Exploratory methods and techniques for space technology development and space mission concept development

IAC-20,A7,1,9,x61093

EXPLORATORY METHODS AND TECHNIQUES FOR SPACE TECHNOLOGY DEVELOPMENT AND SPACE MISSION CONCEPT DEVELOPMENT

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Abstract

This paper hopes to fill a gap in literature by framing the current state of exploratory design methods and techniques within space mission development and laying the groundwork to begin utilizing a wider variety of these methods and accompanying techniques. The purpose of this paper is to review the ways in which design methods and techniques used in other fields may be used in support of the space mission concept development process and space technology development.

Designers are almost synonymous with the consumer product, automotive and entertainment industries. Fields such as Product Design, Transportation Design and Entertainment emphasize finding solutions to problems using exploratory design methods and techniques. Often, they are leaders in their organizations. However, there is not a direct appreciation or understanding of how to utilize these methods and techniques within aerospace. These methods have been shown to support mission concept development, however may also directly support technology development, as is seen in the consumer product industry. Evidence shows that these methods have sporadically been utilized by NASA for habitat design, software development and astronaut wearables.

This paper explores opportunities within the space mission concept development process where these techniques are currently used and develops a design library of methods and techniques used outside of Aerospace that may be supportive of technology development. The current Pre-Phase A concept development process is mapped along with exploratory design methods used in other industries. Design Thinking is a heuristic problem solving method that can be applied to many fields. Human Centered Design and User Centered Design have been utilized for architecture and software development; these same tools could also be used to help inform the design of long term human habitation system on planetary surfaces. The Imagineering process is instrumental in theme park development; this paper argues it should also inform design of robotic science missions such as Mars Sciences. Science Fiction Thinking is a method of extrapolating future technology. How can this type of thinking inform the design of systems that aim to detect life in locations such as the liquid oceans on Europa and Titan? Techniques that are instrumental throughout these methods, such as storyboarding, sketching and prototyping are also defined. Interviews with employees within aerospace, consumer products and entertainment may shed light on opportunities and barriers to utilizing these techniques.

I. INTRODUCTION

Within the Consumer Product and entertainment industries, effective use of Design Methods and Techniques utilized by the Design Discipline are known to be instrumental to project outcome. Footwear companies such as Adidas employ Designers who use Methods such as Design Thinking and Human Centered Design for development of their products. The Walt Disney Company and Universal Studios use similar processes in development of their theme parks, with the addition of utilizing Techniques such as Sketching, Prototyping and Storyboarding to develop concepts of rides for park guests. These Methods and Techniques are seen as essential for product implementation within these fields in problem solving and Idea Generation. [1, 2, 3]

The author defines Design professionals by the core skills of their educational training to more clearly define how they contribute to professional teams. Historically, dedicated Design colleges have been known to emphasize foundational courses in Color Theory, Shape Language, Drawing, and Modernism in their undergraduate studies. These foundational courses were largely inspired by the Bauhaus, a German Art school that found a Method of unifying Artistic practice, Craft and manufacturing at the beginning of the industrial revolution. The Bauhaus closed its doors in 1933, but it inspired the branching out of Design Disciplines, such as Industrial Design, Graphic Design, Concept Design, Fashion Design and Motion Design. [4, 5] Section 4 describes the differences in Sketching Technique between these disciplines.

The Aerospace Industry does not yet have a direct understanding of how to utilize the Methods and Techniques utilized by Designers. Section 5 shows evidence from interviews with Designers in Aerospace of an effort on the Designer's part in attempting to create understanding of their discipline among their Engineering peers. These experiences are reflective of interviews from Industrial Designers from Johnson Space Center's Habitability Design group. [6, 7]
This gap in knowledge is emphasized by insufficient academic research in understanding the impact and benefit of Design Methods and Techniques within Aerospace.

This work attempts to bridge the gap between Aerospace and the professional Design practice in a few key areas: Methods, Techniques and documentation of processes. Researchers at the Jet Propulsion Laboratory, a NASA Field Center, have begun to shift the rigidly linear processes of the federally funded research center to include non-Engineering Disciplines. The work of Dr. Tibor Balint and Dr. Tony Freeman has shown a need to alter the organization's view of non-Engineering Disciplines within their flight project Design processes. [8] In a related field, Dr. Maria Yang, MIT D-Lab Faculty Academic Director, focuses on bridging the Engineering and Design Disciplines, particularly in early phases of the Product Design cycle. Dr. Yang's research includes the analysis of the Sketching skill and it's role in early stage Engineering Design. Her research also involves researching Methods for ideation and Prototyping as well as Design activity and Design outcome. [9, 10]

Leaders in the Aerospace Industry have an opportunity to make effective use of specific Design Methods and Techniques that will likely bring value to the space mission design process. One way to increase understanding and utilization of Design Methods and Techniques is to develop clear mappings between the use of Design tools and needs of the Aerospace mission Design process. This work adds to existing literature by documenting specific Design Methods and Techniques and their benefits within Aerospace in the form of a catalogue inspired by the Netherland's Design Institute's approach to Design Method categorization. Designers at the Netherland's Design Institute catalogue Design Methods along with the costs, staff, time and expertise needed for each Method. [11] Understanding of Methods and Techniques is instrumental to correctly apply the skillsets of the Design Discipline. Consequences of not having a clear understanding of Design Methods and Techniques may be that Design professionals are not utilized at their full potential within Aerospace, and that these Methods and Techniques may be used incorrectly with no benefit gained.

This work opens with an overview of the Design practice within Aerospace. It is important to distinguish the differences between the Design and Art Disciplines to illuminate the systematic problem solving evident in the Design Discipline. Section 2
defines the practice of Design professionals and describes the components of a Design education built on foundational skills in Art. This discussion shows how current education practices evolved based on key historical influences, especially during the Industrial Revolution and World War II. This description is necessary to distinguish the Design Discipline from other systematic practices, such as Systems Engineers who have a science and Engineering foundational education. Section 3 shares that the Design Discipline does exist within NASA today and it contains a catalog

compiled by the author of all publicly documented, dedicated Design Teams within NASA Field Centers to examine the disciplines involved and their current roles within the agency.

Section 4 is a review of Exploratory Methods and Techniques used by Designers that will describe the Methods theorized by the author to support decision making during Space Mission Concept Development. They were selected because they align with goals set by experts in Pre-Phase A mission Formulation, the earliest stages of space Mission Concept Development.

Along with these Methods, Section 4 documents Techniques frequently used by Designers such as Sketching, Storyboarding and Prototyping. These and other Techniques are found to serve as the common set of components within many Design Methods. The author theorizes these Techniques to be supportive of the systems Engineering Discipline. Section 4 ends with the beginnings of a catalogue of Design Methods and Techniques for use in Aerospace inspired by the Netherland's Design Institute's approach to Method categorization. [11] By cataloguing these Methods, a clearer understanding may be facilitated between Design and Aerospace Engineering.

Section 5 is a summary of the formal investigation of Exploratory Methods and Techniques based on personal interviews with employees within the Aerospace, Consumer Products and Entertainment Industries. This summary sheds light on whether certain Methods are used more than others and how often specific Techniques are currently used by the teams represented. This evidence describes opportunities and barriers to the use of Design Methods and Techniques within Aerospace.

Finally, based on interviews, a review and historical evidence, Section 6 describes the NASA flight mission lifecycle through the lens of a Designer. The discussion describes each phase of the lifecycle, proposes Design Methods and Techniques that can be applied within each Phase and highlights where the Methods and Techniques may contribute to core functions and goals of each Phase. Section 7 provides evidence of the use of Design Methods and Techniques used in support of Aerospace and Proposals for how they may be utilized further.

The intent of this work is to provide insight into barriers for Designers working in Aerospace, and begin a Design library and taxonomy, where Exploratory Methods used by Designers can be categorized and utilized within Aerospace.

The author's research question is: What exploratory Design Methods and Techniques are currently utilized formally and informally within Aerospace and what barriers and opportunities exist to expanding these Methods and Techniques?

This question can be broken into two pieces. The first half, "What Exploratory Methods and Techniques are currently utilized formally and informally within Aerospace" and the second half, "What barriers and opportunities exist to expanding these Methods and Techniques." Through interviews and historical evidence, the first half of the question is addressed. Section 4 illuminates the second half of the question through a review and research into Design Methods. Evidence towards answers is noted in each section.

