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EVALUATING ENGINEERING LEARNING AND GENDER NEUTRALITY FOR THE PRODUCT DESIGN OF A MODULAR ROBOTIC KIT

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EVALUATING ENGINEERING LEARNING AND GENDER NEUTRALITY FOR THE PRODUCT DESIGN OF A MODULAR ROBOTIC KIT

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This work is dedicated to the Mechanical Engineer
who inspired me - *Sailaj Verma* (my father).

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An educated man is the product of a system that has multiple cog-wheels working behind the curtains. It goes without saying that my academic endeavors were fueled and sustained by certain people to whom I extend my deepest gratitude.

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While I firmly believe that an educational institution is important for personal and professional learning, I also strongly believe that it is an environment where there is symbiotic relationship among fellow students. To this end, I would like to thank all the members of the C-Design lab's Tangible Group such as Sang Ho Yoon and Ke Huo for their support. My special thanks to the senior members of the lab such as Vinayak, Senthil, Joran, Sujin, Bill and Dev for helping me design my experiments and reviewing my research papers.

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ABSTRACT

Verma, Ansh. MSME, Purdue University, December 2015. Evaluating Engineering Learning and Gender Neutrality for the Product Design of a Modular Robotic Kit. Major Professor: Karthik Ramani, School of Mechanical Engineering.

The development of a system is informed from design factors in order to successfully support the intended usability from the perceived affordances [1]. The theory of 'Human Centered Design' champions that these factors be derived from the user itself. It is based on exploiting these affordances that the boundary of technology is pushed to sometimes invent new methods or sometimes approach a problem from newer perspectives. This thesis is an example where we inform our design rationales from children in order to develop a gender neutral modular robotic toy kit.

To this end we create *HandiMate*, a robotics kit which enables users to construct and animate their toys using everyday craft materials [2]. The kit contains eight joint modules, a tablet interface and a glove controller. Unlike popular kits, *HandiMate* does not rely on manufactured parts to construct the toy. Rather this open ended platform engages users to pursue interest driven activities using everyday objects, such as cardboard, construction paper, and spoons. These crafted parts are then fastened together using Velcro to the joint modules and animated using the glove as the controller.

To understand the usability of the affordances, we discuss the results from user studies. These studies were designed to understand the affinity of *HandiMate* among children. The first study reveals that children rated the HandiMate kit as gender-neutral, appealing equally to both female and male students. The second study discusses the benefits of engaging children in engineering design with HandiMate, which has been observed to bring out children's tacit physics-based engineering knowledge and facilitate learning.

We further investigate the use of a gesture user interface by children for controlling robots made from a modular robotic toy kit. We conducted gesture elicitation studies to suggest embodied hand gestures for invoking motion among user developed robots. We elicit gestures from 23 children, first by portraying the 'effect'(motion from the toy) and then asking the user to perform it's 'cause' (reading gestures by a wearable glove). A total of 276 gestures for controlling 4 referent toys were collected, analyzed and reported. The gesture data, calculated by a kinematic hand model, was analyzed using a visual analytics approach integrating an interactive clustering and visualization technique.

Our findings suggest designs preferences of generic gestures for controlling toys like puppet, robotic arm etc. The results also imply that the sustained period of a gesture pose is about 30 seconds and give us insights into higher level classification of gestures mapped to the motion, topology and logical action based on motion of the toy. We also found that children would prefer using whole body interactions for big robots as compared to using hand gestures for lap-sized robots. We further discuss these design implications which helps designers design gesture systems for modular robotic kits.

1. INTRODUCTION

"It must be borne in mind that the object being worked on is going to be ridden in, sat upon, looked at, talked into, activated, operated or in some way used by people individually or en masse. If the point of contact between the product and the person becomes a point of friction, then the designer has failed. If on the other hand, people are made safer, more comfortable, more desirous of purchase, more efficient - or just plain happier - by the contact of the product, then the designer has succeeded." - Henry Dreyfus, Harvard Business Review (Nov. 1950).

Design legends such as Henry Dreyfus and Don Norman , explain in their respective publications "Designing for people" [3] and "The Design of Everyday Things" [4] the fundamental relations of a product with its users. These teachings have become guidelines for product designers, when it comes to developing 'user-friendly' products. Though the scope of these teaching extends to design of both physical objects and computer base graphical applications, lately the concept of 'Tangible Bits' [5] derives important understanding from the above mention philosophy into the realms of embedded electronics and embedded systems.

The perceived affordances the system has to offer can be converted to usability, when the designer understand which relations between the user and the product he/she needs to exploit. This exploitation in the community of Human Computer Interaction is in the form of inventing new technologies. Together by implementing these new technologies to convert the affordance of a material/product into usability leads to development of novel intelligent devices. For example, the attribute of a thin PET/PDMS film is that it is transparent and flexible i.e. the user can bend it in any direction. Rendl convert this affordance into usability by attaching capacitive circuits to recognize bends to provide new user interactions [6]. These affordances can also be extracted from humans. Sato developed techniques to recognize multiple grasping capabilities from a human hand, by doing a Support Vector Machine classification on Swept Frequency Capacitive Sensing [7]. He demonstrated an example where the system recognizes no touch, one finger, pinch, circle and grasp gesture of the hand for a door knob from the manner the user grasps it. It is based on the fundamental attribute that the frequency of capacitive conductance varies from the contact area of the palm and fingers.

In order to understand the design guidelines for developing a modular robotic kit for the kids, this work reports the explored technologies, insights of using material for robots and the aspect of gestural user interface among children, in order to come up with a gender neutral and engaging system.

1.1 Gender Neutrality

It is a well-known fact that women are underrepresented in STEM fields. A 2014 Intel report indicates that while women receive over half of bachelors degrees awarded in the biological sciences in the U.S., they receive far fewer in the computer sciences (18 %) and engineering (18%). These numbers are alarming in mechanical engineering (6%) and civil engineering (13%). This effect seems to start long before college, as reflected in the NAEP 2009 data, only a small percentage of the students - 34% of 4th graders, 30% of 8th graders, and 21% of 12th graders performed at or above the proficient level in science. These gender biases are further introduced through perception of the materials that children use for play.

Right from a child's younger years, physical items such as building blocks, shape puzzles and jigsaws have been an integral part of their play. They have been encouraged to play with physical objects to learn a variety of skills [8]. Resnick extended the idea to define "digital manipulatives" as familiar physical items with added computational power which were aimed at enhancing children's learning [9]. These manipulatives such as modular robotic kits [10,11], have traditionally attracted a predominant number of males [12]. These kits have manufactured building blocks based on which children construct. On the one hand they do encourage creativity but on the other, they do it in an instructive and constrained manner. Similarly, kits like e-textile where female participation is encouraged via sewing, crafting and decorating, do not cater to development of an electromechanical or robotic systems [13]. There exists a need for kits that encourages the kinds of engineering learning that is outlined in the Next Generation Science Standards [14] such as "Engineering Design" and "Forces and Interactions". As we do so, these kits should also encourage broad participation (i.e., are gender neutral) so as not to continue to reinforce existing inequities.

1.2 Gestural User Interface

As McNeil emphasizes that gestures 'reveal the idiosyncratic imagery of thought [15], we investigate these idiosyncrasies by a guessability study method [16] in the context of Tangible User Interfaces (TUIs). The idea of Digital Manipulative as mentioned in the above section has motivated the creation of multiple construction toy kits [2,10,11,17–21]. These modular robotic kits have traditional control mechanisms such as a joystick [18] or block programing to generate the actions in the robot [21]. Gesture based toys have proven to be engaging by the users [2] however the designers do not have guidance to the design of hand gestures used to control these toys.

1.3 Scope

By contrast, *HandiMate* aims to be both gender-neutral while also encouraging physics-based engineering play. The kit provides a construction platform which merges robotics with narrative play and crafting. This approach enables gender neutrality by emphasizing a broader range of play activities that are more open to divergent design possibilities. The kit itself is made up of 8 joint modules, where each joint module is packaged with an actuator, a wireless communication device and a micro-controller. This modularization makes quick electro-mechanical prototyping, a matter of pressing together Velcro. Animating these constructions is made intuitive and engaging by a glove-based gestural controller. We demonstrate that *HandiMate* attracts both genders to participate more extensively and equally. We discuss the technical implementation of the kit and the studies conducted to asses the compatibility among genders. We designed our studies to observe learning of broader engineering concepts among children.

Similarly to understand the gestural interactions we performed studies to observe and understand natural gestures behavior and inform the gesture design with data supported insights. We adapt a custom analytical software that rapidly provides insights and enhances our ability to design gestural user interface for tangible toys.

After developing a robotic kit, we first explored developing the gestures to control the robot from experts and performed usability studies among users. The results from these studies motivate our work to investigate children preferences in gesture design for controlling the robots. We re-designed the glove and attached a kinematic hand model in order to make it robust. We collected the gesture data from this model and ran clustering algorithm after performing the guessability study. The study method presents the *effects* of the gestures to participants and elicits the *causes* meant to invoke them. As embodied interaction is a feature of the system, we record these gestures using a glove.

1.4 Summary

As a part of understanding the impact of this kit, we sought to conduct studies which were designed to answer the following research questions:

- Does changing the tools and the material, to craft the toys, affect the gender perception of the robotic kit?
- To what extent do children as the designer engage in general engineering concepts with *HandiMate*?

- Generating a taxonomy of children defined gestures for controlling tangible toys for the first time,
- Exploiting a visual analytics system to rapidly categorize gestures, and providing data-supported insights on natural user gestures,
- Understanding the design implications of gestures for the embodied interactions with tangible toys.

1.5 Thesis Organization

Chapter 2 explains the various research topics that are related to this field, the prominent work that have been done in these fields and how the present work is influenced from them. Chapter 3 explains the first phase of the project and how it helped to direct the present work. It concludes by defining clear goals that directed the present work. Chapter 4 gives details about all the hardware structure of the work and how it has developed step by step. It also explains the gesture control structure developed and how the gestures were chosen so as to make them simple and intuitive. Chapter 5 explains the user study procedure followed for evaluating the work. It then explains the results derived from the user study. Chapter 6 explains the possible future directions for the work and finally concludes the work in its present stage.

2. RELATED WORK

Our work threads together themes from modular robotics kits, gender appropriateness, learning engineering concepts, interactions with robot and gesture elicitations methods.

2.1 Modular Robotic Kit

Many researchers have explored different types of configurable robots for purposes such as smart machines capable of locomotion and transformation [22], educational tool kits that children can use to learn about programming [23], and simple toys [24]. These kits allow construction of robots using different materials like predefined plastic shapes [25], user manufactured plastic shapes [17], laser cut shapes [26] and a combination of craft and LEGO [27]. The control techniques in these kits generally use either a graphical programming system, autonomous control [22] or kinetic memory - the ability to record and playback physical motion [25]. This culture of building robots using pre-defined shapes has been widely commercialized via LEGO Mindstorms, Vex robotics and EZ-Robot [17].

These kits were typically designed to make systems with fewer (one to four) motor actuated joints. A majority of these prior works tend to restrict design freedom as they provide a set of predefined physical shapes that could only be assembled in specific ways. Crafting using everyday objects as primitives shapes provides more freedom in creative exploration. Also providing a glove as the controller shifts from the regular methods of control devices such as tablets and phones and potentially more active and embodied engagement.

2.1.1 Interacting with Robots

A vast literature is present from research in Human Robot Interaction (HRI) which gives the evolution of interaction [28]. Cheng explored the use of gesture to perform high level commands in controlling a robot as opposed to prevalent keyboard, joystick and mouse interfaces [29]. They concluded that gesture input schemes with tangible user interface can out-peform a button pressing input design for HRI tasks. This conclusion is also evident in a significant amount of work that has been done using either vision based [30] or glove based mechanisms [31] to capture human arm and hand gestures to interact with robots. A popular method is the use of kinetic memory, where the user actuates the motion by physically moving the robot and at the same time the system records and eventually plays it in loop [25]. This method brings the context of computational tangibles to the user interface as the user operates the toy by physical touch. Jacobson extended this idea of tangible manipulation, where modular pieces would configure real time on the screen graphically as the user assembles tangible tokens and eventually controls them. Other methods involve using joysticks [11] or programming the robot [**?**, 21] which delivers more on the play value of the toy rather than educational learning. Quigley [32] suggests the use of tangible tokens to directly manipulate the pitch and roll of a mini autonomous vehicle (mini-UAV).

2.1.2 Embodied Interaction

Tangible user interfaces (TUIs) exploit embodied interactions, coupling physical objects with computerized qualities. Exoskeletons systems [33–35] have been explored as robotic input systems from human as well. Kazerooni [34] increased the mechanical strength of an individual based on dynamic control forces applied by the user and amplifying them in heavy duty tasks [36]. Caldwell [35] on the other hand explored the use of a 7 degree of freedom input system which ran from the shoulder to wrist. The authors also used a tactile feedback glove to collect inputs from the hand and collectively the system manipulated a robot arm and dexterous gripper. General Electric and NASA made efforts to investigate embodied robot interactions with projects like Hardiman [37] and Robonaut [33]. While Hardiman was the first attempt to develop an exoskeleton suit, Robonaut is an example of master-slave relation where the operator remotely controls the robot using Polhemus tracker enabled gloves. Seehra [2] presents a generic library of gestures from a glove controlled robotic toy kit for the use of children. The authors observed a more engaged involvement from children during play.

Our approach is motivated from this rich literature of embodied interactions with robots. Borrowing computational techniques from the gesture community, we explore for the first time the design of user-defined hand gestures for remotely controlling custom toys build from a modular robotic kit.

2.1.3 Gesture Elicitation

Very few work have been proposed to support the analytical activities in gesture elicitation studies. Vatavu and Wobbrock [38] proposed an analysis tool for generating statistical measures of gesture elicitation studies such as agreement/disagreement score and statistical significance level. This tool provides a detailed statistical analysis of gesture elicitation studies. However, it does not support the categorization of similar user gestures that is one of fundamental analytics activities in gesture studies. Recently, Jang et al. [39] introduced a visual analytics system, *GestureAnalyzer* to support rapid aggregation of similar user gestures, and identification of gesture taxonomies. This approach involves the users in the process of aggregating similar gesture data through an interactive hierarchical clustering where the aggregation level is dynamically adjusted by the users. As a result of the analysis, this system provides a set of gesture categories including the context of elicitation tasks and the perception of gesture similarity. Also, the results are presented with visualizations based on users natural motion acquired during the studies (e.g., motion capture data).

In this paper, we adopt the visual analytics approach to analyze the gestures elicited by 23 participants. Unlike existing work [39], we apply the visual analytics approach to hand motion tracking data rather than upper body skeleton data. As a result of the study, we provide a gesture database supported by users natural gesture behavior and data-supported visualizations.

2.1.4 Children Defined Gestures

Studies have shown that children begin to gesture at around 10 months of age [40] and the dexterity of the hand becomes more articulate from childhood to adolescence [41]. While current work [2, 10, 11, 17, 19–21, 25] is motivated to design system technology for children, they have been overlooked in formal research [42] when it comes to gesture design. While work has been done to elicit gestures in gaming [43], surface computing [42] and whole body interactions [44], additional research is needed - particularly in the area of tangible user interfaces. This will help understand the needs and abilities of young adults in order to ensure that the robot controls are intuitive and easy to adopt, making way for more engaging play experiences.

