

WHAT DESIGN PROCESSES PREDICT BETTER DESIGN OUTCOMES? THE CASE OF ROBOTICS DESIGN TEAMS

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ABSTRACT

This paper describes a design study that was conducted with US high school robotics design teams in order to determine which design activities that a team engages in has a bearing on good design. The goal of this study is to provide a broad, integrated perspective of the design process. Fifteen design activities have been identified as commonly occurring in design practice in a previous work (Mehalik et. al. 2006). Eight of these activities are studied in a controlled design environment of a robotics competition, where design teams are required to build a robot to achieve the same end goal using a constrained set of components. Both surveys and interviews were used as instruments in the study. A study of each of the activities and their impact on the performance of the design is provided through studying whether the engagement in an activity has a positive or negative correlation with the rank of the team in the competition. Interesting statistically significant insights have been established regarding the impact of design activities on success of designs made by robotic design teams.

KEYWORDS

Design studies, engineering design, design process, robotics, best practices.

1. INTRODUCTION

Design problems have an ambiguous specification of goals and design tasks are highly unstructured. There is no predefined solution path or method to a design problem and the solution involves integration of knowledge from disparate domains (Ball, L. J. et al., 2000). Numerous techniques have been suggested in literature for solving design problems (Hubka et. al. 1988, Cross 1994, Pahl et. al. 1996, Ulrich et. al. 2003). Each of these approaches proposes activities that form a best practice for design problem solving. Following the determination of customer needs and a market analysis, design is considered to comprise of three phases viz. conceptual design, embodiment design and detailed design. Each of these phases involves a prescription of specific activities which, if the designer follows, should result in a “good” design solution. Mehalik et al. (2006) identified a set of 15 design elements or activities commonly found in the design process by surveying an extensive body of literature on empirical studies of the design process. Among the 15, the activities strongly associated with success include exploring the problem representation, using interactive or iterative design methodology, searching the space for design alternatives, exploring graphical representation, exploring and redefinition of constraints, validation of constraints and

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assumptions, and examination of past design artifacts. Through assembling the findings of the surveyed literature by Mehalik *et. al.* say it would be possible to extend the value of the findings by providing a broad, integrated perspective. The meta-perspective obtained also results in identification of ways in which design can be used as a learning tool.

The goal of this current work, which is in its early stages, is to study which of the 15 elements that design teams engage in commonly contributes to successful design. The elements identified in the work by Mehalik (*ibid.*) were from disparate design studies with differing design problems. The intention in this preliminary work is to study the 15 elements with the design problem as the control variable. This allows design success to be attributed to design personnel and design practice. We identified the US FIRST Robotics competition as the suitable platform for such a study (US FIRST 2007).

A future aim is to study how these robotic design teams innovate and thereby determine a set of best practices for generating creative and innovative designs. For example, Christensen *et. al.* (2007) identified that greater creativity in design resulted from usage of analogies by design teams.

The FIRST Robotics competition provides an ideal platform for studying the practices of design teams for the following reasons:

1. Defined design goal for all participants
2. Defined set of components for certain functional aspects of the design ensures parity across teams
3. Large number of teams
4. "Successful" design is easily gauged through competition rankings

In this paper we attempt to identify correlations between design practice and team performance, thus identifying which of the elements result in better design.

The paper is organized as follows: Section 2 discusses current literature in the area of design practice studies, Section 3 describes the design problem and the US FIRST Robotics competition, the methodology used for the study and the coding approach. We then close with findings and results in Section 4 and conclusions in Section 5.

2. RELATED LITERATURE

Numerous studies have been conducted into various aspects of design teams such as teamwork,

communication and information technology (Baird *et. al.* 2000), characterizing social behavior of electronics design teams (Jagodzinski, P. *et. al.* 2000), comparison of designers from practice and designers with systematic design education (Gunther *et. al.* 1999), and understanding differences between novice and experience designers and their approach to design tasks (Ahmed *et. al.* 2003). A good summary of different design research techniques and topics is available in Coley *et. al.* (2007).