II. Design and Art

Before beginning to discuss the possible benefits of the professional Design practice within Aerospace, this section distinguishes the differences between professional Design and the Art Discipline. In the author's experience, people from the Aerospace Industry often group the two disciplines together or confuse them with one another in the workplace. This section explains the definitions used for Design and Art and aims to reduce confusion between the two disciplines.

The American Institute of Graphic Arts (AIGA), the professional association for Design, describes Design as "…improving the visual appearance and function of messages and information." Designers often work in business innovating marketing, Designing messages, branding and "services that express the character of a company and define its relationships with consumers." [4] Various disciplines of Design are highly specialized and work in technology and product development. Design Disciplines include, but are not limited to: Advertising, Information Design, Illustration Design, Motion Graphics Design and Industrial Design. While these disciplines are highly specialized, all Design Disciplines use Drawing, Typography, graphic elements, and photographs to solve problems. Looking further than Aesthetics, Designers support technology and its role in our future. [4] It can be said that the Design Discipline is constrained to focus the problem it is trying to solve rather than creating for the sake of expression.

Whereas all Design Disciplines focus on solving problems, Artistic Disciplines can be vastly different in their focus.

Art is defined by the Oxford dictionary as "the expression or application of human creative skill and Imagination, typically in a visual form such as Painting or Sculpture, producing works to be appreciated primarily for their beauty or emotional power." In an exploratory interview with an MIT Media Lab Artist and former Artist in Residence at CERN, they describe Art and Design as having fundamental differences. The Artist sees Art as "posing a question" and Design as "solving a problem." In some instances, an individual can be both an Artist and a Designer. This work will use the Oxford definition of Art primarily for appreciation of beauty and emotion, which is fundamentally distinct from Design's focus on systematic problem solving.

In recent years, the Consumer Product Industry has faced tension in their Innovation practices. With the advent of Computer Aided Design software such as Autodesk and Solidworks, product development time has reduced and customers now have more options to choose from. [13, 14, 15] Professionals in disciplines such as Industrial Design frequently work with Engineering professionals to improve the ergonomics and function of a product. Design is recognized as a catalyst for product change in the Consumer Products Industry for its commitment to systematic Design Methods. [13] The Design process can take various forms; it can focus on "Intuitive Creativity" or be "Science Based", focusing on calculated decision making. [13] The following is a brief review of the Industrial Design practice, because of its overlap with other systematic Design Disciplines that span other industries including, but not limited to: Product Design, UX Design, UI Design and Concept Design.

It can be seen that the Design and Art Disciplines are distinct in their approaches: Art meaning to pose a question and Design intending to solve a problem. The Design Discipline's roots in Artistic Technique education perhaps leads to misinterpretations of both disciplines. A professional Designer is defined in this work as an individual who has gone to a Design school and studied foundational courses in Design including: Color Theory, Shape Language, Modernism, Drawing and Design Methodology.

Section number 6 shows that teams working on space mission architecting often need to both "pose a question" and "solve a problem" when opening a trade space and narrowing down to a solution. Space Mission Architecting is the process of creating a plan and specifications for the implementation a spacecraft mission.

III. Designers within NASA

This section provides a catalog of where Design Teams exists today within NASA and teams that are not considered dedicated Design Teams for the scope of this work. This section also provides historical examples of the professional Design practice within NASA to begin to document the emergence of this discipline, however further research is needed and will be conducted in the future for a more complete historical view. Design teams within NASA are comprised of the Design Disciplines mentioned in Section 2, such as Illustration Designers, Graphic Designers and Industrial Designers. It is intended that the term "Design Team" in this section is a team comprised of mainly individuals who have foundational education in Design as described in Section 2.

The author could find no evidence of data that provides the exact number of dedicated Design Disciplines within NASA, however a summary of team objectives may imply specific disciplines involved. There are teams within NASA that are not considered dedicated Design Teams for the scope of this work, such as Mission Design Teams that are comprised of Engineering Disciplines. They are further described in Below.

Design Teams Within NASA

Aerospace agencies have within the last 10 years begun establishing their own in-house Design Teams. One example is Johnson Space Center's Habitability Design Center, which is described by team members as NASA's "Human Centered Design studio." This team of Industrial Designers support the development of Human Habitation. On their work, they have stated that "Things have changed so much since we started, people here don't really understand what Industrial Design is or how it fits into the bigger picture. But once they work with us and see the services we provide—visualizing information, realizing concepts—they see the value of what we do." [7]

Additionally, their interview with journalists at Core77 states, "there isn't a place for industrial Designers at NASA. Here the Engineers are considered the Designers, and the team has only been able to exist under the guise of Human Factors, a quantifiable soft science that is acknowledged as necessary." [7] NASA recognizes Human Factors as an Engineering Specialty within NASA that imposes requirements on systems, however Engineering

Specialties are usually not integral to solving the problem of Design itself. This quote infers that the speaker experiences a lack of appreciation for Design among Engineering colleagues. Anecdotal evidence from interviews in Section 5 suggest this attitude may be true throughout the Aerospace Industry.

The chart below depicts the author's findings of NASA Centers and the publicly available information on formal Design Teams within them. Information on NASA was collected because of the quantity of publicly available data on Design Teams. For each NASA Field Center, terms such as "Design Teams", "Graphic Design", "Industrial Design", "Illustration", "UX/UI Design" were searched for through an online search engine and academic literature database. This analysis defines Design Teams here as those in which a majority of the members are Designers, with a foundational education in the Design practice as seen in Section 2. Leaders and supervisors of these teams may be Engineers. This chart does not distinguish between technical Design specialties within teams; the chart lists teams because of their use of Design Methods and Techniques, which are a staple of a Design Education. This list may be inconclusive because teams may not publish publicly available information.

Designated Design Teams within NASA	
Ames Research Center	Human Centered Systems Lab, Graphic Design Team
Jet Propulsion Laboratory	The Studio, Ops Lab, Visualization Technology Applications and Development Group, Human Centered Design Group, Graphic Design Team
Langley Research Center	Graphic Design Team
Goddard Space Flight Center	The Scientific Visualization Studio, Graphic Design Team
Johnson Space Center	Habitability Design Team, Graphic Design Team
Marshall Space Flight Center	Exhibits and Artifacts Team
Armstrong Flight Research Center	Web Team, Photo and Graphic Design Department
Kennedy Space Flight Center	Graphic Design Team
John C. Stennis Space Center	Graphic Design Team
Glenn Research Center	Graphics and Visualization Lab

The discussion below describes the Design Teams within different NASA Field Centers based on publicly available information from web pages, job descriptions, web Articles and academic literature.

Ames Research Center

Ames Research Center has expertise in Information Technology, Aerospace and Aeronautics Engineering and Research. They also conduct research in Space, Earth, Lunar and Biological Sciences. Expertise within Ames includes topics such as the following: The design of systems to enable spacecraft to safely enter other planets; designing advanced computing & IT systems; studying future Methods to help planes, drones and spacecraft operate safely in the atmosphere; asking how to identify whether life exists on other planets (a field called astrobiology and life sciences); and work on space missions in the fields of Space and Earth Science. Ames Research Center is supported by two Design Teams: the "Human Centered Systems Lab" and a Graphic Design Team. Their Human Centered Systems Lab researches human and system interactions, often with the aid of Human Centered Designers to implement and analyze software products. Lab lead Quang Dao's published research in Human-Machine Interaction is focused on interactions between aircraft and pilots. [16] Not much is publicly known about the Ames "Graphic Design Team", however it is known that most NASA centers have a dedicated Graphic Design Team that provides graphical asset development and visual language. They may be embedded within the Communications Team as is done with other NASA Field Centers.

