approach for creating and fabricating a functional gamepad. The approach begins by first extracting a source gamepad's layout (mainly the relationship between the buttons) intended for use as a template. Our approach also allows the user to specify his/her own layout of buttons and constraints for designing a gamepad. In any case, one can follow the same subsequent process to create a gamepad. For illustration convenience, we refer only to a commercial gamepad layout for now.

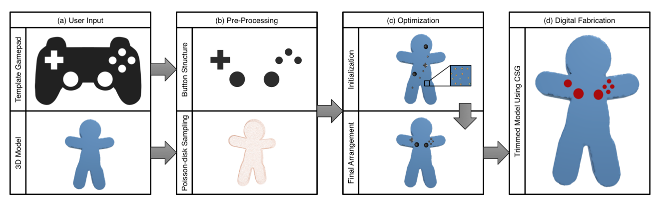

Figure 2: Our approach for converting a 3D model into a gamepad. The process begins by (a) asking the user to specify a template gamepads and a target 3D model. Then, during the (b) pre-processing, the template gamepad's button layout is initialized, and the Poisson-disk sampling method is used to re-sample the mesh so the 3D model's vertices are evenly distributed. During the optimization process (c) the system initializes the buttons in the mesh; and finally, an optimal arrangement is synthesized and later used for digitally fabricating (d) the input 3D model.

Given the source gamepad, we use a semi-automatic method to compute the button constraints (see Section 3.2). Specifically, the user specifies the buttons' position and the system computes and stores the relationship of the buttons into a list. Then, the user specifies the target 3D model onto which he/she wants to place buttons based on the layout of buttons on the source gamepad.

To place buttons on the target 3D model reasonably, it is necessary to pre-process the mesh of the target 3D model. In this step, the mesh is re-sampled by using the constrained Poisson-disk sampling method [Corsini et al. 2012] so that its vertices are evenly distributed. By default, we use 5,000 sample vertices which give us

[1] https://thecontrollershop.com/
[2] http://thecontrollerproject.com/

reasonable results in our experiments, and the user can adjust the number of sample vertices if needed.

Given the button layout and the mesh with sample vertices, the proposed optimization approach (Section 4) searches for the optimal placement of the button's layout on the target 3D model. Then, using the subtraction operator of the constructive solid geometry (CSG) algorithm [Foley 1996], the 3D mesh is trimmed, thereby preparing the final mesh for fabrication. After 3D printing the fabricated gamepad, the designer places the necessary electronics inside the fabricated gamepad so it becomes fully functional and can be used for playing games.

3.2 Initializing Button Layout

Given the template gamepad, the layout of the gamepad's buttons should be initialized. This is a semi-automatic process. The user simply specifies the positions, the radius, and the rotation (forward vector) of the buttons, and the system automatically computes the constraints (i.e., the relationship between a button $\mathcal{B}_i$ and any other button $\mathcal{B}_j$). Figure 3 depicts the constraints that characterize a button.

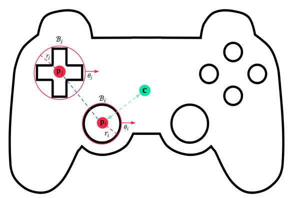

Figure 3: Graphical representation of a gamepad's layout.

In our problem, a gamepad design is represented by the layout of its buttons. Let $\mathcal{B} = \{\mathcal{B}_i\}$ be the set of all buttons. Each button $\mathcal{B}_i$ keeps as parameters its position $\mathbf{p}_i$, its rotation θ_i and the radius r_i of its bounding circle. Therefore, each button $\mathcal{B}_i$ is represented as $\mathcal{B}_i = (\mathbf{p}_i, \theta_i, r_i)$, where $\mathbf{p}_i$ and θ_i are altered during the optimization.

Note that in case of a non-circular button like the D-pad (directional pad) shown in Figure 3, a tight bounding circle that encloses the whole button is used. Finally, since a symmetric alignment of the button layout with the user-defined 3D mesh is required (we discuss in Section 4.1), the center-of-mass $\mathbf{c}$ of the buttons of the template gamepad is also computed from the positions of the buttons.

Based on the above representations, button $\mathcal{B}_i$ is given the following constraints:

- the prior distance (D'_{ij}) between the position $\mathbf{p}_i$ of button $\mathcal{B}_i$ and the position $\mathbf{p}_j$ of another button $\mathcal{B}_j$;
- the prior angular displacement (A'_{ij}) between the rotation θ_i of button $\mathcal{B}_i$ and the rotation θ_j of another button $\mathcal{B}_j$;
- and the prior distance (D'_{ic}) between the position $\mathbf{p}_i$ of button $\mathcal{B}_i$ and the center-of-mass $\mathbf{c}$.

