AC 2011-1110: STUDYING IDEATION IN ENGINEERING DESIGN

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Studying Ideation in Engineering Design Education: Application to Highly Mobile Robots

Introduction

Developing innovative ideas as part of engineering design can be limited by the field of technology and the engineer's or design team's understanding of the field. Without sufficient understanding of an emerging technical field, ideation may be hampered by reinventing the proverbial wheel or by a lack of knowledge of the underlying physical principles and state of technology. When starting to solve design problems, designers may not fully benefit from ideation methods alone due to problems such as design fixation [1-6]. Pursuing flawed designs or designs that will underperform existing solutions may likewise occur from the lack of understanding of the field.

Existing research examines supplementing the ideation process as well, such as seeking and using analogies, fostering creativity and examining transformation principals in order to achieve greater innovation [7-30]. These mentioned studies cover important topics and are shown to assist designers achieve improved innovation.

The engineering education research presented here seeks to develop a tool and methodology intended to strengthen a designer's or design team's understanding of a field and relevant technologies in order to foster creative and innovative solutions. A relevant finding in the psychological literature is that individuals who acquire experience with classes of information and procedures tend to represent them in relatively large, holistic "chunks" in memory, organized by deep functional and relational principles [31-33]. Many researchers have argued that this ability to "chunk" underlies expertise and skill acquisition [34,35]. However, if the task at hand requires the individual to perceive or represent information in novel ways, e.g., to stimulate creative ideation in design, representation of that information in chunks might become a barrier to success, particularly if processing of component parts of the information chunks helps with re-representation [36-38].

To accomplish the goal of this research in the context of these findings, first a thorough search must be performed to collect all possible information in a technical field. Data is consolidated in an electronic spreadsheet programmed to ease data management and provide the ability to efficiently analyze design solutions. Critical metrics for the given application are generated and comparative results are plotted. Analysis of the plotted information may lead to understanding existing trends, identifying voids where opportunities exist to expand the design space, as well as general insights into the field leading to more beneficial concept generation sessions and effective use of concept selection tools.

The effectiveness of the stated design methodology and tool are investigated for the problem domain of developing a mobile cave and tunnel exploration type robot. Senior cadets from the U.S. Air Force Academy (USAFA) perform concept generation sessions before and after utilizing the presented tool to understand the existing technology, where the results are examined to determine the impact and utility of the tool in design and as part of engineering design curricula. A second experiment is also conducted with graduate students from The University of Texas (UT) at Austin to further analyze the effectiveness of the tool on quantity and quality of the concepts generated. These experiments aim to demonstrate that state-of-technology design tools provide an effective foundation and platform for designers to generate a larger quantity of concepts, with higher quality and novelty. There exist significant implications on engineering design education from this process. For example, the systematic mapping of the state-of-the-art in a field is an important learning objective and skill to be nurtured in our engineering students as they explore and solve design problems.

Background

Techniques to foster creativity have long been researched. One of the most popular methods is Osborn's brainstorming [39] though hundreds now exist [40]. Another pioneering technique is Brainsketching, attributed to Rohrbach [41]. Both these techniques aim to aid individuals or groups to generate the largest quantity of ideas so that solutions may be pulled from as large a solution space as possible, which is crucial to the designer as the quantity of initial solutions to a problem is correlated to the success of a product [42]. In addition to the fundamental ideation methods, much study has been focused on how to properly administer and supplement ideation. One large area of research is the use of analogies to increase innovation [7,43,44]. Analogies allow connections to be drawn that are otherwise much harder to generate, thus, understanding the psychology behind how persons conceive analogous solutions is beneficial. More specific approaches to supplementing ideation have been examined as well, such as utilizing transformational design principals to increase innovation [45]. The research at hand seeks to understand the influence of a thorough examination of a particular product field on the ideation process. Namely, understanding where current technologies perform, in general and relative to each other, as well as identifying insights, gaps in technologies, and current technological limitations allows designers to see opportunity for new combinations of existing solutions, new applications, or otherwise positively affect ideation.

Development of Design Tool and Methodology

Application to Highly Mobile Robotics

In order to test the proposed methodology of systematically collecting and reviewing existing technology in a field, the proposed methodology is applied to solving a robotic design problem. Among the many uses of robotic systems, there is an increasing demand for them to both increase accessibility as well as remove humans from hazardous or toxic environments or situations. Often applications require robotic systems to possess high traversing mobility. Such applications include search and rescue robots for manmade and natural disasters, intelligence reconnaissance and surveillance (ISR), and exploration (terrestrial or extraterrestrial). These environments provide for challenging mechanical designs for the robotic systems, often with conflicting objectives. Low mass is desirable for portability as well as lower energy consumption, thus lower energy storage requirements which is often a limiting factor. Size may also influence portability, where smaller is desirable but may negatively affect the maximum obstacle size a robot can surmount. This application is thought to serve as a practical, interesting and challenging area, ripe with opportunity for innovation, making it an ideal test bed for the methodology validation. A summary of the derived performance requirements for such applications follows, which sets the goals for participants to try to meet during the validation processes.

Design Problem

The specific design problem presented to the participants deals with the design of a robot to explore an underground cavity such as a cave or tunnel. The access to the cavity will be through a bore hole, roughly 8 inches in diameter. Once in the tunnel, the robot must traverse up to 450 yards along the tunnel, be able to negotiate rubble, rocks, water and mud. Expectedly the most challenging requirement is for the device to negotiate a two foot shear ledge as well as traverse across a two foot crevice. The robot should also be able to return to the point of insertion for retraction to the surface. Additional requirements include a payload carrying capacity (volume) of 4in x 4in x 5in, use a minimum amount of energy and have a low mass to both aid portability and energy consumption.