Jet Propulsion Laboratory

The Jet Propulsion Laboratory focuses on robotic missions for Earth Science and Space. JPL sends robotic missions to study asteroids, planets, comets and Earth's moon. They have perhaps the highest quantity of dedicated Design Teams of all centers. "The Studio" describes themselves as a team of "Designers, Thinkers and Makers" that develop ways of Storytelling and translating science through visuals as well as use Design Thinking Methods and Techniques to help Engineers "think through their thinking." They apply these Techniques to help Mission Formulation Teams and Space Mission Teams meet their goals. [17] In a similar vein, the "Visualization Technology Applications and Development Group" creates interactive apps and visuals to communicate to the public and internally. An example of an interactive visual is their "Eyes on the Solar System," that provides the user access to solar system data in an interactive map. [18] Their Graphic Design Team develops internal and external communications graphical assets as well as internal communications materials. JPL's Human Centered Design Team, part of the Operations Lab (Ops Lab) utilizes Methods from Human Centered Design to develop natural user interfaces to support NASA's robotic space missions. [8]

Goddard Space Flight Center

Goddard Space Flight Center builds spacecraft, sensitive Instruments and technology such as telescopes to study the universe, solar system and our sun and Earth. They also manage communications between mission control and the International Space Station. Apart from a Graphic Design Team, Goddard houses a Scientific Visualization Studio that creates Visualizations and multimedia in order to foster a greater understanding of Earth and space science research activities. These teams further NASA's goals of enhancing public knowledge of space. A research paper sharing the hardware used for these Visualizations describes the use of Visualization focused super computers applied to science data sets. [19] [20]

Johnson Space Center

This Field Center is the base for astronaut training and mission control. It currently leads Operations for the International Space Station, development of NASA's Gateway project and the Orion Spacecraft while also advancing technology, Engineering and medicine to support space exploration. While this center houses a Graphic Design Team, Johnson also employs a Habitability Design Team. [7] It is composed of Industrial Designers and Human Centered Designers that focus on the human experience when developing vehicles and environments for space that humans will interact with. [21] A research paper by the former Associate Chief of Human Systems Integration at Johnson Space Center supports the inclusion of the Human Centered Design Method in the Flight Mission Life cycle. [21] Section 6 further discusses Human Centered Design in the Flight Mission Lifecycle. Additionally, Johnson's Integrated Graphics Operations and Analysis Laboratory develops Engineering Visualizations for Johnson as well as other centers. [22]

The Chart below briefly describes the Design Disciplines within NASA, based on the author's research into dedicated Design Teams.

Design Disciplines within NASA	
Technical Illustration	This discipline uses static and dynamic images and illustrations to explain the relationships between technical objects.
Concept Design	The development of an initial idea, often illustrated for visual aid and communication with clients.
Model Making	The creation of an object, often with a high level of detail at varying scales of size. Used as prototypes or for communication purposes.
Web Design	The production and maintenance of a website. This discipline can include skillsets such as Graphic Design and User Interface Design.
Graphic Design	Visual communication through Photograpy, Typography, illustration for communications purposes.
UI/User Interface Design	These Designers make interfaces for software, often focusing on stylization.
UX/User Experience Design	The Design of an entire product including branding, usability, Design and function.
Illustration Design	This discipline creates Illustrations for a specific purpose. Within NASA, this is the translation of scientific data.
Animation	This discipline creates moving images that communicate an action or data set.

The word "Design" within Aerospace has a procedural meaning, often implying the development of a plan for the construction of a technology or for the implementation of a project. An example might be a space mission project, such as the development of the Mars 2020 Rover.

Some NASA Field Centers follow a Matrix structure for their operation. Matrix organizations can be identified by most individuals having two supervisors; one that can organize and supervise work to meet objectives, and another that gives the organization proper capabilities to accomplish work. In other cases there may be multiple project specific managers. [23] Design Teams, often referred to as "Project Design Teams" consist of Engineers and other disciplines, sometimes including Designers, who are brought together to work collaboratively on what can be referred to as an Architecture for a space mission project. [24] NASA's Mission Design Teams can be found in the chart below. The Science Mission Design process is described further in Section 6. Mission Design Teams, such as the Ames Mission Design Division, conduct early stage concept development and technology maturation for space mission Proposals. Normally, team members have experience in Designing spacecraft and associated Instruments. They might be Systems Engineers, Electrical Engineers and other subject matter experts. [25] They are not included in the definition of design teams because they are largely composed of engineering disciplines.

Mission and Concept teams within NASA	
Ames Research Center	Mission Design Division [56]
Jet Propulsion Laboratory	Team X, A-Team [57, 58]
Langley Research Center	Engineering Design Studio, Integrated Design Center [59, 60]
Goddard Space Flight Center	Mission Design Lab, Instrument Design Center, Integrated Mission Design Center [61, 62, 63]
Johnson Space Center	Habitability and Environmental Factors Team, Human Adaptation and Countermeasures Team, Space Medicine Team [64]
Marshall Space Flight Center	Advanced Concepts Office [65]
Armstrong Flight Research Center	*No other teams publicly available*
Kennedy Space Flight Center	*No other teams publicly available*
John C. Stennis Space Center	*No other teams publicly available*
Glenn Research Center	COMPASS Engineering Team [66]

Mission Project Design Teams that exist at various NASA Field Centers such as Ames Mission Design Division, while housing Graphic Designers, are not dedicated Graphic Design Teams. [25] This may be an example of individual Designers spread throughout divisions within NASA, sometimes without a specific Design Team. Graphic Designers and Visualization Teams use their skills to help complete the work required for Mission Concept Development and Proposals.

IV. Review of Exploratory Methods and Techniques

This Section describes Exploratory Methods and Techniques used by Designers within their professional practice. This work defines "Exploratory Design Methods" as Methods used by Designers that focus on the compilation, evaluation and blending of both qualitative and quantitative data in a collaborative setting to produce a proposal or solution to a problem. This definition is gathered from the definitions of the American Association for Graphic Arts, Stanford D. School, and Design firm IDEO. [4] All are pioneers in using Exploratory Design Methods. Techniques are defined different from Methods. Collin's Dictionary defines Techniques as a "skill and ability in an Artistic, sporting, or other practical activity that is developed through training and practice." Corporations in the past that have had limited Design capabilities are now implementing in-house Design Teams and assigning executive roles to Designers. [26] Design Methods and Techniques are often the foundations of a Design Education. They can be seen as systems and processes for tackling problems. The following Design Methods are documented for their wide use within and outside of Aerospace: Design Thinking, The Disney Imagineering Process, Human Centered Design and Science Fiction Thinking. The author's reasons for selecting these Methods for analysis in this work are described in Section 5.

Design Methods	
Design Thinking	A non-linear process that emphasizes understanding a user, challenge assumptions and create solutions to problems. [77]
Human Centered Design	A process that aims to make systems useful by focusing on the user, their need and requirements by applying Human Factors. [78]
The Imagineering Process	A process used by Disney Imagineering when Designing theme park Attractions. [79]
Science Fiction Thinking	A process of purpose driven Innovation to develop concepts using science fiction Methods. [80]
Design Techniques	
Sketching	A quick Drawing that is not intended as a finished work.
Prototyping	An early model of a product created to test a concept.
Storyboarding	A drawn representation of a sequence of events.

<u>Defining Methods</u>

<u>Design Thinking</u>

Designers in the past have focused on improving the Aesthetics and function of objects, however, Designers have recently begun applying their Methods to professional Design work that addresses social challenges. [27, 28] It is often thought that IDEO.org evolved the Design Thinking Process, however, as IDEO.org explains, it has history in conversations that have been growing for decades in the Design Discipline. [27] After calls to address client problems out of their traditional scope of Design, normally within the "Human Centered Design Process", IDEO coined the term "Design Thinking" to characterize and categorize the components they found most essential from Human Centered Design. This Method can be broken down as a series of overlapping elements, rather than a linear process. The three big elements of Design Thinking are "Inspiration, Ideation and Implementation". They can be further broken down into these categories: empathy, optimism, iteration, creative confidence, experimentation, and an embrace of ambiguity and failure. [27, 28]

While Human Centered Design is "cultivating deep empathy with the people you're Designing for, generating ideas; building a bunch of prototypes; sharing what you've made with the people you're Designing for; and eventually, putting your innovative new solution out in the world," Design Thinking is "a human-centered approach to Innovation. It draws from the Designer's toolkit to integrate the needs of people, the possibilities of technology and the requirements for business success." [27, 28]

Design Thinking can and has been applied to various fields, including K-12 education, Government, Business, Food Innovation, Design Research, Equity Design and Sustainable Futures. [28] The following Institutions contribute to the research and advancement of the Design Thinking Method, including MIT D-Lab, Designmatters at Art Center College of Design, Berkley Haas Innovation Lab, School of Design and Creative Technologies at the University of Texas at Austin, Stanford D. School and Northwestern's Segal Design Institute. [28]

Human Centered Design

The Human Centered Design process is very similar to Design Thinking, however while Design Thinking focuses on business practices and societal challenges at a systematic level, Human Centered Design focuses especially on health, human ergonomics and emphasizes Participatory Action Research (PAR). PAR is a research Method that encourages action to understand the environment and attempt to change it after reflection. [29, 30] The definition of Human Centered Design used here is from Design Firm IDEO, the Interaction Design Institute and Stanford d. school. This Method is traditionally used in Design fields that deal with medical devices or software. Notably, this Method is used by NASA Johnson Space Center's Habitability Design Team when Designing life sustaining vehicles and environments. [6,7] This Method was popularized by Stanford's D. School and IDEO.org. [31] It shares the thematic elements of Design Thinking, but provides greater detail for accomplishing tasks using Design specific Techniques. [31]

The Walt Disney Imagineering Process

Historically, Disney has been known to utilize the skills of Designers for Concept Generation, the production of illustrations depicting an idea, and Attraction Formulation; the process of developing a ride, resort or themed space. Imagineering is described by Walt Disney as the blending of creative Imagination and technical know-how. [32] Storytelling, Imagination and Creativity are front and center in this process. Storytelling for Disney can mean following a specific narrative when entering a space and emotional influence on an individual. [32] While the detailed Imagineering process may be a trade secret, the following process is a simplified version, taken from publicly available texts on the subject.