In Stempfle *et. al.* (2002) three main strains of design research have been outlined; normative strain, which relates to design methodology (Pahl *et. al.* 1996), empirical strain which says that designers rarely follow any methodology (Gunther *et. al.* 1999) and the design-as-an-art strain, which says designers flexibly apply different methods while reflecting on the design problem constantly (Roozenburg *et. al.* 1998). Each strain has its drawbacks and studies in each focus on different aspects of design thinking. In this work, we study design as a set of design activities that each team engages in and their effect design outcome.

Different researchers have argued for the importance of various processes for design, either in the form of elaborate overall procedures (e.g., TRIZ) or particularly important steps (e.g., brainstorming or rapid prototyping). Mehalik *et. al.* (2006) examined the empirical literature on design to see which processes from a list of 15 were studied most often and under which conditions, and then which processes had strong prior evidence of being important for design outcomes. Overall, they found that most empirical research focused on the early stages of design, much of the literature had focused on programming tasks rather than physical design (e.g., mechanical or electrical), and only a few processes had been studied in enough depth to be clearly effective (or clearly ineffective). Thus, more work is required to study earlier and later stages of design together, looking at the broader set of design processes, and examining product design other than computer design.

3. DESIGN STUDIES

This section outlines the details of the studies that were conducted in order to assess the design practice of robotic design teams. Section 3.1 describes the design problem that the teams were required to solve. In Section 3.2, the procedure used to study design practice is described including a description of

subjects, instruments used in the study viz. surveys and interviews, and methodology of the study. The encoding method used for the interviews is outlined in Section 3.4

3.1. The Design Problem

The US First Robotics competition is a program that assimilates teams, sponsors, colleges and technical professionals with high school students to develop their solution to a prescribed engineering challenge in a competitive game environment (US FIRST 2007a). The competing teams are given the engineering challenge at the beginning of a six-week period during which they conceptualize, design and construct their own solution to the challenge posed. The program enables high school students to learn through design. For example, taking a gearbox from a power drill and modifying it for use on the robot, they gain insight into the design of the original gearbox's purpose, learn to characterize the performance of the original design, and implement the engineering design process to create their customized application for the gearbox (example from US FIRST 2007a).

The game involves forming six of the participating teams into two alliances of three teams each at a time for each match and then allowing them to compete at scoring the most points. The game for the 2007 season involved robots picking up toroidal tubes made of inflatable plastic called "ringers" and placing them on a centrally located rack with "spider" legs. Each team is given a total of 21 such tubes of three different kinds, each type affecting scoring in different ways as specified in the rules. Furthermore, the teams can score additional points by having one of the robots elevating the two other robots in the alliance by some means, say, a ramp. The competition takes place in an arena of a set dimension (Figure 1). Details of the game are provided in the manual (*ibid.*).

The teams are required to fabricate their robots from a kit of parts provided by the organizers of the competition in a fixed time frame of 6 weeks. The kit ensures that the maximum power level is the same across the different teams. Components include motors, batteries, solenoid valves, fittings etc. Additionally, teams are allowed to spend up to \$3500 on other components, which are limited by rules that govern the electrical circuitry, control systems, operator interface, wiring, pneumatic and other systems.

The design problem for the robotics study provides a unique platform to study the design process. Since the end goal is defined specifically as scoring as many points as possible for a particular shared and repeated task, the functionality that all teams are seeking to achieve with their robots is the same. While the solutions will be different, the end goal is close-ended across all participants. The teams are required to use components that are mostly standard across all teams. This results in the variation in the performance of a team to be on account of their design approach and competition strategy, the robot design itself and the skills of the team members. Furthermore, since the robots are pitted against each other at a single location under the same exact conditions, it allows for an evaluation of different robot designs with the same yardstick. The rankings of the teams at the end of the competition can be attributed to the qualities of the design team and the design. The large number of teams participating from different geographic locations allows for statistically significant findings.