2.1.5 Gender Appropriateness

Robotic kits have been popularized in after-school informal educational settings for all genders. Even with efforts of neutralizing the gender perception on robotic kits, an imbalance of gender participation still exists where girl's participation rate is about 30% in a robotics program [45]. Previous works suggest a way to broaden the gender participation through merging art and technology in cross-disciplinary activities [27, 46]. Rather than fixating on a particular task-oriented application, girls exhibit interest towards designing motion path and clothing for robots which are regarded as creative activities [47]. Thus, girls should be considered as potential learners in robotics educational programs [48]. Efforts have been put to introduce toys and kits that are designed to attract female participation in engineering fields.

Commercial kits like GoldieBlox [49] encourage building and rudimentary mechanical engineering concepts by their kit. Similarly Roominate [50] is targeted for girls to develop dynamic and electrical structures. These kits are aimed for smaller age group and are constrained by their manufactured material for usage. Thus they tend to be of a smaller scale and are less extensible. Meanwhile, work has been done with creditable research for the development of toy kits that support a more creative environment for STEM learning [51]. Our approach with *HandiMate* is to encourage craft materials and Velcro as constructing elements to provide an open-ended design environment for broadening the gender participation,. Apart from the gender participation, *HandiMate* is aimed to appeal a boarder age group.

2.1.6 Learning Engineering Concepts

Piaget has argued that tangibles provide opportunities to reformulate our existing mental models [52], which has motivated a lot of research for developing pedagogical tools. Engineering concepts such as center of mass, friction, stability of structures, materials for construction and dynamic structure serves as important concepts to be taught to high school students [14]. These concepts would then serve as the foundation for design considerations in fabricating dynamic systems. Topobo is a system that supports children in exploring various physics concepts with manufactured primitives based on kinetic memory [25]. Similarly, Kinematics [24] allows children to assemble increasingly complex structures by re-combing different predefined elements. This kit allows the children to learn via iterating and reassembling the constructed structure. EnergyBugs [53], a wearable energy-harvesting device for kids, made children to develop a tangible and emotional connection to energy. Schweikardt introduced roBlocks [20], a computational kit which enables the young users to explore complex ideas in science, technology, engineering and mathematics. The kit consist of manufactured sensor, actuators and logic modules to play with. By contrast, *HandiMate* encourages a more open ended design approach. We do not have any manufactured primitives, apart from the joint modules, for the users to build their toy with. This kit enables the user to use everyday materials like cardboard, craft paper, and kitchenware in constructing the toy, thereby exploring various engineering concepts with materials and structures.

3. EXPLORING TECHNOLOGIES TO EXPLOIT AFFORDANCES

In this chapter we discuss the exploration and development of technology developed in order to explore gesture based devices and capacitive sensing. The intention for developing the technology was to explore methods of exploit existing affordances in the objects.

3.1 Chiron

We introduced Chiron A wearable device for the hand that reads the digital and analogous signals from capacitive sensor patterns and orientation sensors, to interpret user-intent. Here, we explore two cases (a) an unconventional and low-cost method for intuitive shape modeling and control, (b) ergonomically designing these patterns from conductive ink, for reading localized finger interactions (swiping or pinching). We also exploit Chirons thumb-based interaction mechanism and discuss future novel applications.

Design Rationale: Chiron implements a naked thumb-based interaction mechanism. Based on finger ergonomics, patterns are laid on three fingers: (1)Forefinger (2)Middle Finger & (3)Ring Finger (Figure 3.2). Since the usage of forefinger is most comprehensive, due to its available area for the thumb, we use it to provide a slider-based output. The middle and ring finger are used for menu driven outputs. These menus were allocated based on the ergonomic accessibility of the thumb to those areas.

Hardware: The device comprises of the Arduino Nano microcontroller, MPR 121 Multiplexer, MPU 6050 IMU and a BlueSMiRF Bluetooth (Figure 3.2), which the user can wear on his hand. The locations of these components are defined to provide ergonomic comfort without compromising any intuitive feedback(Figure 3.2). The

IMU devices algorithm outputs 6 values the acceleration in the three axis and the Euler angles. These values are interpreted to define the dynamic pose of the users hand at any instance. The communication between the IMU and the microcontroller is based on the i2c serial protocol that performs measurement and signal analysis.

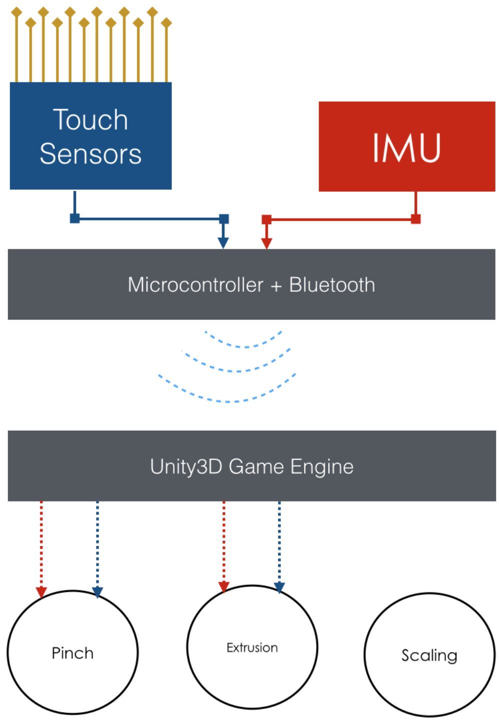


Figure 3.1. The Hardware pipeline for Chiron.

Sensor Patterns: We implement a sensor pattern to get feedback from the user. These are interpreted as shape modeling operations using a pre-defined mapping (such as rubbing of the index finger implies scaling of the cross-section). Going with the current trend of sketch-able electronics, conductive ink was used to make capacitive sensor patterns. Two types of patterns were fabricated based on the functionalities: pattern for (1) slider-based recognition (2) ergonomic menus on fingers (Figure 3.2). The slider-based pattern is constructed of 5 pins, defining the resolution of slider-activity. It is designed in a two-column matrix (Figure 3.2). The algorithm understands the position of the finger based on which pins are active. The menu driven sensors are simple touch points, which are ergonomically placed based on the fingers usage area (Figure 3.2). The MPR121 Capacitive Touch Sensor, which is a multiplexer to sense touch events, uses a total of 12 electrodes whose capacitance increases when a finger touches it.

Software: The software of the system has three modules (a) Microcontroller program, (b) Mapping and (c) Shape Modeling. The latter two, because of their dependency, are implemented within the Unity3D application. Analogous values from the IMU and digital states from the pin, is being read by the micro-controller and sent to the modeling application. In the modeling application, the change in the imported values is associated to modeling functionalities (such as movement of hand implies extrusion). Based on a mesh algorithm, these shape-modeling functions are performed. By interpreting these changes in value, user intent is mapped to modeling tools.

Usage Scenarios: Chiron recognizes the following actions 1. Slider action to increment the value. 2. Spatial movement of the hand. 3. Orientation of the hand pose. 4. States of the menu driven electrodes. For shape modeling, these actions are mapped to the following operations: (1) Primitive Selection, (2) Scaling, (3) Extrusion and (4) Pinch.

Primitive Selection: Since the task of selecting a primitive to extrude has a lower significance, the ring finger was used to house the menu-driven pattern for this task. It consists of 4 capacitive electrodes, which detects the touch state and associates each electrode to a primitive shape. The user via their thumb can reach out to these electrodes and select the appropriate primitive (Figure 3.2). A smooth interaction is achieved, since the area of contact for the thumb is comparatively greater on the finger, making it extremely easy for the user to understand and use.

Scaling: Scaling of the cross-section area is best emulated in a slider mechanism for which the forefinger was used. Based on the slider action, the user can scale up or down the exposed cross-section area (Figure 3.2).

Extrusion: The very top electrode in the middle finger is for activating the extrusion state. The user has to keep the state of this electrode active by maintaining a contact. By moving their arm in the air the object will extrude (Figure 3.2)). To map it in an intuitive manner, we extracted the acceleration value in the z- direction of the IMU to play as the variable responsible for the depth of extrusion. Thus the user experiences that they picked up the primitive and extruded it in air. Hence a pinch and elongate metaphor was achieved.

Pinch: Based on usage preferences, pinch command comes after extrusion. The second electrodes activity is associated with this aspect. After keeping the state active, the user can change the angle of the exposed cross-section by changing the orientation of their hand as sensed by the IMU (Figure 3.2). The user thus experiences a grab and rotate action while performing this operation. Activating the last electrode in the middle finger completes the current modeling event (Figure 5a).

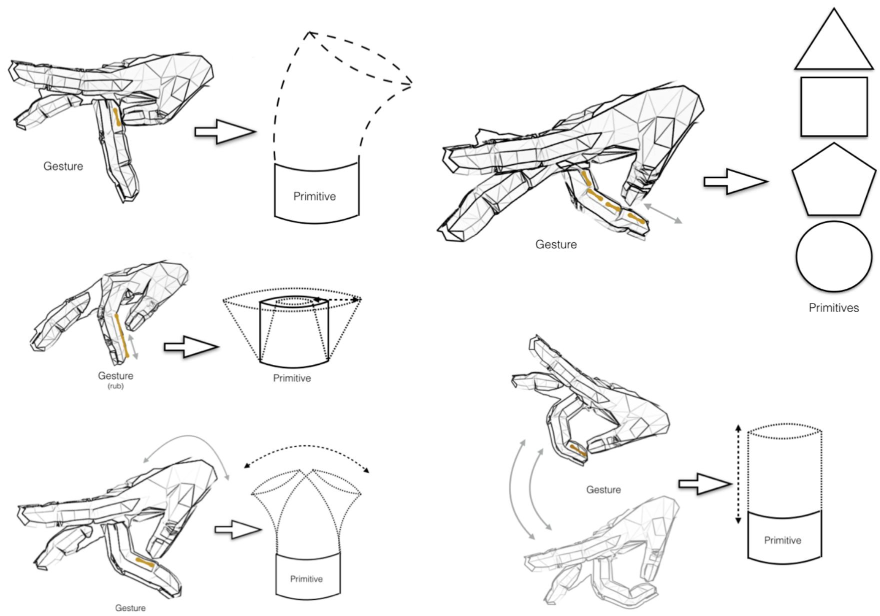


Figure 3.2. The gesture library for Chiron.

Implications towards usage - Cognitive Load: In a heavy menu driven application; the user develops a split attention effect: dividing their attention between the task and the control mechanism. By leveraging proprioception and tactility of the hardware coupled with a visual mechanism to educate the user of functionalities, we hypothesize that the user will be more immersed in the task rather than dividing a greater attention for the control mechanism. We predict the learning time to be short provided the user develops a muscle memory that maps the gestures to the shape. Based on kinesthetic learning and dexterity of the user, the muscle memory may help us maximize the Germane Cognitive Load. The future user study will account for verification of these claims.

3.2 SOFTii / BendID

We developed SOFTii, a flexible input system for topography design and continuous control via external force. Our intent is to provide a tactile metaphor for pressure-based surface input. In this study, two prototypes of SOFTii have been fabricated: (a) The first prototype has one pressure surface for topography design with everyday tangible objects, (b) the second prototype, having two force input surfaces, performs as a deformable controller for video games and continuous shape modeling using a SVM algorithm. Both prototypes of SOFTii are constructed by layering Polymethylsiloxane (PDMS), ITO coated PET film, and conductive fabric and foam. The layer configuration allows the capturing of local pressure on the SOFTii surface via distributed electrodes. Here we further discuss the implementation of the device with possible usage scenarios.

SOFTii utilizes a layer configuration of non-conductive and conductive soft materials. This combination produces a distinct elastic and conductive behavior which can be used to measure shape deformation. The distributed pressures are employed to provide a pressure-based soft input metaphor for 3D topography design and video game applications.

Hardware: Two prototypes of SOFTii have been fabricated to perform topography design with coarse silhouette and continuous control with pressure-based deformable input. Prototype 1 - Coarse Silhouette Sensing and Prototype 2 - Local Bending Sensing.

The first prototype consists of conductive foam with distributed electrodes underneath one side, while the other is covered by conductive fabric. This configuration allows capturing the imprinted surface deformation. The conductive foam performs as a soft pressure sensor and provides passive haptic feedback simultaneously.

This prototype is constructed by mirroring two conductive foam layers through a PDMS insulator. The device is wrapped around by conductive fabric. The ITO coated PET films offer thin, flexible electrodes which are suitable for the construction of flexible device (0.175 mm thick, 50 ohm /in resistivity). PDMS1 is selected because of the flexible, soft, and non-conductive properties. The electrode grid supports tracking local pressures on both surfaces. In this study, we hypothesize that users often apply pressure on both sides to bend the prototype. This hypothesis is applied for the training process with the SVM algorithm.

Sensor Evaluation: In both prototypes, the readings are managed by voltage divider via analog multiplexors (CD74HC4067 16-Channel analogous multiplexer), then processed by an Arduino microcontroller2 (ATmega328, clock speed 16MHz). Therefore, the local pressure resolution is customizable for the purpose. The conductive foam (Open Cell Polyurethane, density 50lb/cuft, tensile strength 25 psi) provides a flexible, tactile and responsive layer. We hypothesize that connecting a wire directly to the foam is not effective in distributing the voltage across its porous structure. Thus the conductive fabric is used as a voltage distributer (surface resistance: ¡ 50 ohm/in, thickness 0.45 mm, 78% nylon and 22% elastomer). We perform point pressure tracking test and pressure-based bending test to evaluate the discretely distributed electrodes (Figure 5). The test results indicate that it is visible to capture coarse shape outline with imprinting mechanism. Also, it is possible to identify local deformation (location, direction, and magnitude) using surface distributed pressures.

Sensor Interpolation: In this setup, the deformation of the conductive foam is recorded with 25 electrodes. These pressure readings are used to derive the coarse shape outline that causes the deformation from the top of the conductive foam. We employ bilinear interpolation to interpolate the sensor values over the active surface. We observed that pressure readings from a sensor diminishes as the point of load is moved away from the sensor. Additionally, loads applied directly on the sensor has negligible affect on the nearby sensors. The interpolated values at each vertex is linearly mapped to the mesh deformation. Moreover, the current setup can run in a single touch tracking mode by estimating the position of touch event.

Bending Estimation: The difference in readings between the upper and the bottom layer represents the local deformation at the corresponding node. They are plotted against the magnitude levels to derive the polynomial trend line. A range of 90 degree in each direction is mapped to the bending angles. Thus, an accuracy of 91% is obtained from our polynomial model. SVM Training: In this setup, SOFTii is trained with 17 different patterns of local bending states using SVM algorithm via Weka3 library. These patterns include 8 nodes with 2 bending directions (clockwise and counter-clockwise) for each node, plus a stationary resting position. We obtain a clearly classified training data result by adopting 4 different intensities for each bending state. In this paper, the location and the direction of the bending states are obtained from the patterns of 18 analogous readings.

Interactions: We put effort in utilizing SOFTii as a multimedia input device. The purpose is to provide an intuitive tangible interface between user and computer via force input domain. These interaction methods serve as our proposed ideas for developing application scenarios for Softii.

3D Topography Design with everyday objects: Design Motivation: Here, SOFTii is implemented as a tool for detecting coarse shape silhouette based on the pressure distribution. The system imitates the stamping metaphor to recognize the coarse shape outline. The pressure readings are interpolated. Here SOFTii performs the task using convex objects. The physical objects can be employed directly as the pointer to generate various shapes for the task.