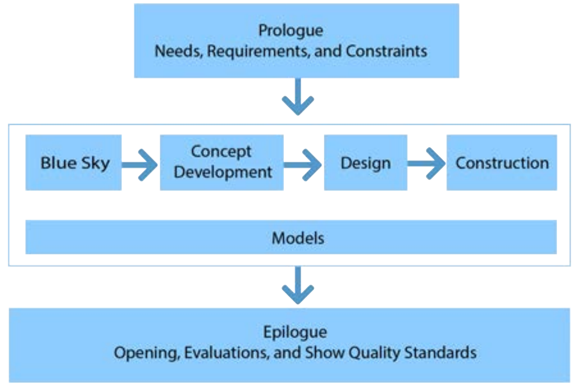


Fig. 2 The Imagineering Process, as described in "The Imagineering Process: Using The Disney Theme Park Design Process to Bring your Creative Ideas to Life." By Louis J. Prosperi. [32] Image by: Lizbeth B. De La Torre

This process seemingly shares elements with Design Thinking and Human Centered Design, however the end product and disciplines involved vary widely in theme park Design. While Design Thinking is packaged so that non-Designers can utilize the Method, Disney employs hundreds of disciplines, including Concept Designers, Model Builders and experience Designers that provide advanced Techniques unique to the Design Discipline. These disciplines are also present at NASA, definitions of which can be seen in Section 3. Perhaps the caliber of the Disney process is enhanced by the advanced level of Sketching, Painting, and diversity of Techniques, leading to more refined visual communication during their development. [2]

It is the combination of the adopted principles and Methods from over 140 disciplines over time that allowed them to develop the Imagineering Process. [2] Information on specific disciplines is not publicly available. While in the past the process was more informal, today it is formalized with the specific steps depicted in Figure 2.

Science Fiction Thinking

Science Fiction Thinking is a Method and term coined by Perception Studios. [33, 34] Perception Studios is a Design Firm that imagines and develops the futuristic technology seen in Feature Films, such as Black Panther (2018) and Iron Man (2004). Their process involves extrapolating technology innovation through Storytelling and World-Building. Storytelling here means creating a narrative, while World-Building means crafting an imagined environment through which a technology is intended to be used. An example of this is the World-Building guide for the Feature

Film Black Panther. [33] Designers create a World-Building guide when a film is in development. Through this World-Building guide, any technology or Artifact created for the film contains narrative elements that imply the Artifact exists within that world. While this Method has its roots in Feature Film, Perception Studios has recently begun applying their Technique to Aerospace corporations as they have discovered that Design for film can be supportive to other industries. [33]

An MIT course titled, "Science Fiction- Inspired Envisioneering and Futurecrafting," or "Science Fiction Fabrication," emphasizes a variation of this Method to create technology through "critiques of classic and modern science fiction, data-science extrapolation, digital and experiential simulation, evocative Design Imagination and holistic integration of select elements." [34] The MIT course, led by Dr. Dan Novy [35] and Joost Bonsen, [36] utilizes proven technology extrapolation Methods, such as the "Zwicky Box" and the "Artifact from the Future" to allow students to fabricate and reverse Engineer Artifacts from Feature Film. [37] From the class, ideas such as Spiderman's "Spidey Sense" come to life through working prototypes. [38] Below is a breakdown of the Science Fiction Thinking Method as popularized by Perception Studios:

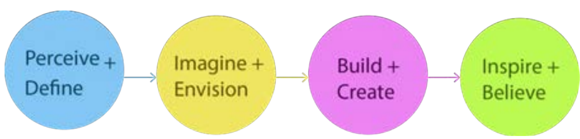


Fig. 3 A chart depicting the "Science Fiction Thinking" Method as defined by Perception Studios. Image Credit: Lizbeth B. De La Torre

Defining Techniques

This section describes Techniques used by Designers in parallel to the Methods above. The Techniques below describe Sketching, Prototyping and Storyboarding, which are Visualization and Communication Techniques used by the different disciplines in Design. There are variations of all of these Techniques, such as different forms of Sketching, Prototyping and Storyboarding specific to different disciplines. These Techniques are often included in the Foundation Education of Designers and follow them throughout their careers. Engineering Disciplines have not been seen to emphasize an Arts foundation in their foundational studies. The Methods above all emphasize using the Techniques to be discussed in this section.

Sketching

The word "sketch" can be described as a loose, quick Drawing that is intended to quickly get across an idea, but is not a finished work. [39] Sketches can be created in any Drawing medium, digital or analog, however it is most often associated with pencilwork, charcoal or pastel. Various disciplines of Design emphasize the use of Sketching to communicate an idea visually. [39, 40]

Fig. 4 Rembrandt, A Satire on Art Criticism, 1644, pen and brown ink, The Metropolitan Museum of Art, Robert Lehman Collection, New York, inv. no. 1975.1.799

There are various forms of Sketching specific to different Design Disciplines. Industrial Design, Fashion Design, Entertainment Design, and Architecture all emphasize specific Shape Languages, knowledge and skill in their sketches. Sketching is often said to be a language through which a Designer can facilitate dialogue with others. [40, 41] There is research that shows the significance of the Sketching Technique. A study by Dr. Maria Yang at MIT hypothesizes that "not all Sketching skills are related equal in the context of the Engineering Design process," implying a difference in Design outcome concerning sketch quality. Additionally, her research shows that quantity of Drawing may correlate to higher skill level in Sketching while focused on the Engineering Design process. [9]

The Engineering curriculum in the United States focuses on the teaching of drafting and CAD, which is normally used when a product concept is at a high fidelity. The Engineering curriculum does not emphasize Sketching for the first stages of Design, when it is important for an idea to be malleable. [10, 9] The work of Dr. Yang suggests that Engineering institutions should be informed of the type of Sketching being instructed and how it is distinct from drafting, which focuses on realistic Drawing. Sketching is necessary as a communication tool, with similar value to other languages such as math and verbal language. [10] An early example of Sketching applied to Engineering may lie in the work of Leonardo Da Vinci, whose work is admired today for both Artistic Painting and Engineering excellence. [42]

Research shows a statistical significance in the correlation between quantity of sketches and Design outcome in Idea Generation and Brainstorming. [9] The quantity of Drawings created during the earliest stages of the Design process were found to correspond to Design outcome. [9]

Sketching Categories	
Thinking sketch	Used to guide and focus nonverbal thinking.
Prescriptive sketch	Intended as a higher fidelity sketch for production purposes.
Talking sketch	Created during technical exchanges to clarify information.

The chart below describes the stylistic differences of the Sketching Technique within the professional Design practice. These discipline specific sketches are described because their educational foundation courses emphasize a specific style of Drawing.

Sketching Styles	
Industrial Sketching	This form of Sketching is for products intended to be manufactured. There is an emphasis on lines of an object profile and material emphasis, such as the shine of glass. They may be accompanied by annotations describing materials. [107]
Entertainment Sketching	This form of Sketching emphasizes characteristics of Characters, environments, vehicles and objects through exaggeration of perspective, material and shape. It is meant to convey an idea, emotion and Story. This Sketching Technique equally emphasizes the Drawing of objects, vehicles, humans, animals and environments. These sketches may be used for Film, Animation and Video Games. [108, 109]
Fashion Sketching	This Sketching Method has an emphasis on garment Design. Figures are often exaggerated to define the fluidity the wearing of a garment. Materials play a large role in this Sketching Method. This form of Sketching is often accompanied by discipline specific language defining stitching placement and style of clothing. [110]
Architecture Sketching	This style of Sketching is for building Design. It emphasizes user flow, aspects of a space that require interaction, and may be accompanied by discipline specific annotation. [111]
Transportation Sketching	This style of sketch is for the development of vehicles. Ergonomics may also be Designed. It emphasizes Aesthetics of emotion through Shape Language and Color Theory when Designing a vehicle. This Sketching can include any vehicle that will transport people. [112]

Prototyping

A Prototype is considered a low fidelity model of a product used to test the object, obtain user feedback or communicate a concept. It is used in various disciplines, from Design, Engineering, Software and Electronics. In the Methods discussed in Section 4, Prototyping has been described as essential in the phase of going from idea to final product. [43]

Designers can build Prototypes with media, however, they normally use lower quality materials. The Imagineering process uses models made of clay and foam to Design Attractions, while in Software Development, paper products may be used. Engineering Disciplines may define Prototypes as higher fidelity than the Design Disciplines. [44]

Storyboarding

Storyboarding can be considered an organizational series of illustrations formatted in chronological order to depict the Story of a film, Animation or experiential piece. A Story is a narrative account meant to describe a person or events. Walt Disney Studios refined Storyboarding in its current form in 1930. [45, 46] It was Walt Disney that developed the first "Story department," within an Animation studio, with a dedicated Storyboarding Discipline after recognizing the importance of emotion and narrative to Audiences. [45] All Animation studios today utilize Storyboarding.

