Evolution of Design Concepts from a Highly Successful Graduate Student Design Team

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***Abstract*— This research paper describes the concept evolution of a student design team's early design process as they participated in NASA's 2021 BIG Idea Challenge. The team and final design concept began as a course project that was accepted by the BIG Idea judges and led to the filing of a patent application. The BIG Idea Challenge addressed the high-risk issue of lunar dust mitigation, requiring the team of student engineers to design for an environment in which they had no previous knowledge or experience. An analysis of the students*' use of design tools and methods* that led to this successful design result in the context of a difficult and unknown problem, as well as the pedagogical framework within which the methods were taught, can be instructive for design course pedagogy and for guiding design methods in the industry. An analysis of design team documentation required by the course and digitized for team-sharing during the COVID pandemic produced a detailed understanding of the concept generation, evolution, and selection process. The structured application of multiple concept generation and refinement tools, including 6-3-5, TRIZ, and bioinspired design, allowed for the student to explore a wide range of solutions, and contribute meaningful improvements to their leading concepts. Additionally, extensive background research conducted before and during the concept generation phase enabled the design team to incorporate existing technologies in novel form factors. The final concept selection phase also included multiple consultations with experts and a critical analysis of the lunar environment to ensure that the team might be best positioned to have their product considered for implementation.**

Keywords*— *Design Competitions, Innovation, Mechanical Engineering, Product Development, Student Experience

I. Introduction

The purpose of this study is to draw results from a successful design project that was conducted in Fall 2020 as a part of a design class at Georgia Institute of Technology. The project focused on NASA's 2021 BIG (breakthrough, innovative, and game-changing) Idea Challenge [1], which prompted student teams to provide solutions to problems posed by lunar dust. The design team that is the subject of this study developed a novel concept for a dust mitigation device that was selected by the competition judges for continued development of the concept, eventually leading to a patent filing. Due to the success of the project, the plentiful documentation of the concept generation and selection process, and the authors' involvement in the design process, it is of pedagogical interest to understand how the design team made use of the tools and methods taught in the course to produce the final concept.

This paper begins by providing background context on the design competition, project, and student team and then presents a participatory, retrospective analysis of applied design methods, student behaviors and collaborative decision making. Because of the breadth of ideas explored, the analysis focuses primarily on the tools, methods and selection process that led to genesis, adaptation, and selection of the final concept. There is then discussion on the team's lack of knowledge regarding the technical details of existing dust mitigation techniques and how that ignorance in the context of specific pedagogical decisions, combined with the variety of tools used, may have enabled further innovation.

A. Participants

This study entails a participatory retrospective analysis of a design case, from the perspective of two participants in the course, from two different roles. The first participant-author, designated Author-Participant 1, was part of the design team that consisted of two doctoral and three master's level mechanical engineering students enrolled in a graduate level design course.

The second participant-author, designated Author-Participant 2, designed and taught the course, which they have taught at the graduate level for the previous 10 years. The course was taught in the usual manner, modified for COVID, without consideration of this retrospective study. The method of study is discussed further in section III.

B. Project Based Design and Associated Methods

The design process was structured and guided by Author-Participant 2 and included 8 mandated design methods that student design teams were required to use. The 3-stage design process of study took place during a one-semester course, and included a background research and problem definition stage, then a concept generation and selection stage, and finally a proof of concept and concept refinement stage. Multiple assignments were required and collected as part of the regular course process, including reports at the conclusion of each design stage. An important pedagogical choice made for the course was the restriction of eliminating ideas early, thus encouraging the expansion of the design space. Prevention of early idea

