Design Ideation Through Speculative Fiction: Foundational Principles & Exploratory Study

Maulik C. Kotecha
J. Mike Walker '66 Department of Mechanical Engineering
Texas A&M University, College Station, Texas 77843
Email: mkotecha_1992@tamu.edu

Ting-Ju Chen
J. Mike Walker '66 Department of Mechanical Engineering
Texas A&M University, College Station, Texas 77843
Email: carol0712@tamu.edu

Daniel A. McAdams
J. Mike Walker '66 Department of Mechanical Engineering
Texas A&M University, College Station, Texas 77843
Email: dmcadams@tamu.edu

Vinayak Krishnamurthy*
J. Mike Walker '66 Department of Mechanical Engineering
Department of Computer Science and Engineering (by Affiliation)
Texas A&M University, College Station, Texas 77843
Email: vinayak@tamu.edu

ABSTRACT

The objective of this work is to position speculative fiction as a broader framework to stimulate, facilitate, and study engineering design ideation. For this, we first present a comprehensive and detailed review of the literature on how fiction, especially science fiction, has played a role in design and decision-making. To further strengthen the need for speculative fiction for idea stimulation, we further prototype and study a prototype workflow that utilizes excerpts from speculative fiction books as textual stimuli for design ideation. Through a qualitative study of this workflow, we gain insights into the effect of textual stimuli from science fiction narratives on design concepts. Our study reveals that the texts consisting of the terms from the design statement or closely related to the problem boost the idea generation process. We further discover that less directly related stimuli may encourage out-of-the-box and divergent thinking.

*Address all correspondence to this author.

Using the insights gained from our study, we pose critical questions to initiate speculative fiction-based design ideation as a new research direction in engineering design. Subsequently, we discuss current research directions and domains necessary to take the technical, technological, and methodological steps needed for future research on design methodologies based on speculative-fictional inspiration. Finally, we present a practical case to demonstrate how an engineering design workflow could be operationalized by investigating a concrete example of the design of automotive user interfaces (automotive-UI) through the lens of speculative fiction.

1 Introduction

For years people had been operating radios through pressing buttons and turning dials. Then as the technology became more sophisticated, with the touch-sensitive controls, you merely had to brush the panels with your fingers. Now all you had to do was wave your hand in the general direction of the components and hope. It saved a lot of muscular expenditure, of course, but meant that you had to sit infuriatingly still if you wanted to keep listening to the same program. — Douglas Adams, Hitchhiker's Guide to the Galaxy 1980 [1].

We can do much more than changing the channel; we can create 3D models with our hands in the air [2–4]. The "infuriating" lack of kinesthetic control in Mr. Adams' radio has been a subject matter of haptics [5], tangible and embodied interaction research [6, 7], and perception modeling [8] for the past few decades. Given that the imagination of literary stalwarts has led to many engineering innovations [9–12], it is not entirely difficult to conceive that imaginative stimuli from speculative fiction have the potential to affect the development of new products and services directly. It is interesting that in some engineering domains, especially human-computer interaction and robotics, it is often difficult to know whether sci-fi literature and media inspired the design of new interfaces [13] or research inspired new books and movies in the sci-fi genre [14]. For instance, many sci-fi works (particularly in films such as *Minority Report* and *The Matrix Reloaded*) revitalized spatial user interfaces and gesture-based interactions in virtual reality literature. While this does not necessarily establish a causal relationship between sci-fi and new product development, there is a strong indication that the use of ***speculative fiction as a framework for creative ideation*** could be an instrumental paradigm to pursue. Having said this, explorations towards a generalized framework or guidelines for utilizing existing science fiction literature as a pool of ideas with speculative technology remains little explored. Our broader goal in this paper is to explore speculative fiction as a framework for creative ideation and conceptualization in engineering design to complement existing techniques for design ideation. Specifically, our focus is to investigate how such an approach could be potentially operationalized, what novel research questions it will lead to, and how this paradigm will affect a wide variety of research directions on cognitive support systems for creative ideation. To this end, we take the following

approach in this work:

1. We present speculative fiction as a framework for socio-technical design and characterize different critical aspects of design ideation in the context of speculative fiction literature.
2. We study a concrete design workflow that utilizes speculative fictional literature as a means to stimulate design conceptualization.
3. We integrate the key findings from the study and pin-point the necessary technical, technological, and methodological steps needed for future research on design methodologies based on speculative-fictional inspiration.
4. We pose novel research questions arising from the preliminary user experiment and present them to the design research community.
5. We delineate how the designers could operationalize an engineering design workflow by presenting a concrete example of the design of automotive user interfaces (automotive-UI) through the lens of speculative fiction.

To investigate the idea of gainfully leveraging speculative fiction for socio-technical domains, we first explore the literary backdrop of speculative fiction and its role as a socio-technical framework for design (see Section 3). Then, we envisage a conceptual framework of a design ideation system that could, in the future, help designers draw ideas from science fiction literature for engineering design problems. To investigate this prospect, we created a minimal functional prototype of a design ideation workflow that curates and provides science fiction excerpts that contain mentions of speculative technologies to designers to assist in ideation. We conducted a study with eight participants to gain qualitative insights on how a designer may use such a system (Sections 3 and 5). Speculative fiction offers a unique perspective — it is imaginative, futuristic (depends on the time of publication), and thematically technical. Because of the combination of these specific factors, we believe that the value of speculative fiction, specifically for engineering design, needed to be explored. By exploring technical knowledge bases or regular searches (e.g., Google search), the designers do not usually encounter the kind of ideas or stimuli they would find in science fiction. The uniqueness of speculative fiction makes it difficult to compare existing methods meant to evaluate the effect of external stimuli on the design process. So, instead of comparing the existing methods, we aim to showcase our observations in the designers' design ideation process when exposed to science fiction-based text stimuli.

Subsequently, we lay the groundwork for future research on speculative fiction as a complementary framework for design ideation. For this, we integrate our key findings from our qualitative content analysis with the current literature in text mining and natural language processing (Section 7). Finally, we present a concrete example of automotive-UI design, a current niche domain in human-machine and human-computer interaction (HMI/HCI) (Section 8). The storyboard of an example automotive-UI design offers a concrete example of how one could use

speculative fiction in a real-world design scenario by tapping into an unexplored solution space that is opened up through stimulation by speculative fiction.

2 Background & Motivation

While investigating the notion of *structured imagination*, Thomas Ward [15] conducted a series of experiments where he tasked college students with imagining "animals that might live on a planet somewhere else in the galaxy". Upon comparing the student sketches with Barlow's Guide to Extraterrestrials [16] (a book with visualizations of different extraterrestrial life forms from various works of science fiction), Ward found that the structuring of students' sketches also holds for visualization of extraterrestrials as developed by science fiction writers. He further noted that the designs of alien creatures made by the participants reflected human assumptions of alien creatures. Both groups displayed bi-lateral symmetry, major appendages (arms, legs, and wings), and prominent sensory organs. The observations ultimately led Ward to conclude that in imagination-based creative tasks, there is a tendency hat stems from a predictable knowledge base. Ward's conclusion puts forth an important prospect of exploring whether design creativity could be improved by equipping the designer with the imaginative concepts of technical systems that science fiction could potentially offer. Our motivation for this work stems from the observation that the same notion of structured imagination could provide a rich toolbox for engineering design as well. After all, next to alien creatures, technology is one of the prominent themes in speculative fiction.

Experienced designers possess vast knowledge accumulated over time that may help them in performing design-tasks efficiently [17]. The prior knowledge may also generate fixative biases in the designer's thinking. Primarily for novice designers, and to some extent for experienced ones too, creative idea generation can be enhanced through provision of a repository of ideas or ideation tools [18, 19] that are driven by technical knowledge [20] or based on analogical reasoning [21]. We posit that having a knowledge resource consisting of the speculative advancements in technology and science found in fiction novels, magazines, blogs, short stories, or essays could complement the existing design idea generation tools.