3.3 Electronic Circuit

To turn a 3D model into a functional gamepad, the designer needs to put gamepad electronic circuit inside the model. Even though there are methods [Mendach et al. 2005; Umetani and Schmidt 2017] for customizing an electronic circuit for optimized placement, we do not consider such methods in our implementation, since our approach focuses on the design and fabrication of the gamepad's layout, and the user experience that the fabricated gamepads provide. We leave electronic circuit customization for future work.

Specifically, instead of customizing the gamepad electronic circuit, we re-use the existing structures of electronic circuits extracted from commercial gamepads. In other words, we retarget the electronic circuit to the fabricated gamepad. We note that the retargeting approach proposed by Zhang et al. [Zhang et al. 2017] can be applied to generate an optimized placement of electronics inside the gamepad. However, for simplicity, we do not incorporate their approach in our implementation. Figure 4 shows a part of a 3D-printed gamepad with the electronic circuit has been placed inside.

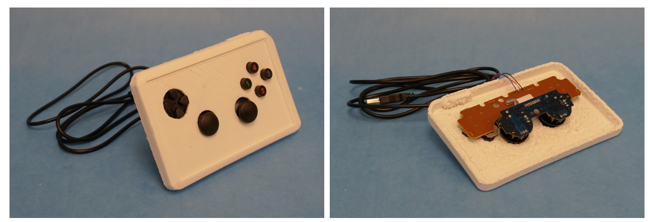

Figure 4: The electronics of a commercial gamepad retargeted to a 3D-printed gamepad. The buttons and the underlying electronics are shown on the left and right respectively.

4 PROBLEM FORMULATION

We describe the problem formulation of our proposed gamepad design approach in this section. To solve the problem of retargeting the layout of the buttons to a 3D mesh, we define a total energy function to evaluate a gamepad's button layout as follows:

$$E_{\text{total}}(\mathcal{B}) = w_{\text{sym}} E_{\text{sym}}(\mathcal{B}) + w_{\text{prior}} E_{\text{prior}}(\mathcal{B}), \quad (1)$$

where the E_{sym} term keeps the button layout near the symmetrical line of the 3D mesh, and the E_{prior} term contains the prior knowledge of the buttons' layout. w_{sym} and w_{prior} are their respective weights. The designer can also control which criterion should be more emphasized by controlling the weights w_{sym} and w_{prior} of the total energy function, and our optimizer can generate designs (variations of buttons arrangement on the 3D mesh are shown in Figure 5) that emphasize the corresponding criteria accordingly.

4.1 Symmetry Cost

An important consideration that we want to incorporate in the energy function is the symmetry that the buttons' layout should maintain when they are placed on the target 3D model. Such symmetry is also considered in common commercial gamepads, to distribute the gamepad's weight roughly equally in the player's hands when grasping the gamepad. To achieve a similar weighting in the synthesized gamepad, we include a symmetry term accordingly.

The symmetry term first considers the symmetry line of the 3D mesh (see Figure 6) computed by the method described by Mitra et al. [Mitra et al. 2006]. We use the distance between the center-of-mass $\mathbf{c}$ of the gamepad's layout and the symmetry line to define the symmetry term. Assume that the symmetry line has end points

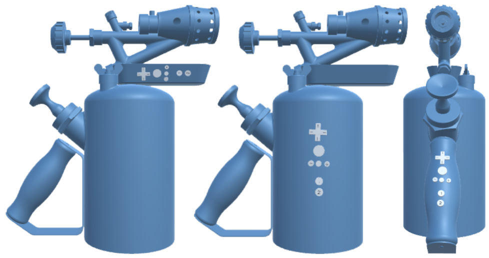

Figure 5: Example of multiple design results automatically generated by our method using a blowtorch 3D model and the Wiimote controller. These results are obtained by changing the symmetry cost term's weight (left and middle results generated with $w_{\text{sym}} = 0$, and right result generated with $w_{\text{sym}} = 1$).

$\mathbf{s}_1$ and $\mathbf{s}_2$, the symmetry term is defined by the standard point-line distance equation:

$$E_{\text{sym}}(\mathcal{B}) = \frac{|(\mathbf{c} - \mathbf{s}_1) \times (\mathbf{c} - \mathbf{s}_2)|}{|\mathbf{s}_2 - \mathbf{s}_1|}, \tag{2}$$

where $\times$ denotes the cross product.