TABLE I. COURSE MANDATED DESIGN METHODS

Method	Goals	Reference
Individual Idea Generation	Obtain initial ideas and concepts from individuals before application of other methods.	
Analogous Domains	Consider other domains to seek existing solutions and expand solution space	
Mind Maps	Document linking of ideas to aid in exploration of solution space	[2, 3]
WordTree	Follow linguistic connections to seek out analogous domains	[4, 5]
BID Methods (AskNature & Biothesaurus)	Use database of biological structures to inspire new ideas	[6, 7]
TRIZ	Overcome design conflicts using structured approach	[2, 8]
SCAMPER/CREATIVITY	Modify existing designs using structured approach	[9]
6-3-5	Enhance group brainwriting using structured approach	[2]
Morph Matrices	Determine alternative approaches to meet functional requirements through functional decomposition	[2]

elimination was done by each assignment requiring students to generate a minimum number of ideas for a given method. Students are also taught that it is common to generate a reasonably good solution within the first handful of ideas, but it generally takes 50 to 60 ideas or more to obtain high-quality, novel ideas that are extremely effective in meeting design needs. Throughout the idea generation phase, emphasis is placed on quantity, not quality, and on avoiding evaluation at this phase of the design process. The course mandated design methods are summarized in Table 1 and presented with greater detail in the following paragraphs. The order in which the methods are presented is the same order in which they were taught in the design course.

Individual idea generation is an unstructured method by which individuals think of concepts on their own. It was encouraged as the first method in the ideation process, immediately following the problem definition stage.

Using *Analogous domains* designers seek out similar settings to the one in which they are designing for and explore that similar setting to gain inspiration for new designs. This was included in the team's individual idea generation process and can also be found through the WordTree method. While analogous domains that are sought are often technological in nature, this is not a requirement. Biological and social domains are frequently considered.

Mind maps are graphical tools that use diagrams to represent ideas linked around a central concept, aiding in the documentation of brainstorming sessions. The technique clusters ideas into hierarchical groups, using the fact that ideas in memory are linked by association. Mind maps are useful in organizing information by visually mapping relationships, which improves understanding of the design problem [2, 3].

The WordTree method makes use of linguistic connections between functions to expose analogous domains for exploration. They can be generated intuitively, from the designer's own vocabulary, or using databases. Intuitive word trees tend to span a narrower range of domains but act as a useful thinking exercise for the designer to further probe their own knowledge. Database-driven word trees tend to be much broader, allowing for farther reaching analogies that the designer might not have considered, but can provide too many or useless suggestions [4, 5].

Biologically inspired design encourages and supports the exploration of biological domains. AskNature and Bio-thesaurus are online databases that support bioinspired design (BID) by reducing the need for the designer to have a broad content knowledge of biological systems. They provide easily digestible cross-domain information on biological sources that many engineers lack [6, 7].

TRIZ/TIPS assists designers in overcoming conflicts within their engineered systems by suggesting various design principles [2, 8].

SCAMPER and *CREATIVITY*, collectively referred to as Checklist methods, provide direction on possible alterations to a design to encourage creative thinking and uncover beneficial design modifications through checklists of words intended to spark ideas [9].

6-3-5 is a group idea generation method where teams quickly obtain feedback on sketches of their concepts [2]. Due to COVID, the team conducted 6-3-5 asynchronously with scanned documents instead of synchronously with sketches. The subjects of this study used this method in an unintentional way, modifying existing design concepts instead of generating new ones.

Morphological matrices are tables that help break down the functions of a design to then encourage seeking other approaches or methods to accomplish those functions [2].

C. NASA 2021 BIG Idea Challenge

The NASA BIG Idea Challenge is an annual design challenge organized by the National Institute of Aerospace (NIA) that tasks student teams at universities across the US to solve difficult problems on NASA's horizon [1]. Teams develop proposals detailing their design concepts and development plans. A panel of NASA scientists and engineers along with two other experts select the top concepts to receive funding and enact development plans.

For the 2021 program, student teams were tasked to address problems that lunar regolith dust poses to future missions on the lunar surface [1]. Lunar regolith dust (referred to as lunar dust) is incredibly abrasive and easily adheres to surfaces. Mechanical joints exposed to lunar dust rapidly eroded, spacesuit fabrics from the Apollo missions experienced dangerous levels of wear, and radiators coated by lofted lunar dust particles degraded in performance [10, 11]. The specific issue that the design team focused on was the risk that lunar dust posed to astronaut's spacesuits.

D. *Relevent Dust Mitigation Technologies*

A short definition of key technologies referenced or used by the design team is provided to scaffold understanding of the analysis to follow.