3 Speculative Fiction as a Socio-Technical Design Framework

It can be argued that design, in general, is a socio-technical phenomenon. A designer never designs in a vacuum. The problems identified by designers have a host of non-technical elements ranging from social, geo-political, cultural, economic, and of course, personal needs of the stakeholders. However, we believe that literary works, especially science fiction, have already profoundly influenced on the design of engineered artifacts. A beautifully crafted 2015 cover-story by Brown and Logan summarizes this the best as "What makes science fiction valuable is not that it produces predictions, but that it provides inspiration [22]."

It's easy to see this in the names of companies and products. For example, iRobot, maker of the ubiquitous Roomba and military robots, is a sly nod toward Isaac Asimov's groundbreaking book, I, Robot. (The modem manufacturer U.S. Robotics adopted its name from a company in that book.) Big data pioneer Palantir Technologies is named after the seeing stones in Lord of the Rings. "TASER" was originally an acronym for "Thomas A. Swift's Electric Rifle." Even the terms robot and android were popularized in fiction before they were adopted by technologists.

3.1 Literary Backdrop: Sci-Fi & Technology

There are several fascinating examples of the realization of speculative technologies. Arthur C. Clarke, a science fiction author and physicist, in an article published in 1945, proposed the use of space stations for the broadcasting of television signals, which later became a reality in only seventeen years when the first TV broadcast satellite was launched in 1961 [23]. The modern-day smart-watches have astounding similarities with the communication devices mentioned in *Star Trek* movies. 'Tricorder' and 'transparent aluminum' from *Star Trek* are claimed to have been the inspirations behind the present-day lab-on-chip devices and aluminum oxynitride (ALON). Jules Verne, a well-known science fiction writer, had predicted the changes in aspects of life due to technological advances such as departmental stores, electronic music, hotel constructions, musical device equivalent to a synthesizer, etc. Verne described these technologies in a then-controversial book 'Paris in the twentieth century.' in the 1960s, which was 97 years in his future. Verne also predicted the endeavors of the moon-landing by humans in his novels, although he mentioned the use of a catapult to overcome the gravity pull. In contrast, today, we have rocket propulsion technology for that purpose. There can be seen some indirect inspiration from science fiction in the development of technologies. For example, the concept of invisibility, first introduced by H.G. Wells in his novel 'The Invisible Man' in 1897 and then frequently reintroduced by many others in different forms, has inspired the development of stealth technologies and military camouflage strategies. During World War II, American and British military analysts looked through science fiction for novel ideas and defense strategies. The *Galaxy Science Fiction* magazine reported that the military would, from time to time, take guidance from fiction writers to come up with outlandish plans for the attacks that were to be released to deceive the rival armies [24]. In a report on 'Augmenting human intellect' [25], Engelbart detailed a conceptual framework of augmenting the intellectual capabilities of humans with a sense of generality. Engelbart focused on determining current factors limiting the effectiveness of people's problem-solving abilities and developing the systems, methods, or procedures to match these capabilities to the social or technical needs better. He emphasized the use of modern electronics and digital computing for capability enhancements. As speculative examples of augmentation, he speculated some technologies that are realized today, such as stylus text-reader (pen scanner) and modern-day 2D/3D modeling software

(e.g., AutoCAD, Revit) for architects.

Following rather strict writing directives on speculative writing by Heinlein, speculative fiction became more and more popular after the 1960s, partly because fictions, written decades ago, were becoming a reality in the post-World War II era of industrial progress and innovations and partly owing to the so-called 'New Wave' movement in fiction writing in that era [26]. **However, within the scope of this article, we have used the terms 'science fiction' and 'speculative fiction' interchangeably at many occasions.** Exploring different categories of science fiction (e.g., soft science fiction, hard science fiction, speculative fiction, and science fantasy) and their impact on design ideation could help develop more profound insights into the specific nature of the solution. However, such exploration is beyond the scope of this article.

3.2 Science Fiction Connection to Design

Taking inspiration from science fiction, and fiction in general, is not entirely new in design theory. Some prominent examples are science fiction prototyping (SFP) [27], *Zygotics* [28], diegetic prototypes [29], and design fiction [30–32]. There are instances where solutions to the problems have arisen from science fiction in the fields of business [33], education [34], engineering, finance [35], and solutions in the form of innovative ideas inspired from science fiction writings or other types of creative arts [36–39]. There have been efforts toward making the speculative enactments of the future envisioned through fiction, which we know as design fiction. Design fiction is a design practice that helps in creating fictional designs, artifacts, scenarios with an intent to explore or criticize probable futures [31,32]. According to Lindley and Coulton, design fiction is something that creates a story world through narratives and has something being prototyped within that story world to create a discursive space [30]. Through design fiction, researchers have explored the possible implications of future developments in the rapidly developing fields of importance such as HCI [40]. In their book named 'Speculative Everything,' Dunne & Raby connect fiction with the philosophy of technology and social dreaming [36]. The increasing popularity of science fiction as a creative thinking tool gave rise to a new research area of Science Fiction Prototyping (SFP). SFP predominantly involves science fiction stories explicitly written as prototypes of the future to explore different possible futures. SFP involves descriptions of futuristic technologies and their implications on their surrounding society [27]. Pioneered by Brian Johnson in 2010, Science Fiction Prototyping finds its roots in the articles by Callaghan et al. [41, 42]. SFP has now evolved to become a systematic tool that provides a step-by-step methodology for using creative arts in science and engineering [27]. Design fiction has played a critical role in improving the technological fluency of society [43]. A paper by Blythe describes 'research through design fiction' where the authors used design fiction as a novel technique for exploring the potentials of innovative designs, and their repercussions [44]. Grimshaw and Burgess studied a co-creative design activity in a technology-enhanced

work-space, embedded with Science Fiction Prototyping under the name *'zygotics'* [28]. *Zygotics* caters a unique tool of creativity to the designers by providing the rigor of conventional design combined with the imaginative aspect of SFP in a grounded manner. Kirby coined the term "*diegetic prototypes*" to describe the cinematic depictions of future technologies and explored the possible role and consequences of diegetic prototypes on the real-world technologies [29]. The readers can find a more detailed report on the latest progress in strategies, techniques, and guidelines on design prototyping methods in recent work by Camburn et al. [45]. These works present distinct ways of establishing connections of design or related activities such as prototyping to fiction. However, the possibility of leveraging science fiction narratives as a resource for design idea generation remains to be explored.

3.3 Science Fiction in Decision-making

At any stage of the decision-making process, corporations require a large pool of ideas from their employees. As reported in a study by Liedtka [46], corporations often employ design thinking methodologies to boost idea generation. In their paper, Zhang and Miller [47] outline a step-by-step process of the decision-making for concept screening in the corporations through a case study conducted at an electro-mechanical engineering company. Their study attempted to answer some crucial questions in decision-making after the generation of ideas addressing the factors impacting idea screening, perception of each approach towards higher market potential, and differences in decision making by idea-generators and executives. Roberts and Middleton explored the use of Science Fiction Prototyping to describe how networked electronic products might evolve in the future digital economy [48]. Raven wrote in an article on the feasibility of using science fiction prose to portray and critique energy and infrastructural future that ultimately could help in decision-making [49].

We posit that borrowing decision-making strategies from fiction writers could be particularly beneficial to designers. Fiction writers are accustomed to thinking outside the confines of feasibility criteria (money, time, resources, etc.) and beyond the boundaries of the imagination of the general populace, which makes science fiction a potential source of ideas providing a fertile ground for development of futuristic technologies. Bruce Sterling, a science fiction writer, talks about the interlinks between literature and designs and how they can synergize with each other [50].

3.4 Design Fixation

In their paper on design fixation, Jansson and Smith established that blind adherence to a set of concepts limited and inhibited the output of conceptual designs. They note that fixation is a measurable hurdle in the conceptual design process [51]. In their experimental investigations, Jansson and Smith split their participants

into fixation and control groups. They provide instructions to all participants to create novel design solutions for a given problem. Visual hints are provided to the fixation group. They observed that the control group participants indicated more measures of creativity, flexibility, and originality of the ideas compared to the fixation group. Maier [52] has tested various fixations such as 'mental set,' 'functional fixedness,' and 'mechanized thought,' and proved in cleverly designed human-centered experimental studies. Kohn and Smith [53] studied fixation effects of collaborative brainstorming and found that collaboration helps in creating more ideas in totality. On the other hand, they also observed that the number of new individual thoughts and breadth of creative ideas was negatively affected due to the tendency to conform to other participants' ideas. The observation of fixedness in design activity is a motivation to provide external stimuli to the designers to mitigate fixedness and boost creative idea generation. Researchers have explored various approaches to aiding the engineering design process, including design by analogy (DbA) [54–59]. Researchers have successfully attempted to make design analogies within (other disciplines of engineering), and outside of engineering like biology [60–62], and origami [63, 64].

