Analysis of Feature Development during Iterative Design in First Year Engineering Course

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Abstract
University engineering programs have been recently implementing more first year cornerstone courses [1] aimed at introducing students to engineering experiences while teaching them basic technological skills, problem solving techniques, and communication strategies. Many of these include hands-on project work, leveraging this opportunity to engage the students in more authentic engineering practices. Detailed in this paper is a case-study analysis of the designing and building of a robot during a first year introduction to engineering course, to better understand idea fluency and the process of feature development within the group's solution, as measured throughout the iterative creation of the robot.

Presented here is an analysis of how the team worked through the major problems associated with the assignment and how self-defined sub-problems related to their personalized solutions were brainstormed, developed, evaluated, and then ultimately rejected, refined, or completed. Results show many initial ideas never revisited, each negotiated within a set of constraints under which the students are operating (assignment requirements, time limitations, team member skills, etc). For the original feature ideas included throughout the duration of the project, an analysis of the feature development during iterative design is included, highlighting transition moments within the engineering design process associated with each feature.

Index Terms - Engineering Design Process, Robotics, Engineering Education

INTRODUCTION

Many university engineering programs implement/have first year engineering courses to introduce students to disciplines in engineering [2], the engineering design process [3]-[6], and leadership and communication skills [7]. Most of these courses involve projects where students are introduced to the engineering design process and work in teams [8]-[13]. These courses are meant to help students decide the discipline of engineering they wish to pursue, excite them about engineering, and increase retention rates, especially among underrepresented groups. These courses are very important to engage students early in the process of engineering.

These first-year courses are typically evaluated by grades [3], surveys [2,8,9], self-assessments [10], and project evaluations [5,11]. In this work, the authors wanted to gain a greater understanding of the students' design process in which the students engage during projects, especially outside the classroom, and so employed a deeper level of analysis. Groups of students in a first year engineering course were asked to video record all their project work both in and out of the classroom. This paper presents an analysis of engineering practices employed by one of these groups as they designed and developed a robotic haunted house robot.

LITERATURE

The engineering design process is an integral part of any engineering design curriculum and a necessary aid to solving engineering challenges in university courses and engineering practice. Numerous studies have examined how novice to expert engineers design [14-18]. While some synthesize or focus on a specific step [17-20] others investigate how a single person works through a design concept [14-16,21]. Little has been done to understand how students fully engage in the design process in their courses, both during in-class work and at home.

A majority of first year engineering courses involve students engaging in the engineering design process through project work. Some studies emphasize the importance of learning the process early in their engineering education, yet do little to understand how the students are actually engaging in and learning from this process. Project work can be complex, and can include things like teamwork, presentations to peer and client audiences, design/build/test scenarios, competitions, etc. When assignments have these kinds of aspects, students are required to manage many different constraints simultaneously. This work began based on a curiosity of what occurred during student projects outside the classroom. Prior student feedback on the course consistently affirms high engagement but greater insight was needed to understand the students' experience with the design process and learning of technical content. As instructors, it is important to better understand the subtleties of what is happening when students are engaged in this type of work, especially in situations like first-year engineering courses when, as novices, the experience can be a defining moment in defining the young engineer's path. Thus, the structure of the course can benefit from deeper understandings with regards to, for example, details of the group dynamics when engaging in the engineering design process. To access this information, video recordings of group's in-class work/presentations and also self-documented at-home development provided insight into their design process. From the data, this study examined the interactions, in-depth discussions, and evolution of their designs to comprehend how a group of first year engineering students work through problems and related sub-problems en route to completing a robotics project.

PRIOR WORK

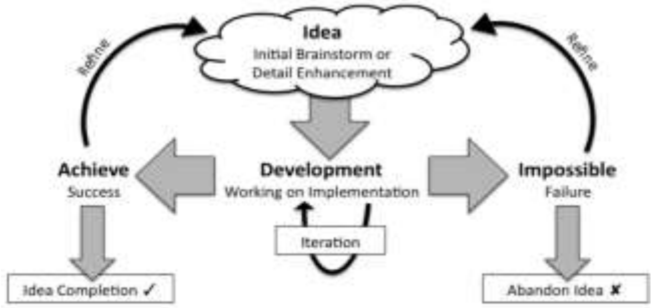

Figure 1: First version of the Idea Flow Diagram [22]