1) *Electrodynamic Dust Shielding (EDS)*

One of NASA's most mature technologies for lunar dust mitigation [12], EDS applies alternating electric fields to a surface to repel small lunar dust grains using coulombic and dielectrophoretic forces. The electric fields are created by patterning thin, narrowly spaced, alternating electrodes across a surface and applying a high voltage alternating signal that can remove up to 90% of dust from a surface in seconds [13]. Applications include solar panels, optical equipment, and thermal radiators [14] with recent advances to incorporate the technology into spacesuits fabric [15].

2) *Photoelectric charging and lofting of dust grains*

Another approach for lunar dust mitigation is the bombardment of dust grains with radiation [16]. Working on similar principles to EDS, incident radiation imparts a higher charge to exposed dust grains, causing them to repel from other dust grains [16]. This method takes longer than EDS and often requires a slanted surface so that the charged dust grains move in a bulk predicted path [17]. At the time of the design project, the first usage of higher powered electron beams instead of UV radiation for photoelectric charging was being documented [18], leading to the team's mixed understanding of the technology.

II. METHODS

Studies of design cases in which the researchers are also participants in the design case, as with other participatory ethnographic methods, can provide unique perspective and insight into the design process. For proper interpretation of such results, however, the nature of the participation and the design goals must be clear. The dimensions of analysis for participatory design studies proposed by van Oorschot et al provide a set of dimensions to characterize participation specifically within the design context [19], and will be applied to the two author-participants in the design. These dimensions include primary perspective, context, condition, process and consequence.

The *primary perspective* of the research team is that of a main participant. The design process of the student team was a collaborative process and Author-Participant 1's experience provided reflection and detail that would otherwise not be accessible as an observer. Likewise, Author-Participant 2 guided the process as an instructor, thereby shaping the trajectory and outcome of the design.

This research's *context* is described as an analysis of a process's design, methods, and tools. Though instruction was not altered in the service of this research study, which was performed post-hoc, the control that was placed over the design process by the existing pedagogical structure of the class provided for both retrospective and introspective post-hoc analysis on the use and combination of design methods. The researchers analyzed and reflected on the implemented practice of design methods in the environment of the design course, through the lens of understanding that the result of the design process was successful. Secondarily, we note the goal within this context is to advance understanding of design practice.

Along the *condition* dimension, the Author-Participant 1 participated in a designing role, while Author-Participant 2 as a course instructor, participated in a facilitating role. Reflective analysis made use of design materials produced within the design role, in a course developed and structured by the facilitator. The research condition is additionally described as a single case since only one student team was analyzed in this study.

The *process dimension* of this study is a case-study side with a large quantity of design artifacts available for analysis, though it also exhibits auto-ethnographic qualities, as some research findings were only uncovered through reflection of the participating authors.

Lastly, the *consequences* of the knowledge uncovered by this analysis are externalized, which is to say the research results are intended for an audience beyond the participants of the study. The application of design tools, especially by student groups, is informed by the findings of this paper, particularly regarding the roles that the design methods served in context each other.

A. *Design Artifacts used for this study*

The COVID-19 Pandemic and the resulting remote teaching style used for the course created the need for digitalization of project files to adequately collaborate on and communicate the work of the students. Consequently, and somewhat fortuitously, many working documents, sketches, and PowerPoint presentations were constructed by the design team, in addition to the deliverables that were normally required for the course. The files contained sketches, descriptions, explanations of decisions, decision matrices, and background research that allows for more detailed analysis of the processes and ideation methods of the students.

Documents that were analyzed for this report include:

- One (1) [32-page] document describing the team's first portion of concept generation. It describes their implementation of the following design methods: individual idea generation, analogous domains, 6-3-5, Mind Maps, checklist approach, and intuitive Word Trees.
- One (1) [45-page] document describing the subject's second portion of concept generation. It describes their implementation of the following design methods: database derived Word Trees, TRIZ/TIPS, Biologically inspired design tools, and morphological matrices.
- One (1) [115-page] midterm report of all concepts generated containing sketches, descriptions, and scanned working documents. This includes content from the first two documents and details on the team's initial down selection process.
- Three (3) top concept presentations to peers and to lunar science experts, consisting of one (1) 8-slide presentation of top concepts, one (1) 5-slide presentation of the final concepts, one (1) 6-slide presentation of the refined final concept.