In the context of a design aid, we believe speculative fiction could become a powerful new tool complementing currently known methodologies such as design-by-analogy, bio-inspired design, and in general, information-based ideation.

4 Science Fiction to Stimulate Ideation: An Exploratory Study

Looking back at the several examples of the realization of sci-fi technologies and potential advantages of applying it as a means for creative design, there are several questions that need to be addressed. For instance, *how do the fiction writers know which scientific idea could potentially change the future or what novel technologies would a device possess in the future? If sci-fi writers could get inspiration from science and technology, is it possible that technology designers could get inspiration from science fiction?* While answering these questions could potentially provide some fundamental insight, we believe these questions enmesh knowledge from a variety of fields, including cognitive science, psychology, engineering, and humanities. Our approach in this work was to conduct a human-subject study wherein our goal was to observe the workflow of the designers when exposed to a sci-fi based design ideation work-space.

4.1 Study Rationale: Textual Stimuli for Ideation

There have been many kinds of research on what could spark ideas in design. In a validation study, Malaga [65] compared the effect of word and visual stimuli to find that the visual stimuli provided better results on the number of ideas generated and the creativity of those ideas. Recently, Borgianni et al. [66] conducted a systematic experiment to investigate the effects of forms of stimuli on ideation (textual, visual, and combined stimuli). Their

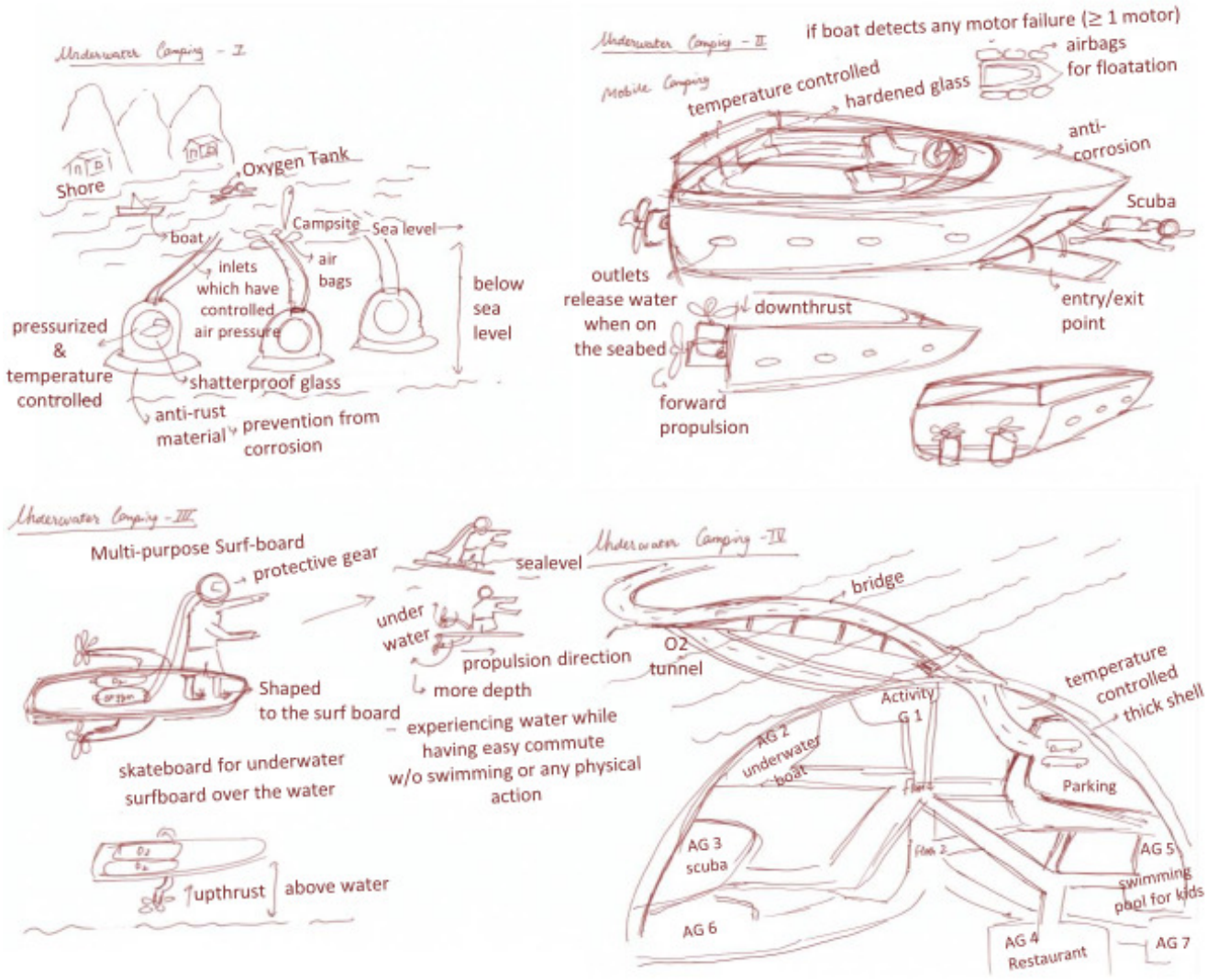

Fig. 1: We showcase the sketches created by a pilot study participant on 'underwater camping'. The participant was allotted one topic for the entire task duration and was allowed to browse only the *technovelgy* website to search for inspiration or borrow ideas. The original hand-writings in the sketches are replaced with typed text to increase legibility.

results indicate that while visual stimuli give rise to generation of non-obvious ideas, textual stimuli result in a higher quantity of ideas. In the meantime textual stimuli play a predominant role (increases semantic distance of ideas) in the ideation process in the combined stimuli scenario. In a fascinating study carried out with a group of industrial design students (novices as designers), Goldschmidt and Sever [67] used textual stimuli to support design concept generation. Goldschmidt and Sever observed that the provision of textual stimuli, be it related to the topic or unrelated, benefited the designers and showed qualitative improvements in the originality of the designs. From a text-based analysis of hundreds of designs collected through a web-based innovation challenge platform, Chan et al. [68] concluded that relatively closer conceptual distances trigger more creative breakthroughs. Assuming that the novice designers do not have ample knowledge or expertise on the topic, they