Empirical Study and Search Techniques

The proposed methodology requires the collection of data for a particular field best accomplished through an empirical study of the field. A summary of the research methodology is shown in Figure 1. Advantages of studying the current state of robotics include minimizing the duplication of previously established technology and identifying gaps in current technology that is yet to be explored. The study of exploration type robotic systems begins by obtaining data from multiple sources including databases of professional societies such as ASME and IEEE and their respective journals and conferences, other scientific journals such as Elsevier, as well as robot manufacturers. Additionally, contacting research organizations seeking initial or additional data helps expand the knowledgebase. Querying the sources to obtain relevant results was done by searching the following categories and keywords: robots and robotic systems relating to ISR, search and rescue, defense applications such as room clearing and perimeter monitoring, obstacle capability and avoidance, climbing, stair climbing, jumping, hopping, and mobility. Interchanging the keywords allows for a larger quantity of search results. For example, results are increased by searching each database for "hopping OR robot", "hopping robot" and similar searches and combinations for the remaining keywords: climbing, jumping, search and rescue etc. Typically, the first 100-200 hits are scanned manually for relevance to the problem, and the relevant articles saved for review. Due to obtaining a large amount of information, it became necessary to systematically record the gathered information in a useful means, which lead to the development of an electronic repository.

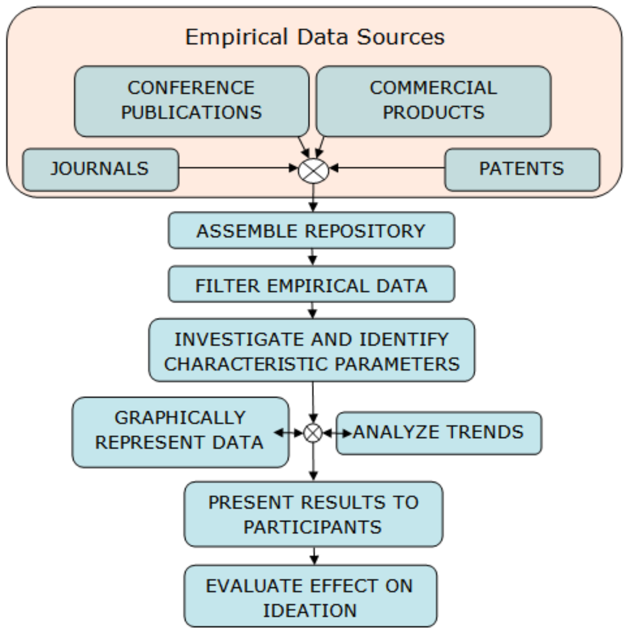


Figure 1 – Research methodology process

Repository Creation

From the results, a software based repository of information is built which aides in the analysis of the information [46,47]. The repository includes information such as dates, people and places involved with the work, the enabling mobility technology and the robot performance specifications. Additions to the repository continue with the discovery of new information or when researchers or developers release new information.

Contents

On reviewing the field, the repository holds data from approximately 70 robotic platforms and consists of the data mentioned above as well as ten raw performance metrics for each device (where available) as well and another twenty derived metrics useful for comparison. Robotic systems consist of locomotive technologies and obstacle negotiating technologies. The existing design space explored results in a collection of robots spanning one legged hopping robots to six wheeled all terrain systems, as well as combustion powered jumping to using momentum to assist climbing. The repository includes a number of plots as they allow for the visual comparison of particular metrics in order to assess the data and gain insights into the field, and will be discussed below. After the creation of several plots, it became clear that organizing the data into two main categories is beneficial: the locomotive technology and obstacle negotiating technology. Allowing for the separation of this information suits the review of metrics that are linked more directly to one metric over the other. For example, desiring to review energy consumption while traversing would apply to the locomotive technology while one would conversely be concerned with the particular obstacle negotiating technology to review how high an obstacle robotic system's technology can surmount. These two main categories consist of 6 and 16 various technology subcategories, respectively.

The subcategories represent the range of technologies discovered, and therefore, the technologies available for comparison and analysis; they are shown in Table 1. Pictures of the devices are shown in Appendix A to help visualize the type of system comprising each group and to understand what a particular technology is, such as the wheg which can best be described as multiple rotating legs but easier to understand visually. Firstly, it is necessary to note that in some instances, the locomotive technology doubles as the obstacle negotiating technology. This is because most locomotive technologies have an inherent ability to surmount obstacles up to a limit. In the case for wheels, the limit would be the radius, for legs or for whegs it may be one half to twice the height of the leg or wheg, for example. The locomotive technologies are the technology a system utilizes for traversing and are self explanatory. Tracked robots are those that use a tread system, similar to a tank, the snake subcategory is for systems that mimic snakes in appearance and motion, VTOL represents vertical takeoff and landing systems (such as a helicopter), thrust devices utilize thrust for locomotion and/or obstacle negotiation, buoyant systems separate systems that are buoyant in air. Systems that have portions that expand, such as a telescoping portion, are categorized together; segmented systems have multiple segments, which may rotate, but if they are able to separate further or closer to each other it would be labeled an expanding technology. Springs and pneumatics systems use either a spring and/or spring with linkages or a pneumatic system, respectively, as an energy system to surmount obstacles. The grasp category is for technologies that can grasp in order to assist surmounting obstacles, whether by hooking or grabbing as such with a human hand. The adhesion category houses systems that adhere to a surface to surmount obstacles; similarly vacuum systems use suction. Van der Waals systems use the said force in order to overcome obstacles, such as natural or synthetic materials mimicking gecko's feet.