- One (1) [23-page] proposal document of final concept, which was sent to and accepted by BIG Idea Challenge judges

In addition to the documents analyzed, the authors discussed their recollections of the events to fill in important un-documented discussions. This included discussion between both the Author-participants and the non-participant authors to piece together the process by which the team arrived at their final design concept. These discussions included presentations summarizing findings from the design artifacts and debates over conflicting recollections of events.

III. Results and Discussion

This section will present the results of the analysis of the design methods, discuss the results of the final design selection, and finally highlight how limitations of student understanding interacted with pedagogical decisions to influence the final design.

A. Impact and roles of the applied design methods

Initial analysis required identification of distinct design concepts across all documents. When first documented, design concepts were all self-identified by the team with descriptive titles such as “Bubble-wrap around the suit” or “Spacesuit dust filters”. This allowed for identification of the genesis of each concept and the associated design method used for its generation. It also allowed for concepts to be tracked through methods which modified them, as the names remained consistent.

Because this analysis is focused on design concept evolution over the span of the project across multiple ideation methods, and is not focused on, for example, the quantity or quality of ideas generated from any particular method, design concepts that were not part of a top design concept were discarded for this analysis. For this process, the 15 top design concepts that the team considered as their top ideas were analyzed. The rejected ideas were deemed unlikely to function or infeasible for a team of mechanical engineering students to develop and were not developed further. Table 2 provides a synthesis of the 15 top design concepts and the 35 associated design concepts that either originated or modified the concept, arranged in columns by the method that gave rise to the concept.

The design methods were broken into two categories: Concept Generation and Concept Modification Methods. Generation methods were used to create net-new concepts while modification methods ideated and improved on generated concepts. Interestingly while TRIZ is included as a modification method due to how it was used by student team to alter existing ideas, it also inspired the net-new concept 13. Similarly, while BID methods were primarily generative, they were also used to modify concept 12, which had been earlier generated using the analogous domains method. Fig. 1 depicts the generation and combination of ideas that occurred in the concept generation stage and the application of design modifications in the modification stage. It also indicates the designs that were chosen to be the final concept, the process of which is discussed in Section IV, part B. Thus, from Table 1 and Fig. 1 we can see that idea 10 “Lotus Leaf/Geck outer fabric” was a combination of 2 design concepts: a leaf inspired concept initially generated using Analogous Domains and a lotus and butterfly inspired design generated using the BID tools. It was then modified during 6-3-5 where the team focused on “material considerations”. It was then incorporated as a part of the final design concept.

Because the team was not required to and did not have the time to conduct the modification methods on every concept that they had generated up to that point, each member self-selected 1-3 of their concepts to use with each method. Therefore, there were ideas not selected for use in 6-3-5 or SCAMPER that might have progressed, but did not.

The concept generation methods that produced the most top concepts for this project were the BID methods. This is notable because they were applied later on in the ideation process after the team had time to generate a wide solution of ideas. The WordTree method was also applied later in the process but resulted in half as many top concepts. Additionally, two of the five analogous domain concepts involved biological domains despite occurring prior to use of the BID methods. Part of the high productivity of the BID methods may have been due to fascination with biology, though it is curious that it was so prevalent when designing for an environment, the moon, that has no biology from which one can draw inspiration. It may be exactly this unfamiliarity and complexity of the environment that drove the team to consider biological examples of dust mitigation.

In considering the modification methods two out of three top concepts received improvements created by application of the 6-3-5 approach. One possible reason for this was that the 6-3-5 method was the only design tool that was applied collaboratively by the student team, albeit asynchronously and online, due to COVID. All other ideation methods were used individually. This collaboration could have resulted in mutual ownership of ideas, making such ideas more likely to be seen as favorable by multiple team members during the discussions that took place during later down selection. It may also be the case that collaboration allowed a wider range of design space to be explored, providing a chance to mature and expand these concepts relative to others. It was also curious that the team implemented 6-3-5 to modify existing ideas instead of its intended use to collaboratively generate net new ideas.