Swenson & Danahy [22] previously created the Idea Flow Diagram (Figure 1) from the patterns of idea development and iteration the students exhibited as they worked on their project. During this analysis, the different project components were considered on two scales: *like to have* vs. *must have* and *possible* vs. *impossible*. There were times when students would quickly reject ideas that were *impossible* due to lack of resources, but other times students would choose to pursue implementations they may not have the knowledge to do initially (*impossible*) but would work to learn how to accomplish (transition to *possible*) because of a group decision that it was a *must have* feature for the project. In that original analysis, the video was coded only for discussions and development of different components created by the group for solving the presented task. While gaining initial insights into the groups' design processes, it lacked sufficient details in terms of the transitions students make when starting/stopping work and iterating on, abandoning, or completing project sub-components.

REFINED CODING SCHEME AND IDEA FLOW DIAGRAM

The analysis (and results) presented in this paper are derived from a deeper examination of how the students work through solutions to both the larger overarching problems and more detailed component sub-problems in a complex first-year engineering project. The analysis is based on six hours of video data documenting a group of students brainstorming in class, presenting their ideas to their peers, working on their project in their dorm, presenting their prototype to the class, and completing their final projects. The discussions and development around problems, sub-problems, and proposed solutions were recorded while the students brainstormed ideas and worked on project components. The video was coded in five minute intervals as to what aspects of idea flow diagram the students were engaging while developing these problems and solutions.

Building off the prior work and in an effort to further understand the specific details of the design cycles used by the students, the data was coded again in more detail. For each sub-problem identified, students were coded if they were brainstorming, making their solution, or evaluating (their ideas or physical artifact). Based on those evaluations (positive or negative), it was noted if components were iterated further, finished, or abandoned.

During analysis, a transition was observed as students moved from brainstorming to making. There emerged two different styles which students employed while exiting the brainstorming stage around a particular aspect of the project. The first is more characteristic of standard brainstorming, where the speaker uses a more hesitant tone and looks for affirmation from within the group. The second is a more declaratory or decisive in nature, where the speaker is not looking for affirmation from their fellow group members with regards to the idea because the individual has already decided what approach to take and is communicating that decision to the rest of the group. Noticing this existence of the brainstorming to make transition, a *decision* step was added to the Idea Flow Diagram and coding scheme. The updated Idea Flow Diagram representing the model used in the analysis here is shown in Figure 2.

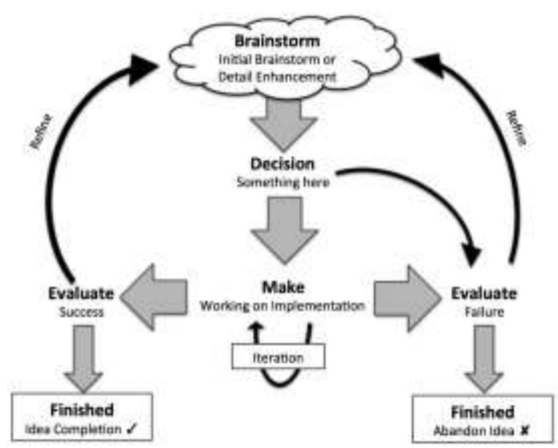

Figure 2: Updated Idea Flow Diagram

Leveraging the updated Idea Flow Diagram, the video was again coded using: brainstorm, decision make, evaluate, and finished. Note for both evaluate and finished the resulting product of the step can be positive (evaluation work or idea was completed/kept in the solution) or negative (evaluation failed or idea was abandoned). For any particular problem/sub-problem the group might have been engaged in only one particular action, or in some instances, cycled quickly through all stages of the Idea Flow Diagram.