Table 1 - List of Technologies Captured in Repository

Locomotive Technologies	Obstacle Negotiation Technologies
Wheel	Wheel
Wheg	Wheg
Leg	Leg
Track	Track
Snake	Snake
Thrust	VTOL
	Thrust
	Buoyancy
	Expand
	Segment
	Spring
	Pneumatic
	Grasp
	Adhesion
	Van der Waals
	Vacuum

Metrics

As mentioned above, the repository holds approximately ten metrics representing raw collected data as well as twenty representing derived values based on raw data, such as the cross sectional diagonal length or power to weight ratios. The majority of the listed metrics relate strongly to the counter tunnel robotics scenario, however, to broaden the applicability of the research as well as for potential future use, commonly reported data is also collected, such as the maximum speed of the robots which is not critical for the research on hand. Not all data sources provide information for all 10 raw metrics, but all available information is recorded when reviewing a particular robotic system. Recording the mobility metrics is critical in order to later compare the relative performance of the technologies and a list of the metrics collected and derived is shown in Table 2.

Initially, one approach considered to increase the value of the metric comparisons is to normalize the metrics. For the given research problem, simply having a high payload capacity, large obstacle height capability or low power requirements is not sufficient to guarantee an acceptable level of performance. For example, even if a particular design overcomes tall obstacles, it is not of use given the specific requirements unless it also has a small cross sectional diagonal. Again, the ability to carry a large payload mass may not be useful if the system itself has a very large mass. Therefore, the goal is to seek systems or technologies that perform *relatively* well as a ratio of their metrics, such as a high obstacle height to cross sectional diagonal ratio. Though utilizing normalized metric is a sound idea, due to holes in the collected data plotting normalized metrics against one another may reduce the information on the charts as well as making interpretation of the information ambiguous and difficult to understand. Working around the lack of plots utilizing normalized metrics is accomplished by examining additional plots that would have otherwise been condensed to a single plot. For example, only one chart is required to analyze mass normalized payload versus size normalized obstacle height, but four may be required with standard metrics including mass versus payload, mass versus obstacle height, payload versus size and payload versus obstacle size.

Table 2 - Recorded Performance Metrics

Performance Metric	Definition
Locomotion Technology	Key technology allowing robot to traverse horizontally
Obstacle Navigation Technology	Key technology allowing robot to traverse vertically
Year	Year the robot was published / made available
Obstacle Height, m	The maximum height of a vertical object a robot can traverse over
Speed, m/s	Maximum Locomotive speed
Mass, kg	Mass of robot
Payload, kg	Maximum additional mass a robot can carry
Original Dimensions, (various)	Dimensions of the smallest rectangular prism that can enclose the robot
Minimum Cross Sectional Diagonal, m	Length of diagonal across the minimum cross section of the enclosing rectangle
Locomotive Power Consumption, W	Power consumed for horizontal motion
Vertical Power Consumption, W	Power consumed for vertical motion

Graphical Representation of Data and insights

The creation of plots allows the visualization of the collected data stored in the repository. Plots may compare any of the metrics against one another and may be used to observe limitations and relative performance against various technologies. Studying the plots and performing trend analysis allows for insights to be made about robots and the associated technologies involved such as current limitations, areas in need of improvement, unexplored design space and the reasons behind the limitations or opportunities. They may also indicate the relationship or lack thereof between particular metrics, and identify expected or unexpected trends within metrics or certain technologies relative to another. Ultimately, study of the data, plots, and trend analysis should lead to the insights that may advance the field. Several specific plots lend themselves to the observation of beneficial insights, which are listed in Table 3. A representative plot is also shown in Figure 2. Explanations of particular features of the plot are provided in the graduate student experiment training session.

Table 3 – Plots and Gained Insights

Plot	Insights
Obstacle Height Vs. Minimum Diagonal	1. Springs produce high obstacle height to size ratios, but limited to small designs
	2. Pneumatics designs can be independent of robot size, i.e. large and small design can be made to surmount large obstacles
	3. Wheels and tracks have small increases in obstacle height capability with increase in size
	4. Some Segmented designs can be made to have high obstacle height to size ratios
	5. Wheels / Whegs / Tracks require additional or complementary technology to surmount relatively large obstacles
Obstacle Height vs. Mass	1. Thrust, Springs, Pneumatics have high height to mass ratios, i.e. can get a given mass over taller obstacle than other technologies
	2. Segmenting can result in >2x higher obstacle/mass ratios
	3. Legs have low obstacle height to mass ratios
	4. Springs are not currently suitable for larger mass applications
Obstacle Height vs. Vertical Power Consumption	1. Instantaneous power can be reduced by spreading work over time
	2. Thrust based designs have large power requirements
Payload vs. Mass	1. Springs have very low payload capacity - innovation required
	2. Tracked vehicles have large payload capacities
	3. Legged designs have high payload to weight ratios
	4. Trust designs have low payload to weight ratios - innovation required
Locomotive Power vs. Mass	1. Tracks use locomotive energy efficiently
	2. Whegs are highly dependent on design, but can be efficient