Flexible Game Controller: Traditional personal computer (PC) system games, are currently handled by a combination of key pressing-and-releasing. SOFTii, however, can be customized as a flexible input device for various games. Here, we implement the flexible SOFTii game controller with car racing and flight controlling. The tactility and flexibility of the materials provide pressure-based and deformable input method.

Flexible E-book Reader: Electronic book (e-book) technology is developing rapidly due to its convenience and security. However, the interaction design still has not caught up with the graphical effects. We use the flexible and distributed pressure readings in flipping e-book pages to further improve the tangible experience in e-reading. The direct mapping between the bending angle with the flipping effect allows using SOFTii as a proxy for the pages to be flipped. Two of the bendable corners support manipulating the top most page on each side of an opened e-book.

Local bending recognition: We implement SOFTii as a novel input device to precisely recognize local bending. The ability to distinguish location, direction, and magnitude of local deformation provides a direct interface for shape manipulation. In this paper, the bending magnitude is directly mapped to the virtual deformation to provide precise control using equation 2. The location and direction of the bending is classified and identified by the SVM algorithm.

Please refer for the full details that are presented in the paper SOFTii [54]

4. SYSTEM IMPLEMENTATION AND EXPLORATORY DESIGN STUDY

This chapter discusses the system implementation for the modular robotic kit. We further discuss the implementation and results we obtained from the user studies performed for the system.

4.1 HandiMate Framework

The combination of technological progress and a growing interest in design has promoted the prevalence of DIY (Do It Yourself) and craft activities. We introduce HandiMate, a platform that makes it easier for people without technical ex- pertise to fabricate and animate electro-mechanical systems from everyday objects. Our goal is to encourage creativity, expressiveness and playfulness. The user can assemble his or her hand crafted creations with HandiMates joint mod- ules and animate them via gestures(Figure 4.1). The joint modules are packaged with an actuator, a wireless communication device and a micro-controller. This modularization makes quick electro-mechanical prototyping just a matter of pressing to- gether velcro. Animating these constructions is made in- tuitive and simple by a glove-based gestural controller. Our study conducted with children and adults demonstrates a high level of usability (system usability score - 79.9). It also indicates that creative ideas emerge and are realized in a constructive and iterative manner in less than 90 minutes. This paper describes the design goals, framework, interac- tion methods, sample creations and evaluations methods.

4.2 Design Goals

The design goals for HandiMate are to provide a platform for the user to easily construct and animate systems using everyday objects as materials. To this end, we

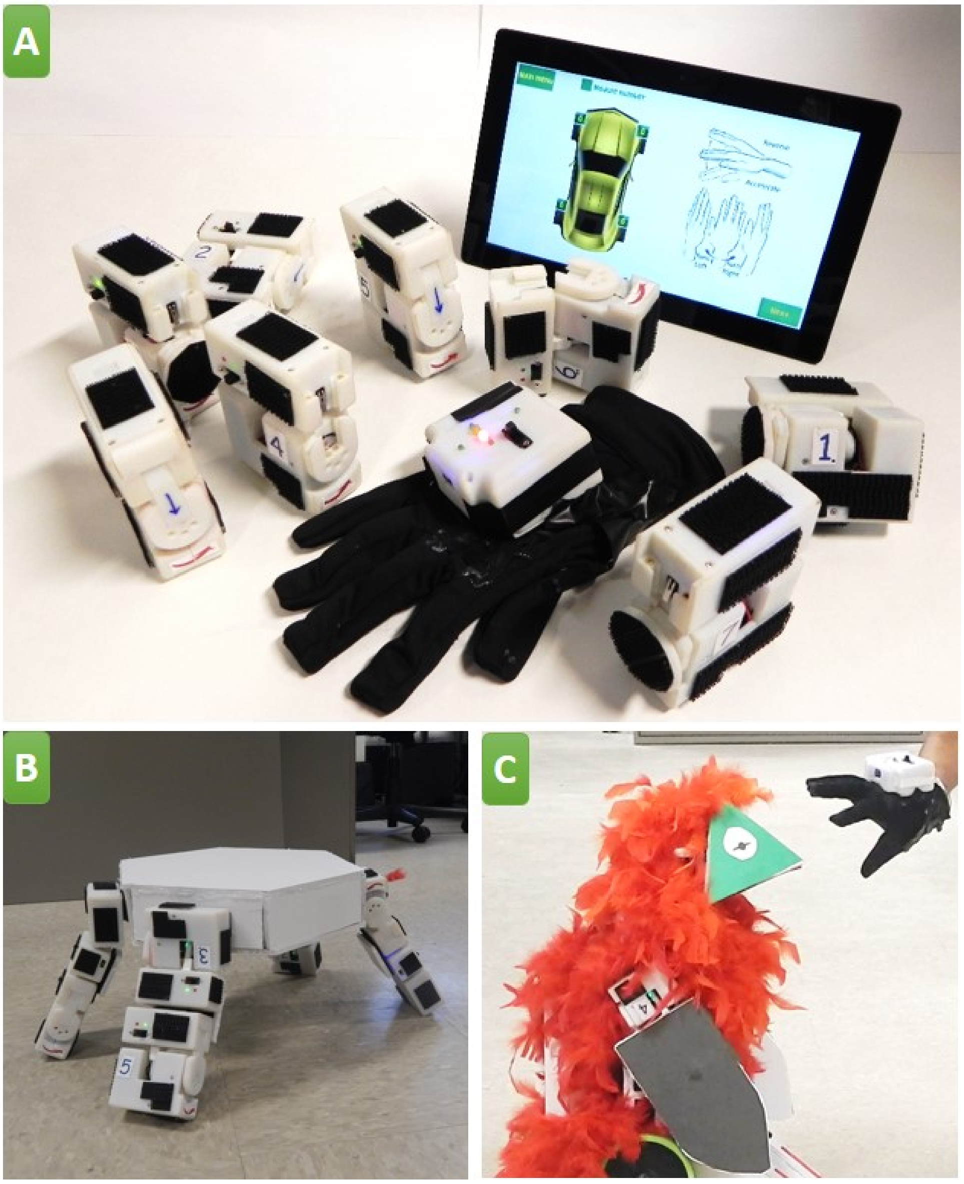


Figure 4.1. Overview of the HandiMate kit(a) HandiMate Kit (b) Sample creation (c) Gesture control of robot.

attempt to take away the technical complexities, while providing more design freedom and encouraging constructionism and creativity. The framework was designed based on the following design goals:

DG1. *Accessible*: The material used for constructing the objects should be easily accessible and be assembled quickly using simple and familiar techniques.

DG2. *Easy to use*: The system should be simple enough to be used by people of all ages including children.

DG3. *Safe and robust*: As the system is to be used by people of different age groups, the device should be safe and should work reliably.

DG4. *Adequate & smooth movement*: The system should be able to recreate most motions (both fixed angle and continuous motion) smoothly to provide an enjoyable experience.

DG5. *Scalable*: In the spirit of a modular design, every individual module should be physically and computationally complete and extensible.

DG6. *Expressive*: Encourage exploration of a topic without prescribing right and wrong activities.

4.2.1 Interface Design

A simple tablet application has been developed to understand the topology of constructions made and to effectively map them for gestural control. The interface is built using the Unity3D[1] game engine. The application can be installed on any tablet or mobile device. A few basic families of constructions are made available with predefined control mappings where the user has to select the position and direction of motion of the joint modules (Figure 4.1). The interface also allows the user to create objects that are different from these predefined families and to assign their own user defined mapping to the object being constructed. Once defined, these mappings are transferred to the glove-based controller using Bluetooth communication. This operation has to be done only once each time the user constructs a new object.

[1]https://unity3d.com/

4.2.2 Glove-Based Controller

The glove-based controller is used to read the hand pose of the user and control the motion of the joint modules. It consists of an Arduino Nano[2](ATmega 328, clock speed 16MHz), flex sensors[3], MPU 6050[4] (IMU), BlueSMiRF Silver[5](Baud rate 115200 bps) and XBee Series 1[6] (Baud rate 57600 bps) . The Bluetooth device receives the joint module and hand joint mapping from the tablet interface. Flex sensors are placed on the thumb (Interphalangeal, Metacarpophalangeal joints), index and middle fingers (Proximal Interphalangeal and Metacarpophalangeal joints) due to the greater dexterity of these fingers from the rest of the hand. A sensor is also placed on the pinky finger (Proximal Interphalangeal joint) for differentiating control gestures from start and stop gestures. The seven flex sensors, are multiplexed by a 16-channel analog multiplexer[7]. When the resistance of the flex sensor changes (34K to 67K ohms) by bending, the micro-controller picks up the voltage across the flex sensor based on a voltage divider circuit. These analog values are then converted into corresponding motor values. This mapping between the analog sensor value to the motor value is not directly based on the actual angle of the hand or finger, but is scaled to allow full rotation of the joint module within a comfortable range of motion of the hand or finger. This range was determined by doing a small pilot test with few people of different hand sizes. The flex sensors are also placed and calibrated in a way to prevent interference between the joints on the same finger. In a similar manner the micro-controller also reads the angle values from the gyrometer and accelerometer in the IMU device by I^2C communication and generates the motor values. The motor values are transmitted to the respective joint modules by a PAN network created by the XBee communication device.

[2]http://arduino.cc/en/Main/arduinoBoardNano
[3]https://www.sparkfun.com/datasheets/Sensors/Flex/flex22.pdf
[4]https://www.sparkfun.com/products/11028
[5]https://www.sparkfun.com/products/12577
[6]https://www.sparkfun.com/products/8665
[7]https://www.sparkfun.com/products/9056

For safety, these electronic components are enclosed in a shell like casing made by 3D printing. A LED based visual feedback system makes the user aware of the state of the IMU and the glove-based controller.

4.2.3 Joint Modules

The joints modules are used to animate the user's construction using the glove-based controller. These modules contain an XBee communication device that reads the information from the glove-based controller, a micro-controller (Arduino Nano) for interpreting this information, and Herkulex DRS-101[8] motors for motion. The parameters of acceleration - time ratio and power input were adjusted to obtain a smooth and non-jerky motion of the motor. The motor, wires and electronics are enclosed in a shell like casing to make the device safe for use. Each module is powered using a 9V lithium ion battery.

The joint modules are connected to each other and to everyday objects using velcro as it is a widely popular temporary fastener. These strips of velcro are provided on all sides to give users freedom to attach objects at different orientations. To allow the device to have both fixed angle and continuous rotation motions (basic forms of motion by a one degree of freedom electric joint), inserts are used. These inserts are held in place with the help of magnets. The fixed angle insert allows for rotation from -90° to 90°. It snaps into the motor connector and locks the upper and lower halves of the module. The continuous rotation insert allows a wheel like continuous motion. It is attached to the motor connector and provides a large surface area for attaching objects. A snap switch is used to prevent damage to the module in case the fixed angle insert is in place when the joint is being used for continuous rotation. Two LED lights are used to provide the user with visual feedback of the state of the device.

[8]http://www.robotshop.com/en/herkulex-drs-0101-robot-servo.html

4.3 Interactions

With the help of our glove-based controller that provides us with eight analog input values, the constructions are controlled by means of hand gestures. These gestures can be classified as global and construction control.

4.3.1 Global Gestures

Global gestures are valid regardless of the construction made by the user. The global gestures are:

Shake: This gesture is used to start the system. After shaking the hand, the user is expected to keep their hand flat for 100 milli-seconds. This allows the construction to always start from rest and the user to have good control over it.

Closed fist: This gesture is used for an emergency stop. When a closed fist gesture is performed in any orientation of the hand, the system comes to a complete standstill. The shake gesture is then required to restart the system.

4.3.2 Construction Control Gestures

These sets of gestures are used for animating the construction. The general control of each type of construction is divided into the relaxed hand state (close to a flat hand position) where the object is at rest and active hand state where the object performs the motion based on the mapping. The constructions made by the user can be of three main categories:

Articulated: The constructions of these types have fixed angle of rotation motions. They are further sub divided as:

Puppet Shaped Constructions: For controlling this type, the user makes use of the thumb, index and middle finger. This mapping is similar to one of the common hand mapping used for controlling hand puppets [55]. When the user moves his fingers from the rest position, based on his motion, the respective joint modules move.

Robotic Arm: As the index finger is the most decoupled from the rest of the hand, the robot arm is controlled using the index finger and orientation of the hand [56]. Similarly when the user moves his hand and finger from the rest position, the respective joint modules move.

Vehicular: These types of constructions consist of 2, 3 and 4 wheeled robots. The speed is mapped based on the principle of a joystick where the speed is proportional to the angular displacement of the hand from the relaxed (flat) position. The steering mechanism for the vehicle is executed by spinning wheels on the two sides of the car in opposite directions. In these types of construction, the user is given the option of adding the different articulated constructions mentioned above, over the vehicle.

Custom Robots: The previous two categories had predefined mappings for the control technique. This is a category that does not have any fixed mapping, allows the user to explore and experiment with different mapping techniques, and select one which they feel is more natural. The user is given the option of choosing the modules which are being used and their desired motion like fixed angle clock wise (CW), fixed angle counter clock wise (CCW), continuous rotation CW, or continuous rotation CCW. Once they select the modules, they have the option of choosing the hand joint number and mapping the hand joint to the respective joint module. The user has the option of mapping multiple joint modules with the same hand joint. To avoid inconsistency and confusion, the option of mapping multiple hand joints to the same joint module is not available.

As hand joints 1 and 2 allow a 180° angle hand rotation, the joint modules controlled by these joints move from -90° to 90° when in fixed angle mode. Since joints 3 to 8 are finger controlled, the joint modules mapped to them can rotate from 0° to 90° or -90°. When the joint module is in continuous rotation mode, the user can control the speed of the joint module rotation based on the deflection from the relaxed (flat) hand position. Joints 1 and 2 allow bi-directional speed control whereas joints 3 to 8 allow unidirectional speed control.

Once this framework of the tablet interface, glove-based controller, joint modules and the gestures to control the creations was developed, we conducted an evaluation of the kit developed.

4.4 User Study

We conducted a user study to determine the usability of our framework, observe the variety of constructions made by the user, and various control mappings used by them. The participants were explained the framework and given freedom to build and construct on their own. Feedback was obtained from them for evaluating the framework and to obtain suggestions for improvements and possible future directions. This chapter describes the user study procedure and the evaluation of the results obtained from it.

4.4.1 Participants

We recruited nineteen participants by distributing flyers at the university. We had twelve participants who were graduate and undergraduate students aged between 20 to 29 years. Seven participants were school going kids aged between 10 to 15 years of age. The participant's pool consisted of six females and thirteen males; seventeen right handed and two left handed individuals. All participants had no prior experience of using the framework.