B. Evolution of the Final Concept

The evolution of the design concepts leading to the final concept is shown in Fig. 2. Each design that influenced the final concept has a descriptive title, a re-created sketch (sketches were re-done to improve clarity), and the method that was used to generate the design. The final concept, the EDS enabled hybrid dust mitigation brush, started off as multiple different concepts. Five key concepts that led to its development and are discussed include:

- Photoelectric charging brush
- Magnet tool
- Mammalian inspired brush
- Spacesuit with integrated EDS
- Bio-inspired suit coating

TABLE II. DESIGN FEATURES ADDED TO CONCEPT

		Concept Generation Methods				Concept Modification Methods		
Concept Name	***Concept Number***	***Individual Idea Generation***	***Analogous Domains***	***Word Tree***	***BID Methods***	***TRIZ***	***Checklist Methods***	***6-3-5***
Pressurized Nozzle System	1			Fan, Winnow			Proposed Variations	Nozzle Variations
Air Hockey design	2		Air Hockey Table					Error tolerance
Magnet tool	3	Ferric dust						Maintenance Features
Smooth outer layer modifications	4		Plastic Sheets				Proposed Variations	Collection grooves
Lunar dust removal brush	5	Modified brushes		Bream				
Self-cleaning with hairy pads	6				Bug self-cleaning			
EDS emitters in suit	7	Modified EDS						User Control
Post-EVA cleaning station	8	Cleaning Closet					Proposed Variations	Dust Collection
Carapace shells on suit	9				Dung Beetle	Smooth Surface		
Lotus leaf/Gecko outer fabric	10		Leaves		Lotus, butterfly			Material consideration
Fur outer layer with cat tongue brush	11				Stonefly, house cat			
Brush-like utensil on outer layer of suit	12		Respiratory cilia		Rhythmic Patterns		Proposed Variations	Electron Beams
Thin film membrane	13					Sacrificial Outer Layer		
Shaking surface	14	Vibrating surface		Fling	Fur Inspiration			Frequency Adjustments
Inflatable layer	15		Car airbags				Proposed Variations	

The photoelectric charging brush introduced one of the key innovations that set the final design apart: the inclusion of an internal UV source to photoelectrically charge the dust grains. It was the prominent design in the team's category of "Cleaning Tools", or hand-held devices that astronauts could use to clean their own suits. This technique was inspired by the concept of "breaming" which was discovered through the Word Tree technique with an initial word "clean". Breaming, or cleaning the hull of a ship through the combined use applying heat with brushing and scraping [20] opened the design space to consider ways to enhance the hand-brushes through the application of a non-mechanical energy source. Upon learning about the application of UV light and electron beams to cause dust grains to move from a surface (see section II), a new concept was developed. Additionally, the paper that inspired this technique, [17], was later found to be the subject of discussion within its field as its method of lofting dust with UV had limited replication in other studies which required relatively stronger power source, an electron beam, to be able to loft particles. Regardless, the team pursued the idea as the conflicting support for the base technology indicated its application could be novel.

The magnet tool and mammalian inspired brush were the two other leading designs in their category of "Cleaning Tools". As metallic iron was found to be present in lunar dust samples [21], the proposed magnet tool device would be able to clean lunar dust off spacesuits through actuation of a hand-held electromagnet. This was the only device that proposed to make use of the magnetic properties of the lunar dust. The mammalian inspired brush aimed to cover the spacesuit with a fur like outer layer that could be cleaned with a barbed tool, similar to how cats clean their fur. In addition to the novelty of being inspired by natural systems, this was the only concept that proposed a modification to the spacesuit to enable cleaning with a tool. While there was deemed to be merit to these ideas in their relative novelty, neither idea was as well backed by existing research as the photoelectric charging brush and were therefore not implemented in the final design.