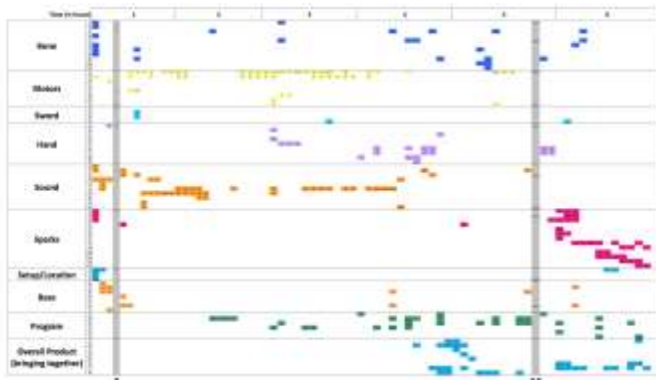

Figure 3: Visual representation of the six-hours (x-axis) coded for problems

The diagram in Figure 3 is a visual aid capturing the overall moments in time (throughout the 6-hours, spread across the horizontal axis) when group members were addressing problems (vertical axis) and sub-problems (rows) associated with the robotic assignment. The colors are used to visually distinguish each project problem, and while not visible, each colored square identifies the particular step(s) being used by the group during design. This coding allows researchers to analyze the use of the design process as various components evolved and provides indication of when each component was worked on during the duration of project development. A larger version, and associated table detailing specific problems/sub-problems, can be found in Appendices A and B.

COURSE DESCRIPTION

The observations occurred in Simple Robotics, one of about 10 first-year courses offered at Tufts University, representing the various departments (and majors) within the School of Engineering. While taught by a professor from computer science, the course seeks to expose (undeclared) students to a wide range of engineering content areas including mechanical, structural, electronics, and programming.

The course is structured around hands-on robotics projects, ranging in length from just a few days to up to several weeks. These projects focus on innovation and creativity while engaging students in developing the practices of professional engineers. Students are required to struggle with conflicting constraints and working in small groups to design, build, program, and test prototypes. Presentation skills are emphasized as well, acknowledging the importance of being able to communicate and share engineering creations beyond just the process of creation.

In Fall 2013, the *Haunted House* project was produced in collaboration with a Tufts dormitory to organize an on-campus Halloween celebration at the end of October. Students were asked to build a creation for class, with the knowledge the top functioning projects would be included in the Haunted House. While building, students were aware that they were not only creating this project for their in class presentation to the professor and peers, but also, if selected, for enjoyment by the wider university.

The Haunted House project occurred about 2/3rds of the way through the semester and was preceded by six smaller projects. This was the first project students had more than a week to complete. In the class for the first half of the semester students worked in pairs for four projects, and then combined together with another pair to form a group of four starting at project five. By the Haunted House project, the seventh assignment, team dynamics among the group had been previously explored, in terms of identifying and negotiating the different personalities, knowledge and level of expertise, etc.

DATA COLLECTION

Three student groups in the class (comprised of members of students who had consented to participate in the study at the beginning of the semester) were given video cameras to record any work related to their projects as they completed them outside of the classroom. Students were also recorded by teaching assistants and the researchers when working or presenting in class.

The case study presented in this paper is one group comprised of two males and two females working on their implementation of a self-selected “Scary Sword” for the Haunted House. One of the males lived in the dorm where the haunted house was taking place and was on the planning committee for the Haunted House, and thus was observed to be instrumental in developing the project concept and how it fit into the event. The group’s prototype was comprised of plastic Halloween decorations, including a bone, skeleton hand, and sword, and components from the provided LEGO MINDSTORMS NXT Robotics kit, including a motion sensor, motor, lights, and programmable brick.

Figure 4: Picture of nearly completed Scary Sword project

ANALYSIS

During analysis of this group's video data, the project was tracked by identifying ten different components on which the students focused: bone, motors, sword, hand, sound, spark, base, set-up and location in the haunted house, program, and overall prototype. As sub-problems were being solved and integrated into the overall working prototype, it was sometimes difficult to specifically code each as certain aspects were being modified at different times.

To understand the design work in which the students engaged, the following analysis presents three different cases (sub-problems) and the associated trajectory through the Idea Flow Diagram by the group. These cases are a sample of the types of paths seen throughout the design process on many of the other sub-problems identified.

I. FOG

In the first five minutes of rapid brainstorming, the group was working on solving location (where their prototype would be in the haunted house) and how they would hide the mechanism to maximize the "scariness" for the attendees coming through the exhibit. One student suggests fog ("If we had like a little fog machine going at the entrance…"). After the initial brainstorm (the first mention of this concept), the idea did not progress any further and was immediately abandoned (see Figure 5).