4.4.2 Procedure

The user study was conducted in two different ways to understand how time and resources affected the finish of the creations that can be made using the present kit. In both the settings the user went through a learning phase for 10 - 15 mins. In this the user was shown a video of the system in action. He/She was explained the physical structure of the joint modules, tablet interface and gestural control methods

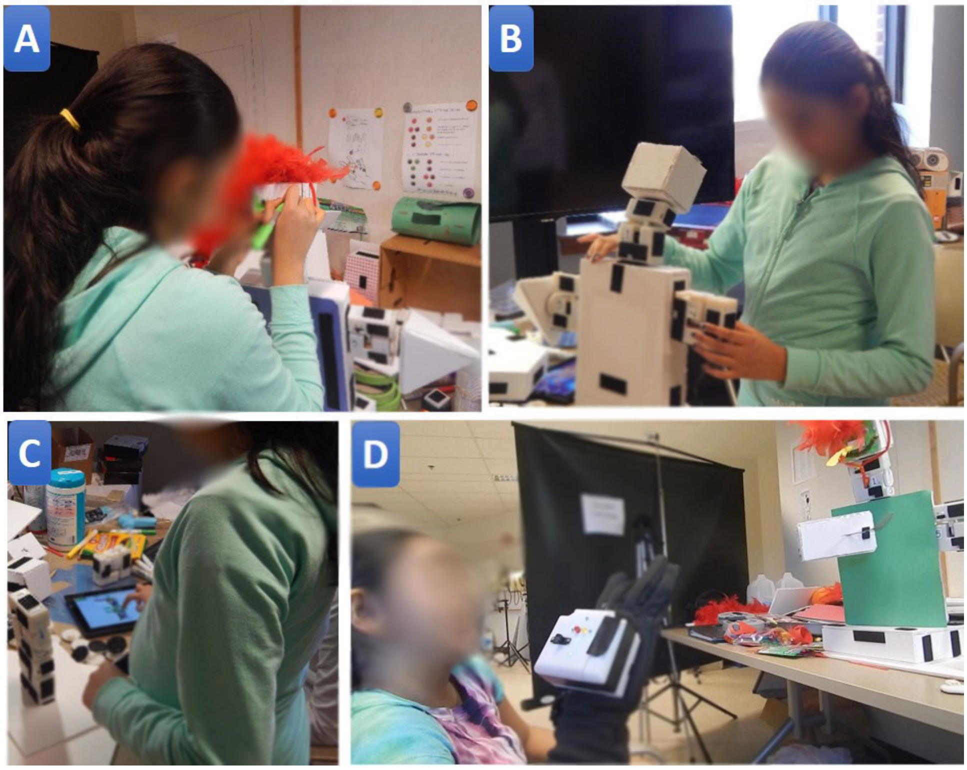


Figure 4.2. Steps Followed During the Study (a) Crafting (b) Assembly Using Joint Modules (c) Setup on the Interface (d) Play.

of the glove-based controller. He/She was then shown some creations (Figure 4.3) made to give them a rough idea of the scale and variety of constructions that can be made using the kit. The user was then asked to make one small robot which was either a two joint robotic hand or a two wheeled vehicle. These were selected because of their simplicity and as they could be made in a short time limit. The participant was then asked to configure and control their construction. This experience gave the user an initial feel of the system.

4.4.3 Setting 1

This study was conducted in a closed environment with the a limited set of raw materials provided. The raw materials consisted of kitchen ware like spoons, fork, and pans, craft material like construction paper, multi-colored thread, colored craft sticks, assorted feather collection, crayons, markers, tape, glue gun, knifes, googly eyes, scissor and foam core board. For quick prototyping, precut basic 2D and 3D shapes of foam core board like rectangles, circles, triangles, hexagon, cubes, rectangular prisms, triangular prisms, etc were also provided. The user was also given the option to cut any specific shape from the raw materials provided. The study with each participant lasted for 60 to 90 minutes. After the initial familiarization with the framework, the participant was asked to build their own desired construction using the raw materials and eight joint modules provided. They were allowed to sketch their idea first and then build in steps, test each step and proceed or directly complete the whole fabrication and play with the system

4.4.4 Setting 2

This study was conducted specifically with one participant from the school of arts. The study was conducted in an open environment where he was made familiar with the kit. He was given a sample joint module for dimensional reference and a period of one week to fabricate his constructions. The participant was given complete freedom to construct using any material desired. After the period of one week he was asked to assemble his construction using the joint modules and to animate them.

4.4.5 Evaluation

After the user study was conducted, the information obtained from it through observations and by a survey were analyzed. This section describes the design motivations, usability, learning though play and the gestural rationale of the system inferred from these informations.

Figure 4.3. Sample Creations Shown to the User for Reference.

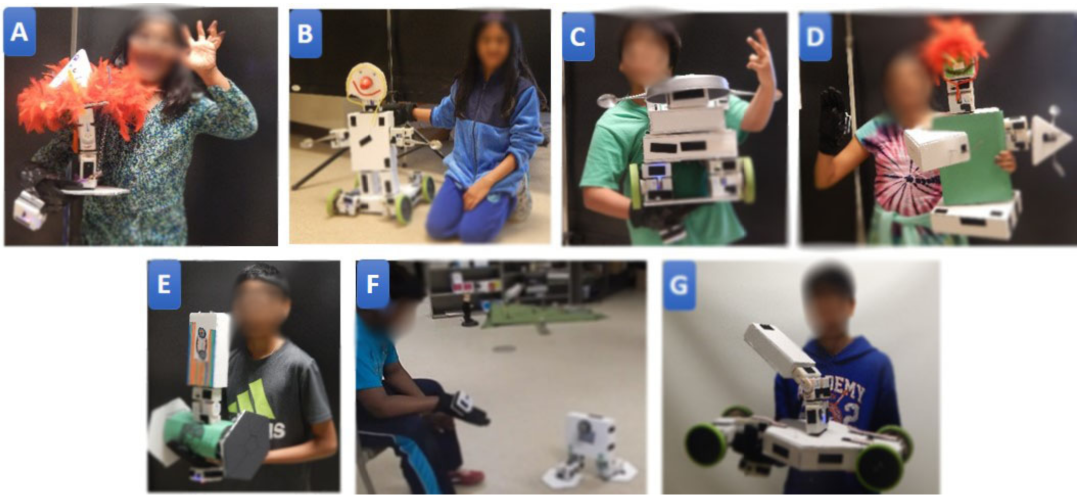


Figure 4.4. Different objects constructed by kids (a) Dance arm awesome (Age 8) (b) Maddie (Age 8) (c) Bat cave moving (Age 8) (d) Pinnochio Hulk (Age 11) (e) Tie Fighter (Age 11) (f) Two legged robot (Age 11) (g) Turner (Age 14).

4.5 Results & Discussions

4.5.1 Design Motivations

We observed that the design motivation of the construction ranged from fantasy to challenge (Figure 4.4, 4.5, 4.6). Most of the kids tried to realize their fantasy by

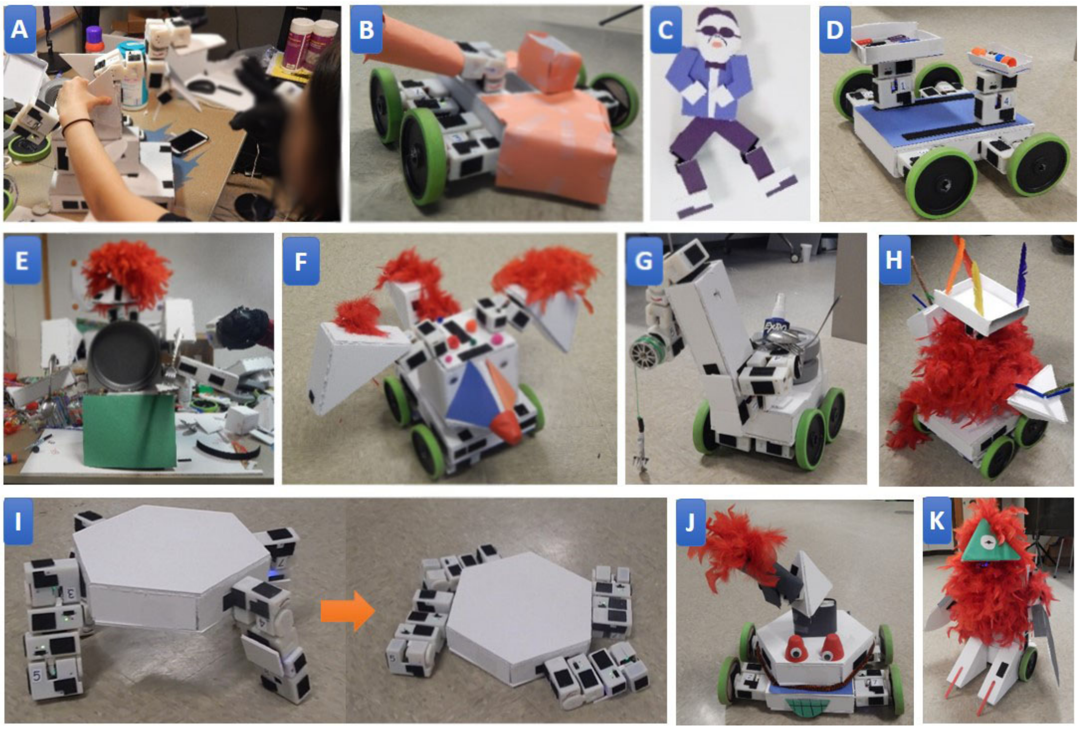


Figure 4.5. Different objects constructed by undergraduate and graduate students (a) Running Chicken (Age 20) (b) Small orange boat (Age 21) (c) Gangnam Style (Age 21) (d) Tooler man (Age 21) (e) Afro-Dog (Age 22) (f) Pup on wheels (Age 22) (g) Spooner bot (Age 27) (h) QuadruBot (Age 26) (i) Preston (Age 28) (j) Indi Robot (Age 28) (k) Anxious bird (Age 29).

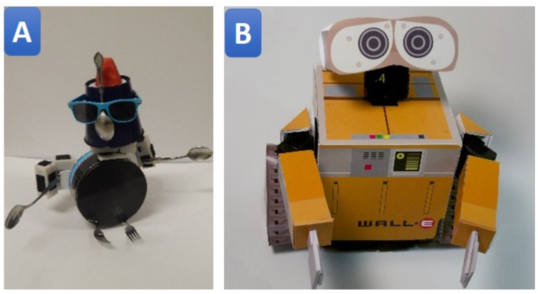


Figure 4.6. Objects made by student of the school of arts (a) Tin Man (b) Wall-E.

constructing popular characters from Star Wars or Disney characters like Pinochio, Tie-fighter, Ella (from the movie Frozen), Batman. Consequently this was reflected in the way they named their creations: Pinnochio Hulk - a green body and face, different color eyes, a feathery head, and fork/spoon hands; Tie Fighter - star-fighters in the Star Wars universe; Bat-cave moving - A Batman inspired vehicle that can produce noise.

In adults we found a mixture of fantasy and goal motivated approach towards construction. These motivations were influenced by:

- *Personal life or current professional work*: A dog motivated by her pet (The pup on wheels), anthropomorphizing a tank (Preston, he shoots red feathers out of his cannon with a constant green smile and a leopard print nose). A student who works with robots tried to create different robotic gaits using the system (QuadruBot).
- *Task Specific*: Cart to enable users to reach objects placed far away (Tooler - man), robot with a crane like mechanism to pick up spoons (SpoonerBot).
- *Creative genre*: Samurai with an insane afro hair style (Afro-Samurai), a native american chief (Indi Robot), a attention grabbing bird that flaps its wings and squawks (Anxious Bird).

This implies that the framework has aspects of play-fullness as it has construction, fantasy and challenge all embedded within it [57].

Some key comments made during the user study were *"It was good to see my design come to life", "Combination of craft and science is awesome", "It is interesting to see how my craft design is implemented quickly for various motions", "I felt accomplished that I created something original".* We thus conclusively demonstrated that the framework allows people to realize their design goals and control them successfully.

Sr. No.	Questions	Mean	SD
1	I think that I would like to use this kit frequently	4.29	0.85
2	I found the kit unnecessarily complex	1.88	0.78
3	I thought the kit was easy to use	4.47	0.51
4	I think that I would need support of a technical person to be able to use this kit	1.76	0.75
5	I found the various components in this kit were well integrated	4.12	0.86
6	I thought there was too much inconsistency in this kit (The object did not work the way I wanted)	1.59	0.62
7	I would imagine that most people would learn to use this kit very quickly	4.47	0.62
8	I found the kit very cumbersome to use	1.65	0.79
9	I felt very confident using the kit	4.35	0.70
10	I needed to learn a lot of things before I could get going with this kit	2.47	1.59

Figure 4.7. Questions in the System Usability Scale.

4.5.2 Usability

The pool of our adult participants had a range of expertise in using electronics and micro-controllers. Seven people had rudimentary knowledge whereas five people had extensively worked with them. We observed that all these participants were able to realize their design goals irrespective of this knowledge constraint. Since the kit involved crafting, building and robotics the kit attracted people of both the gender.

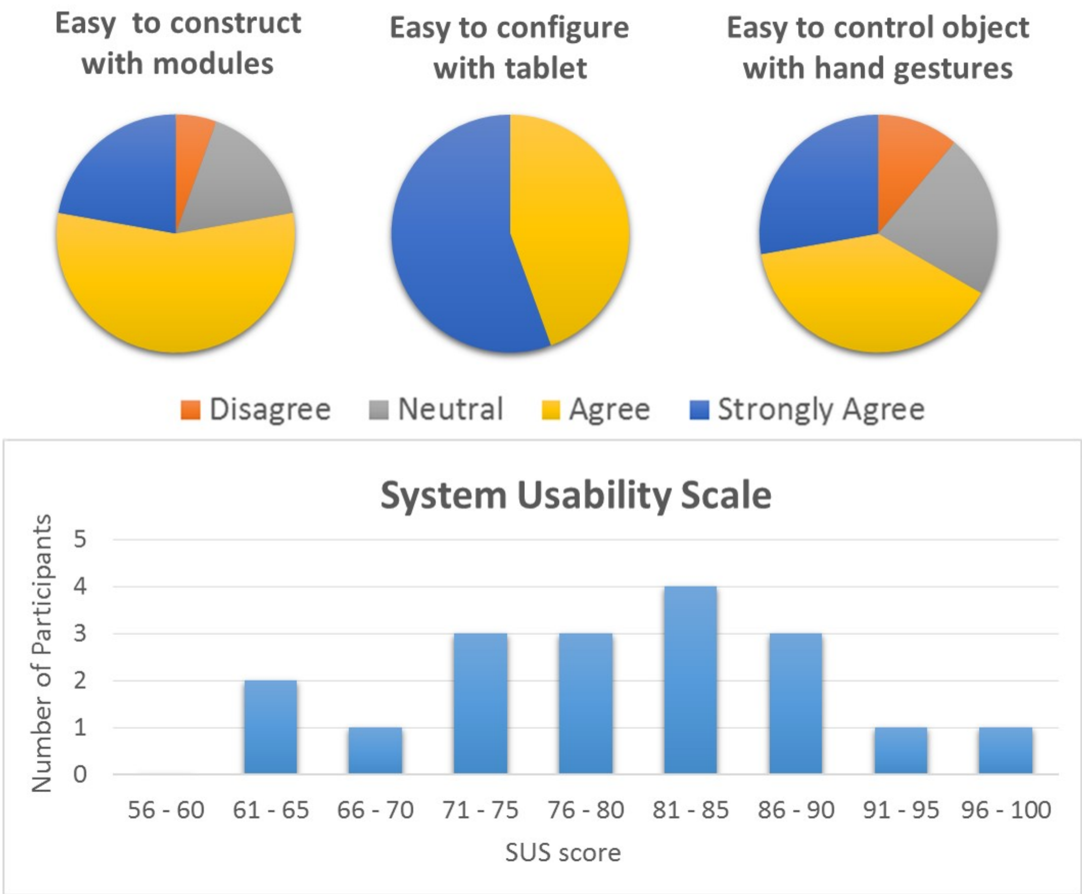


Figure 4.8. Results of the survey.