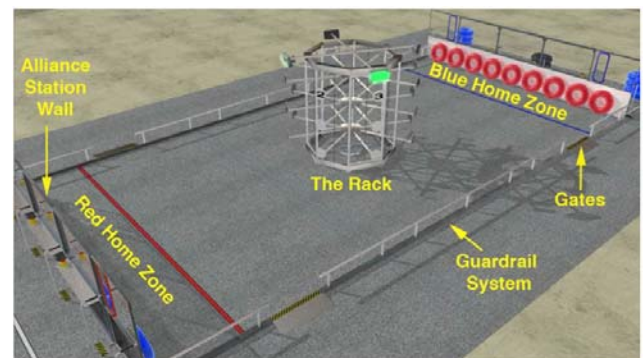


Figure 1: Robotics game area with rack (US Robotics 2007a)

3.2. Procedure of Study

We studied the teams participating in the Indiana Robotics Invitational 2007 competition held in Indianapolis, Indiana. The competition had 72 teams participating from all over the United States and some foreign countries.

Instruments of study

The study of the robotic design teams was divided into two parts – a survey section and an interview section. The first was a written survey in the form of a questionnaire; it contained 22 questions and a set of responses. The survey was divided into two parts; the first part related to the background of the participants which had 7 questions including questions such as reasons for participation, parental education

background etc.; the second part of 15 questions related to design practice such as questions on brainstorming, sketching and prototyping. The interview section had 20 questions all related to design practice.

The survey and interview questions can be viewed at (Titus 2007).

Methodology

Each team consists of students, student leaders and mentors who are usually engineering professionals, technical specialists or collegiate level engineering students. It was decided to attempt to survey/interview one mentor and one student or student leader (henceforth called students) from each team that was interrogated. The teams and personnel were picked randomly. No payment was involved for participating in the study.

Participants

For the survey, we received responses from 33 students and 25 mentors. Of the 38 teams assessed through surveys, 19 teams provided one mentor and at one student respondent.

Interviews were conducted with 34 respondents, 18 mentors and 16 students. A total of 25 teams provided respondents, of which 9 provided one mentor and one student each.

Coding of Interview Responses

Two of the authors separately coded the transcripts of the interview responses and identified clusters and categories of responses for each of the 20 interview questions. The categorization of responses was based on their experience from industry and research in the engineering design process. Following this step, a common set of categories was arrived at through discussion and negotiation. The interview responses were evaluated and categorized using these categories by both coders separately. The category/ies into which responses fell were assigned one and all other category/ies for the question were assigned a zero. Following this process, it was noticed that certain categories having different nomenclatures but referring to the same response category were repeated across questions. The categories were renamed to obtain consistency in nomenclature across questions. The process of coding was repeated. Discrepancies between coders regarding categorization of responses were rectified through discussion. In the event of irresolvable disagreement between coders, each author was

allowed to retain their respective categorization. In this case, the value for a particular category is assigned as a 0.5.

Coder reliability rating

Subsequent to the second coding of interview responses, where categorization of responses was arrived at through consensus as much as possible, the coder reliability rating was found to lie between 95% and 100% for majority (85%) of the questions. The lowest reliability computed was 83%. The remaining reliabilities were in the high 80 to low 90 percentages. The lower reliability rating questions are not reported in this paper.

4. RESULTS

As mentioned earlier, the goal of this paper is to study the design practices of robotic design teams and identify which of these practices could possibly result in successful designs. Mehalik *et. al.* (2006) cited 15 elements that commonly occur in the design process that were identified in 40 design studies papers.

Of the 15 design elements, the current study evaluated aspects related to problem representation, graphical representation and visualization, functional decomposition, exploration of engineering facts, exploration and redefinition of constraints, validation of assumptions and constraints, searching of the design space (exploring alternatives), examining existing artifacts and designs, and whether iterative design methodology was used during the design process. The evaluation of the design elements (*ibid.*) across the body of literature indicated that problem representation, iterative design methodology, and exploring alternatives were reported frequently in the works as being significant for good design. Graphical representation such as sketches, constraint exploration, redefinition, and validation, examination of past designs were also found to be significant to producing good design, albeit they were reported at a lower frequency in the literature. Functional decomposition was determined to possibly be significant for good design.