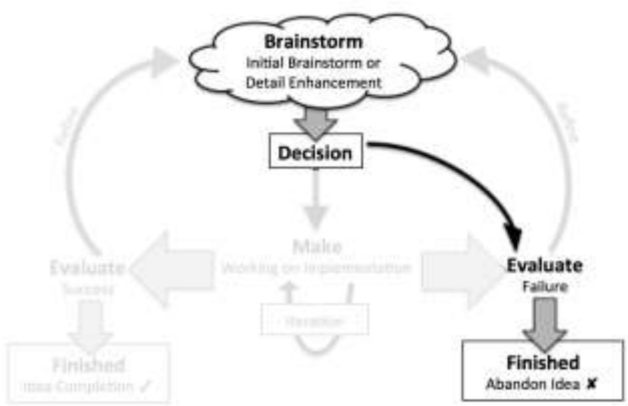

Figure 5: Idea Flow Diagram for implementation of *fog*

The idea of fog was not incorporated into the prototype, tested, nor brought up again by anyone in the group. Since the group did not discuss the idea further, there is no evidence in the video providing insights as to why they did not pursue the concepts and what considerations they took into that decision.

II. SPARK

During the initial brainstorming, one of the students desired to add a spark to the robot to increase the *scary* aspect of the creation. Prior to brainstorming, it is clear he already had experience in creating sparks using a battery and steel wool.

Figure 6: Video coding for sub-problems associated with implementing the *Spark* feature

The spark idea was initially tabled while the students worked on core elements of the design such as attaching motors to the bone prop and making the sound effects work. While working on their prototype, they discussed the concept once again and reported to the class (during a mid-project status presentation) that they were going to add it to the prototype. After the mechanism and sound effect elements were working, they then focused on making the spark idea a reality. During testing, they accidentally lit the steel wool on fire and, as a result, deemed it unsafe to implement in the final version. In the moment, they quickly brainstormed an alternative solution (making a light flash as the sword hits the ground) as a replacement. The implementation of this idea resulted in its own iteration, as small problems arise such as adding weight to the rotating element and attaching the various components to the device. After a few iterations and adjustments of other elements of the prototype, they finished this part of the project. This process, as visualized within the Idea Flow Diagram, is shown in Figure 7.

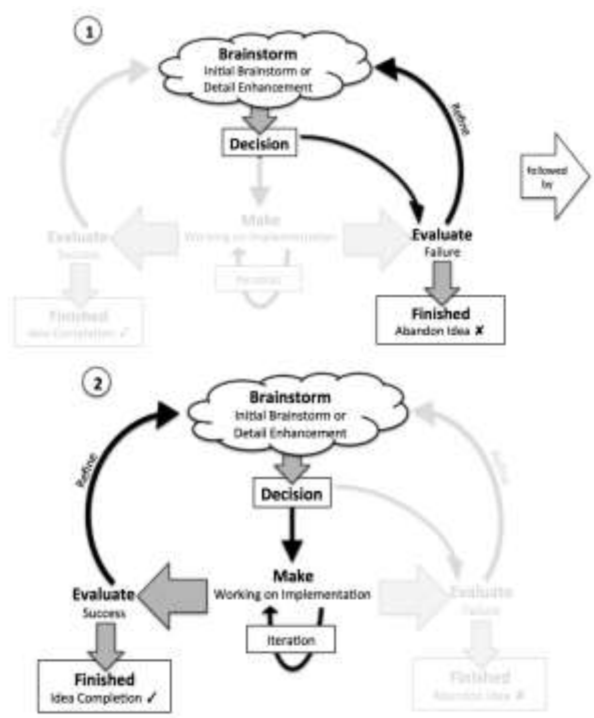

Figure 7: Development of the *Spark*, first through steel wool and battery (top) and then via light (bottom)

III. COMPUTER PROGRAM

The students started working on the computer program necessary for controlling the robot about 85 minutes into the group project. Their program included a number of inputs and outputs they added (or modified) at various times throughout the process.