Even children of ages 8 and above were extremely excited about animating the object as they felt amazed when they built something and brought it to life without implementing any electronic circuits. Thus both adults and kids were successfully able to make creations using the kit. We did observe that kids of ages 8 to 11 needed some guidance during the assembly process.

We also observed that the student from the school of arts was able to create a variety of constructions and animate it using the framework. Thus we observed that when the participant was given more freedom of material and time he could create more artistic and well finished constructions.

The post study questionnaire consisted of a survey based on the system usability scale [58] (SUS) and few questions specific to the system. The ten questions in the system usability scale which are rated on the Likert scale are shown in Figure 4.7 along with the mean and standard deviation of the response for each question. For the survey conducted with kids, few terms of the system usability scale were changed to simpler words like the word *'system'* was replaced by the word *'toy kit'*. For kids the average SUS score was 84.3 (SD - 4.94) and for adults it was 77.1 (SD - 11.11) giving an overall value of 79.9 (Figure 4.8). Based on the responses in the survey we believe this discrepancy in the value was due to the expectations of these different demographics. While kids were excited about the fact that the creation they made moved, adults expected better and precise control of the movements. Similarly adults felt they had to learn very few things to use the kit where as younger kids (8-10 years) felt they had to learn a lot of things ot use the kit. Figure 4.8 also shows the distribution of the responses, on a Likert scale, of all the participants for specific questions about the ease of use of the system.

Thus the kit was used successfully by the user's irrespective of their age, sex or technical expertise.

4.5.3 Learning by Doing

During the study we observed that users made multiple design and control mapping iterations by prototyping and testing within a short duration of 45 minutes.

One 14 year old participant desired to make a robot mounted on a car using the system. Initially he made a two wheeled car as a prototype. On controlling the car he observed that the car was not stable (system had no mechanism to prevent flipping of the body). He thus made an anti-rotation structure to constrain the flipping action. To further stabilize the car in order to attach a robot he changed the car design to a 4 wheeled car. While testing this 4 wheeled vehicular system, he was not satisfied with its default turning mechanism as the turning was not smooth because of the wheel skidding. He brainstormed to derive a method for a better turning mechanism by improving the design of his robot. He realized that by adding another module he could solve the problem. Hence he attached a module in between the body and the front axle of the vehicle that could control the angle of rotation of the axle like a steering mechanism. He tested the vehicle and was successful in efficiently maneuvering it. However when he attached the robotic arm to the main body of the vehicle he observed that the velcro in the single joint module link connecting the two bodies failed due to the overall weight of the system. He then reinforced the system using more strips of velcro. Thus he was able to learn basic engineering concepts of anti-rotation, robot steering mechanisms and structural stability.

Another 11 year old participant wanted to make a robot with legs. For this he constructed a system with 4 joint modules. While testing the motion he realized that for the robot to remain stable it was necessary for the two planes of contact with the ground to remain parallel. By different trial and error processes he configured the mapping to do so. On testing the system on the ground he observed that the robot always fell on its back. He thus realized that the weight distribution on the robot was not balanced and attached a wheel as a counter weight to prevent the robot from falling back. This made the robot to squat only when he controlled the movement by slowly moving his hand. But on moving the robot at a high speed he observed that the robot fell erratically. He thus realized that the stability of the robot needed to be increased and he managed that by putting bigger base structures at the legs of the robot. In this manner, he learnt about the significance of center of mass and dynamic stability of a system.

This process of designing by iterative prototyping was also observed in the user study with adults. As the system allowed independent and complete control of each joint module, many of the participants divided their overall design goal into many different steps of building and testing. One of the participant decided to take on the challenge to design a movable robot to pick up spoons using a crane mechanism. He used the rim of one of the wheels as a pulley, the wires we had provided as rope and magnets in a pen cap as the hook. He initially tested his 3 joint crane mechanism on a base and attached appropriate counter weights to balance the cantilever structure. To firmly attach the crane to the base he also made L-brackets out of foam core and attached it to the base joint (Figure 4.5(g)).

Such cases reflect constructionism experienced by kids and adults in the process of reaching their goals [59]. Children and adults identified the functional issues in their systems and developed design solutions to overcome them by iterative steps of building and testing.

4.5.4 Gestural Rationales for Animating Objects

During the study, the use of gestures was appreciated by the users, *"Felt excited that movement of my hand was controlling the object"* , *"I like the natural and easy-to-use interaction using gestures"*.

The study also provided us with insights into how various aged participants selected appropriate gestures for controlling their constructions. We recorded data on how people mapped finger actions to animate joints on their constructed system. Here we saw that participants preferred to map the PIP (Proximal Interphalangeal) joints for control when they had attached a single moving structure to the base-structure whereas they mapped the MP (Metacarpophalangeal) and PIP joints when they desired a synchronous motion of two structures connected to a common base. Based on usage we observed that many of the participants mapped the important motions of their construction to the index finger. This inclination towards the use of the index finger corresponds with other studies [56].

5. EVALUATING THE GENDER NEUTRALITY

Building from our previous work in the above mentioned sections, this chapter discusses the results from two user studies which were designed to understand the affinity of *HandiMate* among children. The first study reveals that children rated the HandiMate kit as gender-neutral, appealing equally to both female and male students. The second study discusses the benefits of engaging children in engineering design with HandiMate, which has been observed to bring out children's tacit physics-based engineering knowledge and facilitate learning. This chapter evaluates the attributes that can be provided by the crafted objects in a modular robotic kit. Eventually we intend to understand the usability such systems have with respect to the user.

HandiMate aims to be both gender-neutral while also encouraging physics-based engineering play. The kit provides a construction platform which merges robotics with narrative play and crafting. This approach enables gender neutrality by emphasizing a broader range of play activities that are more open to divergent design possibilities. The kit itself is made up of 8 joint modules, where each joint module is packaged with an actuator, a wireless communication device and a micro-controller. This modularization makes quick electro-mechanical prototyping, a matter of pressing together Velcro. Animating these constructions is made intuitive and engaging by a glove-based gestural controller. We demonstrate that *HandiMate* attracts both genders to participate more extensively and equally. We discuss the technical implementation of the kit and the studies conducted to asses the compatibility among genders. We designed our studies to observe learning of broader engineering concepts among children. As a part of understanding the impact of this kit, we sought to conduct studies which were designed to answer the following research questions:

- Does changing the tools and the material, to craft the toys, affect the gender perception of the robotic kit?

- To what extent do children as the designer engage in general engineering concepts with *HandiMate*?

For this we conducted two studies among a total of 53 children over a span of two months. The first enrolled 32 children to better understand how youth perceived the gender of this toolkit and how they situate it among other toolkits. The second engaged 21 children in playing with *HandiMate* and conducted interviews to understand their design processes with learning outcomes. Apart from the above mentioned goals, this paper also contributes towards the design and implementation of a new animatornics kit, which enables users to craft and animate the toys.

5.1 Evaluation with Children

Children lately have been exposed to complex modular robotic kits like Lego Mindstroms and Vex Robotics. In general, robotics has been known to attract disproportionate numbers of boys. *HandiMate* aims for broadening of participation from both the genders. We designed our studies to understand how can crafting, when coupled with modular robotics, attract both the sexes. Also how this kit via its construction exercise, will leverage creativity and help develop intuitions for engineering concepts among children. We conduct two such studies for this purpose. The first study evaluates a comparison of *HandiMate* with other commercial robotic kits. Quantitative data was collected from these sorting tasks. The second study had qualitative interviews which were held after a 90 minute session with the kit.

5.1.1 Gender Appropriateness Study

The goal of proposed study is to evaluate the gender perception of *HandiMate* by children as well as how this kit compares to others on the existing market. We modified the gender sorting methods of Campenni and Raag [60, 61]. Instead of using surveys, we showed users actual components and kits to make their decisions. Throughout the study, we could observe impacts of components on gender perception

Kit	Included Materials	Image	Gender Hypothesis
GestBot	Cardboard, Craft Materials, Velcro, Joint Module, Glove		Neutral
VEX Clawbot	Steel Chassis, Gear Sets, Shaft, Screws, Bearings, Motors, Remote Joystick		Masculine
LEGO Mindstorms EV3	Lego Blocks, LEGO Servo Motors, Remote Control		Masculine

Figure 5.1. Summary of the selected engineering kits.

Figure 5.2. Summary of selected components shown in most masculine (left) to most feminine (right) order based on gender sorting rating task. Selected components include (a) Lego blocks, (b) Wheels, (c) Electrical components such as battery, breakout board (d) Velcro, (e) Cardboard, (f) Textile kit, and (g) Craft kit.

of kits. In order to empirically study the gender appropriateness, we gathered users with various ages and genders.

Participants: The user study took place at a local Boys and Girls Club. A total of 32 children of ages between 6-15 years participated in the user study. The children were involved in the study during their extra-curricular hours. We randomly picked a single user from play area to conduct the study. Among 32 children, 15 were girls (μ_{age}=9.29) and 17 were boys (μ_{age}=9.47).

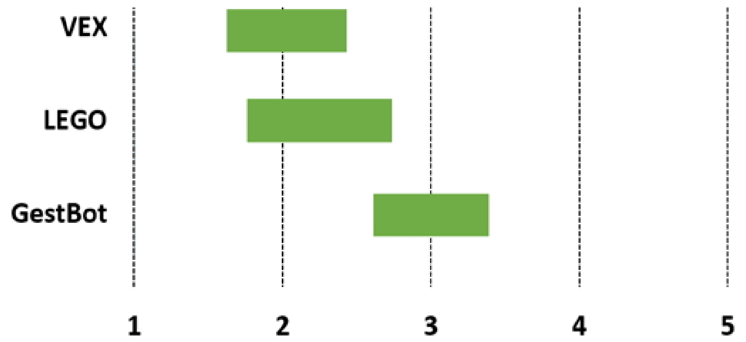
Materials and Procedure: We prepared three exemplary construction kits including *HandiMate* and seven component groups for the sorting task. A total of 10 examples were placed in transparent baggies to explicitly show contents and to limit play. Figure 5.1 and 5.2 illustrate what have been shown during the study.

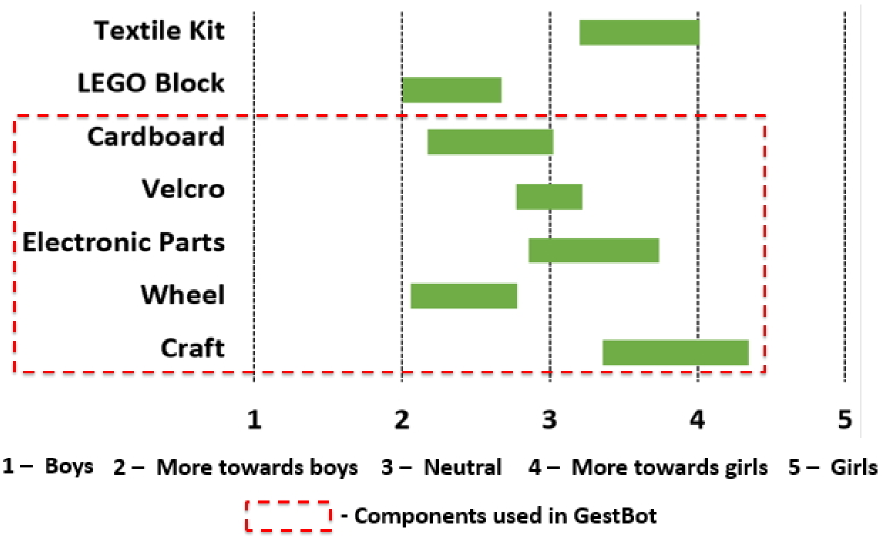
The gender sorting task began with five clear plastic bins, identified with a labeled sticky note. The bin on the far left was labeled "boys", the bin on the far right was labeled "girls", and the bin in the middle was labeled "both boys and girls" (Figure 5.1). We explained the contents of each baggie and allowed participants to explore them. They were asked whether the material or kit in question seemed to be more appealing to boys, girls, both equally, or somewhere in between. Then, they placed baggies in the bin of their choice and researchers moved on to next baggies for same purpose.

5.1.2 Results

Based on five level Likert-like scaled data, we conducted two post-hoc analysis: Bonferroni post-hoc analysis with one-way analysis of variance (ANOVA) and two-way ANOVA. Bonferroni method was adopted to reduce errors during multiple comparisons. One-way ANOVA showed that the gender perception among different kits ($F_{(2,93)}$=11.46, $p<0.05$) and components ($F_{(6,210)}$=17.22, $p<0.05$) were significant. A Bonferroni showed that VEX (μ=2.05, SD=0.83) and LEGO Mindstorm (μ=2.25, SD=0.98) showed similar (masculine) perception ($p>0.05$), the *HandiMate* exhibited a different (neutral) perception (μ=3.03, SD=0.78, $p<0.05$). Components sorting results dissected into three groups based on their perception: masculine (Wheel, Electronic parts & LEGO block), feminine (Craft material & Textile kit), and neutral (Velcro & Cardboard). With these results, we present interesting findings on the relationship among gender, kit, and the components.

By combining crafting and construction activities and not having a predefined form or structure to both the toy or play pattern, we expected to see a neutral gender





Gender	GestBot	LEGO Mindstorm	VEX	Average
Male	2.76 (0.75)	2.47 (1.07)	2.03 (0.87)	2.42
Female	3.42 (0.79)	1.75 (0.75)	2 (0.85)	2.39

Figure 5.3. Gender sorting result for different kits (Top) and components (Middle). Gender sorting result for each gender (Bottom).

perception on *Gestbot*. Figure 5.3 clearly illustrates the result as expected. To verify the effect of merging different activities, we looked into evaluations of individual components. In *HandiMate*, the following items were utilized as components: Craft material (μ=3.81), wheel (μ=2.44), electronic part (μ=2.61), Velcro (μ=3.00), and

Cardboard (μ=3.32). The average rating of these materials came out to be 3.04 which aligned with an overall kit rating. This implies that merging feminine (crafting) and masculine (constructing) activities neutralized the perception of a whole kit.

We performed a two-way ANOVA on different genders and kits to make sure whether one-way ANOVA result fairly represents overall genders' opinion. Although there was no significant difference on each gender's view on all kits, we observed that participants exhibit significant difference ($F_{(1,56)}$=4.49, $p<0.05$) on the gender perception between *Gestbot* (μ_{female}=3.42, μ_{male}=2.77) and LEGO Mindstorm (μ_{female}=1.75, μ_{male}=2.47). A gender rating on LEGO Mindstorm was more towards "boys". In figure 5.3, we observed that girls expressed LEGO Mindstorm as a kit for boys whereas boys rated it more towards for both boys and girls. The user interview contexts supported these rating trends. More than half of girls mentioned "LEGO is for boys, not for us" and some girls said "I like crafting more than constructing". Boys mostly said that "everyone likes LEGO". Moreover, component evaluation on LEGO Block showed the lowest ratings (most masculine) among all other components. Another interesting finding was that both male and female participants expressed *HandiMate* as a kit for their own genders. This indicates that the proposed kit lowers a gender barrier which was not observed in LEGO Mindstorm or VEX. Findings from this study indicates that the engineering learning study should not be biased by different genders and sets the stage for more equitable participation. They all exhibit similar level of interest towards *HandiMate* and hence are equally motivated to create their toys.