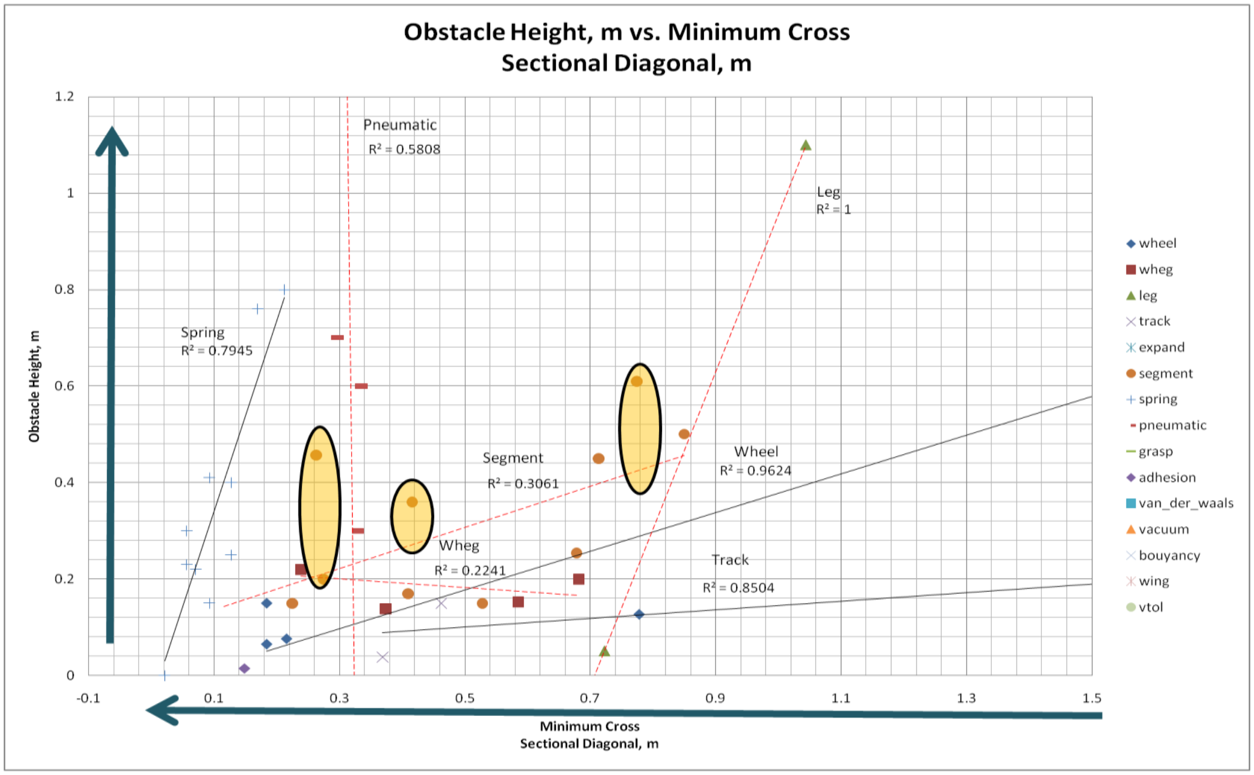


Figure 2 – Representative Plot for Training Sessions

Validation of Design Methodology

Graduate Student Experiment

Hypothesis

The expectation is that when a designer follows the developed methodology in order to understand the relevant technologies, observe the trends and existing design space, and analyze general relative positions of the technologies against critical design metrics, she/he will be able to generate a larger quantity of solutions, be more likely to combine technologies in new ways or otherwise generate novel solutions, and by understanding practical limitations, will generate higher quality solutions.

Participants

The participants for the experiment are master's and doctorate students from UT Austin. All participants have previously been exposed to design engineering concepts either in their course work and/or their research. In particular, most participants will have previous experience with mind mapping and the C-Sketch methods. The experiment is conducted during three one hour sessions with one week between sessions. To encourage participation, a light dinner is provided during each session.

Experimental Method

An experiment is conducted to compare the impact on designers who are exposed to the design tool and methodology. A group of twelve designers is assembled and given a design problem to solve over the course of three sessions. The first session collects solutions that participants form without exposure to the design tool and methodology, the second session familiarizes participants with the design tool and methodology and the third session collects the impact the design tool and methodology has made on the group. For the first session, all participants perform a mind mapping session [48] in the same room so that there is a common starting knowledge of potential design solutions. After the mind mapping session, the group is split into two groups and participants will meet only with their respective group for the remainder of the experiment. During the next portion of the first session, the individual groups perform an initial C-sketch session [49-51] intended to serve as the baseline performance expectation. The second session requires thirty minutes and consists of informing the groups of the design methodology to be evaluated and training them in its use. Groups are given a one week break before rejoining for the third session to perform another C-sketch session to capture the impact the design methodology has had on the participants. The performance of the groups will be determined through examining and comparing the results of each group's first C-Sketch results to their final C-Sketch results.

Procedure

First Session – Combined

For the first session all participants meet together for an introduction to the design problem and to perform a mind mapping session. The facilitator describes the design problem to the participants and distributes a figure (Figure 3) to each participant to help solidify the requirements of the design problem. The facilitator leads the group into identifying all possible technologies available to solve the design problem through populating the mind map. To reduce the amount of time the mind mapping session requires, but to allow the participants to ponder solutions, a partially completed mind map will be distributed on a sheet of letter paper (Figure 4). The facilitator will then lead the group and encourage ideas to be added to the mind map; when an idea is suggested by a member, the facilitator will interpret the idea and suggest the location for all participants to write down the idea or solution on their copy. These activities will be completed in the first twenty minutes of the session and are intended to form a common knowledge base for all participants. The group then divides into two individual groups for the first C-Sketch sessions. The group is split by each participant taking a sheet of butcher paper from a back table in the room randomly labeled with either "A" or "B". Before breaking the assembly into the individual groups, the facilitator reviews the rules for the C-Sketching sessions, which will be identical for both sessions and are: (1) criticism is not allowed, (2) "wild ideas" are welcomed, (3) build off each others' ideas; similar rules to Osborn's brainstorming [40,39].