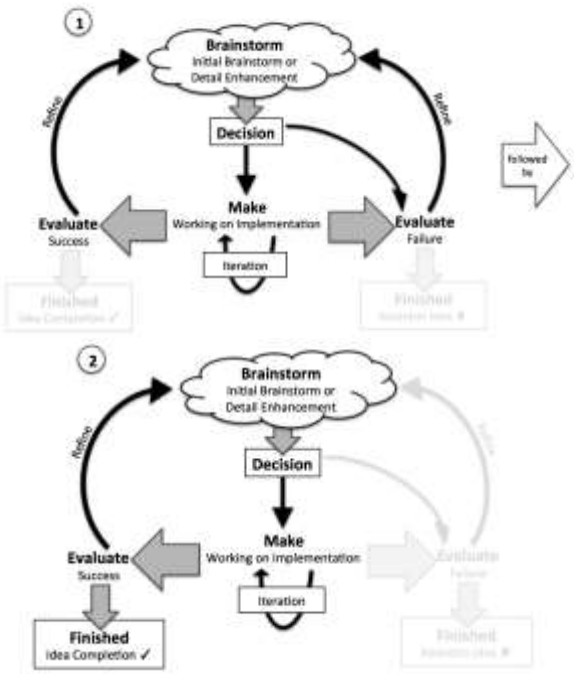

Figure 8: Idea Flow Diagram for Implementation of Computer Program

The students started by writing basic code for the movement of the motors to be triggered by an ultrasonic motion sensor. They evaluated their code by connecting it to the assembled bone and motors and observing the motion. It was clear the students had a specific style of motion in mind, and they iterated on this program until it was satisfactory. Around the 200th minute, the students finally completed putting a sound file onto the NXT microprocessor, integrated it into the program, and evaluated how it worked. For the remaining two and a half hours, they cycled through short and long brainstorm-decide-make-evaluate cycles, iterating on different program components with varying levels of success. As the group added and removed various components to the swinging part of their project, they iterated the required level of motor power needed in short, little cycles, choosing, implementing, and evaluating them quickly. They revisited other components as the prototype was tweaked and modified into its final form. This process, the most iterative of any in the entire project, is visualized with the Idea Flow Diagram shown in Figure 8.

IV. STATISTICAL ANALYSIS

Using Figure 3, a statistical analysis provides a more comprehensive view of the entire design trajectory. With four students in the group, many of the components were made simultaneously. During one five minute period, at times multiple components were being worked on, especially if components were being integrated.

Concept	% of work time
Bone	10.40
Motors	18.79
Sword	1.68
Hand	8.05
Sound	17.45
Sparks	13.42
Set-up/Location	2.68
Base	5.03
Program	11.41
Overall Prototype	11.07

Figure 9: Percentage of time students spent on each concept

Using Figure 3, Figures 9 details the time students spent on each component. Students spent the most time working on attaching the motors to the bone props and the sound file.

Phase	% of work time
Brainstorming	48.39
Decision	10.75
Make	39.43
Evaluate	25.09

Figure 10: Percentage of time student spent in each phase of the Idea Flow Diagram

Figure 10 details the amount of time the students spent on each of the phases from the Idea Flow Diagram. These percentages reflect the percent of 5 minutes periods where a certain phrase was exhibited over the total number of time periods. Brainstorming was the dominant phase of the process. This does not necessarily mean they spent the most total time brainstorming but brainstorming was the most frequent activity during the five minute intervals. During one five minute period, students sometimes were only doing one phase but other times went through multiple phases quickly while they were iterating. For this reason, the percentages total to over 100%.

IMPLICATIONS AND FUTURE WORK

This paper presents a coding scheme leveraged on video data of student group work in a first-year engineering project to try to gain deeper insights into the processes in which students engage when completing ill-defined, design-based activities. Implemented on six-hours of video data collected by a group of four students creating a Haunted House robotic exhibit in a first-year Tufts University engineering course on robotics, the coding revealed a wide-range of practices employed by the students as they negotiated the multitude of constraints (some self-imposed) and group dynamics (from communication to varied individual team member skills). While the group exhibited some expert-like qualities (rapid prototyping, evaluation, and iteration), there were also moments of idea fixation, progress delays due to lack of resources, and early abandoning of ideas without evaluation/justification.

When manually coding the video, it was often difficult to distinguish between iterative making (e.g. tweaking parameters) and the larger brainstorm/decide/make/evaluate cycle. In these instances, researchers' discretion based on available evidence in the video data served to identify the difference. Fortunately, the nature of group work itself leads to more explicitly detailed cycles, as the process of negotiating group dynamics more often requires vocalizing and justifying rationale and actions out loud, which is captured in the video. This activity also ensures more explicitly defining and formalizing ideas for teammates, a practice which can be more "awash" when working solo; while perhaps it is not necessary to always make ideas explicit when an expert, it is a necessary practice as a novice to learn to express and develop. Thus, the structure of group work itself, while perhaps adding complexity to the constraints of the problem, does introduce the need for better developing these skills.