5.1.3 Engineering Learning Study

We also explore *HandiMate*, as an engineering learning platform for children where they are encouraged to apply tacit engineering understanding to construct dynamic structures. The learning is made possible by the ability to iterate with craft materials to assemble and fabricate their toy via the eight joint modules. Due to the open-ended nature of using the craft material as the building blocks, we observed a broad span of engineering concepts in-herently implemented by them. This study was structured towards a systematic artifacts analysis method to build a coding scheme for relating mechanical engineering constructs to childhood play. This resulted in the hierarchical chart of mechanical engineering taxonomies (Figure 5.5). Units of analysis were the final artifacts in the context of the workshop, created by the single user. The artifacts were examined and coded using the key mechanical engineering concepts from Dynamics, Mechanics, Materials, and Design.

Participants: During our second study, users showed a similar level of motivation for playing with *HandiMate*. This unbiased perception ensured us to conducted a follow-up study on children's learning behavior. We recruited 21 children from ages between 8-13 years, by distributing user study fliers in libraries and community centers. Out of the 21 children, 12 were girls and 9 were boys. A compensation for participation included 10 dollars and the option to take home the crafted structures without the joint modules.

Materials and Procedure: This study was conducted in a closed environment where each participant worked with a researcher in one session at a time. We provided raw materials such as spoons, fork, and pans, craft material like cardboard, matboard, construction paper, multi-colored thread, colored craft sticks, assorted feather collection, crayons, markers, tape, glue gun, knifes, googly eyes, scissor and foam core board to work with. For quick prototyping, precut basic 2D and 3D shapes of foam core board like rectangles, circles, triangles, hexagon, cubes, rectangular prisms, and triangular prisms were also provided. The user was also given the option to cut any specific shape from the raw materials provided. Before starting the study, a pre-task interview was conducted where we asked questions regarding their school curriculum to probe their understanding of engineering concepts. These questions were designed with reference to the current state school curriculum [62].

The study with each participant lasted for 60 to 90 minutes. The participant was initially made aware of the *HandiMate* framework. We explained to the participant the physical structure of the joint modules, tablet interface and gestural control methods of the glove-based controller. The participant was then asked to build their own desired construction using the raw materials and eight joint modules provided. They were allowed to sketch their idea first and then build in steps, test each step and proceed or directly complete the whole fabrication and play with the system. The researchers observed the design iterations while they were constructing the toy. Later the participants were interviewed on their design decisions for the toy. These interview questions were open-ended to elicit maximum input from the children. The interview script consisted of questions like "What did you try to build here?", "We observed that while making the toy, you changed this. Why did you change that?", "What will you do to make the toy work better?" and "What did you learn here today, that you will apply while you construct your own toy/robot later?". During the study, researchers carefully monitored word choice to avoid influencing the children's vocabulary. A primary coder with advanced engineering training, coded the transcripts of audio interviews and videotaped observations, noting if any of the targeted engineering concepts was present in the data. Each of these cases was compiled and further analyzed for the purposes of this study.

5.1.4 Results

The results of this second study indicated that boys and girls tended to engage in a different design process with the kit. Universally, all 12 girls enjoyed and came up with interesting crafted toys, dividing their alloted time in three activities : designing, fabricating and decorating the toy. Whereas the boys were very task oriented and wanted to build more functional prototypes. We also noticed that boys would iterate over their toys more, to make the robot perform their intended task more efficiently. However, despite these differences in the goals and process of activity, both the genders explored engineering concepts while constructing their toy in their own manner.

The major domains of knowledge explored by the participants:

Gender	Age	Toy Made	Engineering Concept Explored
Female	9	4 Wheeled Car	Stability Material Vehicle Dynamics
Female	9	4 Wheeled Car with a moving arm	Stability Center of Mass Vehicle Dynamics
Female	11	Yoga man	Stability Center of Mass Friction
Male	11	Car with a bumper	Stability Vehicle Dynamics
Female	10	Puppet	Stability Center of mass
Female	10	Legged Robot	Stability Material
Male	8	Car with windmill	Stability Center of Mass Friction

Figure 5.4. Examples of engineering concept explored by children during user study.

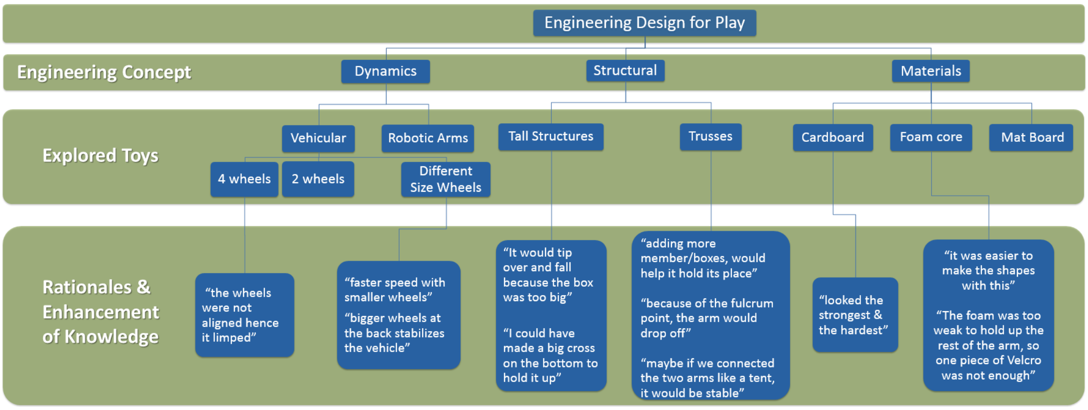


Figure 5.5. Exploring Engineering Design for play (a) Engineering Concepts - The broad classification of concepts implemented by children in their toys. (b) Explored Toys - The various types of toys fabricated by the children. (c) Rationales and Enhancement of Knowledge - Quotes from studies on understanding the failure mode in the process of iterative design to find out solutions.

Materials: From an engineering point, material selection is based on the functionality of the component. Engineers make calculated decisions on what material to use, so that the component as well as the assembly does not fail. Since for the process of crafting, the children were given a lot of materials to construct their toys with. We observed some intuition in them for selecting material based on strength, by the end of the study. While some used cardboard as they defined it was “more flexible” than other materials, other learned that Styrofoam shells are flimsy material for the purpose of a dynamic system. Most of them opted to use Velcro over other temporary fasteners like duct-tape, hot-glue gun as they felt Velcro was “stronger” than others.

Center Of Mass: For dynamic structures the center of mass is a key design factor. The stability of the system, in dynamic conditions, is heavily influenced by the position of the center of mass for that structure. We observed young participants implementing design changes to alter the center of mass of their toy. An 11 year old girl made a “Yoga-Man” toy, where she would constantly iterate her design as it would fail. She finally resorted on shortening the height of the toy and adding wheels at the bottom. In her interview she justified this decision by saying “Because it was heavy and big on the top, and there is gravity. So big objects, if they are heavy, are hard to stand up.”Similarly, we also observed some students shortening the height of their crafted toy so that it could perform a task with stability. On asking, they would say that their toy would “fall off” so they made it short as an improvisation.

Friction: The materials used by the participants were crafted boxes and structures. This lead to rather flimsy designs. Many a time, while the toy was in motion, the components would interact with each or with ground to create friction hindrances. This was observed by a large group of participants and they worked their way out to reduce these frictional losses.

Stability of the Structure: In engineering context, ”Structures” is an application oriented field of study which explores design of trusses and machine. During our study, we observed a lot of examples where participants showcased intuition towards making the static structure stable. A 9 year old girl, who wanted to make a robotic arm on top of a 4 wheeled toy, ended up designing a triangular truss member in the middle to make the system stable. “So there would be some weight in the middle and some on the side, and if it wanted to tip over, it would be balanced on the other side and would not fall as easily.” Another 11 year old male, made a similar toy of a robot arm on top of a wheeled toy. The arm would keep hitting the body of robot and would fall off. He recognized the problem: “ I think so that the point where it was hedging off was responsible for it. It hits there and it has enough momentum to break off and keep on falling.” He successfully understood the concept of fulcrum by seeing it in action and improvised his design by making the arm offset from the body. The common solution implemented by children was to make the base of the structure bigger and wider. This gave them more stability to their dynamic toy. Some of them even added more weight to the bottom structure of the toy, so that it stays more firmly on the ground.

Dynamics: The participants made various types of toys which had 2, 3 and 4 wheels. While constructing the toy, they would fail and improvise their designs. Motivated by the popular concept of ‘Hot-Rods’ one 9 year old girl, used different sets of wheel for the front and the back. In the interview she said “The back wheels should be bigger because they are heavier so they put more weight on the front wheels, it would go faster.” Another 9 year old female, made a wheeled toy that was limping, when it moved forward. She then improved the wheel alignment so that the wheels aligned in the same axis of rotation. On asking why she did that, she replied “It goes slower, because if the wheels are not straight, it’s not going straight”. There were some intuitive solutions for wheel selection like “bigger wheels will lift up the middle”. An 8 year old boy, changed from making a 4 wheeled toy to 2 wheels. In the interview he replied “ when I test drove it, it was slow and everything was breaking so I thought about a 2 wheeler.....it is lighter than a 4 wheeler. So less weight there is, it would go faster.”

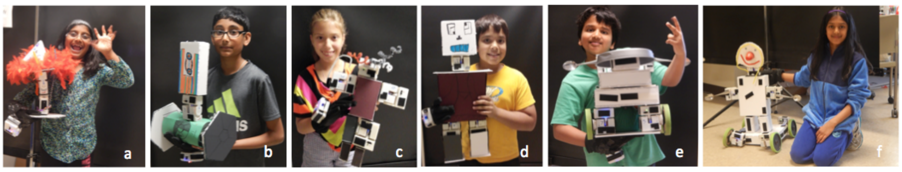


Figure 5.6. Display of tacit concept via toys : (a) & (b) Stability of Structure (c) & (d) Center of Mass (e) & (f) Dynamics.

5.1.5 Engagement

HandiMate also provided motivational benefits to the child, as they had a sense of autonomy over the creation of the toy. When the child wanted to realize his/her toy, he/she would put their best effort to make it as close to their imagination as they can. Since they are using craft material, they had to fabricate every detail from their imagination. Some children wanted to fabricate toys from popular fantasy stories like "Dobby from Harry Potter" or "a Pirate Captain". They define their own tasks and thus are engaged to bring their creation to life . The added advantage of controlling the toy via a glove made a alot of children excited. They felt it was "very cool" to operate the toy with the glove via hand and finger movements. We also noted that, because of the glove the child was more dynamically involved with the toy, as they were immersed in controlling the toy via their hand. It was interesting to note, that while controlling the toy with the glove, they would not look at the hand for gestures. Rather they were constantly watching the toy's motion and controlling it seamlessly with the hand motions. They thus exhibited a very good case for proprioceptive control. This may suggest that the glove, because of it proprioceptive abilities, is an ergonomic controller. The glove also contributed to the emotional responses exhibited by the children.

Emotional Responses: We did not carry any designed experiment to record their emotional response while building and playing with their toy, but we made observations on their reactions (Figure 5.7). Their fabricated toy was a realization of their imagination, be it an anthropomorphic character or a wheeled super-vehicle. So

Figure 5.7. Emotional Response and Engagement: The child becomes excited and amazed to see their fabricated toy come to life. They also control the toy purely on the proprioceptive abilities of the glove.

when they controlled the toy, they were very excited to see the toy come to life. They responded emotionally by excitement and surprise. Some children were completely engrossed in crafting the details of the toy, while building it. This eventually built up their curiosity to see their toy in action. During fabrication, they were emotionally attached to the toy and many of the children ended up taking the crafted components home. “I will give it to my teacher”, replied an 8 year old girl who made a doll. This seemed to indicate the glove’s importance in the designs.

5.1.6 Designing for Play

The study involved the children to first sketch their toys on a paper and then fabricate it. The freedom provided to fabricate primitives from materials made them iterate their design, when a prototype failed. This design process of actively constructing the toy develops deeper understanding of the engineering concept, based on their design iteration experiences [63]. Later after the study, we would ask them “If you were to make this same toy 2 years from now again, what will you change in your drawing? How will you make it better?". They would then acknowledge the mode of failure in their existing design. They suggested on thinking about the failure mode at the sketching phase, the next time they made a similar toy. They were able to showcase learning of engineering concepts via designing and fabricating their toy. Through the iterative design process they enhanced their knowledge towards physics based engineering concepts (Figure 5.5).

5.2 Discussion

The results of the gender sorting task revealed that merging constructing and crafting activities increases interest from both the genders. As proven in our gender appropriateness study, each gender favors *HandiMate* as toy for themselves, where the children can be actively involved in playing with the kit. Margolis [64] mentioned that toys will affect student's comfort, confidence, and willingness to enter engineering educational programs. Unlike previous robotic kits where major users were male students, introducing craft-based activities into such kits can attract more girls to be active users. The platform designed with both feminine and masculine activities can shorten the gender gap in the Science, Technology, Engineering, and Math (STEM) learning field.

The gender perception study with components showed that traditional primitive blocks (such as LEGO , Vex) tend to exhibit masculine perception due to naturally embedded activity like construction. Current robotic kits using these primitive blocks might cause girls to think of it as toy for boys, not for them. The issues of gender imbalance in toy kits has been highlighted in recent articles [65, 66]. Utilizing various materials to fabricate those primitive blocks supports creativity through craft activities among children. Such kits that support an open-ended design environment, leads children to explore broad engineering concepts such as material selection and stability of structures. It was evident that both genders benefited from using such kit, where girls were equally engaged as much as the boys.

While designing and fabricating the toy, we observed that children change their understanding of engineering concepts. In early design stages, they did not expect and understand the behavior of their toy in the first trial of testing their toy. This notion of accommodating the external modal into their mental modal, supports the constructivist theory championed by Piaget [52]. At the same time these iterative activities enhances the child's conceptual understanding. Throughout the redesigning process, children could embed several engineering concepts to their toy such as, adding a fixture to improve the stability. We observed tacit knowledge being put to use such as "it would drag the other end and it would not be able to move", where the children enhanced their understanding of friction from the playing experience with *HandiMate*. This use of tacit knowledge implies that educational kits that introduces the iterative design processes can enhance the learning in children.

Studies with *HandiMate* encouraged participants to be involved in further robotic workshops. To better understand, we surveyed briefly after each study if users would like to take part in further engineering learning activities and whether they were engaged in constructing the toy given their previous robotic experiences. 85% of participants mentioned that they will opt in for such future workshops after the *Gestbot* user study. Engagement was higher in subjects with prior robotics experiences by 21% than participants without experience. These results indicate that children's first exposure to a robotic workshop is a basis to form their involvement and willingness in further workshops. Thereby suggesting that educational toys can encourage broad participation especially for girls towards STEM learning by introducing gender-neutral activities.