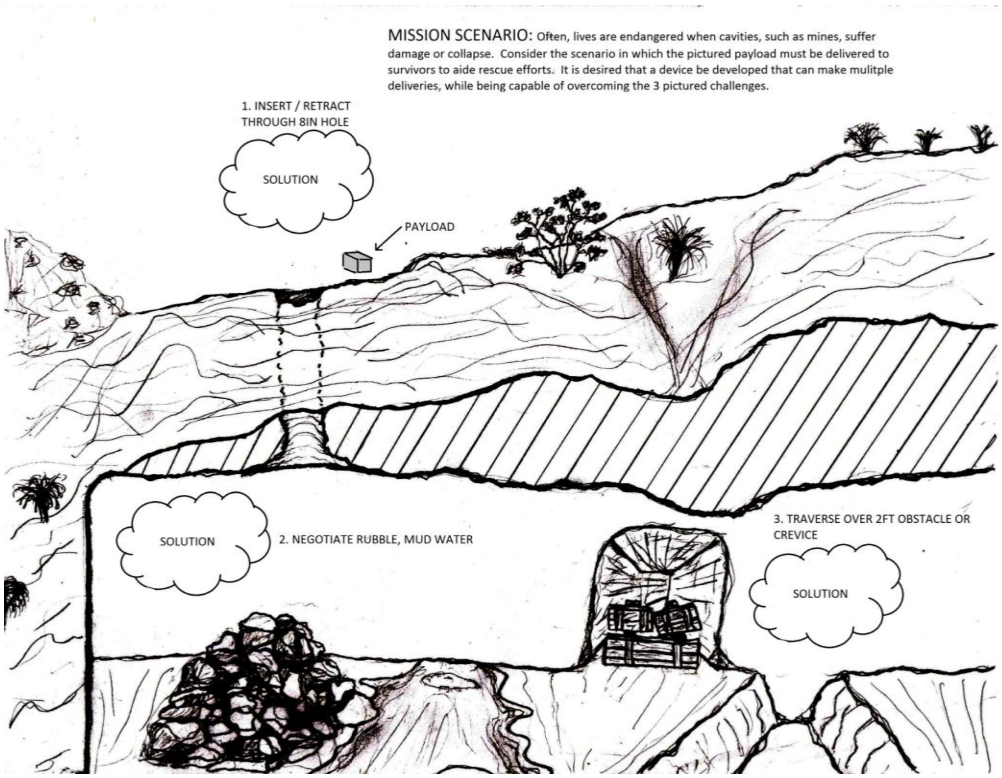


Figure 3 - Figure Depicting the Design Problem

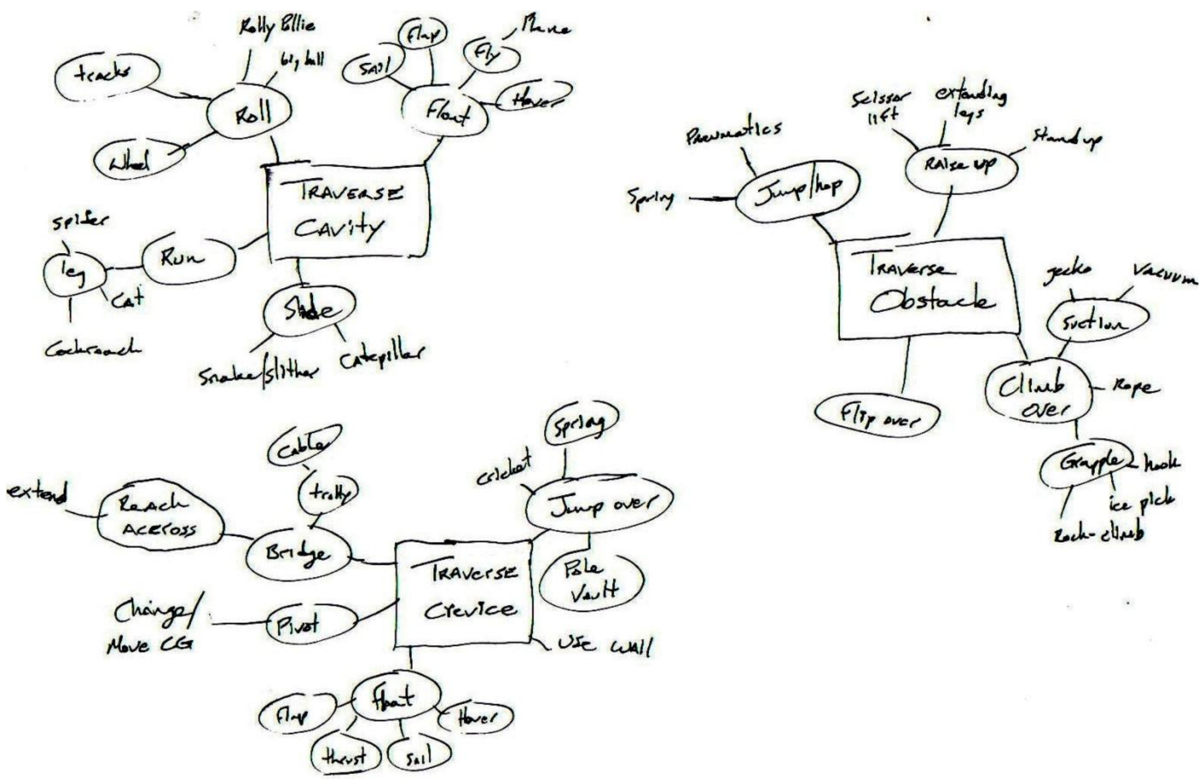


Figure 4 – Partially Completed Mind Map Distributed to Participants

First Session – C-Sketch

After establishing the two groups and they move into different rooms, the first C-Sketch session begins. Short annotations to help clarify a concept will be an allowed variation to the C-Sketch method. To ensure participants understand the level of detail as well as the overall expectation of the session, a printout of a model C-Sketch session will be distributed to each participant. Butcher paper will be provided as well as flow ink pens for the participants to sketch their ideas. Additionally, each participant will have a unique color pen to ease tracking the origin of ideas as well as separating original concepts from addition. The session is run as follows: participants are given 12 minutes total to sketch their three original concepts. The sheets of butch paper will then be rotated 5 times, with 6 minutes per rotation for participants to add onto the original concepts. The facilitator collects all the materials at the conclusion of each session.

Second Session – Training

The second session aims to help the participants understand the technological field and equip them with both tools and an approach intended to increase their quantity, novelty, and quality of solutions. The training session is designed to take half an hour to complete and includes four main focuses.