The spacesuit with integrated EDS concept was developed later in the project when the team began exploring existing dust mitigation techniques. Exploring existing solutions later in the design process was an intentional pedagogical choice to encourage teams to explore a broad solution space by limiting potential fixation on existing technologies. The team thought to

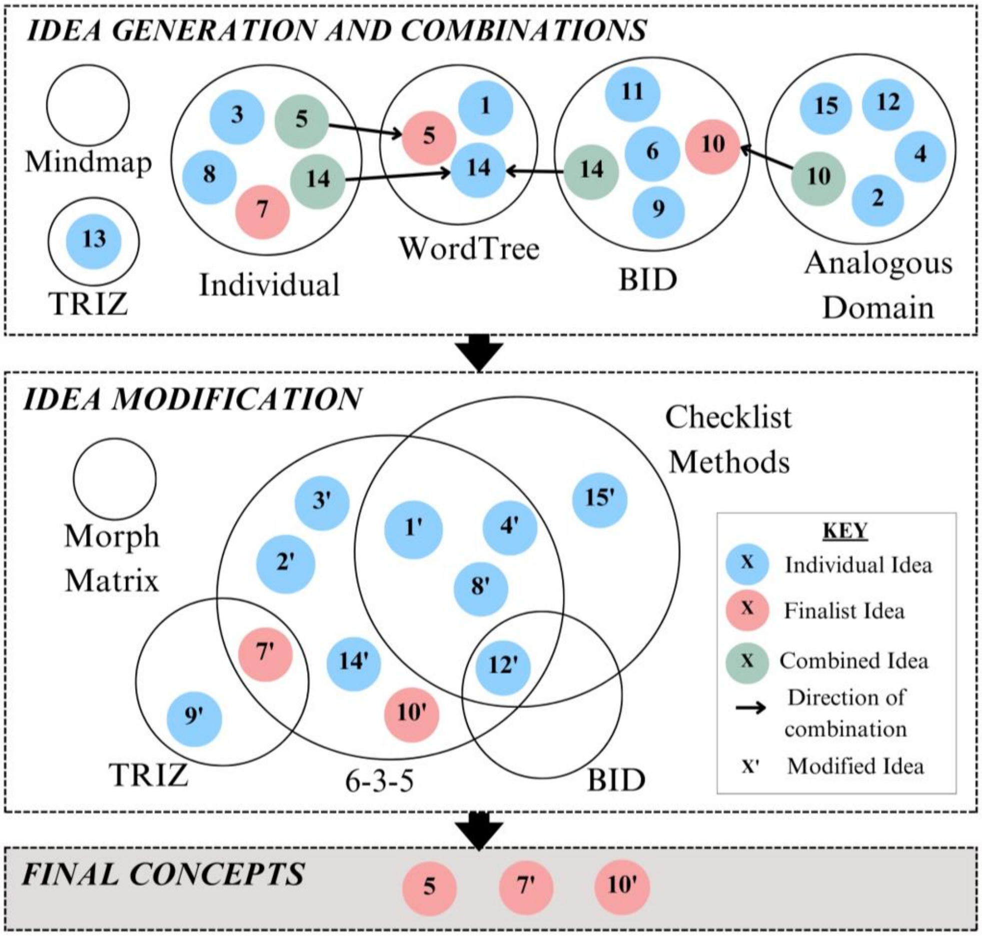

Fig. 1. Diagram showing which ideas were generated or modified from which methods. Combined ideas were design concepts which were similar to and combined with another concept during initial downselection. While not all 15 ideas were the subject of modification, they all were involved in the process that led to the final concept selection.

move away from the surface applications of EDS and to embed it into spacesuit components that would be most affected by lunar dust exposure, such as joint bearings. While considered as lower in novelty by the team, being a different application of an existing technology, this idea motivated the team to think about other ways that this EDS technology could be used..

The biologically inspired suit coating was the last influential concept in the evolution of the final design. This device took inspiration from naturally dust-repellent surfaces, such as lotus leaves, butterfly wings, and dung beetle carapace shells [22], and proposed developing a spacesuit coating that would accomplish the same effect in a similar manner. While similar to the mammalian inspired brush fur layer in that it would be an outer layer modification to the spacesuit, this coating would reduce dust adhesion on its own instead of needing to be paired with a specialized tool. This concept also had more technical backing as the lotus leaf pattern is better understood and has been implemented in commercialized products [23].