5.3 Conclusions

Recent modular robotic kits attract predominately boys. But by introducing crafting into these kits, our research demonstrated that such kits attracted both the genders of children. *HandiMate* encourages girls and boys to fabricate the primitive blocks for their toy from craft materials. Because of the open-endedness of the primitives and imaginations to build from, it encourages a broad participation among children. Such ideas of merging construction with craft activities can effectively channelize and further help increase female participation in the STEM learning activities.

We also studied the constructive learning using this kit. In our study with 21 children, we observed iterative design process of the users. The iterations resulted in a conceptual change and better understanding of how things work. The ability to embed ones own design ideas and iterate on aspects of it in an open play environment, leads to broad engineering learning in children such as stability of materials, center of mass, structures, friction, and dynamics. By incorporating such open-ended gender-neutral design environments, next generation education tools may help scaffold more students to learn STEM fields.

6. GESTURE DEFINITIONS

In this chapter, we investigate the use of a gesture user interface by children for controlling robots made from a modular robotic toy kit. To this end, we conducted gesture elicitation studies to suggest embodied hand gestures for invoking motion among user developed robots. We elicit gestures from 23 children, first by portraying the 'effect'(motion from the toy) and then asking the user to perform it's 'cause' (reading gestures by a wearable glove). A total of 276 gestures for controlling 4 referent toys were collected, analyzed and reported. The gesture data, calculated by a kinematic hand model, was analyzed using a visual analytics approach integrating an interactive clustering and visualization technique.. Our findings suggest designs preferences of generic gestures for controlling toys like puppet, robotic arm etc. The results also imply that the sustained period of a gesture pose is about 30 seconds and give us insights into higher level classification of gestures mapped to the motion, topology and logical action based on motion of the toy. We also found that children would prefer using whole body interactions for big robots as compared to using hand gestures for lap-sized robots. We further discuss these design implications which helps designers design gesture systems for modular robotic kits.

6.1 Sensing Glove and the Hand Model

To perform data-driven analysis of hand gestures, we designed a computational hand model in conjunction with newly designed glove. In this hand model, each finger joint is defined by the PIP joint angle values and wrist orientation angles. Then, we calculate the co-ordinate points of all the joints relative to the wrist. This method is inspired by the inverse kinematic model implemented by Kim [67]. The model made the system robust, as the dependencies reduced from 10 to 5 sensors.

We re-distributed the electronics in the glove to make it more stable in dynamic conditions. 2.2 inch bend sensors were laid on the PIP joints of each fingers. These bend sensors output an analog value in the range of 350 to 520 as we used a 22k ohm resistor. These values were chosen for headrooms for a hand that flexes or extends beyond the typical hand. As piezo electric material have a polynomial relation with output voltages, we modified Kessler's model [68] to convert the bend sensor's voltage values to joint angles. To make the electronics more organized, the bend sensors were connected to the micro-controller (ATMEGA 328) via an analog multiplexer (CD74HC4067). Finally the orientation of the wrist was calculated using an IMU (MPU 6050) device. The glove with the thin algorithm would ouput seven angle values - five fingers and two from the wrist.

Kinematic Hand Model: Once we collect the angle values of the PIP joints from the glove, we calculate the co-ordinates of the 15 joints using a forward kinematic model (Figure 6.1). As Kim [67] suggested that the three finger bones - proximal, middle, and distal phalanges do not entirely move independently. The 1 dof joints which connects them, therefore has a mathematical relation established amongst themselves. The joints are called the distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint, and a 2DoF spherical joint called the metacarpophalangeal (MCP) joint. The relation between PIP and DIP is 1.176 and 1.851 for PIP to MCP respectively. We use predefined values of l_0, l_1 and l_2 which are the average length of the finger bones [69]. We derive equation set based on the above mentioned relations between the angles via 2D geometrical analysis methods, which gives us the y and z co-ordinates of the joints in the finger B, C and D (Figure 6.1). We then develop relations between x and y for each finger by a first order regression mathematical model. We use the IMU values to calculate the orientation of the wrist and use rotation matrix to develop the pose of the hand with respect to the wrist. Please refer to the Appendix for details.

$$B = [x, \underbrace{(P_0 + l_0 \cos(0.54\theta_p))}_{y}, \underbrace{(l_0 \sin(0.54\theta_p))}_{z}]$$

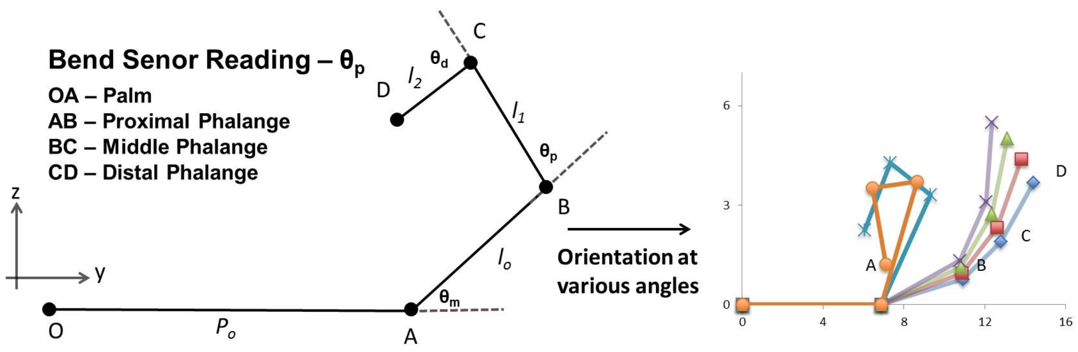


Figure 6.1. Hand model in the y-z plane followed by graphical representation of the index finger based on PIP joints (20 - 120 degrees).

$$
\begin{aligned}
C = [x, &\overbrace{(P_0 + l_0\cos(0.54\theta_p) + l_1\cos(1.54\theta_p))}^{y},\\
&\underbrace{(l_1\sin(1.54\theta_p) + l_0\sin(0.54\theta_p))}_{z}]\\
D = [x, &\overbrace{(P_0 + l_0\cos(0.54\theta_p) + l_1\cos(1.54\theta_p) - l_2\sin(270 - 2.38\theta_p))}^{y},\\
&\underbrace{(l_1\sin(1.54\theta_p) + l_0\sin(0.54\theta_p) - l_2\cos(270 - 2.38\theta_p))}_{z}]
\end{aligned}
\tag{6.1}
$$

$$
\begin{aligned}
IndexFinger &: x = 0.2961y + 0.2794\\
MiddleFinger &: x = 0.0843y + 0.0891\\
RingFinger &: x = -0.1159y + 0.0182\\
PinkyFinger &: x = -0.4499y + 0.1213\\
Thumb &: x = 1.3028y + 0.3225
\end{aligned}
\tag{6.2}
$$

These set of Equations 1 are able to provide us with the *ordinate* (y) and *applicate* (z) of the joints B, C and D in the y - z plane. Since the fingers have a similar anatomy, it is reasonable to assume that these relations will remain valid for all the fingers. Similarly based on the average lengths of all the finger joints, we derived a first order equation for each finger to relate the abscissa to the ordinate of point B, C and D (equation set 2). These relations ultimately yield the three co-ordinates of the 15 joints based on just the PIP joint angle, relative to the wrist. Finally the MPU6050 IMU outputs analog voltage values that is used to calculate x and y angles of the wrist. By using the rotational matrix from the product of R_x and R_y, we were able to get the set of co-ordinate of the joints which were relative to the wrist.

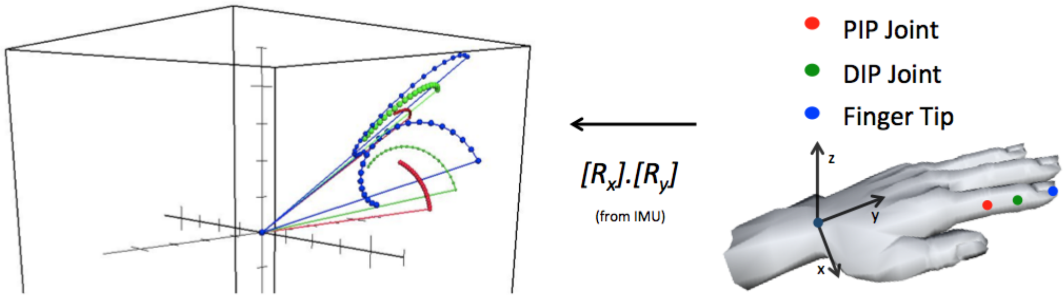


Figure 6.2. Rotational matrix multiplication to the co-ordinates in order to come up with poses of index finger at different orientation of the wrist.

6.1.1 Visual Analytics for Hand Gesture Analysis

To analyze hand gesture data, and provide a result with data-supported visual representations, we adopted the visual analytics system, *GestureAnalyzer* introduced by Jang et al. [39]. This system enables rapid identification and characterization of gesture patterns from motion tracking data set without prior knowledge of the data. The main benefit of the system is involving a human analyst in the process of aggregating similar user gestures including his/her insight and intuition through interactive visualizations. In this section, we briefly describe the data model and components of the system.

6.2 User Defined Gesture Studies

To study gestures for controlling the toys, we recruited 23 children who were between the ages of 8 - 15 years. 11 of them were females (12 were males) where each of them were paid $10 for taking part in the experiment. All the children reported having had experience with robotic kits, where many had played with Lego Mindstorms kit. All of them reported that they were interested in robots - building, controlling or programming them. They would also express their excitement when the researcher show them the robotic kit and they felt the glove controller was '*cool*'.

6.2.1 Task and Procedure

We followed an *effect* and *cause* model, where we show the actuation of the referent toy, and elicit gestures from the participants. Based on the categories of the toys suggested by the designers (AG1 - AG4) and our observations from exploratory studies, we found these toys themes to be popular: (A) Upper Torso Puppet, (B) Robotic Arm, (C) Robotic arm on a vehicular toy, and (D) Vehicular Toy in Figure 6.3. We designed these toys using the developed robotic kit. These four themes of the robots act as referent toys that had three actuators. In total, we collected 12 gestures from each of the 23 participants. After the completion of the study, we provide the user questions such as *"What were your reasons on deciding the gestures?", "Where you comfortable with just the glove, or would you have liked to use your elbow, shoulder, upper torso for input?", and "Does the size of the robot matter in the level of input embodiment?".* We implemented basic structures of the above mentioned toys, giving minimal DOFs in the toys. The design of the toy and the number of DOFs to use was based on our previous heuristics from exploratory studies. Following were the action commands that were used to elicit gestures from each toy theme:

1. Vehicular Toy: A four wheeled robot, which could go *forward, turn left and right* (Figure 6.3D).

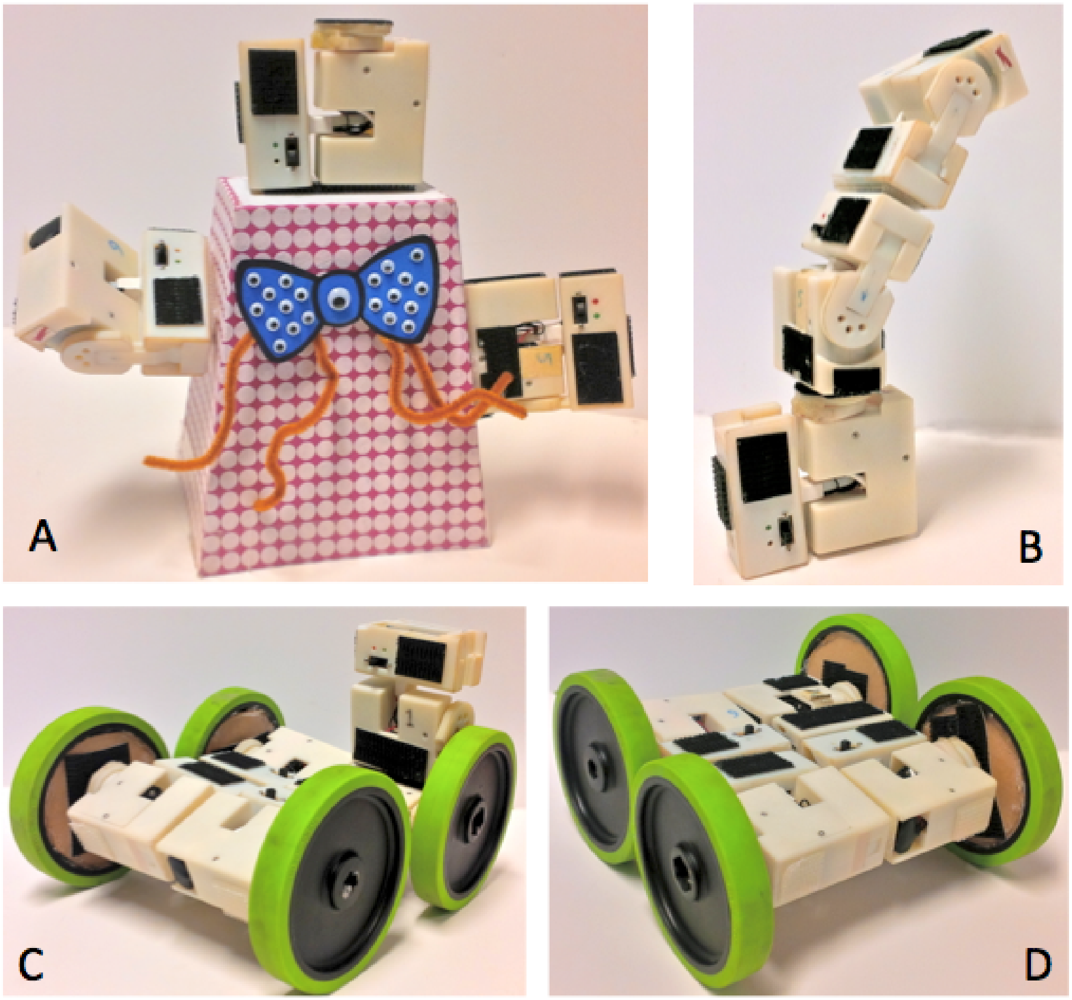


Figure 6.3. The four referent toy configurations. (A) Puppet, (B) 3-DOF Robotic Arm, (C) Robotic arm on a vehicle, and (D) Vehicular system.

2. Robotic Arm: A three dof robotic arm, whose base could rotate and the upper two joints could bend down and up. So gestures to control these three actuations in the toy (Figure 6.3B).

3. Robotic Arm on top of a Vehicular Toy: Gestures for a four wheeled robot which could travel forward and can control the two dof robotic arm, i.e. control the two joints (Figure 6.3C).

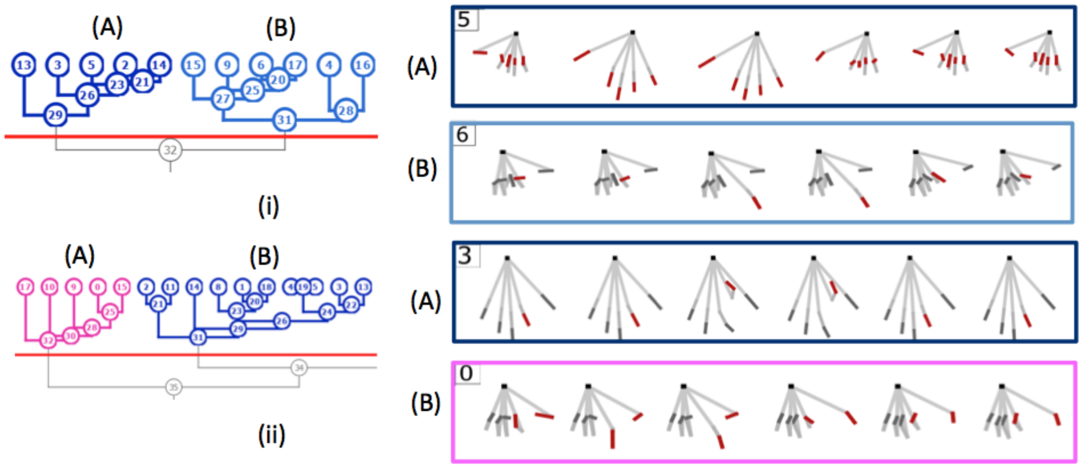


Figure 6.4. Sample clusters for the gesture data from multiple users of (i) Car moving forward and (ii) articulating the left arm of the puppet. The following images are the visualization (small multiples)of the major clusters in a particular context. They are gestures pose over various time steps.