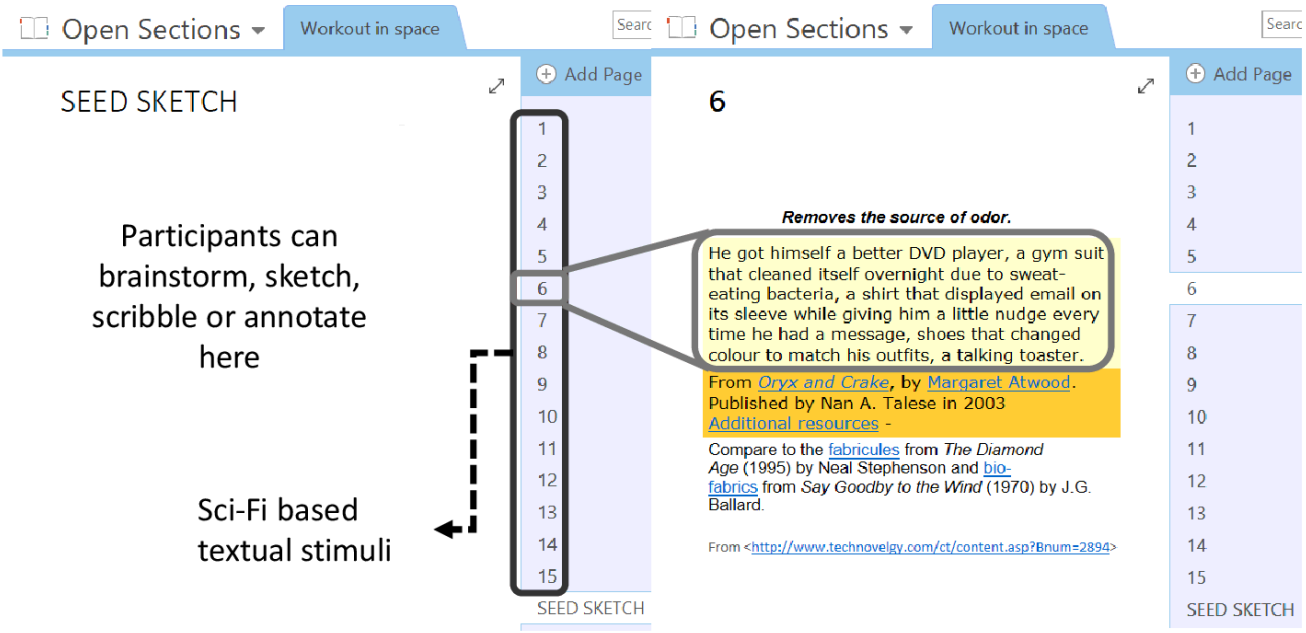

Fig. 2: A prototype of the ideation tool provided to the participants. Each selected science fiction paragraph is stored in one page.

would benefit from external stimuli [67].

Our goal in this work is not to measure, in any statistically significant way, the effect of speculative fiction on the creative outcome or to make any conclusions regarding the quality or quantity of the ideas that the participants generated. Our aim is instead to qualitatively study (a) how stimuli based on speculative fiction affect the workflow of the designers, (b) the importance of stimuli' relevance to the design problem, and (c) what actions do designers take when exposed to speculative fiction based texts. For this, we conducted a human-subject experiment where we observed the actions of the participants before and after the exposure to external stimuli (for (a) and (c)), and when exposed to stimuli with different relevance to the given problem (for (b)). The experiment is detailed in the following subsections.

4.2 Experiment Design

Participants: We recruited eight participants (ages: 20-29 years) who were senior undergraduates and graduate students from engineering, architecture, and visualization departments with some prior experience related to design. We selected the participants based on their design experience, including academic projects or industry experience.

Choice of Design Problem Statements: The intent behind introducing speculative technology-based external stimuli to the designers is to find novel solution ideas to novel/challenging problems. To that end, we intentionally

chose to provide challenging design problems to the participants in place of typical problems (e.g., designs for stapler, nut-sheller, kitchen utensil, etc.). We provided each participant with two design problem statements — Underwater camping (UC) and Work-out in space (WS). We asked the participants to develop design solutions to these problems using annotated sketches. We selected the design problem descriptions to be descriptive enough and encouraged participants to explore ideas for problems that seem unsolved or straightforward solutions are not easy to find. The design problems were also generic enough such that the participants from different disciplines with diverse background knowledge shared a similar level of understanding and familiarity with the context of the problems. We show the exact design problem statements in Appendix A.

Choice of Sci-fi Passages: For each design problem, we chose 15 science fiction passages from *technovelgy* as textual stimulation to the participants. Paraphrasing Goldschmidt's conclusion from their user-study [67], "the reading of text passages, be it either related or unrelated to the central problem, can inspire the designers and enhances originality and creativity of designs." We went a step further, and as a preliminary experiment, we carefully selected the descriptions from science fiction that represent both *related (R)* and *unrelated (or orthogonal; O)* concepts as sci-fi-based stimuli (see Appendix A for examples). By *related (R)*, we mean that the selected passages were suggestive of one or more solutions to the assigned design problem. Whereas the *orthogonal (O)* stimuli consisted of the passages that do not seem to suggest a solution approach directly. The intent behind choosing two different categories of stimuli was to observe how the participants perceive the content presented to them and relate it to their design problem. We can think of further improving and enhancing the framework by feeding the insights gained from the participants' responses to the different categories of stimuli in the design ideation process to natural language processing and machine learning algorithms.

Implementation of the Ideation Workflow (Minimal Functional Prototype): We used Microsoft OneNote-16 to present the textual stimuli to the user-study participants. Each OneNote file contains 15 science fiction passages selected from *technovelgy* and a blank space for the participants to use as working space (Figure 2). The participants were free to use paper and pencil to perform the task if they were not comfortable using the touch-pad device. However, all the participants used the digital interface.

4.3 Pilot Experiment

Before conducting the formal user-studies, we conducted two pilot experiments to (1) observe the response of the participants to our experimental procedure and the provided sci-fi knowledge, and (2) determine the appropriate time allocation for initial brainstorming and going through the textual stimulation. We also tested different methods of presenting textual stimuli, such as directed web-browsing (Figure 1).

Participants were intrigued by the given problems and curious to explore science fiction knowledge while developing solution-oriented ideas. For one of the pilot studies, we allowed exploring of sci-fi-based ideas by browsing the *technovelgy* website [69]. Browsing this website, the participant could find a mix of text and images related to speculated technologies. The participant expressed his/her ideas and concepts in annotated sketches for the design topic 'underwater camping'(Figure 1). Examining the video and screen-recording, we observed that the participant first searched for the terms related to the given design problem, clicked on the links to the relevant passages, and tended to emulate the results from some of the passages directly. Even though there were very few occasions where the passages were accompanied by some images, the participant showed a preference to get inspiration from images compared to reading the whole passage whenever possible. To eliminate any bias arising from the mix of two different stimuli, we decided to extract the text passages from the *technovelgy* website and put them on a OneNote file in separate pages while removing the additional information such as images and reference links. To observe how the participants perceive different types of textual stimulation, we further divided the participants into two groups: one received R-type stimulation on the topic Underwater camping, and the other received R-type stimulation on the topic Work-out in space (Table 1).

Table 1: The order of the topics assigned to the participants. Here, UC stands for 'underwater camping,' WS is 'workout in space.' R and O in the parentheses are for 'related' and 'orthogonal' (unrelated) stimuli, respectively.

Participant	1	2	3	4	5	6	7	8
P-1	UC (R)	UC (R)	WS (R)	WS (R)	UC (O)	UC (O)	WS (O)	WS (O)
P-2	WS (O)	WS (O)	UC (O)	UC (O)	WS (R)	WS (R)	UC (R)	UC (R)

4.4 Procedure & Tasks

The total study duration varied between 90 to 120 minutes (45 to 60 minutes for each design topic). For each study session and under their consent, we recorded the participants throughout the process. We also asked the participants to think aloud during the study session and explain their sketches/designs from time to time to understand their thinking process. Each participant was given one OneNote file containing 15 pieces of science fiction knowledge for each design topic (Figure 2) and was asked to develop ideas via sketching or writing within the given time frame. The procedure is detailed as follows:

1. First, the study investigator provided a walk-through of the overall task and familiarized the participants with

devices available to them for the study. The participants were further asked to complete a pre-task survey before starting the study to collect demographic information.

2. Subsequently, The study investigator provided the first design task to the participants. After reviewing the design task for around 5 minutes, the participants were asked to answer a second survey to gauge their familiarity with that design topic. They were also asked to explain their understanding of the problem and design expectations verbally.
3. The participants then took 15-20 minutes for brainstorming and preparing seed sketches to present their solution ideas without using any external stimuli. The study investigator instructed the participants to provide clear annotations and descriptions of their design concepts.
4. After the preparation of seed sketches, the study investigator asked the participants to go through the 15 passages (excerpts from *technovelgy* used as stimuli) in a specifically provided order. While reading, they were also asked to highlight the words or lines they found interesting or relevant to the design problem. They were allowed to modify and improve their designs upon completion of each passage. The order of the passages was randomly shuffled for each participant to prevent any possible biases created by the sequence of the passages.
5. After completing the first task, the participants filled a questionnaire regarding their experience and started the second exercise with another design topic. The participants completed the second exercise in the same way as the first one. The only distinction being the set of text stimuli provided to the participants was R or O (as per Table 1) to the topic assigned.
6. After completing the two design tasks, the participants responded to a post-study questionnaire regarding the individual perception of the experience and the usage of speculative sci-fi knowledge for design. We also collected open-ended feedback on the study and conducted informal interviews.