The results that follow will present the survey and interview results and notable findings. It will examine the design elements mentioned above for engineering design teams and their importance on design performance. The design elements importance will be determined through determination of

correlation between teams performing a particular activity and their rank in the competition.

Overall, students and mentors gave similar responses. There were only a few statistically significant differences between response rates and even those effects were minor. Therefore we collapse the student and mentor data together. Unless otherwise state, it should be noted here that for interviews only correlations greater than the Pearson correlation coefficient of 0.33 for 34 responses and $p=0.5$ were reported. Similarly, only correlations for survey results greater than the Pearson correlation coefficient of 0.255 for 58 responses and $p=0.05$ are reported. Also, a lower number for rank is better and so negative correlations imply that a design activity has a positive impact on design success.

4.1. Problem representation

The problem representation design criterion refers to the approach designers take to frame the design task or problem. It refers to how they explore the problem and develop a definition of the task that needs to be solved. The construction of the design task has an impact on how the solution to the design task evolves since the task definition will stress certain solution approaches over others.

In the current investigation we focused on metadata regarding the problem formulation and representation i.e. what approach they used to pick the tasks the robot should perform, the design goals and the key issues they had to make decisions on regarding the design.

Approach for picking which tasks to focus on when building robot

Most teams picked the task the robot would focus on based on a strategy that would result in scoring the most points. The task 65% of the teams focused on involved snagging the ringers on the spider legs of the rack, which is a highly offensive task unlike the defensive task of elevating the robots.

Key design issues to focus on prior to building prototype

Time (24%), weight (26%) and performance (15%) were cited as the main design issues. A small percentage of respondents (9%) cited simplicity as a key design issue. Teams citing simplicity as a design issue exhibited a negative correlation (-0.33) with rank, indicating that simpler designs that perform the

required task are associated with better performing designs.

4.2. Explore graphical representation and visualization

Designers represent different aspects of a design through graphics or visual media in order to communicate ideas, as a means to contrast with a verbal representation. Graphical representations also serve to quantitatively represent a design through geometry, such as through CAD, and to explore overall design configuration.

Sketching

Ninety-four percent of respondents used sketching, with 50% using sketches in the first two weeks of the design process and 43% of respondents saying they used sketches throughout the design process.

CAD

In the survey, an overwhelming number of respondents, 84%, said they used CAD for purposes of layout planning, complete robot design and kinematics. An even higher percentage of interview respondents said they used CAD (97%) primarily for the purposes of visualization (40%) and dimensioning (22%). A smaller proportion said they used it since it is easier than prototyping (16%), for machining (15%), and kinematics (10%). An interesting result is that CAD, when used for planning the design before prototyping and for kinematical studies, had a negative correlation of 0.33 with rank. This could be on account of the fact that the teams using CAD for these purposes had a greater certainty of generating successful designs since the design issues would have been identified and rectified during generation of CAD drawings and through simulations.

4.3. Functional decomposition

Functional decomposition is the breaking down of the complex aspects of the design into smaller, manageable units. This allows for easier investigation of the design problem.

Functional units of the robot

Most respondents (51%) used their engineering judgment in order to decide what functional units were important in order to achieve their goals. Teams that kept their design strategy in mind (see Section 4.1, approach for picking tasks) in order to generate the functional units of the robot was the next

commonly used approach. This approach exhibited a correlation of -0.26 with rank, which while not quite reaching the threshold of -0.33, came the closest of the different methods to being statistically significant. Voting was a relatively infrequently used selection method for determination of functional units of the robot (12%).

4.4. Exploration of engineering facts

Exploring engineering facts refers to studying the specific domains of knowledge that are pertinent to some property or behavior of the design. Awareness of the different areas and its principles will ensure a more successful design. Engineering facts are also important when it comes to understanding what assumptions are reasonable to make when developing a design. Examination of greater areas of additional learning such as physics, engineering, mechanics, more types of outside expertise consulted, and whether more areas of knowledge were understood by a team did not show any correlation with rank outside that of chance.

Engineering and materials specialists were the most consulted followed by robotics.