Most recently, Industrial Designers, Experience Designers, UX and UI Designers utilize the Technique in a format that is used to define how a customer is expected to use a product or service. These disciplines are described in Section 2. Designers within these disciplines create detailed Storyboards describing body movement and emotion of a user utilizing a product. It is also used in scientific research, often in linguistic fieldwork. A subject is provided with illustrated representations of objects or situations and then implored to describe it. [46]

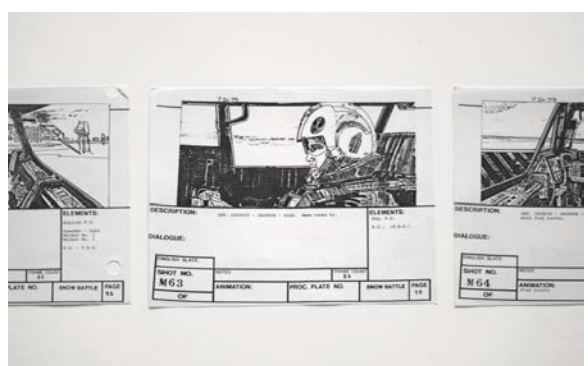


Fig.5 Storyboard reference copies used on set during the filming of The Empire Strikes Back in 1979. The

original Storyboards were created by Designer Joe Johnston. Image Credit: Matt Popovich

Legend of Definitions	
Expertise	The number of individuals needed that are subject matter experts.
Time	The amount of time the process takes from start to finish.
Staff	The total number of personnel needed, including experts.
Costs	How much this Method costs to utilize, considering amount of paid staff and not counting travel.

<u>Methods and Techniques Catalogue</u>

This section shares the beginning of a catalogue of Design Methods and Techniques for use in the Aerospace Industry. The following chart is in a format developed by the Netherland's Design Institute. It breaks down Methods and Techniques described in Section 4 of this work. Input is also documented, meaning the intended amount of time, disciplines required and amount of staff needed to support a project through estimated gauges. [12] In light grey below, other prominent Design Methods that are not discussed in this work are listed. Expertise, Time, Staff and Cost bars are grey where data could not be found.

<u>Methods Chart | Design Methods and Techniques</u>

Design Thinking: Input referenced from IDEO.org and the Interaction Design Foundation [31, 27]
Human Centered Design: Input referenced from "The Human Centered Design Toolkit" [21]
Science Fiction Thinking: Input referenced from the website of "Perception Studios" [33,34]
Imagineering Process: Input Referenced from literature on the subject where available. [32]

V. Investigation into Methods and Techniques

The author's research question is: What Exploratory Design Methods and Techniques are currently utilized formally and informally within Aerospace and what barriers and opportunities exist to expanding these Methods and Techniques?

This Section includes a summariy of data collected from interviews with Designers and Engineers within and outside of Aerospace in order to answer the research question above. Codes are used to protect the privacy of individuals and organizations. It is the intent of the data to shed light on opportunities where Design is supported in technical institutions and where Methods and Techniques are utilized. It is expected that Designers use some form of systematic process in their problem solving and utilize Design Methods and Techniques. The Analytical Narratives may include historical supportive evidence.

Key findings include evidence of Design Methods and Techniques being utilized within Aerospace. Evidence shows that a barrier for Aerospace Designers includes a lack of knowledge about the Design Discipline among colleagues of an Engineering Discipline.

Research Design

This work aims to develop a taxonomy and Design language for use in Aerospace through exploring the space mission development process and Designers that work in parallel fields outside of the Aerospace Industry. A research Design using case studies allows for developing data patterns through referencing of historical documentation, anecdotal evidence and in-person interviews.

This research design consists of a multi-case study including direct observation and personal interviews. The case study is unique in its ability to catalogue a wide variety of evidence, including artifacts, documents, interviews, and observations. The author selected a case study approach for this work because the data being documented is happening in the present time period and includes information that is not able to be replicated in a laboratory setting. [47] An experiment based on my research question would not be beneficial because of the separation from context and focus on few variables. [47]

The Case Study as used in this work is an in-depth study of an event or episode regarding an individual. It gathers empirical data on an event, circumstance, experience and phenomenon. Especially relevant for this work is the Case Study's ability to gather data and evidence from multiple sources; persons, decisions, periods and policies can be analyzed through the Case Study. [47]

This research Design makes use of qualitative data from in-person interviews through coding and patterning from use cases. After collecting information from the interviews, the author searched for key themes that arose from the data that supported the research question. Data was grouped into these arising key themes. It was expected that Aerospace organizations would not have as clear an understanding of the value of Design because of anecdotal evidence from public interviews from NASA Designers. [7] Little literature exists on the topic of Design Disciplines within Aerospace. This work is not meant to test a hypothesis, rather, to build an early foundation from which to develop potential theoretical statements about the research question.

The units of analysis were constrained to organizations. Data collected from employees was compared across organizations, including perspectives of organizations concerning the Design Discipline. The author began by collecting qualitative data through a series of personal interviews with a variety of stakeholders within individual companies. These interviews were collected from Management and Line employees. The units of analysis supported defining the dynamics of the relationships, understanding why opportunities do or do not arise and dissect the culture of individual companies. The author received permission from current contacts at these institutions to interview their staff. Through personal and virtual interviews, it was hoped to gain additional insight into their Methods that may not be attained in surveys.

Answers to the research question were supported by data summarized in a chart at the end of this section. Data shows evidence of Design Methods being utilized within Aerospace and evidence of an unclear understanding of the value of the Design Discipline that may imply a barrier for Designers in this field. Evidence from interviews also suggests opportunities for utilizing Design Methods and Techniques within Aerospace. The Sketching and Prototyping Techniques were found to be most utilized outside of Aerospace in this data set, while elements of Design Methods were referenced sparingly.

	Methods				Techniques						
	Design Thinking	*Human Centered Design*	*Science Fiction Thinking*	*Imagineering Process*	*Sketching*	*Prototyping*	*Storyboarding*	*Painting*	*Drawing*	*Photography*	*Collaging*
Company A	X			X	X	X	X		X		
Company B	X	X	X		X	X					
Organization C	X	X			X	X			X	X	
Organization D	X	X			X	X			X		
Company E	X	X			X	X		X	X		X
Company F		X			X	X			X		
Company G	X										

	Tools																		
	Microsoft Word	*Microsoft PowerPoint*	*Microsoft Skype*	*Google Suite*	*Notes*	*Confluence*	*JIRA*	*Cinema 4D*	*AutoCAD*	*Adobe Illustrator*	*Adobe Photoshop*	*Adobe AfterEffects*	*Rhino*	*Matlab*	*Revit*	*Alias*	*Wacom Tablet*	*Pen, Pencil and Paper*	*Unspecified 3D Modeling Software*
Company A		X				X			X		X		X	X	X	X		X	
Company B		X							X									X	
Organization C								X		X	X	X					X	X	
Organization D	X	X	X	X		X	X		X									X	X
Company E										X								X	X
Company F			X			X												X	X
Company G	X	X			X													X	X

VI. Space Mission Concept Development

NASA, the United States' National Aeronautics and Space Administration, is the civil government agency responsible for science and technology related to space. It was developed to oversee and guide aeronautics research. NASA's vision is "To discover and expand knowledge for the benefit of humanity." [48] Their missions of scientific discovery include Earth, the solar system and the cosmos. NASA expands knowledge in these areas through exploratory missions of the solar system via humans, robotic probes and spacecraft. The four strategic themes at the foundation of NASA's plan for space exploration include: Discover, Explore, Develop and Enable. [48]

NASA follows a specific process for developing Architectures for its science missions. Space mission Architectures are Designs and plans implementation and operation of spacecraft. This section discusses the current Flight Mission Project Lifecycle through the lens of a Designer, taking reference from materials on the topic, such as the "NASA systems Engineering handbook" and "Space Mission Engineering: The New SMAD". [49, 11] The author additionally uses evidence from interviews and dedicated NASA Design Teams. Areas where this discipline may be supportive are detailed based on literature in section 2 and 4 of this work. A Method and/or Technique has shown to be supportive if it aligns with and supports each phase's requirements to meet the next Lifecycle Phase.