5 Results and Observations

In this section, we showcase some of the sketches made by the participants during the design exercise and report the observations of the study. Our study followed the think-aloud protocol [70], where participants verbally elaborated their thoughts during the tasks. We also recorded participant videos and their screen activity during the design task to allow us to and draw insights from their thoughts and responses to the sci-fi based textual stimuli. We mapped the participants' sketches to their verbal comments to better understand their thought process during ideation. We compared the participants' sketches and highlighted texts and made observations on how they differed between design-tasks and the type of stimuli provided.

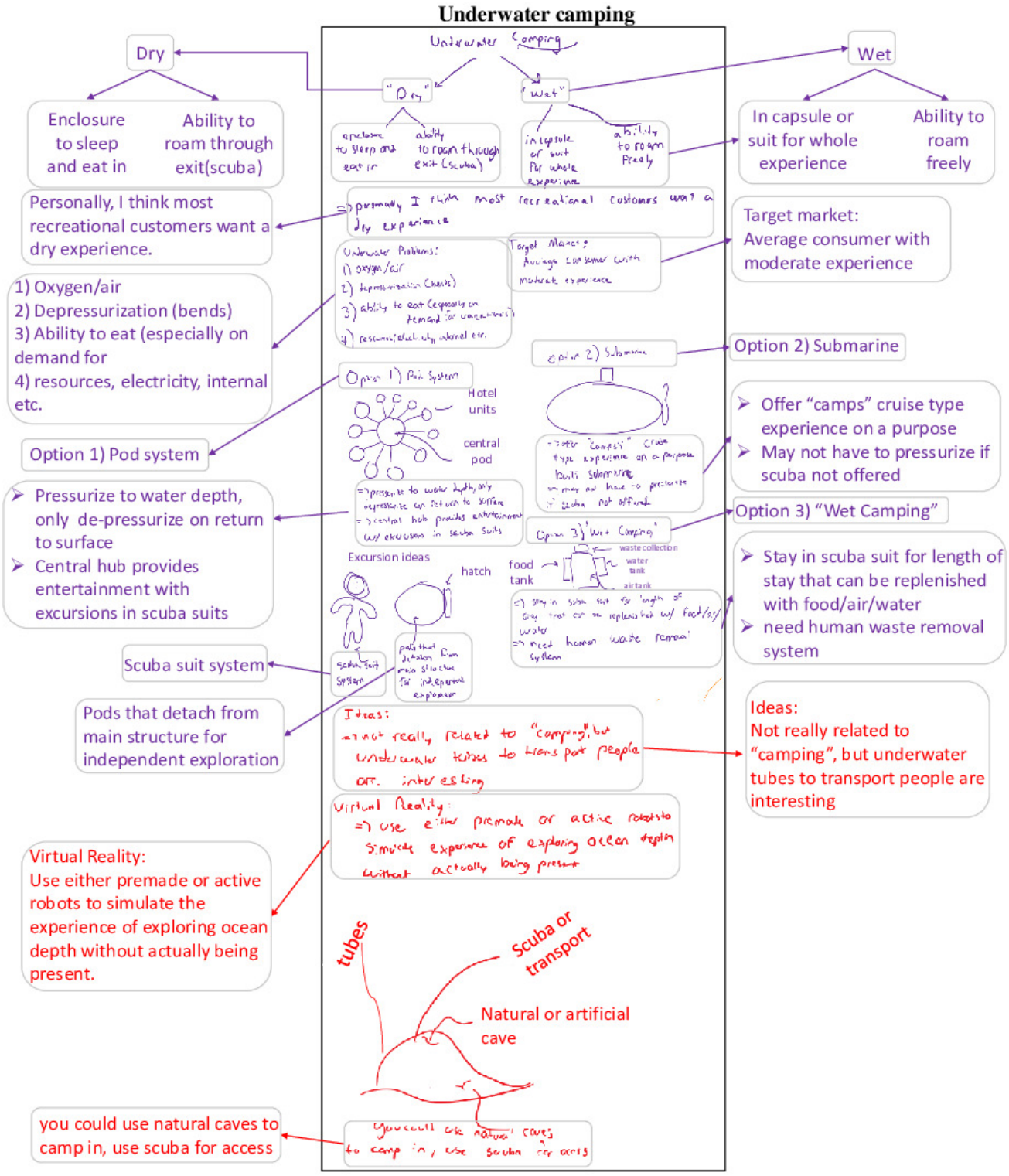

Fig. 3: We present the sketches drawn by a user on 'underwater camping.' The sketches and annotations with red ink are the changes made on top of the 'seed sketch' prepared by the user. These annotations are indicative of the addition of new ideas after going through the relevant or orthogonal textual stimuli. The original hand-writings in the sketches are either replaced or accompanied with typed text to increase legibility.

5.1 User Perception on the Usage of sci-fi

Here, we note a few qualitative observations of the tasks that the participants completed in this brief design exercise. Overall, we see a strong positive agreement on sci-fi usage during design exercises for both design

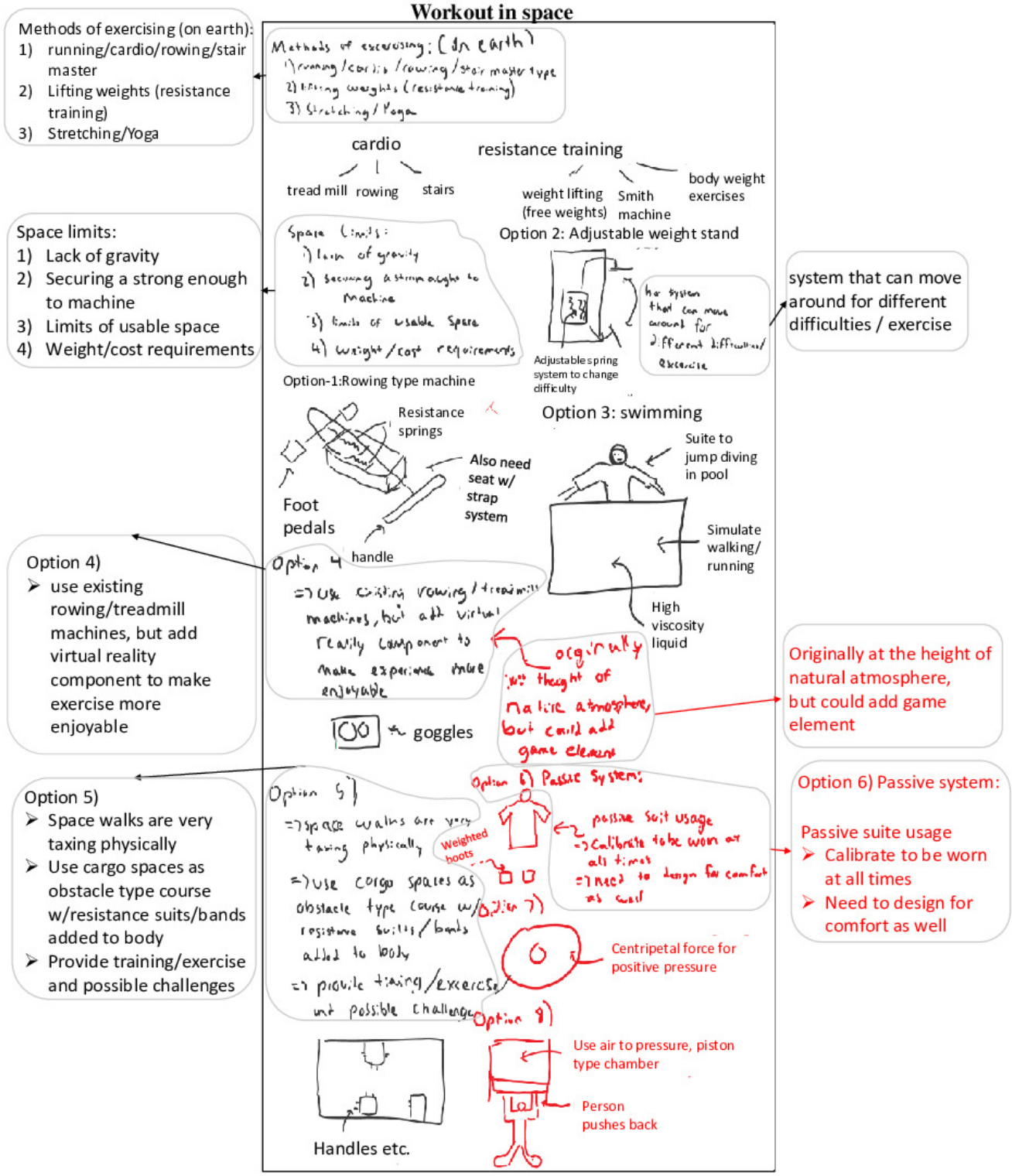

Fig. 4: We present the sketches drawn by a user on 'workout in space.' The sketches and annotations with red ink are the changes made on top of the 'seed sketch' prepared by the user. These annotations are indicative of the addition of new ideas after going through the relevant or orthogonal textual stimuli. The original hand-writings in the sketches are either replaced or accompanied with typed text to increase legibility.