Note that when 3D printing an object, the center-of-mass can be easily controlled and moved by printing a shell with spatially-varying thickness. However, in the current implementation, the center-of-mass of the button layout is used in order to symmetrically align the buttons of the gamepad onto the 3D mesh. It would be interesting to experiment and conduct additional user studies to understand the effects of the mass distribution of a gamepad in future work.

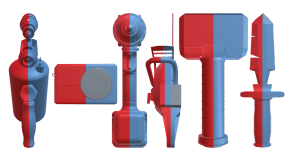

Figure 6: The symmetry of different objects used in our implementation.The grey areas on the camera and chainsaw models are excluded from the partial symmetry detection and approximation process.

4.2 Prior Cost

Given an input mesh, the template gamepad's buttons need to be placed appropriately on the mesh. This is achieved by incorporating prior knowledge about the buttons' placement on the template gamepad in the synthesized gamepad. The total energy function includes a prior term accordingly:

$$\begin{aligned} E_{\text{prior}}(\mathcal{B}) = \sum_{ij} \Big[& a_{\text{p}} \| D_{ij} - D'_{ij} \|^2 \\ & + a_{\text{r}} \| A_{ij} - A'_{ij} \|^2 \\ & + a_{\text{c}} \| D_{ic} - D'_{ic} \|^2 \Big], \end{aligned} \tag{3}$$

where a_{p}, a_{r}, a_{c} denote regularization weights for the position, rotation, and center alignment factors of Equation 3.

In the above equation, the first term aligns the position $\mathbf{p}_i$ of button $\mathcal{B}_i$ with the position $\mathbf{p}_j$ of another button $\mathcal{B}_j$, given the prior distance (D'_{ij}) between the buttons. This step ensures that the spatial alignment between the buttons is kept. The second term aims to align the rotation θ_i of button $\mathcal{B}_i$ with the rotation θ_j of button $\mathcal{B}_j$ given the prior angular displacement (A'_{ij}). Thus, the buttons would face each other properly on the target 3D mesh. Finally, the third term aims to align the position $\mathbf{p}_i$ of button $\mathcal{B}_i$ with the template gamepad's center-of-mass $\mathbf{c}$ given the prior distance (D'_{ic}) between them, thereby ensuring the buttons are correctly distributed on each side of the new mesh. It should be noted that the priors D'_{ij}, A'_{ij}, and D'_{ic} are learned from the template gamepad, and D_{ij}, A_{ij}, and D_{ic} are computed during the optimization process.

4.3 Optimization

We synthesize a gamepad design (represented by the layout of its buttons, $\mathcal{B}$) by optimizing it with respect to the total energy function E_{total}. To solve the optimization, we apply a Markov chain Monte Carlo technique, namely, simulated annealing [Kirkpatrick et al. 1983] with a Metropolis-Hastings state searching step [Chib and Greenberg 1995]. To employ the technique, we first define a Boltzmann-like objective function:

$$f(\mathcal{B}) = \exp\Big(-\frac{1}{t} E_{\text{total}}(\mathcal{B}) \Big), \tag{4}$$

where t is the temperature parameter of simulated annealing.

4.4 Moves

At each iteration of the optimization, our approach applies a move to alter the current gamepad design $\mathcal{B}$ to create a proposed gamepad design $\mathcal{B}'$. To apply a move, a button is randomly selected. Then a move belonging to one of the following types is applied to the button:

- translate along a random direction;
- rotate by a random angle;
- translate along a random direction and rotate by a random angle.

Each move type is selected with an equal probability. In applying a translation move, the button is translated by a distance x along a certain direction, where x is a random number uniformly drawn from the range $[-\frac{D}{2}, \frac{D}{2}]$ and D denotes the diagonal of the bounding box of the controller. Similarly, a random number ϕ uniformly drawn from the range $[-30, 30]$ degrees is used for rotating a button along a certain axis.

For translation, in case the new position of the button does not lie on a vertex of the mesh, the button is moved to the vertex nearest to the new position. With this hard constraint, the button is ensured to always move onto a valid position on the 3D mesh. It should be noted that if there is a collision between buttons (i.e., some buttons overlap) in the proposed solution, the optimizer will just reject the proposed solution and continue for the next iteration of the optimization. The radii of buttons are used for quick collision detection.