<u>NASA Flight Mission Lifecycle</u>

NASA competed and Assigned Missions follow this strict series of reviews and checkpoints on their way to becoming a mission. The light grey portions are space Mission Concept Development, identifying how the program or project supports the Agency's strategic goals. Systems Engineers develop and allocate program requirements to initial projects. The dark grey portions indicate the steps taken after a mission concept has been approved (program start).

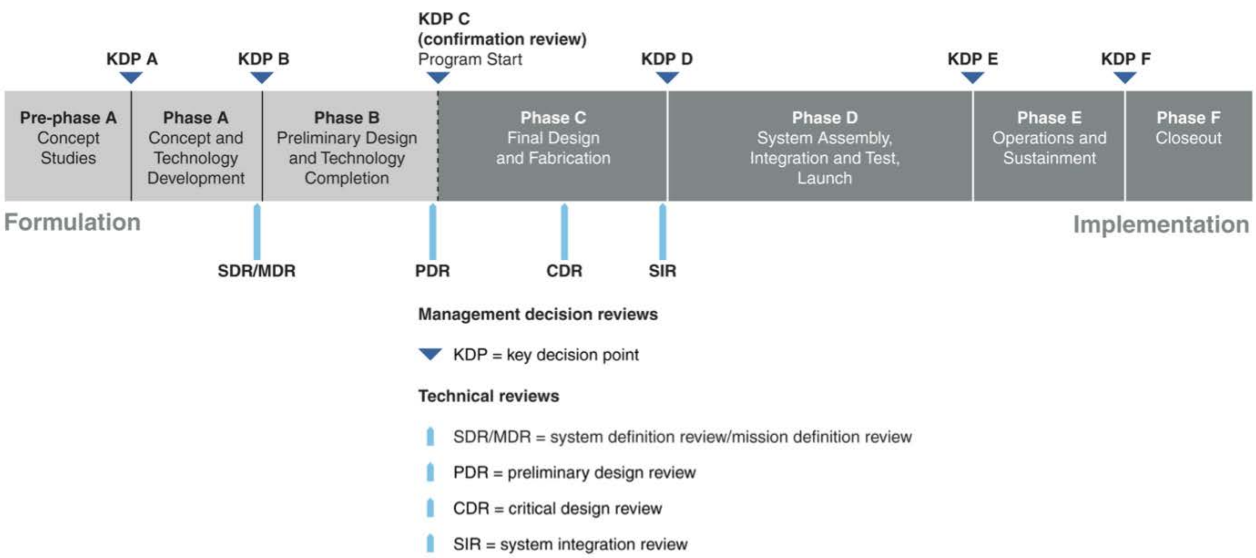


Fig. 9 NASA Flight Mission Lifecycle Credit: NASA/GAO

A crucial aspect of the Mission Architecture process is the management of the project lifecycle. Separated by Key Decision Points (KDP)s, the phases are distinguished in such a manner that each portion can be reviewed for readiness prior to continuing into the next phase. Key Decision Points are events during which the decision authority determines that the project is sufficiently ready for the next steps. [50]

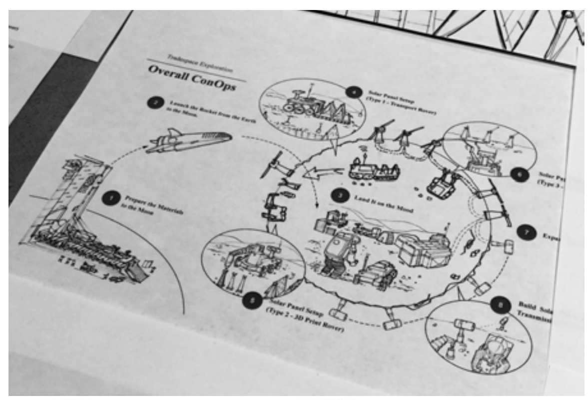
The process begins with the recognition of a need or an objective. Tasks performed by Systems Engineering such as optimization and analysis are completed in the early stages. [11] A key creative step in Systems Engineering is referred to as synthesis, which involves transition from a functional architecture (what a mission has to do) to a physical Architecture (what a mission looks like). This section will describe the various phases below and note areas where the Design practice is currently present.

<u>Project Formulation</u>

The first stage of the mission lifecycle is Pre-Phase A, also known as Formulation. Concept Studies are conducted during this stage. The purpose of this phase is to provide a multitude of mission options and analyze whether they fall within scope and cost, budget and scheduling. Through analyzing various concepts, a team can identify promising ideas for Space Mission Architecture. Architectures are Designs and plans implementation and operation of spacecraft. Systems Engineers are extremely involved in the concept development process. [11]

All of these improvements provide stability and quality control for a normally ambiguous time in a mission's lifecycle. JPL has additionally supported including non-Engineering disciplines, such as Designers, in this phase going so far as to support changes within the rigidity of government processes to include them. It is recognized that the Design discipline and Storytelling are important parts of the Innovation Foundry process.[8] It is unknown whether other NASA centers support the Design discipline in this manner within Pre-phase A. As noted in section 4 of this work, visual communication Techniques, such as Sketching and Storyboarding differ within specific Design disciplines and an understanding of the specific Techniques at their disposal is needed for optimal utility. It may be implied that the Storyboarding Technique used primarily by Concept Designers, for example, may be able to support the scheduling or ConOps (Concept of Operations) process, providing a powerful communication tool. ConOps has been described as a document outlining leadership's expected process for implementing a project. Clarity of information is important for ConOps. This document captures the architecture of a system. [51]

In an MIT course, Fundamentals of Systems Engineering, Designer Sheng-Hung Lee utilized Design Techniques as described in Section 4 of this work to communicate the ConOps in addition to the traditional written document. [52] While graphic visuals are used to communicate ConOps, they may be created by Engineers that have been shown in Section 4 to not have foundational studies in Design Techniques. Sheng-Hung Lee applied the Design Thinking Methodology and his Sketching and Drawing Techniques as a Designer to the systems Engineering Method "OPM" (Object-Process Methodology). OPM is a systems Engineering Method of capturing knowledge based on "two main components: elements/process and process/feature". [52, 53] Lee envisions a "creative approach to solving systematic challenges in the future." [52] The Visualization achieved through the Sketching Technique crosses discipline specific languages and is clear in its communication. The example below shares elements of the Story boarding Technique described in Section 4 of this paper. The visual illustrates an event in chronological order.



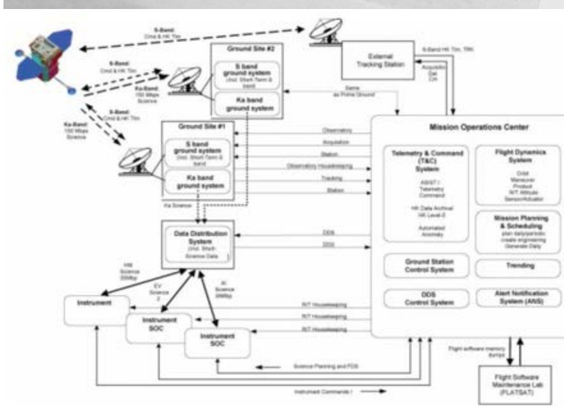


Fig. 10 Top: ConOps Design by Sheng-Hung Lee. Bottom: ConOps from the NASA Systems Engineering Handbook, 2007

While the top Design in figure 10 may be seen as a finished piece, these sketches can be completed during meetings and brainstorms of Design Teams. Graphics similar to these are usually completed much later in the process, often as a key graphic for a Proposal and not as early in the process. Perhaps a Designer's competence in the Sketching and Storyboarding Technique specifically may be supportive to the systems Engineering Discipline in Pre-Phase A.