Training Sessions and Materials

As the methodology consists largely of examining the collected robotic performance information, it is crucial to present the information in a manner that is intuitive to understand as well as accurately represent the relative performance of competing technologies as well as the voids in the design space. Plots were created with several features to ease the interpretation of the information. Trends identified on the plots show where a technology would likely lie across the design space. Trends are shown on the plots as solid lines for R^2 values greater than 0.75, and as red dashed lines for lesser R^2 values in order to indicate their unreliability; however, they are included to indicate the likely trend. Ovals highlight instances where the expected trend was broken. Highlighting the trend breaking technologies is meant to illustrate that novel solutions usually break trends, and are due to new combinations of technologies or redesigns of existing technologies. Lastly, arrows along the axis indicate which direction along the axis represents increasing performance. A representative plot was shown previously in Figure 2. Additionally, including photos of each technology category is meant to help participants visually solidify the nature of each category since the written labels may be difficult to accurately interpret (see Appendix A).

The first five minutes are used to reiterate the design problem along with encouraging the participants to find innovative solutions, mentioning design conflicts found in the design problem and introducing participants to the proposed design methodology. The emphasis on innovation is to help stimulate original thought among the participants, but is also true of the design problem as no known solution fulfills the requirements of the design problem to an acceptable level. Mentioning key design conflicts is done to help participants seek innovative ideas to solving the conflicts when plots are reviewed. The conflicts include two size conflicts, as well as energy conflict. The first size conflict is that the robot must surmount vertical obstacles and crevices up to three times higher or wider than the allowable maximum cross section diagonal of the robot. The second size conflict is that when the payload is placed in the bore hole, there is little room for supporting structure to be placed around the payload. Lastly, there is a conflict with the energy requirements. Maximum service or deployment time requires an increasing amount of energy storage which means an increasing amount of mass. However, decreasing the mass of the robot will reduce power requirements and increase the deployments time. It is also mentioned that increasing the efficiency of the device is crucial in order to reduce power requirements and therefore increase deployment time. Toward the end of the five minute introduction, the proposed design methodology is briefly described.

The second focus of the training takes ten minutes and is meant to review the collected data relevant to the design problem and serve as an introduction to the plots. Participants are introduced to each of the five plots, reasoning for their inclusion, and the use and distinction of log and linear scale. Next, participants are asked to seek certain information found on the charts to increase familiarity. As the trainer and participants review the included plots, questions are presented to the audience for them to ponder and verbally respond. The questions mainly center on asking the participants to review the plots and identify which technologies perform well or poorly against certain metrics, and about apparent limitations of certain technologies.

For the third focus, also ten minutes in duration, the participants are introduced to how the methodology and training materials are intended to be used to increase the quantity, novelty and quality of solutions to the design problem. The two main techniques discussed are seeking combinations of technologies from the data and combining personal knowledge or intuition with the data to form new ideas. The third focus is concluded with an example to show how the data may be applied to a practical problem. In order to showcase how combinations of technologies often results in innovation and in expanding the design space, exemplar combinations are discussed. These exemplar designs include an urban hopper that uses combustion to fill a pneumatic cylinder rather than a compressed gas, a device that utilizes ducted fans to fly over objects using short bursts of energy, and a track-snake hybrid that uses multiple segments to mimic snake-like motion, but utilizes tracks to drive eliminating the difficult control previously synonymous with snake like devices. Next, it is pointed out that including personal knowledge and intuition can be very helpful in interpreting apparent trends as not all trends are necessarily correct. It is also mentioned that there are holes in the data, and some technologies may be misrepresented or completely absent due to lack of data. By imagining where missing data may lie, or where a particular technology trend should lie, it may be possible to spark new ideas. To conclude the third focus, participants are given the following design problem and challenged to seek solutions using the plots and proposed method. The design problem is to seek combinations of technologies (presented or intuitive) that would make for a good bug squishing device which must be capable of jumping over walls as well as carrying a payload of insecticide. It is explained that extra mass is beneficial to ease squishing, and the environment in which it is to be used will have an uneven floor with walls or dividers that the device must overcome. Participants are encouraged to view charts relating mass to obstacle height capability and payload capacity to obstacle height capability in order to find combinations of technologies that would suit the design need.

The last focus is a five minute conclusion to highlight what is expected of the participants regarding the use of the tool for the third session and key points of the training. Participants are encouraged again to seek combinations of technologies shown on the chart as well as personal knowledge of shown or unrepresented technologies in order to form new solutions to the design problem. Additionally, participants are instructed to seek these combinations or new ideas instead of repeating ideas they recall from the first C-Sketch session on the second C-sketch, but that it is allowed to reuse an idea from the first session if they think of a way to alter or modify the idea in a way that significantly increases the performance of that idea.

Third Session – Final Mind Map and C-Sketch

The format of the third session is much like the first, but the groups are separated for the entire third session. There is a 20 minute mind mapping session for each individual group, followed by a 40 minute C-Sketch session with a 12 minute initial sketching period, and 6 minute rotations. A scan of the final mind map from the first session is printed and distributed on legal size paper to give participants more room to record new ideas. Participants are again led by a facilitator and are encouraged to completely verbally explore the design space. The facilitator again interprets the vocalized solutions and suggests a location for the participants to write the suggestion on their mind map. Upon conclusion of the mind mapping session, the groups perform the final C-Sketching session. Materials are then collected and analyzed by the primary researcher.

Evaluation of Results

Metrics

In order to interpret the results and determine the effectiveness of the design tool and methodology, the solutions are quantified in regards to quantity, quality, and novelty. Analysis techniques are similar to Lindsey's adaptation of several methods as previously developed my Shaw. [51,52].

Quantity

Measuring the quantity of ideas serves as a useful means to determine the tool and methodology's effectiveness as the quantity of unique solutions has been shown to be crucial in the success of product development [42]. Defining the total number of single ideas based off hand drawn sketches can be a difficult task to standardize. Utilizing a method adapted from Shah et al. [49] by Linsey et al. [40] allows for the quantity to be defined. The rules for defining a single idea are summarized in Table 4. Prior to evaluating the C-Sketches for quantity, a function list is generated, and, in general, the number of functions a given concept fulfills represents the number of ideas that the concept represents. The list may be modified as reviewing the concepts may lead to a more comprehensive list then initially created.