problems (Figure 5). One of the participants who had a strong background in engineering design shared his/her view on the differences between this and typical design exercise: *"It was very different. The design process was*

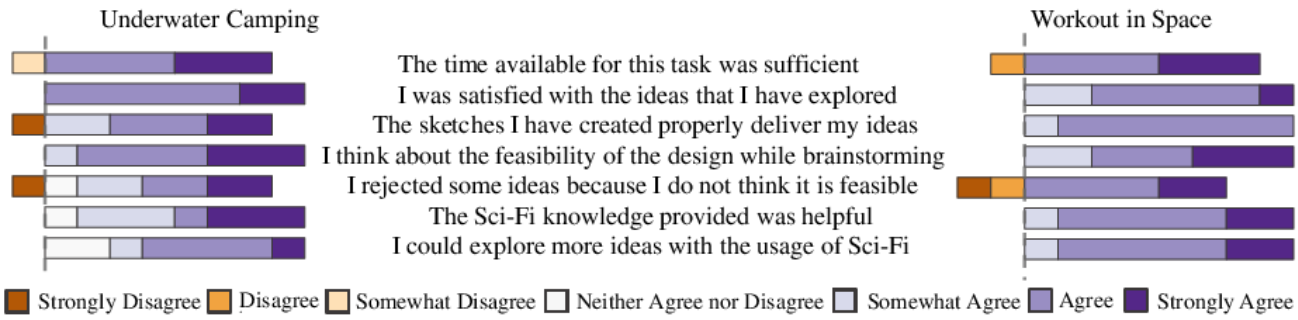

Fig. 5: 7-point Likert scale feedback from the user study showing general perception on the usage of sci-fi knowledge during conceptualization for atypical problems. The left-hand side of the dashed line shows disagreement.

very organic and I used excerpts from sci-fi novels and literature along with my idea of feasibility to come up with more ideas". He further note: *"I really enjoyed the experience, it was very unique and unusual which is how I imagine great products are born"*. This type of response was commonly recorded across all participants about their experience. While these responses, in themselves, do not directly help assess the efficacy of our approach, they certainly indicate that our methodology resulted in a good amount of engagement which could be useful in facilitating the ideation process. We also noticed that in such a brief study, the participants were excited about using science fiction passages to generate new ideas and iterate on existing ones for atypical problems by saying *"Surprised at how providing external notes can generate new ideas"* and *"More out-of-the-box ideas, reconsider(ed) my original design"*.

5.2 The Feasibility Factor

During the 'seed sketching' stage, the decision-making process varied according to participants' background knowledge on the assigned problem. Some participants rejected a few ideas with the rationale that those ideas didn't meet specific 'feasibility criteria' within their knowledge. When provided with 'relevant' stimuli for the design task 'workout in space,' one of the participants, while rejecting a potential idea during the design task, said *"The centripetal force – I thought about it beforehand, but I didn't add it. So, I think [it's] really just something that depends on other costs and limitations for something to do just for exercise."* Another participant tasked to design for 'workout in space' thought of including a sound system in the workout room and then thought of the feasibility of sound propagation, which led to the rejection of the idea. However, we would like to reiterate that we did not evaluate or intended to evaluate the designs based on any feasibility criteria or similar metrics at this stage. The users with more prior knowledge on the specific topic rejected more ideas. They explained that it did not match the 'feasibility criteria' upon which they decided while working on the seed sketch. A participant, who had prior design experience in an aerospace organization, rejected a few ideas suggestive of mimicking gravity. The participant mentioned that for suborbital missions where gravity exists, we don't need to emulate it. The

participant added that for outer space, the use of proper supports and electromagnetism-based equipment should suffice.

5.3 The Impact of Orthogonal and Related Stimulation

We show example sketches that one of the participants prepared during the design study exercise on topics 'underwater camping' (Figure 3) and 'workout in space'(Figure 4). This participant received the 'relevant' stimuli in the form of excerpts selected from science fiction books for the first topic ('workout in space') and 'orthogonal' stimuli for the latter. We differentiate the design prepared by the user before and after providing the stimuli by different ink colors (Figure 3 and Figure 4).

Overall, we observed that the external stimuli in the form of text passages proved beneficial to the participants. The participants found many of the concepts overlapping with their ideas that they sketched in the 'seed-sketch.' We examined the seed sketch and the additions in the seed sketches after their exposure to external stimuli. We observed that the text stimuli that directly catered to the design task or consisted of possible solutions (pre-selected by the authors) led the users to make more additions to their design.

Observing the highlighted words and sentences from both the design tasks for each participant, we noted that the designers highlighted in the passages at more instances for the 'relevant' stimuli. When provided with orthogonal stimuli, the participants marked more highlights for the topic 'underwater camping' compared to 'workout in space.' When we examined the highlighted text in coordination with the recorded video and screen-recordings across the participants, we noticed that there were instances where the same passages, when provided in the context of different problems, led to different solutions. For example, reading a passage on 'self-powered brooms' led to the provision of cleaning facilities for the 'underwater camping' problem. It helped the participants to think of performing daily chores like moping as a workout regime for the 'workout in space' task.

On the other hand, there were instances where more than one participant reached similar ideas by getting inspiration from different passages. For example, several participants thought of including 'electricity' to 'underwater camping' design from two different stimuli. One participant found his/her inspiration in a passage on 'undersea city' while the rest got inspirations from a text related to generating electricity using 'undersea mining.' We observed that the words that were incidental in leading the designer to solutions were semantically related. Apart from that, we also found multiple instances of participants generating more than one idea from a single stimulus.

Depending on the topic and the stimuli, each participant's time spent going through each stimuli varied significantly. The participants who had relatively more background knowledge on the assigned topics spent less time on the 'relevant' stimuli.

5.4 Preliminary Inter-Coder Analysis

To study the designers' behavior during the ideation task, before and after browsing through the cues that were provided to participants, we coded the video recording and screen-recording of the design tasks. The main purpose of this study is to (1) corroborate the user behavior we observed in the previous subsections (Section 5.1, 5.2, and 5.3), and (2) understand the *read-and-reflect* pattern which may benefit the design of future computer-supported ideation workflows. The coders followed a standard procedure for protocol analysis [71]. First, each coder independently came up with a set of designer actions. Subsequently, the coders debriefed and compared action categories to determine the final set of codes, as shown in Table 2. After that, both coders independently coded the same video. Using a five-second time tolerance to compare codes, the coders came to an inter-rater agreement with Cohen's Kappa (κ) of 81.45%, $p \approx 0$. A coded sample for a small segment of one of the participants' videos documented by one of the coders is shown in Figure 6. From the analysis of the video and screen-recordings of

Table 2: Video coding categories and descriptions

Code/Action	Description
Express	User expresses problem or solution verbally or through actions
Sketch	User sketches/scribbles ideas
Annotate	User provides lists, descriptions, symbols or words
Browse	User reads through the passages provided to them
Highlight	User highlights the words/phrases/sentences relevant to the task
Modify	User goes to the 'seed sketch' and adds details or sketches new ideas

the users, we found that they spent most of the time annotating ($\sim$25%), sketching ($\sim$20%), and browsing through