4.5. Exploration of scope of constraints and redefinition of constraints

Constraints present a limitation on the form the design can take. Constraint exploration allows the designer to assess the implications of different constraints on the design factors. Redefinition of constraints is necessary in the event that a given design instantiation does not satisfy the constraint. In this circumstance either the constraints can be redefined or the design instantiation can be changed to satisfy constraints.

Time taken for constraint exploration:

Forty-one percent of respondents said that they evaluated constraints in the first two weeks of the design process, while 21% said it was a process of constant review.

Constraints

Most constraints arose from those imposed on the design from the competition rules and regulations. However, of the user defined constraints, teams that had robot strength as one of their constraints exhibited a negative correlation with rank (-0.34).

4.6. Validation of assumptions and constraints

Not all designs generated by a design team will satisfy the design goals and constraints. It is important to test the designs in order to confirm that the constraints are satisfied. There are numerous ways to validate, and hence select, a design. For example, it can be done on the basis of computer simulations, performance of mock-up models or prototypes. Results of mathematical models that are formulated as equations involving the design variables and reflect the behavior and functionality of the design can also be used for the validation activity.

In this study we examined the usage of mathematical models and mock-up (pre-prototype) models by design teams.

Mathematical models

Mathematical models can be used for initial fact checking to verify whether a design would work as intended. Interview results showed that 68% of respondents said their teams used mathematical models. This was consistent with survey results, in which 69% of respondents said they used mathematical models. The survey results indicated that using mathematical models had a correlation of -0.31 with rank. Interview results exhibited similar behavior though the correlation of -0.23 was above the threshold of -0.33. This indicates that using mathematical models will result in better design performance. Using mathematical models is a predictor of success.

Most teams used mathematical models for kinematics (21%) and drive train or gear ratio (28%) calculations.

Mock-up models

Respondents reported in interviews that 50% of them built mock-up models for components or partial designs of the robot and 28% built mock-up models for the complete robot. Building complete mock-ups for the robot exhibited a correlation of -0.34 with rank. This seems to indicate that each stage of examining and validating the design (mathematical models → mock-up models → prototypes) results in design improvements and elimination of faulty designs. Hence, success is more likely on account of the feedback that the designer gets because the feedback permits for corrective actions.

4.7. Searching of the design space (exploring alternatives)

Design has been considered by Simon (1996) as a goal directed heuristic search process in which goals are not necessarily fixed. In design it is important to examine different design alternatives to find out which of the candidate configurations will meet the design requirements. We examined meta-data related to the design space search process and techniques used to select candidates from the set of design ideas.

Time for idea generation:

Both the interview and survey results reported, within statistical limits, that 75% of teams took ten days or less to generate ideas, which is about 23% of the allotted time. Time taken to generate ideas did not have a bearing on rank, and hence, design performance.

Number of ideas generated

For the interview data regarding the number of ideas generated, it was found that there is a sweet spot for number of ideas generated per design task that the robot has to perform, though at this stage we cannot comment on an exact number of ideas. For 4-6 ideas generated per task there was a negative correlation with rank (-0.37) i.e. design performance but when 10-12 ideas were generated per task, there was a positive correlation with rank (0.33). A similar observation was made in the survey results where a trend was observed of negative correlation with rank for 3 – 5 and 5-10 ideas but when 11 – 20 ideas were generated per task the correlation with rank was positive. However, the correlation values were not above the Pearson correlation coefficient threshold values for the survey results.

It can be concluded that generating too few or too many ideas does not lead to good design since too few ideas leads to singular solutions, and too many ideas can lead to lack of focus on a particular solution.

Selection of design ideas from a pool of design candidates

A number of different methods were used by the teams for selection of ideas. A summary of the methods used for selecting and discarding design ideas from the encoding of interview results is given in Table 1(a) and 1(b) respectively. Table 2 provides the results from the survey. Note that the numbers possibly add up to more than 100% since teams could have used more than one method for design

selection. Also, some teams did not respond to the question in which the numbers could total to less than 100%.