Table 4 – Rules for Counting Single Ideas

1. An idea solves one or more functions in the functional basis
2. The same idea (or component) being used in multiple places counts as one idea
3. Each idea counts as only a single idea even when solving more than one function
4. New Combinations of already-counted ideas are counted in a separate measure
5. Categories of ideas only count as ideas when no subordinates are given*
6. Ideas count even if they are not needed or cause systems not to function
7. Ideas must be shown and not implied
8. When an idea reframes the problem, they are placed in a category called "Problem Reframing" These ideas may not address the problem but meet higher level customer needs a. These ideas do not typically fit a defined function well b. They must add a function to the system c. They count as an idea if they produce a product different than the original customer needs
*If a general pulley and a timing pulley are given, it counts as one idea as one is a sub-type of the other

Comparing the quantity of ideas the teams produce before and after exposure to the methodology indicates whether or not the method has a positive impact on the participant's ideation process.

Quality

One aspect of the hypothesis is that reviewing existing technologies, and seeing a physical comparison of their performance data relevant to the design problem will help designers generate new ideas that are of higher quality, thus, more useful to solving the problem. In order to measure an abstract idea quantitatively, quality is measured similarly to Lindsey [52] by applying a variation of a Likert scale summarized in the flow chart of Figure 5.

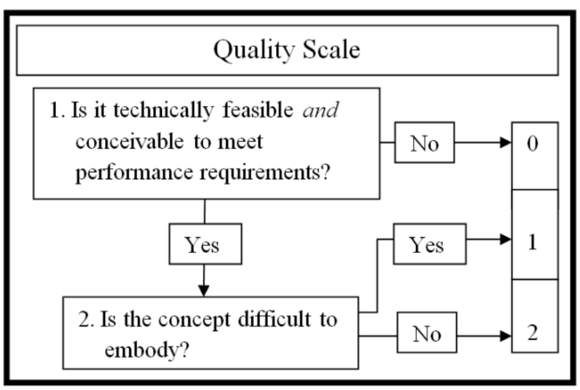


Figure 5 - Quality Scale Flowchart

If the concept is thought be technically feasible, meaning known to the designer to be both realistic in applications of known technologies as well as manufacturable (regardless of cost) then the concept receives a minimum quality value of 1 but possibly 2 if the concept does not seem overtly difficult to actually embody and prototype. If the concept is not considered technically feasible by the designer, the concept receives a value of 0.

Novelty

Often the trend breaking and high performing solutions are unique solutions, so another metric chosen to evaluate the effectiveness of the design tool and methodology is Novelty. Novelty is measured as a function of variety. As in Linsey's work [52], the variety is calculated by having a rater group similar solutions into bins, the more a group spans the total number of bins with their concepts, the higher variety score they receive. Calculating the novelty is done by applying Equation 1 which is Jansson and Smith's measure of originality [1]. Novelty scores are calculated for each bin in which a concept lies, and averaged for each team and session.

$$Novelty = 1 - frequency = 1 - \frac{Number\_of\_Similar\_Concepts}{Total\_Number\_of\_Concepts} \qquad \text{Equation 1}$$

For this work, the total number of concepts will be the number of bins created when all concepts from both C-Sketch sessions and both teams are sorted and grouped; doing this is meant to create the largest design space for the relatively small experimental population. The number of similar concepts is the number of bins the concepts from a particular session form. To evaluate whether novelty increased or decreased as a result of the exposure to the design methodology, the novelty value for a team's third C-Sketch session will be compared to each team's first C-sketch novelty value.

Cadet Exposure

Presentation of Design Tool

Cadet exposure to the design methodology follows an initial 6-3-5 concept generation technique to generate solutions to the robotics problem. Presentation to the Cadets serves to evaluate if detailed knowledge of the field, presented in graphical format to ease comparison of technologies and the design space, can increase the number of solutions as well as the quality of solutions. Cadets were given instruction to the use of the trends and insights from the data were discussed.

Cadet Use of Design Tool

When the tool was implemented, cadets had previously generated over 100 solutions. The first use of the tool was for the various technologies represented in the tool to be reviewed by groups of cadets. Each group reported on their respective findings and discussed what they thought would be beneficial to solve the design problem, and from these discussions the cadets discussed ideas that they would be interested in pursuing. Cadets also used the tool to research and expand on initial concept generation ideas by circulating existing sketched design solutions and adding new ideas which had resulted from reviewing the tool data. Using appropriate plots, cadets ranked technologies based on mobility capability by using tool data. The ranking served to rate existing conceptual solutions and assist in concept selection.

Validation Results

Graduate Student Experiment Results

The C-Sketching sheets from the graduate student experiment were examined and the quantity, quality, and novelty quantified based on the method presented above. The numerical results are shown below in

Table 5. Team A shows a 36% increase in ideas after exposure to the tool, a 17% decrease in the quality score, and a 17% increase in novelty. Team B's results conflict with team A's showing a 21% decrease in ideas post tool exposure, a 10% increase in quality score, and virtually no change in novelty score.

Table 5 – Graduate Validation Experiment Results

Experiment Results						
Team	Quantity		Quality		Novelty	
	Session 1	Session 2	Session 1	Session 2	Session 1	Session 2
A	42	57	1.28	1.06	0.830	0.971
B	57	45	1.17	1.28	0.971	0.975

Cadet Exposure Results and Perception

Cadets developed a numerical ranking system for mobility, based on data represented in the plots, to assist in concept selection. Wheeled robots received a score of 0, whegs 1, threads -1, and airborne devices at 2. Whegs had initially been an idea the cadets were pursuing, but reconsidered after concluding their inability to clear sheer steps would be problematic. Tracks, airborne, and extending push-rod type solutions for obstacle negotiation and mobility were ruled out as well after proposed solutions to increase their mobility were ruled infeasible or too unpredictable to provide reliable performance in the operating environment.