In a later discussion with lunar experts, the idea was posed to incorporate embedded EDS into the team's other concepts as the EDS would not conflict with the principal forces at work. This discussion led to a design concept of a combination of dust mitigation technologies that included a cleaning tool as well as active and passive suit modifications. Thus, the three leading ideas previously mentioned were combined into a single design. This required additional features to be added to each concept, including the addition of EDS into the bristles of the photoelectric charging brush. As previously mentioned, all former iterations of EDS acted along a surface. This new idea proposed a volume-affecting, as opposed to surface-affecting, form of EDS that contained electrodes along the lengths of the bristles to enable the creation of electric fields throughout the bristle volume. It was theorized that this would improve the dust rejection of the brushing action by moving dust grains with both mechanical and coulombic forces. This innovation synergized well with the photoelectric charging of dust grains via UV light, as the imparted charge on the grains would increase the resulting force on the particles when exposed to the electric fields of the EDS system. Lastly, it was suspected that the embedded EDS system would aid in removing dust grains that could become lodged between bristles, an occurrence that became prohibitive during the Apollo missions [12].

Finally, to eliminate dependencies on the already well-developed existing suit system, the team decided to focus solely on the hybrid dust mitigation brush, which could be designed and researched independent of the suit system. This allowed the team to pursue their most innovative concept while also paring

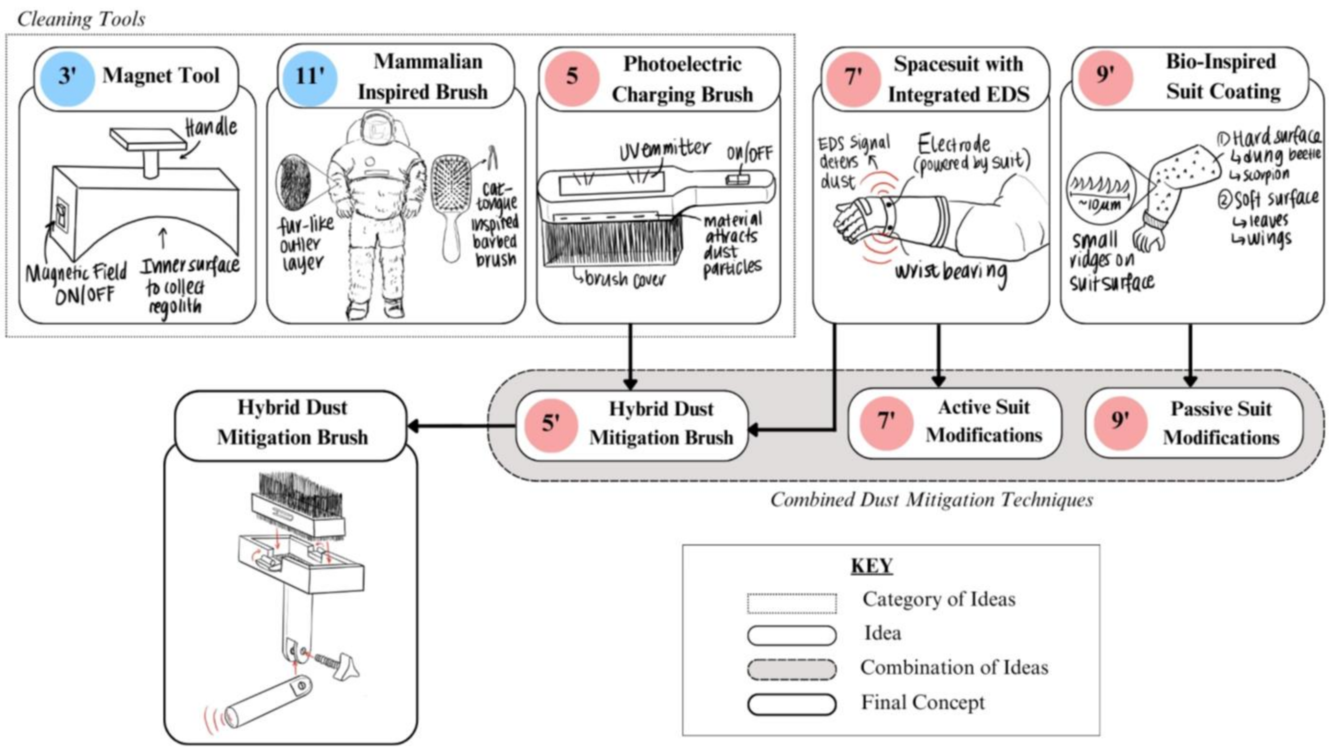

Fig. 2. Flowchart detailing the evolution of the "EDS Enabled Hybrid Dust Mitigation Brush". Sketched images were redrawn on an iPad using the digital sketching tool Procreate for better clarity and visibility.

down the scope of the design to something achievable by a student group within a year. This final concept was the topic of the team's winning proposal.