In case the designer wants to enforce a pairwise distance as a hard constraint between a pair of buttons $\mathcal{B}_i$ and $\mathcal{B}_j$, our approach allows the user to easily set an infinite cost if the distance between $\mathcal{B}_i$ and $\mathcal{B}_j$ deviates from target pairwise distance. Accordingly, in our moves, we rotate $\mathcal{B}_i$ and $\mathcal{B}_j$ or translate $\mathcal{B}_i$ and $\mathcal{B}_j$ together as a group, so as to allow them to move while maintaining their relationship. For such a case, our approach also initializes $\mathcal{B}_i$ and $\mathcal{B}_j$ to be from each other by the target pairwise distance.

4.5 Acceptance Probability

To decide whether to accept the proposed gamepad design, our approach compares the total energy value E_{total} of the proposed gamepad design $\mathcal{B}'$ with the total energy value of the current gamepad design $\mathcal{B}$. To maintain the detailed balance condition optimization, our approach accepts the proposed gamepad design $\mathcal{B}'$ with the following acceptance probability $P(\mathcal{B}'|\mathcal{B})$ specified based on the Metropolis criterion:

$$P(\mathcal{B}'|\mathcal{B}) = \min\left(1, \frac{f(\mathcal{B}')}{f(\mathcal{B})}\right). \tag{5}$$

We apply simulated annealing to efficiently explore the solution space, which is controlled by the temperature parameter t. At the beginning of the optimization, temperature t is set to be high such that the optimizer aggressively explores the design solution space. Throughout the optimization, the temperature t is lowered gradually. By default, we set $t = 1.0$ at the beginning of the optimization and decreases it by 0.1 every 500 iterations, until it reaches zero. Essentially, the optimizer becomes more greedy to refine the solution. The optimization is set to terminate if the change in the total cost is less than 2% over the previous 50 iterations.

Unless otherwise specified, we set the weights as $w_{\text{sym}} = 1.0$, $w_{\text{prior}} = 0.5$, $a_{\text{p}} = 1.0$, $a_{\text{r}} = 0.5$, $a_{\text{c}} = 0.5$ in our optimization. Note that the designer can control the synthesis to emphasize certain design goals by changing the weights if he/she wants.

5 EXPERIMENTS

To test the proposed approach, five different gamepads (see Figure 7) and, consequently, five different button layouts used as the input template models were retargeted to 3D models. Specifically, the first four are well-known gamepads of the PlayStation, Xbox, NES and Wii game consoles. In addition, a fifth template controller was designed by the authors. The controller's appearance originates from the widely-used smiley face emoticon. The implementation details and output results of the presented method are discussed in the following subsections.

5.1 Implementation

The complete pipeline was implemented in C# and tested on a 3.4GHz i7-6700 Processor Quad Core desktop with 16GB of CPU memory, with a GeForce GTX 1060 GPU with 6GB of memory. Given the template gamepad with 7 buttons (either PlayStation or Xbox gamepad) and the target 3D model, the search process for the optimal arrangement of the buttons took less than a minute for placing the buttons on a valid position on a 3D model with a total number of 5,000 vertices. Finally, it should be noted that gamepads were 3D-printed with a MakerBot Replicator Desktop 3D printer with the standard PLA filament. Due to the actual volume the MakerBot prints, the 3D models were segmented manually and the separate 3D-printed parts were glued together to compose the final gamepad.

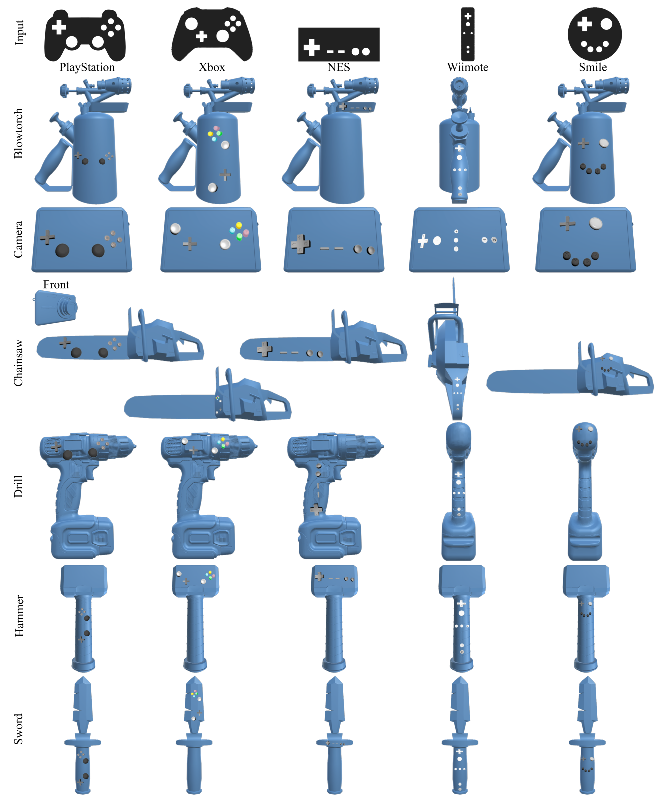

Figure 7: 3D models converted to gamepads by our approach.