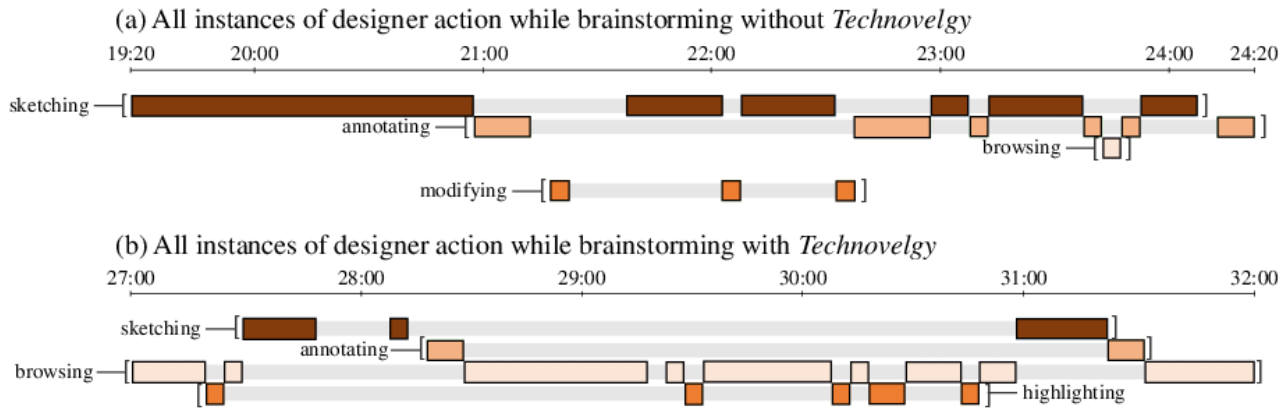

Fig. 6: A five-minute sample of coded designer actions carried out by one of the raters. Excerpts from the analysis of the video for design activity before and after providing external stimuli.

the provided textual stimuli (∼30%). Generally, we noticed that the users were highly engaged in the phase of reading through the provided textual stimuli. Also, most of them tended to discuss/explain their thoughts verbally to the study investigator after going through each stimuli, indicating that they were intrigued by the science fiction story and thinking about how to incorporate it into their seed designs. Several users were extremely active in the browsing-reflection cycle, as their actions switched between browsing, annotating and sketching frequently (Figure 6(b)). Other participants took some time to digest the textual stimuli provided to synthesize new ideas. For example, one user added to the seed sketch only after continually highlighting and jumping back and forth between four passages provided.

6 Implications from Study

6.1 Key takeaways and observations

From the observations noted in the previous section and the above analysis of the results, this user study has broad implications on the features of some proposed design ideation tool. Implications include selection and implementation of the text mining algorithms used for automatic reading and processing of the large speculative fiction text corpora, the type of information to be provided to the users as stimuli, the amount of time the user is to be exposed to the particular stimuli, and proportions of 'relevant' and 'unrelated' passages or words provided the user. The words, phrases and sentences that the users highlighted in our study can be the potential basis for deciding the nature of stimuli that designers would prefer. When viewed with the context of the designer's intent, the sketching and annotating patterns and tendencies of the designer could provide the basis for the design of the proposed interface and functionalities.

We make the following observations that could further be used as a basis to create a framework for ideation

Ideation task	Observations	Technical treatment
Initialize idea generation	Words or phrases could be sufficient to spark idea generation. Narratives provide better context when domain knowledge is lacking.	- An interface that provides 'related' and 'orthogonal' words/phrases as stimuli could be integrated into the design ideation workflow. - Narratives could be provided for each stimuli if necessary. - NLP and text-mining algorithms could be used to identify words/phrases that represent speculative technology.
Increasing the quantity of ideas generated	Semantically and contextually related stimuli improve the number of ideas generated.	- Algorithms for 'topic-modeling' and 'event detection' in NLP could be modified to categorize the passages and identify speculative technologies. - Syntactic Topic Models (STM), Latent Syntactic Analysis (LSA), Latent Dirichlet Analysis (LDA), etc. could be used to find semantically and syntactically related words/phrases.
Increasing variety and novelty of ideas	'Orthogonal' or 'Unrelated' stimuli could inspire divergent thinking and ideas.	- From the previously identified words/phrases related to speculative technologies, the words that are conceptually/contextually closer to the design problem could be classified as 'relevant' and the ones that are farther (but not too distant) could be provided as 'orthogonal' stimuli.
Leveraging prior domain knowledge and eliminating fixative biases	The quantity and quality of ideas depend on prior domain knowledge of the participant.	- Existing ontological databases and tools such as WordNet, ConceptNet, TechNet, etc. could be employed as well as novel ontology based on speculative technologies could be built. - Metrics to evaluate quality of ideas (novelty, variety) could be validated and employed

Fig. 7: We present the observations from our user-study experiments relevant to design ideation activities. We also list the possible technical treatments to incorporate the takeaways from the observations into the design ideation tool workflow.

tools.

1. The designers may not necessarily require passages as stimuli. Words or phrases could be sufficient to spark idea generation. However, the passages do provide context to the user and thus provision of passages helps establish context.
2. We observed that semantically and contextually related stimuli improve the number of ideas generated. For example, one of the participants in our user-study highlighted the words "*generates electricity...*" and added the ideas for providing electricity underwater on to the seed-sketch for the design topic "Underwater camping" with 'Related' stimuli.
3. 'Orthogonal' or 'Unrelated' stimuli inspire divergent thinking and ideas. For the design topic "Workout in space", when provided with 'Orthogonal' stimuli, one of the participants highlighted the sentence "...Larry's chair was part of Larry. It had no back." and came up with the idea of "A resistance chair— a chair fixed to

the floor of the space shuttle that has dumbbells attached to it using elastic bands." This idea was observed to be newer compared to the other ideas drawn in the seed-sketch. The idea was 'divergent' in the sense that the participant thought of using chair in a functionally different way than its conventional/intended use.

4. The proportions of 'related' and 'orthogonal' stimuli should be decided based on the designer's prior knowledge.

6.2 Research Questions to the Design Community

Our study gives rise to several questions that are fundamental to the use of speculative fiction as a broad framework for enabling, enhancing, and studying creative ideation, as listed below:

1. What will the workflow of sci-fi based design ideation look like?
2. What, in science fiction, is particularly significant in the context of design idea generation?
3. How do different types of stimuli (i.e., textual, image-based, video, sketch-based, or prototypes) affect design ideation using sci-fi?
4. How does the interface affect the design ideation workflow?
5. What kind of science fiction (i.e., science-fiction, hard science fiction, speculative fiction, fantasy fiction, etc.) effectively helps in the context of typical design problems? Or what kind of design problem would get the most benefits of sci-fi based design ideation workflow?
6. What are the different types of design problems that could be addressed using speculative fiction based text stimuli of different length (i.e., words, phrases, technology descriptions, or situation narratives)?
7. What is the role of context in the case of sci-fi based idea generation stimuli? Does context matter, or just some particular words or phrases suffice?
8. Is it possible or even necessary to differentiate the ideas generated using speculative fiction from the ones stemming from conventional technical knowledge resources?
9. How does designer prior disciplinary knowledge impact the sci-fi based idea generation? What will be the differences in the design idea generation processes between novice and expert designers?
10. Can we use the conventional novelty/concept evaluation measures/metrics for the sci-fi based ideation?
11. How do the ideas generated/inspired from sci-fi based stimuli translate to the final design/prototype/product?

Each of the above research questions demands a proper problem formulation, detailed and controlled experiment, and thorough analysis. We explore a few of these questions in the subsequent sub-sections by suggesting a possible design ideation workflow, examples, and reviewing relevant existing literature within the purview of the above questions.