Evident in the data were moments where idea fixation, especially on sub-problems where students lack the necessary skills, resources, or tools to efficiently implement solutions. This means too much time gets spent on logistics and not enough on the brainstorm/decide/make/evaluate cycle. Thus, there is a definite tension between the barriers or idea fixation and enabling the learning the engineering design process. The students also spent a significant portion of their time brainstorming. Further research would have to be done to determine how many of these ideas were productive, leading to a solution, or if a significant portion never came to fruition. For instructors, this presents the challenge of providing the appropriate resources to the students and limiting the scope of the assignments, while maintaining an open environment allowing the students the freedom to still explore their own personal ideas. It is important in to have students reflecting and being self-aware of their own limitations while still cognizant of the full range of possibilities.

Finally, while the coding used here identified and highlighted instances where students employed multiple design cycles to refine their project, it simply tracked the existence (and steps) of the iteration, but did not provide details regarding the actual quality of the iteration (or the quality of the results from the iteration). There still exist several questions regarding the work the students are doing. Even though iterating, is the product they are making actually getting progressively better? During decisions and evaluations, are they employing good reasoning when iterating? While it is important for initial work, as in what is presented here, is to ensure they are engaging in design cycles at all, there exists a need to also evaluate the quality of the learning experience, but examining the particular steps and aspects of those steps (e.g. when evaluation leads to iteration, are the students scientifically isolating variables as they seek optimal performance, or simply guess & test their way to a functioning solution?). Deeper investigations at those moments in the design process would help identify this, and then it would be possible to better understand the circumstance that led to one behavior or the other.

While this work provided many insights to students' engagement with the design process while working on projects outside the classroom, more specific studies need to be conducted with a greater number of participants. A number of pathways are currently being considered. Insights from this work have begun to influence next year's course design. This work is also being shared with other instructors of first-year courses at Tufts University with the hope of expanding data collection to other courses.

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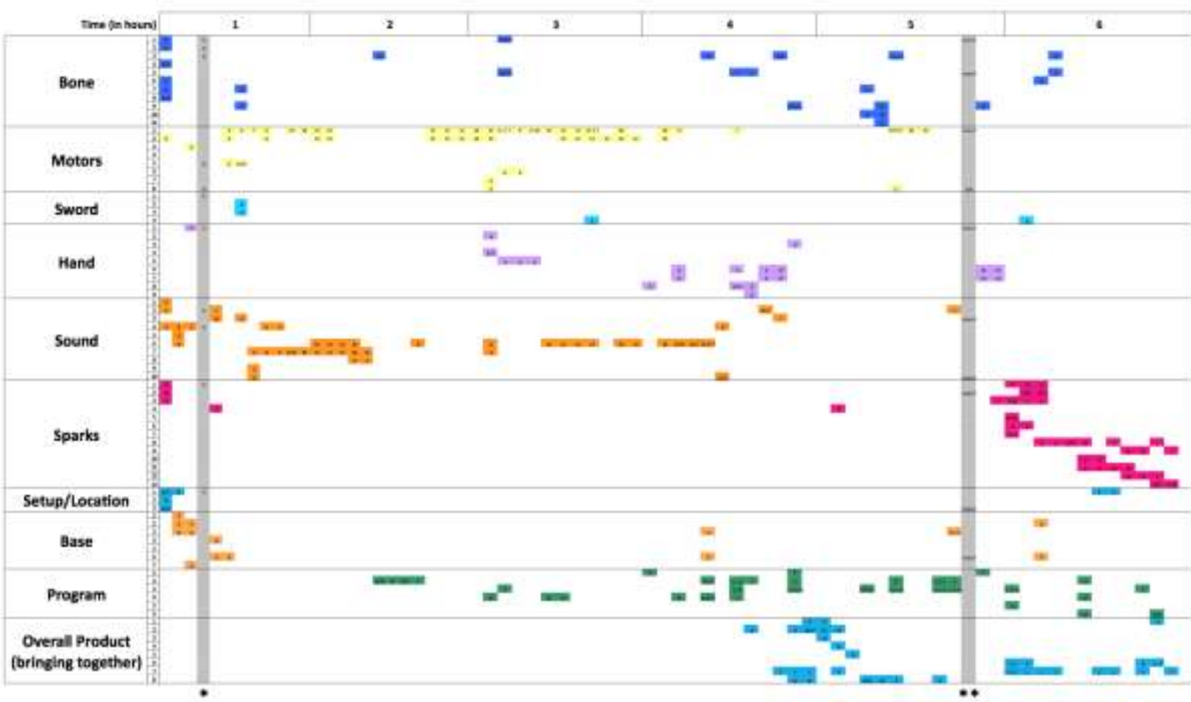
APPENDICES