5.2 Retargeted Results on Different 3D Models

Our automatic method for converting 3D objects to gamepads is scalable, which means that for a target 3D model we can get multiple design results/suggestions (see Figure 5) while handling complicated geometries. In all cases, based on the output results, the placement and the arrangement of the buttons appears plausible. The five different template gamepads were retargeted to several different models, as shown in Figure 7, to understand the efficacy of the proposed method. From the obtained results, the optimization approach could efficiently handle both costs terms. By exploring the solution space we converted 3D meshes to various types of gamepads, which are presented in Figure 7. We also discuss the validity of each gamepads later in this section.

Figure 8: Screenshots of the game developed for the user study.

For testing purposes, models with different topology were chosen. The camera, hammer, and sword are models with simpler topology compared with those of the blowtorch, chainsaw, and drill models. Thus, the retargeting process of the template buttons to the blowtorch, chainsaw and drill models was more challenging. Though

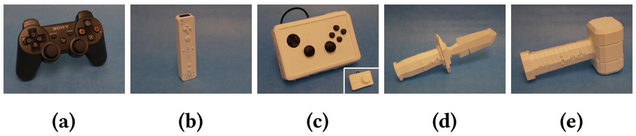

Figure 9: The commercial gamepads (a–b) and the fabricated gamepads (c–e) that were used in the user study.

the topology of these models is more complicated, the buttons are arranged properly.

Finding the models' symmetry line is vital for the proposed approach's success. Based on the chosen 3D models, aside from the chainsaw and camera, the symmetry line was easy to estimate. Most methods dealing with the objects' symmetry were unable to directly estimate it due to the deformation or the complexity of the object structure. This is a disadvantage of models like the camera and chainsaw, although the partial symmetry detection method proposed by Mitra et al. [Mitra et al. 2006], which was used in the current implementation, provided the required results. Consequently, the symmetry cost works properly, and the buttons are arranged in their proper positions in case the weight of the symmetry term is set to $w_{\text{sym}} = 1$.

The chainsaw model, however, was a challenging model for correctly retargeting the buttons of the template gamepads. As the chainsaw's surface is quite complex, it was difficult to retarget the buttons there. By relaxing the symmetry term in the optimization function for the PlayStation, Xbox, NES, and Smile gamepads, however, our approach found plausible solutions, resulting in buttons placed in optimal positions. However, constraining the symmetry to its initial values, our approach synthesized plausible designs for the Wiimote gamepad.

6 USER STUDY

To understand the efficiency of using fabricated gamepads and the experience that such gamepads provide to users, we conducted a user study and present its results in this section. The procedure and the results of evaluating the gamepads as physical objects and of user experience are reported in the following subsections.

6.1 Participants

The user study included 27 participants (18 males, aged M = 23.34, SD = 0.79 and 9 females, aged M = 22.63, SD = 0.47). All participants had prior experience with video games. The participants were students recruited by e-mail and in-class announcements. For the user study, a third-person action game was developed in the Unity3D game engine (see accompanying video), in which the user is called to explore the unknown environment, fight against enemies and find a hidden wooden box containing treasure. Screenshots of the gameplay are shown in Figure 8.

6.2 Settings and Procedure

The fabricated gamepads were evaluated against the PlayStation and Wiimote gamepads. During the user study, the participants were asked to play the game under five different conditions:

- $C_{\mathbf{PS}}$: use the PlayStation gamepad;
- $C_{\mathbf{Wii}}$: use the Wiimote gamepad;
- $C_{\mathbf{Cam}}$: use the fabricated camera gamepad;
- $C_{\mathbf{Sword}}$: use the fabricated sword gamepad;
- $C_{\mathbf{CSH}}$: use the fabricated camera, sword, and hammer gamepads simultaneously.

The five different conditions' order was randomized for each participant, and these gamepads (both commercial and fabricated) are shown in Figure 9. Moreover, Figure 10 depicts a user playing the game during C_{CSH}. We evaluated user experience and the fabricated gamepads on these five conditions.