C. Designing with incomplete understanding

The design course enforced several pedagogical techniques to avoid fixation. The design process prescribed in the course required the team to start their background research and concept generation without knowing much about existing dust mitigation solutions. As mentioned previously, this prevented design fixation on existing solutions and encouraged the students to explore a broader solution space.

However, when the team finally did explore the existing solutions at the end of the ideation process, it was clear that their understanding of them was limited and, in some cases, incorrect. This can likely be attributed to the short amount of time available to understand the technologies and the relative complexity of the technologies themselves compared to that which a team of students had likely been exposed to. The team's poor understanding was observed in the documents where they frequently made errors regarding the principal forces at play in EDS systems. It was also noticed in their multiple incorporations of "energy emitters" into design concepts instead of more specific sources of photoelectric charging. Moreover, with regard to the EDS technology, a team member explicitly states in an idea generation document that "since this idea has been pursued by other groups… I will not investigate it further".

When viewed retrospectively, this incomplete understanding worked to the team's benefit. Assumptions that could have limited the solution space for better informed designers were not present or as heavily considered by the student team, allowing them to pursue a broader range of ideas. For example, as they were unaware of possible assumed limitations of EDS technology, they created designs that incorporated it in moving components of the spacesuits when its only existing applications at the time were for flat, rigid surfaces. They also sought to implement UV radiation as a dust mitigation technique despite its applications for UV based dust mitigation being still the subject of lab experiments. This allowed the team to ideate with fewer restrictions and propose ideas that those more versed in lunar dust mitigation might've written off. Ultimately, this led to the proposal of synergistic use of UV with EDS which was later shown to be effective [24].

IV. Conclusion

This paper investigated a successful student design team and uncovered useful details of how students apply design methods, and how those methods interacted with key pedagogical decisions. Among the methods used, they were generally used for concept generation or concept modification, and not frequently for both. This led the team to structure their overall ideation process in two stages consisting of a generation phase and a modification phase. Additionally, many top concepts contained references to biological analogies, likely done as a way to drive the perception of novelty in the unrelated problem frame of the lunar environment. It was also seen that the method that most required collaboration, the 6-3-5 method, generated two of the three ideas that reached the top stage. When selecting the final concept, the team sought to balance novelty with feasibility, ultimately choosing a novel design rooted in existing technologies.

While much further research is required, this research demonstrates the potential benefits of the following design education practices. First, the pedagogical choice to not reject ideas until the designated design selection phase may assist in avoiding design fixation and could permit designers to consider a wider solution space. Second, the novice perspective (lack of domain knowledge) could possibly be beneficial as it could permit exploration and discovery of solutions in design space that be otherwise avoided or deemed impossible. Third, seeking a large quantity of solutions and requiring a minimum number of ideas being generated for each method also likely impacted the results. Lastly, there may be benefits for design teams to employ multiple idea generation methods, tools, and processes as the combined results of these activities can lead to improved final concepts. For the impact of the pedagogy to be effectively evaluated, data would need to be collected from a representative sample of teams and not just a team that achieves superior results.

This study was limited in that it was conducted multiple years after the design experience, therefore reducing the benefits of the participatory aspect of the analysis as some details were certainly forgotten. It also only considered the top ideas instead of considering all concepts generated by the student team. While this would introduce its own complexity as not all concepts were equally detailed, it could have permitted a quantitative analysis of which design methods resulted in the most top concepts.

Future studies could explore the impact of limited collaboration on the down-selection process to ascertain if there is an increase in ownership or concept favorability. Another study could explore the role of ignorance of technical limitations and if that expansion of the solution space is an avenue for innovation or a happenstance fluke. More research in both design pedagogy and engineering design research needs to evaluate the impact of idea-generation methods over a longer span of the design process. Lastly, there should be further investigation of the effects of waiting till later in the design process to begin rejecting potential design concepts.

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