Appendix A



Appendix B

Problem/Component		Sub-Problem/Discussion
Bone	1	Rotation of the bone
	2	How to trigger the contraption?
	3	Inclusion of motion sensor
	4	Will the fog trigger the motion sensor?
	5	How will it work physically?
	6	Inclusion of counter weight
	7	How to attach the sword to the bone?
	8	Location: In between two bones
	9	Duct tape to the bone
	10	Cut a slit in the bone
	11	Fuse the bone loosely
Motors	1	How will motors attach to the bone?
	2	Drilling holes in the bone
	3	Wrapping bone in black duct tape
	4	How many motors will we use?
	5	Using 3 motors
	6	Using 2 motors
	7	Using 1 motor
	8	Can/how will bone move back up?
Sword	1	Overall sword discussion
	2	How to attach this to the bone?
	3	Duct tape to the bone
	4	Red nail polish as blood (blood on sword)
Hand	1	Attach a hand
	2	Use foot bone
	3	Use half a hand bone
	4	Make a sleeve for the bone to cover up it's a foot
	5	How to get a hand?
	6	How to attach hand to bone
	7	Duct tape to the bone
	8	How to attach the sword to the hand
	9	Sewing/duct tape
Sound	1	How will the sound be triggered?
	2	Use of touch sensor (has to hit the ground)
	3	Stand for touch sensor
	4	What will the sound files be? (finding sound files)
	5	When will it play? (sequence)
	6	How to get the sound file on to the NXT?
	7	How to get the sound file into the right format?
	8	Can you record on the NXT?
	9	Two sound files (one sword hitting, one scream)
	10	Using 3 or 4 sounds
Sparks	1	Set up: where will it be?
	2	How will it work?
	3	Does the steel wool work?
	4	How to attach the battery?
	5	Low weight of battery (light)
	6	Location of wires
	7	Location of terminals
	8	Flashing light alternative
	9	How to put the FL on?
	10	Use of tape
	11	Incision in bone
	12	Trigger by touch sensor
	13	Trigger by motion sensor
Setup/Location	1	Where will this be in the haunted house?
	2	Use of fog machine
	3	Cigarette Washroom (location)
Base	1	How are we going to support it? (aka base)
	2	Needs to be heavy
	3	Tape it to the ground
	4	LEGO + weight
	5	Tie it to a bar
	6	Cover NXT in black paper (disguise)
	7	Materials for base
Program	1	Programming (overall)
	2	Motor movements
	3	Power considerations
	4	Including sound
	5	Low battery power
	6	Flashing light
Overall Product (bringing together)	1	How to reduce the weight?
	2	Cut off (remove) top of the bone
	3	Remove handle of the sword
	4	Remove the top part of the hand
	5	Substitute a different hand
	6	Deck it up
	7	Bone + Hand + Sword (bring together)
	8	Bone/Sword (elimination of hand)

Appendix C

	Time (min)	0	5	10	15	20	25 to 240	245	250	255	260	265	270	275	280	285	
Sparks	Set up: where will it be?	B			B												
	How will it work?	B															report
	Does the steel wool work	B															
	How to attach the battery?					D		B									
	Low weight of battery (light)																
	Location of wires																
	Location of terminals																
	Flashing light alternative																
	How to put the FL on?																
	Use of tape																
	Incision in bone																
	Trigger by touch sensor																
	Trigger by motion sensor																

	Time (min)	290	295	300	305	310	315	320	325	330	335	340	345	350	355	360
Sparks	Set up: where will it be?			B	B	B										
	How will it work?				B/E	E/D										
	Does the steel wool work		E	M/E	E	E/F										
	How to attach the battery?															
	Low weight of battery (light)			B/D/E												
	Location of wires			B	B											
	Location of terminals			Prof												
	Flashing light alternative					B	B	B/M	M		E			E		
	How to put the FL on?											M	M		E	
	Use of tape								M	B						
	Incision in bone								B	B	M	M				
	Trigger by touch sensor											M	M	E		
	Trigger by motion sensor													B/E	E/M	