6.3 Game Scenario

In the user study, participants were instructed to play the develop game and interact with the virtual world. The main character in the developed game scenario was an explorer called upon to find a treasure in a place full of zombies. The virtual explorer held a camera in her hands; this camera was the same one held by the user. By retargeting the buttons of a commercial gamepad to the camera model, the fabricated camera was used as the basic gamepad for navigating the virtual world. Additionally, the main character fought using a sword and destroyed virtual objects (e.g., the lock on the wooden box in which the treasure was located) using a hammer. Thus, the sword and hammer used by the virtual character in the game were fabricated and 3D-printed for use as gamepads. The Wiimote gamepad was used as a template in both cases. By retargeting the Wiimote buttons and electronics to the sword and the hammer, the user could make simple gestures (the gestures were predicted by the Wiimote's accelerometer) to generate the corresponding animation of the virtual character. The gesture recognition process was achieved using a simple dynamic time warping (DTW) method [Liu et al. 2009]. As can be seen in Figure 10, the user was equipped with facsimiles of objects utilized by the virtual character.

6.4 Procedure

The process for the user study was as follows. The participants entered the lab in which the game was set up. The experimenter informed them about the study, game, and procedure, as well as what they should pay attention to in the game. After each iteration of the gamepad condition, the experimenter asked the participants to respond to a few questions (see Table 1). No iteration exceeded seven minutes, and the procedures lasted no more than 45 minutes per participant.

6.5 Questionnaire

The first part of the questionnaire, Q1 to Q4, evaluated the gamepads as physical objects (C_{PS}, C_{Wii}, C_{Cam}, and C_{Sword} conditions were tested). We were interested in investigating whether the fabricated gamepads were experienced as different from the commercial ones. C_{CSH} was excluded because, in this part, we investigated the physical validity of the gamepads as single objects, not in combination. The second part of the questionnaire, Q5 to Q8, investigated the ways the participants experienced the game using the commercial and fabricated gamepads. The participants were asked about all five gamepad conditions because we were also investigating user experience with either a single gamepad or a combination of fabricated gamepads. It should be noted that Q5 originated in [Brockmyer et al. 2009], Q6 and Q7 originated in [Jennett et al. 2008], and Q8 was developed by the authors. Q5 to Q7 were altered to suit our purposes. For questions Q1 to Q8, the participants were asked to respond using a 7-point Likert scale (akin to [Jennett et al. 2008] and [Brockmyer et al. 2009]).

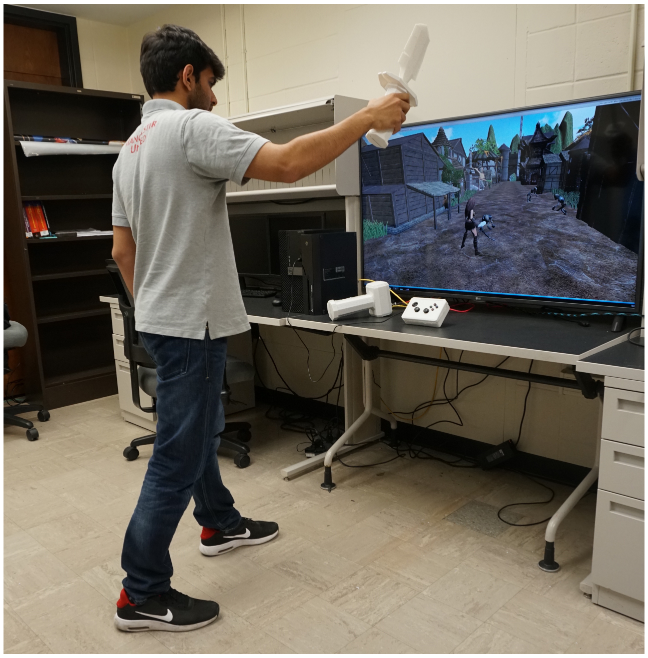

Figure 10: A user plays a game using fabricated gamepads which resemble the controllable objects in the game.

6.6 Gamepad Evaluation

The first part of the user study evaluates the gamepads as physical objects under the four different gamepad conditions. A repeated measures analysis of variance (ANOVA) with a Greenhouse-Geisser correction determined no significant difference on gamepads between the four examined gamepad conditions [$F(2.479, 64.459) = 0.185, p = 0.874$]. Based on the obtained results (see Figure 11), it can be said that the participants perceived the weight, size, balance, and stability of the gamepads similarly.

Regarding the size of the fabricated gamepads, some participants suggested incorporating hand measurements in a future implementation. Regarding the balance of the fabricated gamepads, some participants mentioned that the asymmetrical balance helped them to understand the feel of the sword. Finally, regarding the stability of the fabricated gamepads some participants mentioned they had not expected the fabricated gamepad to feel so stable. We believe these suggestions are quite important and we are planning to address them in future work. Nevertheless, considering that the fabricated gamepads were prototypes developed only for testing purposes, the obtained results give us the necessary boost to continue experimenting in this direction.