The goals of Pre-Phase A include providing a multitude of options and analyze whether they fall within scope and cost, budget and scheduling. The following Methods and Techniques may be of support of Pre-Phase A's goals in the areas of Idea Generation, analyzing a multitude of options, and identifying promising solutions. The author has defined the style of Sketching that may be most beneficial based on interviews and research. The definitions of Sketching styles can be seen in Section 4.

Methods	Techniques
Design Thinking	Sketching- Entertainment, Industrial
Science Fiction Thinking	Prototyping
	Storyboarding

Within the Jet Propulsion Laboratory's Innovation Foundry, the A-Team utilizes the sketching and Design Thinking skillsets of Entertainment Designers as a core function of their team. The A-Team is an architecture team that leverages the knowledge of JPL subject matter experts to facilitate and guide advanced studies from concept to proposal. Management staffs each study conducted in an effort to match the topic and scope.

The core team member with a Sketching and Design Thinking skillset is called a Visual Strategist. The author often supports JPL's A-Team in this role. During studies, a Visual Strategist is called upon to collect information from subject matter experts through sketching. Visual Strategists have found that interpreting information through visual means inspires lines of thought that support the goals of maturing a concept.

A Visual Strategist might utilize Storyboarding as a visual communication tool during studies when there is a need to describe events that are discussed in chronological order.

Elements of Design Thinking are already utilized within A-Team. Idea generating and categorization processes such as idea storm and binning are used to achieve the goals of individual studies.

In the past, prototyping methods have been experimented with. The A-Team environment features bins of Legos, pipe cleaners and Styrofoam that are available for use by participants during studies.

It is hypothesized that science fiction thinking's emphasis on morphological analysis may support defining options in early formulation.

Phase A | Concept and Technology Development

The aspiration of Phase A is to advance a proposed system architecture developed in Pre-Phase A that is plausible and meets the requirements of the objective. Systems Engineers assign responsibilities for technology development and resources during this stage. Leaders provide documents to their team outlining expectations for advancement and maturity of the program requirements. Systems Engineers are also involved in development of architecture and distribution of requirements to the various elements. [11]

The goal of this stage is to define a concept and advance a proposed system architecture. Because cost becomes more significant during this stage, the Science Fiction Method and its use of Morphological analysis may support the team in reviews of objectives, requirements and constraints. [11]

Techniques such as Sketching and Storyboarding can support Idea Generation, visual communication and defining concepts during group meetings to reach consensus. Additionally, Prototyping can be started early at a low fidelity as can be seen in most Design Methods in Section 4. They can be Methods and Techniques below may support this phase:

Methods	Techniques
Science Fiction Thinking	Sketching- Entertainment, Industrial
	Storyboarding
	Prototyping

Science Fiction Thinking can be used to imagine the broad spectrum of ideas and directions that an idea can take. The Zwiky Chart is a method of problem solving that is visually recorded in chart form. This format explores possible solutions to a problem by categorizing them as a structured inventory. It is multidimensional, quantifiable and can be subjective.

This analysis may pair well with the addition of the sketching technique. The ability to visualize a variety of options quickly may be beneficial to achieving the goals of this phase.

In addition to the Science Fiction Thinking Method, The low fidelity prototyping technique utilized by design disciplines may support architecture explorations. Designers frequently utilize low cost materials such as paper when developing product concepts.

Phase B | Preliminary Design and Technology Completion

Phase B of the process is meant to complete critical tasks such as Engineering Prototyping, software assessments, heritage hardware and risk-mitigation. At this stage, the project should establish and demonstrate consistency in schedule, cost, technical and planning guidelines. During this phase, the team confirms that the mission concept is feasible and that there are no major risks that might make it impossible to complete the mission. Objectives specified in the ConOps should be used to validate Design choices. This phase is a collection of baselines that cover both business and technical portions of the system. Any changes at this stage should be measured against baselines. [11]

Opportunities for inclusion of Design Methods and Techniques include Prototyping, and software assessment clarification through visual aids. Additionally, the Sketching Technique can support clarification of the ConOps and visual communication amongst team members during meetings. Visual communication can also include clarification of information for PDRs (Preliminary Design Reviews). Changes to the collection of baseline documents can be supported by the Science Fiction Thinking Method's morphological analysis charts and are further described in Section 4. Supportive Design Methods and Techniques are placed in the chart below:

Methods	Techniques
Science Fiction Thinking	Sketching- Entertainment, Industrial
	Storyboarding
	Prototyping

ConOps is a document that chronicles the elements of a prospective system. This detailed document may be illustrated through the sketching discipline, and may emulate sections of a storyboard. The speed of sketching additionally supports quick, visual iteration of ConOps.

Originally, the format of this document was developed as a unified method of communicating operations and is often depicted as blocks of text.

Phase C | Final Design and Fabrication

Detailed Designs of the system should be complete at this stage and fabrication should be realized, including coding. Engineers in this stage fabricate hardware, breadboards, and code that are meant for integration. Integration within this context means to combine subsystems and their interactions into the whole system of a spacecraft. [54] While items are now finalized, trade studies continue and are meant to certify the system against goals, objectives and ConOps. Engineering prototypes are developed to review and certify that Designs will function appropriately. This Prototyping stage is prime for Human Centered Designers, Interaction Designers UX and UI Designers whose skillsets align with Human Factors when human space flight is involved. The Boeing Company has a dedicated User-centered Design Team, something seen in few NASA centers. [56]

Phase C's goals are to fabricate hardware, breadboards, software coding and are meant for integration. While this is happening, trade studies continue and prototypes continue to be developed. The Science Fiction Thinking Method's morphological charts and the Sketching Technique can contribute to visual communication during team meetings about trade studies. Storyboarding can additionally be utilized during team meetings in the event that an operation needs to be clarified. Low fidelity Prototyping as described in Section 4 can be used during hardware fabrication. The Design Methods and Techniques discussed in this interview are listed below.

Methods	Techniques
Science Fiction Thinking	Sketching- Industrial
	Storyboarding
	Prototyping

Phase D | System Assembly, Integration and Test, Launch

This phase includes assembly and integration and also includes verification and validity of the system in preparation for the Flight Readiness Review (FRR). Assembly means the process of combining the final hardware together. [11] Verification within this context is defined as the testing of hardware under simulated environmental conditions. [11] Flight

Readiness Review (FRR) is a review that examines the tests and analysis to ensure flight readiness. [11] At this stage there are rehearsals and training of operating personnel and crew members along with testing of the flight system for the expected environment. Systems Engineers are on hand to resolve issues, provide advice and to asses results. They give input to decision makers when a choice is made whether to move forward into the next phase. Any changes at this point can result in a high cost. At this point, Designs are finalized and the final system is capable of reaching its objectives. [11]

The system has been finalized at this stage, however Designers play a role in Communications. Graphics and Concept Designers work with scientists on highlighting the objective of the mission to the public. Phase D goals include tests and analysis, results of which can be visualized through Design Techniques when clarifying detailed information for stakeholders. Teams during this stage also rehearse and train for spacecraft Operations. Storyboarding proves to be beneficial for describing events and occurrences in chronological order. The Human Centered Design Method, through its focus on individuals, may be beneficial for Systems Engineers when developing Operations processes. These Methods and Techniques are described in Section 4.

Human Centered Designers focus on design of processes and products that emphasize ease and clarity of use. Human Centered Designers may be able to support the area of operations and the development of the processes that individuals must go through to train.

Methods	Techniques
Human Centered Design	Sketching- Industrial, Entertainment
	Storyboarding

Phase E | Operations and Sustainment

During Phase E, the mission is implemented for the objective it was Designed for and sustained for that objective. Systems Engineers often play a role in this phase because of their prior experience with complex systems. Systems with complex needs and adjustments may need updating beyond the duties of an operator. As an example, there may be information that needs to be sent to the satellite via radio link. Any large changes to the objectives, or "needs" would require restarting of the project lifecycle. Systems Engineers additionally determine faulty behavior called "inflight anomalies" when they occur. At this late stage, NASA Field Centers develop operating software with the support of an interface or Human Centered Designer.