4. Puppet: Gestures for a simple torso puppet where the user can control the rotary neck, and both the arms that move in fixed angular displacement (Figure 6.3A).

We categorized each gesture as a single context and evaluated them across multiple users, thereby clustering gestures on the basis of context.

6.2.2 Children Defined Interactions Techniques

We collected an estimate of 579,600 (23 X 12 X 7 X 300) data points, where each gesture trail would be conducted in approximately 300 time steps. These data points where then used to calculate the co-ordinates of the 15 joints, analyzing 310,500 data points (23 X 300 X 45). We populated the clusters and visualized using the implemented tool (Figure 6.5).

6.2.3 Vehicular Toy

Three gestures actions were recorded from the users - forward, steer left and steer right. As evident in (Figure 6.4(i)), for the forward gesture we observed three dense clusters - 29, 30 and 31. Cluster number 31 (pointing the index finger) was the most dense with 31.57% of the users eliciting a similar gesture as compared to 26.31% for the other two (closing the fist and tilting the wrist in the downward direction). For making the car turn left we observed two major clusters - closing the fist (18.18%) and changing the orientation of the wrist to in the left side direction (22.72%). We also observed two smaller clusters of opening the middle and index finger from a closed fist collectively and just opening of the index finger (13.63% each). Clearly for making the vehicle turn right, the major cluster was twisting the wrist to turn right (31.81%), as for the right hand it is very comfortable to twist the wrist to the right hand direction. Smaller clusters were also observed such as opening the index finger (13.63% each); closing the fist, collectively opening the middle and the index finger and opening just the pinky finger (9.09% each).

6.2.4 Robotic Arm

We recorded the gestures to control the rotation of the base, the first and the second joint for the robotic arm. The two major clusters that emerged from the data for controlling the base was the gesture of opening the fist and bending the index finger with 22.7% each. Other clusters included tilting the wrist downwards and twisting of the wrist sideways (9.09% each), bending the ring or middle finger or the thumb (4.5% each). For controlling the first joint of the robotic arm, 27.27% of the children used their middle and index finger collectively. Among them half of them used to in extension mode where as other half would bend the two fingers in a closed fist. Other major clusters were bending the index finger, closing of the fist and bending the thumb with 9.09% of the users executing them. Finally for the second joint of the arm, 22.72% would bend their middle and index finger combined whereas 27.27% would either open their fist (9.09%) or close their fist (18.18%).

6.2.5 Robotic Arm on Vehicular Toy

The complexity for the control of the robot was increased from the previous as we asked the users to provide the gestures for making the toy move forward and control the two joints of the robot arm. The major clusters observed were opening the fist (18.18%) tilting the palm forward, bending the middle finger and bending the middle and index finger collectively (13.63% each). As evident the children wished to use macro gestures such as tilting the palm, or opening/closing the fist to control macro actuation of the toy (moving the toy). The gestures for controlling the upper joint of the robot were clustered with 22.72% of the total children collectively bending middle and the index finger. Other clusters included bending of the index finger (13.63%), closing of the fist, opening the index, bending of the thumb and bending of the middle finger with 9.09% each. For the control of the second joint we would observe major cluster of the middle and the index finger collectively to either bend (22.72%) or open from a closed fist (9.09%). Other major clusters included gestures of bending the middle finger and the index finger (13.63% each).

6.2.6 Puppet

The gesture cluster for controlling the left arm of the puppet showed that 52.63% of the participants used their index and middle or just index finger to bend and control the toy. For these gesture the users would collapse their finger to form a fist. Whereas 23.61% of the users would do the opposite. They would extend their thumb or index finger to control the left arm of the puppet. Other gesture would include the bending of the palm at various orientations (25%). Due to the hierarchal nature of the clustering, we could further break down the majors clusters to form minor clusters in order to access use of fingers. For example, from the 52.63%, 30% would use their index and middle finger collectively and 20% would use just their index finger.

We similarly observed 50% of the users would either bend their pinky finger and ring finger combined, or middle finger and ring finger combined as gestures for controlling the right arm of the puppet. Similarly from the hierarchal scheme we observed 30% of the users would clinch in their pinky and ring finger. 25% of the users would start from their fist and open up the pinky finger or the pinky, ring and middle finger to control the right arm of the puppet. This characteristic of mapping the topology (index and middle for left arm and pinky and ring for the right arm) of the puppet to their hand is later discussed in the design implication section. These observed gestures from various clusters gave us insights towards some design guideline for designing gestures for such toys. Apart from giving us a percentage of preference (density of the cluster), we also observed some overarching trends.

6.3 Design Implications

We enlists the implications observed from this study towards the design of gestures for such modular robotic toy kits.

6.3.1 Comparisons between Designer and Children Gestures

While we observed some agreements in the preferences for the design of the gestures for specific toys (Figure 6.5), we also noticed that majority of the children would suggests gestures different from the designers. As mentioned by Wobbrock [70], experts could cover only 60.9% of actual users gesture design. While for the vehicular type of toys, 26.31% of the users suggested similar gestures of tilting the hand forward to make the car move ahead where the participants produced similar gestures as that of the designer: tilting the wrist right (31.81%) and tilting the hand left (22.72%). We observed similar patterns of mapping the topology of the toys to the hand in controlling the left and right arm of the puppet toys. It implies that as the children

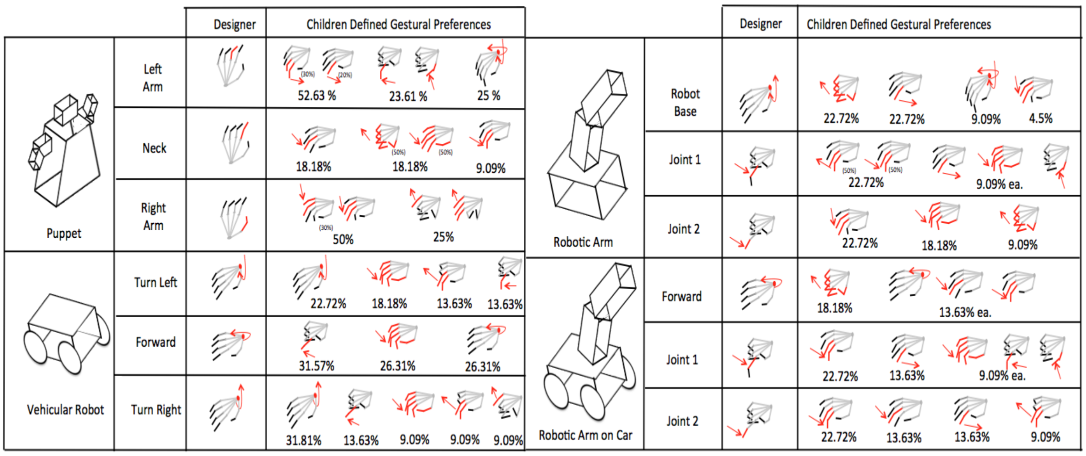


Figure 6.5. Taxonomy of the observed gestures from the clustered data followed by the percentage of preference. We observe gesture agreement between the designer and children in toys like vehicular robot and puppet arms, contrary to robotic arms and robotic arm on top of a car.

articulation prowess is lower, they would tend to use commonly elicited gestures in this study, such as tilting the wrist and bending two finger, to actuate macro motions like steering car or moving the arm of the puppet. On the contrary as evident when they would design gestures to control the robotic arms, we see almost no agreement (Figure 6.5). Rather we observed that the children would progressively design gestures with respect to the structure of the toy. The structure (base-joint 1-joint 2) and level of operation contributed in the design of the gesture (opening the fist - middle and index finger collectively for the other two) based on the articulation ability of the children.

We also observed that gestures like closing the fist or opening the fist, bending the index and middle finger combined being the popular gesture to use. For the children, these gestures are easy and require less efforts to articulate, they would assign these gestures to actuate major operations in the robot. This justifies the system gestures as predicted by designers (SG1 and SG2), that it can be used to switch the system on/off.

6.3.2 Higher Level Classification of Gestures

Apart from classifying the gesture based on their movements as observed from the analytics tool, a higher level of classification was also observed from the researchers.

Imitating Motion of Toys. The participants imitated the movement associated with the actuation of the toy, and assign the joint of the hand which can perform that action. For example, if they want the neck of the puppet to rotate left or right, they would rotate their wrist to replicate the action instead of using their finger (Figure 6.6(E)). They later stated that they felt comfortable in mapping and remembering the gesture. While designing gestures, the designers should consider to provide the same number of DOF from the hand that is corresponding to the robot actuation capabilities.

Imitating Topology of Toys. Many children mapped the way the toy looked to their hands. This can relate back to our designed gestures AG1 and AG2. But unlike the suggestions of the puppeteer's, they did not implement a sock puppet method (AG1). Rather they mapped their pinky and index finger to right and left arm of the puppet respectively (Figure 6.6(A)). This suggests that the characteristics of such robotic toys extend beyond the metaphor of existing toys as these toys presents itself as a new medium for expressionism among children.

Number-based Discreet Commands. Children would assign different numbers to each actuation that was needed to be performed by the toy. In order to call a motion, they would then flash the associated number using their fingers. This method was extremely logical and was used by 5 children, all above 10 years of age. For example, they would flash their index finger to make the vehicle move forward, gesture two fingers to make it turn right and then flash three finger to make it turn left (Figure 6.6(B,C,D)). This approach is very similar to 'switch-case' method of programing, where actions are called based on discreet commands. Designers can take into account this gesture methodology, which can help execute low level commands that do not fit the above two categories.

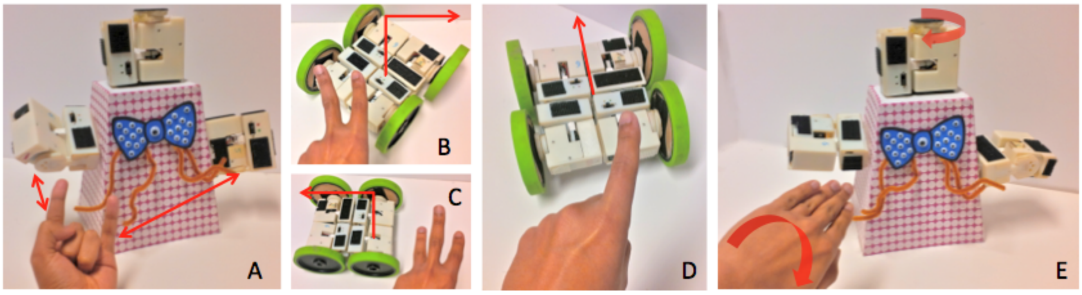


Figure 6.6. Higher level classification of gestures - (A) Imitating the topology of the toy; (B)Making the car turn right by flashing two fingers (C) turn left by flashing three fingers (D) go forward by flashing one finger; and (E) Imitating the motion of the toy, by controlling the neck of the puppet via wrist joint.

6.3.3 Sustained Period of the Gesture Pose

On viewing the speed plots for the tip of the fingers, we observed that the participants held the gesturing pose for about 30 seconds to indicate their gesture intent. As evident from the car forward gesture cluster number 29(Figure 8(i)), the child sustains the gesture for an average of 30 seconds (Figure 6.7), where they initiate the gesture within 35 seconds from when the system starts. This time value for sustaining the gesture is also evident from cluster 32 (Figure 8(ii)). This time is indication of the threshold value for sustaining such gestures comfortably. Similar results are evident when we observed the speed plot of middle fingers for gesture clusters of Puppet Arms.

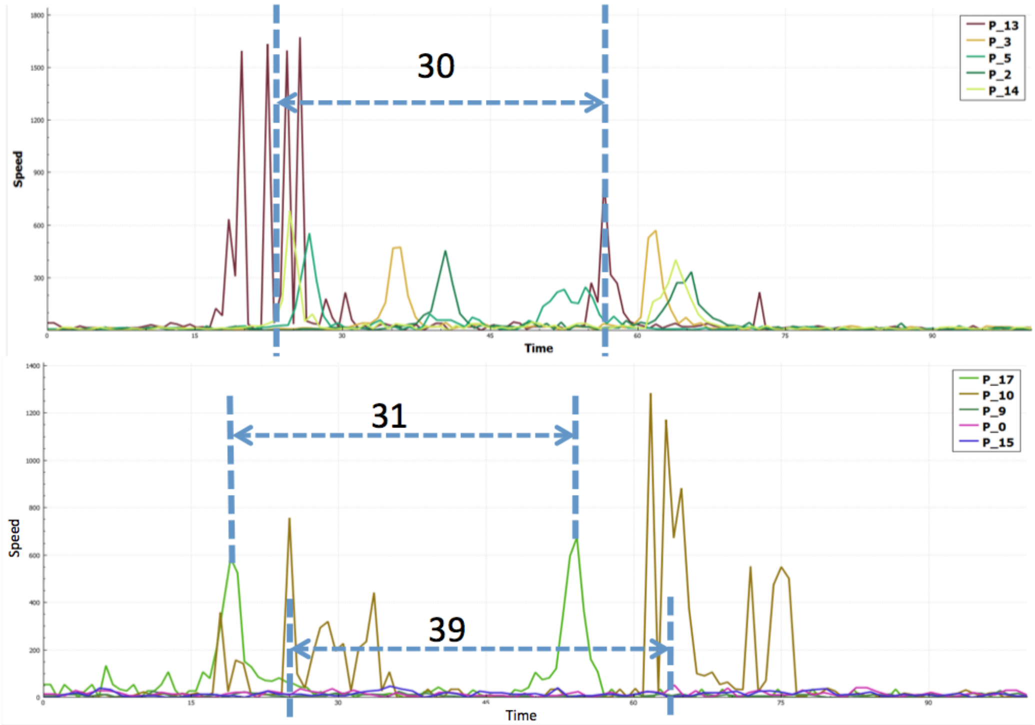


Figure 6.7. Sustained period of the gesture pose for 30 seconds across contexts. The x axis represents the time and the y axis represents the speed at which the tip of the finger moved.

6.3.4 Cross Context Analysis

As the analytical tool was able to quickly categorize and make clusters rapidly, we performed a cross context analysis where we used the gesture data for the puppet left arm and the right arm. This was to understand the usage of same gestures for controlling more than one operation. Out of the 46 data sets, the clustering recognized 18 sets i.e 9 users using the same gesture to control both the arms of the puppet. The gestures included bending the index and the middle finger, closing the fist, bending the thumb, bending the index finger and tilting the wrist forward. This provides evidence that children used

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