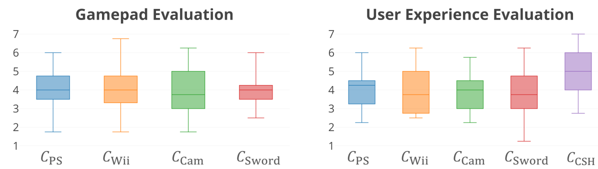

Figure 11: User study results. Notations on the plots denote the followings: C_{PS} (PlayStation), C_{Wii} (Wiimote), C_{Cam} (fabricated camera), C_{Sword} (fabricated sword), C_{CSH} (fabricated camera, sword, and hammer).

6.7 User Experience

The second part of the user study evaluates the level of participant engagement under the five different gamepad conditions (see Figure 11). A repeated measures ANOVA with a Greenhouse-Geisser correction determined significant differences across the five experimental conditions [$F(3.402, 88.465) = 6.329, p < 0.001$]. Post hoc tests using the Bonferroni correction revealed that the participants' user experience during the C_{CSH} condition ($M = 5.05$, $SD = 1.31$) was significantly higher than the C_{PS} ($M = 4.10$, $SD = 0.95$), C_{Wii} ($M = 3.89$, $SD = 1.09$), C_{Cam} ($M = 3.83$, $SD = 1.01$), and C_{Sword} ($M = 3.69$, $SD = 1.24$) conditions. Therefore, we can conclude that the use of multiple gamepads directly related to the game could enhance user experience

Here, we would like to mention some comments of participants that they made after the end of the user study. Regarding the engagement, some participants mentioned they reacted as they did in real-life tasks without having to think about it. Regarding the interaction realism some participants mentioned that during C_{CSH}, they felt like they cause harm to their enemies in the game, and others mentioned they almost believed they could throw the controller toward their enemies and hit them. Thus, the combination of controllers helped the participants to become even more immersed in the gaming experience. Finally, regarding the skillfulness, some participants mentioned that during C_{CSH}, they did not feel as much like game observers as they did during the remaining conditions (especially during C_{PS} and C_{Cam}). During C_{CSH}, they reportedly felt that they had to be active and vigilant during gameplay. They also mentioned that, because they had to switch between gamepads, speed and reaction time were very important. These findings indicate that the use of multiple gamepads directly related to the game could enhance not only user experience, but also enjoyment.

6.8 Summary

To conclude the results section, fabricated gamepads are valid physical objects one can use to interact with video games. Because most players are more familiar with specific gamepads such as PlayStation-related gamepads, it is difficult to change their habits and make them feel comfortable with new types. Nevertheless, considering that the developed gamepads were prototypes in which parameters such as stability, balance, weight, and size were not considered during the design phase, the results from the user study motivated us to continue working in this direction. However, from the user experience viewpoint, the fabricated gamepads outperformed the remaining examined conditions, especially in the C_{CSH}

Table 1: The questionnaire of the user study.

No.	Question	Anchors of the Scale
	Gamepad Evaluation Questions	
Q1	Does the weight of the gamepad feel right?	1 indicates not right at all, and 7 indicates totally right.
Q2	Does the size of the gamepad feel right?	1 indicates not right at all, and 7 indicates totally right.
Q3	Is the gamepad balanced properly?	1 indicates not right at all, and 7 indicates totally right.
Q4	Is the gamepad stable in your hand?	1 indicates not right at all, and 7 indicates totally right.
	User Experience Questions	
Q5	I play without thinking about how to play.	1 indicates not at all, and 7 indicates totally.
Q6	I was in suspense about whether I would win or lose the game.	1 indicates not at all, and 7 indicates totally.
Q7	It was like I could interact with the world of the game as if I was in the real world.	1 indicates not at all, and 7 indicates totally.
Q8	Did you feel skillful?	1 indicates not at all, and 7 indicates totally.

condition. This is an interesting finding because it indicated that gamepads have a game-centered relationship with games, enhance the way users experience them. Our findings are quite important and enhance the previously published work on the efficiency and influence of gamepads [Cairns et al. 2014; Skalski et al. 2011] on the gaming experiences. Thus, based on the results from the user study, a pipeline for the fabrication of functional gamepads is worth further investigation.

7 LIMITATIONS AND DISCUSSION

In this section, we discuss several limitations of our approach and provide insights for improvement.