In regard to software and interfaces during operation, a recent example from 2018 describes the need for Designers involved in Software Development. On the morning of January 13th, 2018, a false ballistic missile alert was sent to Hawaii via television, radio and cellphone. This alert told residents to seek shelter, and that it was "not a drill." Governor David Ige later apologized for the miscommunication and the House of Representatives began an investigation, which ended with the resignation of the state's emergency management administrator. The administrator of the Hawaii Emergency Management Agency has stated the alert was inadvertently triggered by an employee. Following the event, leading Design journalists at Core77 dissected the User Interface. [57]

An Article by The Daily News, states, "The employee [responsible], who has not been identified, selected a missile launch warning from a drop-down menu instead of selecting an internal test alert that kicks off a new shift, [Hawaii Emergency Management Agency] spokesman Richard Rapoza said. Not knowing he had selected the wrong option, he clicked "yes" when the computer prompt asked if he would like to continue. The worker realized the epic proportions of his error after receiving the same frightening missile alert on his own phone." [57]

To an Interface Designer, User Centered Designer or Human Centered Designer "human error" is often evidence of larger, systematic problems. Some of the time, it's the case that errors that seem to be caused by humans are actually the fault of systems that are not designed with human interaction in mind.

During Phase E science is obtained that needs to be communicated to the public. Designers use Techniques such as Sketching to take the complex data and make it digestible to the public. It may evolve into graphic Visualizations, video, illustrations and sometimes concept Artwork. Human Centered Designers may be able to assist Engineers in development of software that is intended for use by humans. Some programs within this stage have multiple flights or Operations. They may need configuration changes and may have new mission objectives each time. [11] The Design Thinking Method may assist Systems Engineers in organizing ideas and concepts through visual means. This Method may provide an additional way of documenting information. Storyboarding may be beneficial when documenting events and occurrences in chronological order. The following Methods and Techniques support Phase E:

Methods	Techniques
Design Thinking	Sketching- Industrial, Entertainment
Human Centered Design	Storyboarding

Phase F | Closeout

Phase F may occur many years after the launch and operation for a mission begins, though the plan for Phase F is addressed beginning in Pre-Phase A as part of the overall mission architecture. This step indicated the mission has completed its objectives and plans for a mission's decommissioning and disposal. The team, in previous phases, has established plans for decommissioning of their project. For a long term space mission, decommissioning may come unannounced in the form of hardware or software failures.

NASA additionally has requirements for reducing orbital debris. The "NASA Procedural Requirements for Limiting Orbital Debris", has requirements for the decommissioning of Earth focused spacecraft at the end of their lifecycle. Often, Low Earth Orbit Satellites are de-orbited and can burn upon re-entry, however larger satellites are intended to de-orbit into a targeted region of the ocean. Geostationary satellites, the farthest from Earth, cannot be practically de-orbited, and so are instead pushed into a higher orbit. In a project's earlier phases, a closeout plan has been developed, along with a series of options for when and how it will happen. [11]

Designers can be seen in this stage gathering final data from scientists for organization into graphical elements for research papers based on findings. One example of Communications can be seen in the Cassini mission's grand finale at Saturn. It won an Emmy for its production of interactive mission coverage, producing high quality web, news, social media and television products. The Sketching and Storyboarding Technique as described in Section 4 enable the production of these graphical assets. [158] When developing concepts for graphical assets, Design Methods such as Design Thinking and the Imagineering Process can be used to support Idea Generation and Storytelling as seen in Section 4.

Methods	Techniques
Design Thinking	Sketching- Entertainment, Industrial
Imagineering Process	Storyboarding
	Prototyping

The Flight Project Lifecycle below catalogues the Methods and Techniques defined in Section 4 and their relevance to each phase of the Flight Mission. Information is organized based on evidence from interviews and goals for each phase discussed in Section 6. Techniques have been shown to be used more often than any specific Method. Distinctions between styles of Sketching are indicated.

Formulation | Implementation

KDP A | KDP B / SDR/MDR | PDR / KDP C (confirmation review) Program Start | CDR | SIR / KDP D | KDP E | KDP F

Pre-Phase A Concept Studies	**Phase A** Concept and Technology Development	**Phase B** Preliminary Design and Technology Completion	**Phase C** Final Design and Fabrication	**Phase D** System Assembly Integration and Test, Launch	**Phase E** Operations and Sustainment	**Phase F** Closeout
Design Thinking Science Fiction Thinking	Science Fiction Thinking	Science Fiction Thinking	Science Fiction Thinking	Design Thinking	Design Thinking Human Centered Design	Design Thinking Imagineering Process
Sketching (Entertainment, Industrial) Protoyping Storyboarding	Sketching (Entertainment, Industrial) Protoyping Storyboarding	Sketching (Entertainment, Industrial) Protoyping Storyboarding	Sketching (Industrial) Protoyping Storyboarding	Sketching (Industrial) Protoyping Storyboarding	Sketching (Entertainment, Industrial) Protoyping Storyboarding	Sketching (Entertainment, Industrial) Protoyping Storyboarding

KDP = key decision point

Technical Reviews

SDR/MDR = system definition review
mission definition review

PDR = prelimenary design review

CDR = critical design review

SIR = system integration review

VII. SYNTHESIS

The Aerospace Industry, unlike the entertainment and Consumer Products industries, does not have a culture of recognizing the Design Discipline as a contribution to meeting core function goals and objectives. The argument of this work is that Design Methods and Techniques used by Designers have characteristics that can support Space Mission Concept Development. Evidence shows that some teams within NASA and Aerospace companies are already utilizing the skills of Designers. There is an opportunity to increase the use of specific Design Methods and Techniques at certain phases of the flight mission lifecycle.

Answering the Research Question

This work has shown evidence of the use of Design Methods and Techniques in support of Aerospace and has presented proposals for how these Design Methods and Techniques may be utilized further. Evidence from multiple interviews performed in this study implies that the activities of Aerospace teams can draw from several Design Disciplines, including Human Centered Design, Industrial Design, Entertainment Design and Graphic Design. Sections 5 and 6 show evidence of answers to the author's research question: "What exploratory Design Methods and Techniques are currently utilized formally and informally within Aerospace and what barriers and opportunities exist to expanding these Methods and Techniques?" This research question is broken into two parts below.

Part 1
What Exploratory Design Methods and Techniques are currently utilized formally and informally within Aerospace?

Interviews show evidence that the following Design Methods and Techniques are currently utilized within Aerospace. Some Designers within Aerospace utilize elements of entire Methods informally. One example from interviews depicts a Designer selecting to utilize the Design Thinking Method's "Card Sorting" element, rather than the entire Method. Aerospace Designers use Techniques more frequently than any specific Method as can be seen in Section 5. The Use Centered Design Method was shown to be used within NASA's Jet Propulsion Laboratory for the creation of a smartphone application. This instance is further described in Section 6.

Design Methods	Design Techniques
Design Thinking	Sketching
Human Centered Design	Prototyping
Imagineering Process	Storyboarding
Science Fiction Thinking	Collaging
User Centered Design	Photography
	Drawing

Part 2
What barriers and opportunities exist to expanding these Methods and Techniques?

Interviews and historical evidence show that a common barrier within Aerospace for Designers is cultural. Designers within Aerospace are seen to acknowledge that there is little knowledge within Aerospace of contributions offered by the Design Discipline, particularly within the Engineering Discipline. The development of a Design language and taxonomy for Aerospace may influence this barrier. The beginnings of a catalogue can be seen in Section 4.

Opportunities exist within the space mission flight lifecycle to utilize Design Methods and Techniques. Evidence shows that Designers can support accomplishing goals and objectives within the different phases. These are further elaborated on in Sections 2,3, 4 and 6.

Barriers	Opportunities
Lack of knowledge of the Design Discipline and its processes within Aerospace.	The flight mission lifecycle: Pre-Phase A, and Phases A, B, C, D, E, F.

VIII. Conclusion

In conclusion, this paper distinguishes between the Design and Art Disciplines while providing recent examples of Design within NASA. Current, dedicated Design Teams within NASA centers are catalogued. Evidence from interviews suggests there are opportunities for the Design Discipline to be of support during Space Mission Concept Development. It was noted by Designers currently working in Aerospace that possible barriers for opportunities may be due to lack of knowledge of the Design Discipline.

Methods hypothesized as supportive within Aerospace include: Design Thinking, Human Centered Design, Science Fiction Thinking, and the Imagineering Process. Evidence from interviews shows elements of these Methods being utilized in various forms already within Aerospace, though rarely in their entire form. This paper highlights that the Techniques discussed are beneficial to project outcome and used more often than the Methods within Aerospace. Initial evidence shows that an inclusion of Design Methods and Techniques may benefit the Space Mission Lifecycle, either in support of the systems Engineering Discipline, visual communication or reaching consensus during trade studies. In order for leaders of space missions to apply Design Methods and Techniques effectively, they will need to understand the purpose of each Technique and how to implement it in the context of their work. The results of this research provide a tool that project managers of space missions can use to select which Design Methods and Techniques may be utilized in each phase of their work on a space mission.

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