Cadets then narrowed their findings down to fourteen ideas they felt were best by reviewing relevant charts showing historical performance for the various technologies. Information from the tool was utilized again to determine the strengths and weaknesses of each concept, and the top three choices were chosen from the final fourteen. Cadets felt the analysis led them to climbing type devices which would provide a more stable platform to pursue through prototyping and testing.

Cadets felt that overall, the tool was easy to use and the graphs provided good data analysis. The graphs helped optimize designs by selecting the best technology, as well as providing a feasibility analysis on how certain technology would perform. They did report that a lack of data may have hindered more detailed analysis. They also felt the tool did not promote innovation, but rather represented technologies as being pigeon-holed, instead of revealing limitations to be improved upon.

Discussion and Conclusion

Graduate Study

Results from the experiment are mixed as quantity and quality are shown to both increase and decrease with exposure to the design methodology. Group A shows that exposure may lead to an increase in novelty, but group B demonstrates that it is also possible to produce good novelty without exposure. Several additional conclusions are drawn upon further non-quantitative analysis completed to help interpretation of the results. Since quantity only considers non-redundant ideas, the average ideas per sheet including redundancies is calculated in order to determine if exposure increases combinations of identical ideas on various concepts, or potentially more hybrid concepts. This was not found to be the case as the quantity of ideas per sheet follows the same trend as quantity of ideas. The number of ideas unique to the first and second C-Sketch sessions was also evaluated. Combining results from both teams and both sessions, there are 120 total ideas. Of these total 120 ideas, 31 relate to session 1 and 38 to session 2, and 51 were shared between both sessions meaning they are likely independent of the design tool. It is noteworthy that the majority of the unique ideas related to the 2nd session were refinements made to existing ideas in order to make them more feasible; this does not mean the concept as a whole increased in feasibility, however. For example, 10 of the 38 unique ideas were various refinements of the idea to transport or creating a portable bridge or ladder to traverse obstacles. It is difficult to attribute the refinements to exposure to the tool, idea loitering time, or other sources. The cause of a decrease in quality in team A was evaluated as well. It is concluded that the cause of the decrease is due to the complexity of ideas increasing in the 2nd session, thereby containing more concepts that earn a “1” quality score instead of “2” because they become considered difficult to embody, but not necessarily decreasing the likelihood the concept could lead to a successful product.

Most notable is the result on quantity. Lindsey shows that the number of ideas generated drastically reduces over time by tracking the generation of ideas during 6-3-5 sessions [40]. The effect of the proposed methodology on increasing the quantity of ideas and likelihood of success is very positive in that participants were able to match their number ideas in the second session, after exposure to the methodology. This strongly suggests that the methodology was successful in spurring a new surge of ideas to the same design problem, where typically, participants would be exhausted of ideas following a 6-3-5 session.

Cadet Work

Cadets found the tool to be useful as a means to compare and rank concepts to aid selection for further work, as well as bringing additional ideas to existing concepts after reviewing the field. However, the tool was not received as intended, as an aid to encourage innovation. This perception highlights the need for a more strategic approach to presenting a particular group with both the method and tool. Collected data can certainly show limitations for existing technology, as well as holes in the design space that will, if explored and filled, present breakthroughs for the current state of technology. However, the presented methodology may need considerable refinement to help serve as the connection between identifying the limitations and gaps and recognizing feasible solutions.

Future Work

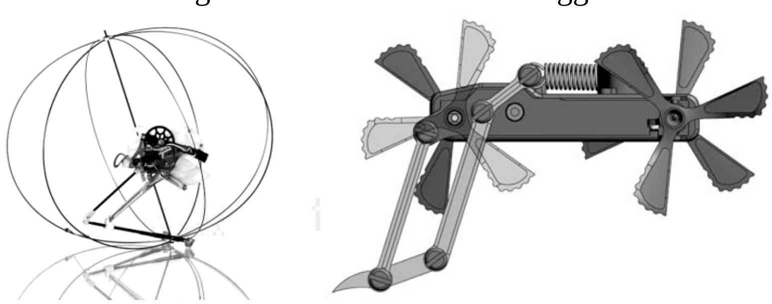
A greater population of participants is necessary in order to verify or counter the results that have been observed and discussed so that the results would be more statistically significant and less ambiguous as to whether the particular method of reviewing the technical data of a field helps the ideation process. Further, there are a number of factors whose influence are difficult to isolate. One large unknown is if having the design problem linger in participants minds for one week or more influences results as well as the presentation of new data. One way this unknown may be controlled in the evaluation of the design tool would be to utilize a control group who does not receive the tool data and training but has similar C-Sketch sessions as the groups who receive the training. This would allow for the observation of the effect time has on solving a design problem with respect to the mentioned metrics. Inter rater reliability analysis will also be conducted on existing and future data sets to provide a higher level of confidence in the results.

Additionally, the way in which the information in the electronic database is presented as well as the intricacies of the mateerials and presentation used in both training and introduction to the design problem can easily fixate or lead the participants and if a greater population will be utilized to examine the methodology these variables should be standardized and monitored closely. Also, for future experiments, it is preferable to eliminate the partially completed mind map and, instead, have participants generate a complete mind map from a clean slate. Lastly, as with any human science experiment, effects such as social loafing, and personality dynamics, such as participants feeling they are performing better or worse than actuality [53,54], may be beneficial to monitor.

Appendix A

Photographs of representative technologies

Row 1 – Segmented tracked robot / Legged robot



Row 2 – Legged spring hopper / Whegged spring hopper

Row 3 – Thrust robot (VTOL) / Pneumatic wheeled hopper

Row 4 – Miniature whegged robot / Snake-track hybrid robot

Row 5 - Segmented tracked robot / Whegged robot / 2 wheeled robot

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