Table 1(a): Method used for selecting design ideas (Interview results)

Method	Percent of respondents using method
Simplicity	16%
Vote	41%
Engineering judgment/ gut feel/ past experience	32%
Prototype performance	26%
Decision matrix	7%
CAD/ Simulation	9%
Other	4%

Intuition (engineering judgment etc.) seems to be a fairly common approach for selecting designs. While this could be a suitable method for experienced design team members, it will be important to study the differences in quality of design decisions between novice designers and experienced designers when using engineering judgment, if any. It would seem likely that a tool that allows novice designers to make more informed decisions will result in higher rates of “good” design that are at par with experienced designers.

Table 1(b): Method used for discarding design ideas (Interview results)

Method	Percent of respondents using method
Impractical	19%
Vote	18%
Functionality	10%
Prototype not working as planned	18%
Cost	3%
Time available	12%
CAD/ Simulation	6%
Other	19%

While only 12% of respondents discarded design ideas based on the time available, it was found that there was positive correlation with rank (0.35)

possibly indicating that teams that had to discard ideas based on time available were poor at planning their design process resulting in later stage “fire fighting”.

Table 2: Method used for selecting design ideas (Survey results)

Method	Percent of respondents using method
Analysis based on mathematical models	28%
Intuition or judgment	72%
Emotion/ “I liked it”	14%
Rating method based on votes	52%
Cost considerations	29%
Time considerations	57%
Simplicity	74%
Other	12%

The results from the interview and survey are not completely consistent, as can be seen from Table 1(a) and Table 2. Further study is required to understand this discrepancy.

Analysis models were second lowest to emotion in selecting concepts. As seen in Section 4.6, using mathematical models is a predictor of success. A possible reason for why mathematical models are not used in early design could be because of the lack of tools to quickly model and evaluate designs with incomplete information.

4.8. Whether iterative design methodology was used during the design process

This criterion refers to whether the design process followed by the design team involved a purposeful jumping around through various aspects of the design activities versus a fixed sequential model of design. The non-linear design process will result in interactions between designers, stakeholders and various processes that initiate or structure shifts in activities.

In order to understand the test-evaluate-redesign cycle and to study the reasons for shifts in design activities, we attempted to understand events or assessments and problems that caused design teams

to change their track. The most common problems encountered that spurred design change were the prototype not working as planned (34%) or the design not satisfying the design constraints (21%). The prototype not working as planned was cited as the most common reason for reengineering the prototype (43%), consistent with the previous statistic. The second most common reason for reengineering the prototype was for making design improvements (35%).

In the event that design teams encounter a problem, the most common path to circumvent the problem involved firstly, realizing there was a problem, then understanding why the problem occurred and revising the causative factor to address the design problem (66%). The remaining results are summarized in table 3. Realizing and understanding that there is a problem and then pursuing a new or different design idea to solve the problem showed a correlation of -0.27 with rank. This could on account of the fact that the relatively low complexity of the robot design leaves less scope for fixing a problem, making a new design approach a more judicious choice.

Table 3: Approach to circumvent design problem

Method	Percent of respondents
Realize problem → terminate design	10%
Realize problem → solve problem by trial and error	26%
Realize problem → do nothing to understand problem → pursue new idea	5%
Realize problem → understand why problem occurred → pursue new idea	55%
Realize problem → understand why problem occurred → revise causative factor to address design problem	66%
Other	2%

4.9. Examine existing design/ artifacts

Designers often borrow solutions from designs that already exist and apply them to the design problem at hand. Approximately 86% of respondents said they referenced past robotics related design material, with the intention of reusing an existing idea from an old design (64%) and getting ideas for the current build

season (48%). No correlations of significance with rank were observed.

5. CONCLUSIONS

Design activities having a positive impact on design outcome are summarized below:

1. Making simplicity part of a design strategy
2. Developing mathematical models for the design
3. Generating CAD drawings prior to prototyping

The other notable finding is that too few or too many ideas during the exploration of the design space negatively affect design success.

Future work will involve studying all 15 design activities, ironing out and understanding discrepancies between survey and interview data, verifying the current results and expanding the study to understanding how design teams create and innovate during design.

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