7.1 Buttons Placement

The first limitation is related to button placement. For example, when dealing with models like the blowtorch, chainsaw, hammer, and sword, cases arise where the buttons are not placed in positions providing users with valid ways to hold the fabricated controller comfortably in their hands. To solve this problem, the designer needs to adjust the weights of the proposed energy minimization formula. This is an interactive process, which is done manually by the designer. In such a case, since the ideal arrangement is not a valid one, the designer needs to make decisions regarding the final results. Examples of designer-specified button arrangements include the PlayStation gamepad retargeted to the blowtorch, chainsaw, hammer and sword 3D models, and the Xbox gamepad retargeted to blowtorch, chainsaw, and sword 3D model. For these examples, the weight of the symmetry term was assigned by the authors to $w_{\text{sym}} = 0$.

7.2 Haptic Feeling

The haptic feeling provided by the gamepads might also be a limitation of the chosen 3D models. The surface of the blowtorch, and hammer are quite smooth; therefore, users generally felt comfortable grasping the fabricated controller. This might be also true for the camera and drill models, but the chainsaw (PlayStation and NES examples) and sword (Xbox example) models might not provide a comfortable haptic feeling due to sharp edges near the area grasped by the users. Thus, the chosen models should either have smooth surfaces, or methods for handling the smoothness of the grip should be considered to better deal with this issue.

7.3 Electronics Placement

Another potential limitation a designer might face relates to the placement of electronics. Especially when considering directly retargeting the electronics of a commercial controller, the designer might not be able to place the electronic circuits in an area with high curvature; therefore, additional considerations should be made. Moreover, when dealing with 3D models like the chainsaw, additional limitations should be considered. The buttons of PlayStation and NES of the template controllers have been placed on the chainsaw's guide bar. Considering how thin the guide bar is, issues might arise related to where the electronic circuits should be placed.

7.4 Model Size

The final limitation is related to the size of the model, and, more specifically, to the size of the guide bar in cases like the chainsaw. Such a model might provide negative experiences to the user for multiple reasons. Specifically, the guide bar could experience air resistance, inhibiting the natural flow of the user's gestures. Secondly, the way that the 3D model is extended should also be considered when choosing a target model for use in retargeting the button layout. An example would be when more than two persons use a controller like the chainsaw or the sword model when playing a game simultaneously. In this case, they could potentially hurt one another.

Moreover, the camera model might be too large when trying to maintain the ratio between the size of the model and the constraints of the buttons and their initial distances. This might not be a limitation if both hands are used to hold the controller. Considering that when a single hand controller such as the Wiimote is retargeted, it seems too difficult for the user to continuously grasp it firmly. Such limitations can be solved by deforming the model in the approximated grasping areas; this is an improvement that should be examined in future. Note that when retargeting the Wiimote controller to the hammer and sword, grasping issues related to size might not be applicable.

8 CONCLUSIONS AND FUTURE WORK

This paper proposed a complete pipeline for converting 3D objects into functional gamepads. The motivation for developing this method was to enhance users' gaming experience using equipment (translated to gamepads) like those used by characters in the virtual world (game-centered gamepads concept). In addition to the basic pipeline introduced in this paper, a user study was conducted to verify our initial assumptions. The results indicated that using gamepads like those used by virtual characters do indeed enhance users' gaming experience.

Even though the gamepads were fabricated in a basic semi-automatic pipeline, some additional steps would make the pipeline even more functional and automate some of the manual work done by the authors of this paper. Several important issues should be solved in the future. According to the results of the user study, size, weight, stability [Lu et al. 2014], and balance [Prévost et al. 2013] are factors that should be addressed in the future. Furthermore, the current research and development pipeline does not deal with object interiors. For example, electronics should be easily attached to gamepads instead of glued on. Thus, solutions such as the Makers' Marks [Savage et al. 2015] could also be considered for attaching electronics. Moreover, ways to easily customize electronics [Mendach et al. 2005; Resnick et al. 2009; Umetani and Schmidt 2017] would also enhance the future pipeline.

The conducted user study was able to provide interesting and also important results that can be later used to design and fabricate more user-friendly gamepads. In order to even better understand the way that users interact with the customized gamepads, we would like to investigate the benefits of having an automated design workflow compared to the ability of a user to manually design the gamepad's layout. In addition, a user study that would deal with some important criteria, such as the size of the gamepad, the way that the gamepad is balanced, the ability to reach all buttons, the ability to grip and hold the controller and the ergonomics of the gamepad should also be investigated. To conclude, we believe that different types of gameplay and controller usage may have significantly different usability requirements. Therefore, an obvious future work would be the investigation of the usability of controllers on different types of games.

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