7 Speculative Fiction for Design Ideation: A Computational Framework

7.1 Sci-fi Based Design Tools: A Conceptual Prototype

We use the insights gained on the design workflow from the user studies to propose future research directions for developing a design ideation tool or method based on speculative fiction. We delineate possible technical treatments to incorporate the takeaways from the observations into the design ideation tool workflow (Figure 7). A tentative workflow of the proposed ideation tool has three main components (Figure 8). The first component, the right part of the figure, depicts a possible workflow of a conceptual design activity where the designer starts with a problem, explores the problem space, and then moves on to the solution space. The second component is a design ideation tool or methods based on technical resources like research papers, patent databases, and technical articles. We review a few of such tools and methods later in this section. The third component is a speculative fiction based idea or stimulus generation that complements the other ideation methods in aiding the design process.

The first observation leads us to the notion of ideation tool that provides stimuli in the form of passages as well as words and phrases extracted from speculative fiction texts. Following up on the remaining observations, there is a need to categorize the words, phrases and passages into 'relevant' and 'orthogonal' stimuli. For a small scale user study that we conducted, careful manual selection of stimuli was possible for us. However, to accomplish the above tasks at a larger scale, we need sophisticated algorithms that can mine for relevant and contextual words from the large corpora of speculative fiction. To this purpose, in the following section, we review natural language processing (NLP) and text mining algorithms specifically in the context of mining and understanding speculative fiction databases.

7.2 Text Mining and Natural Language Processing (NLP)

In recent years, the utilization of text mining, and in general, NLP in design literature has gained significant interest. It is reasonable to assume that these techniques would be directly usable in our speculative-fiction based workflows as well. However, we believe that the nature of speculative fictional narratives requires careful consideration regarding what methods to apply and how to tailor them toward our proposed framework.

We identify several seminal works that have utilized text mining and NLP on structured data for facilitating design ideation. For instance, TechNet introduced by Sarica et al. [20] provides a semantic network of technological terms using patent data where they used context-aware word embedding models such as skip-grams to provide better semantic networks. Goucher-Lambert et al. found latent semantic analysis (LSA) useful for generating stimuli based on the initial designs by the designers during the idea generation phase [72]. Gilon et al. introduced an analogical search-engine based on NLP that extracts conceptually near or far analogies for specific design needs [73]. Similarly, NLP could be useful to find analogies from sci-fi databases to look for 'relevant' and

'orthogonal' stimuli.

From our study we noted that the task of extracting terms that specifically refer to speculative technology is generally challenging. Since speculative technologies are fictional, the language used to describe them in passages is very different from a typical technical narrative such as patents, journal articles or manuals that are extremely structured and formal types of texts. As a result, the general classification methods that have so far been successful with patent and other technical databases, may produce inconsistent predictions with speculative fictional databases.

For the sake of argument, let us consider Latent Dirichlet Allocation (LDA). This method is known to be well-suited for topic modeling to identify relevant text from large corpora [74]. LDA, however, may not necessarily work for speculative fiction corpora since LDA is not particularly well-suited to short passage topic modeling while speculative fiction corpora are generally shorter than those for general texts. To address this, there have been recent developments that enable topic modeling on short texts [75–77]. For instance, a probabilistic Bayesian topic model named Sparse Dirichlet mixture Topic Model (SparseDTM) could be useful to infer scientific concepts from large text corpora (i.e., fiction books or collection of passages) consisting of short texts after dividing the whole text into relevant micro-passages [78].

Unsupervised learning models such as skip-thought vectors [79] could be particularly useful for extracting technical concepts from speculative fiction texts. We posit that their specific ability to reconstruct surrounding sentences of an encoded passage using the continuity of text from books will be instrumental in sci-fi-based ideation where the context of the surrounding text will help generate better stimuli. Wenlin and Huang presented a weakly supervised method for temporal event detection using identified narratives of before/after events [80]. One way of inferring concepts from sci-fi texts could involve event detection where observing specific changes in before/after events could lead to a possible involvement of technology. Combined with event detection, available design databases on functional basis could be used to our advantage [81].

An important future step to enable robust and open-ended ideation would be to connect speculative fiction databases is to connect with other known databases based on lexical, semantic, syntactic or ontological organization. These may include WordNet [82], Word2vec [83], GloVe [84], LexVec [85], ConceptNet [86] etc. that could be used for speculative technology exploration or stimuli generation from texts. The pre-trained language models (e.g. GPT-3 [87], BERT [88], ULMFiT [89], etc.) followed by a task specific training on sci-fi text corpora can be used for problem specific stimuli generation or for speculative technology recognition. As for our purpose of using speculative fiction as a technology pull, we recommend the researchers and ideation tool designers take advantage of a publicly available blog of inventions, technology, and ideas conceptualized in science fiction called *technovelgy* [69] to build a database similar to the ones listed above. The *technovelgy* site lists over 3,200

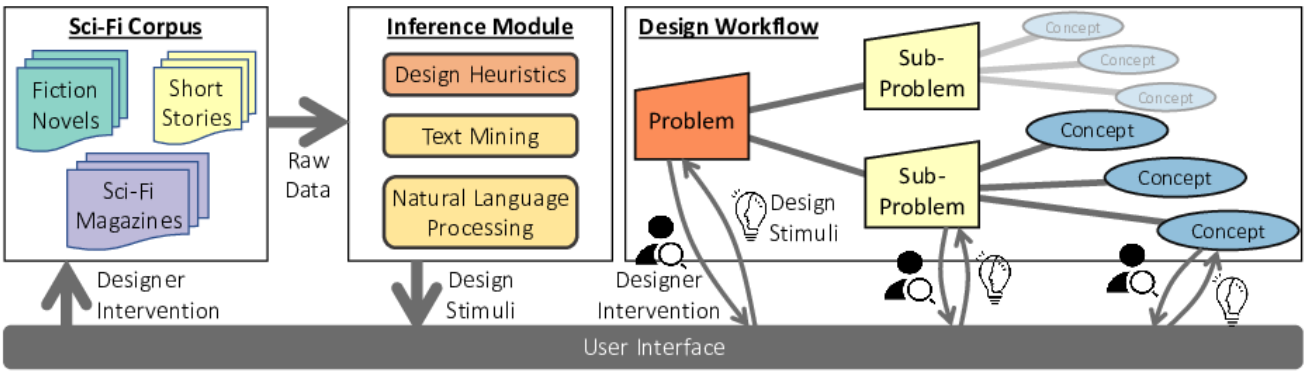

Fig. 8: In this schematic representation, we show how a future design workflow could be created by incorporating speculative fiction based stimuli generation with the designer's digital work-bench. Here, we considered a problem that has two sub-problems. The designer provides problem specific information via a user interface. The interface module uses text-mining algorithms and design heuristics to generate textual stimuli from sci-fi corpora. The stimuli could lead to one or more concepts and also helps to refine or expand over the problems.

speculative technologies and over 5,800 news articles reporting the realization of these speculative technologies. Co-retrieval of information from *technovelgy* and other known data-based will offer a unique ability to customize the design tool to different applications.

7.3 Metrics for Idea Generation

Ultimately, we recognize the potential need for a deeper understanding of evaluation metrics and methodologies suitable specifically for ideation using speculative fiction. For instance, our study indicated a clear difference from Goldschmidt and Sever's original work on textual stimuli [67]. From our study, we observed that related and orthogonal sci-fi passages stimulate different modes of cognitive support. This observation adds to Goldschmidt and Sever's findings that both related and unrelated textual stimuli help generate novel designs. Although orthogonal ideas activated different cognitive modes, the words that the participants highlighted were semantically related (so not orthogonal). To the best of our knowledge, currently established metrics for design ideation [18,45,51,54,57] may not suffice for developing deep understanding of speculative fiction based ideation. Therefore, the methods and metrics to evaluate the design outcome and the design process for sci-fi based design workflows need careful consideration. To this end, we reviewed several other metrics [55, 56, 66, 90–93] that could potentially be combined with currently prevalent metrics [18, 45, 51, 54, 57] to tailor specifically for speculative fiction based ideation. For instance, in one of the early works, Sarkar and Chakrabarti [91] developed a metric based on a causality model called State-Action-Part-Phenomenon-Input-oRgan-Effect (SAPPhIRE). More recently, Siddharth et al. [92] demonstrated the use of NLP to assess the novelty of engineering design concepts automatically. Kershaw et al. explored an approach based on 'decision-tree' for evaluating the originality of technical designs using different evaluation metrics [93].

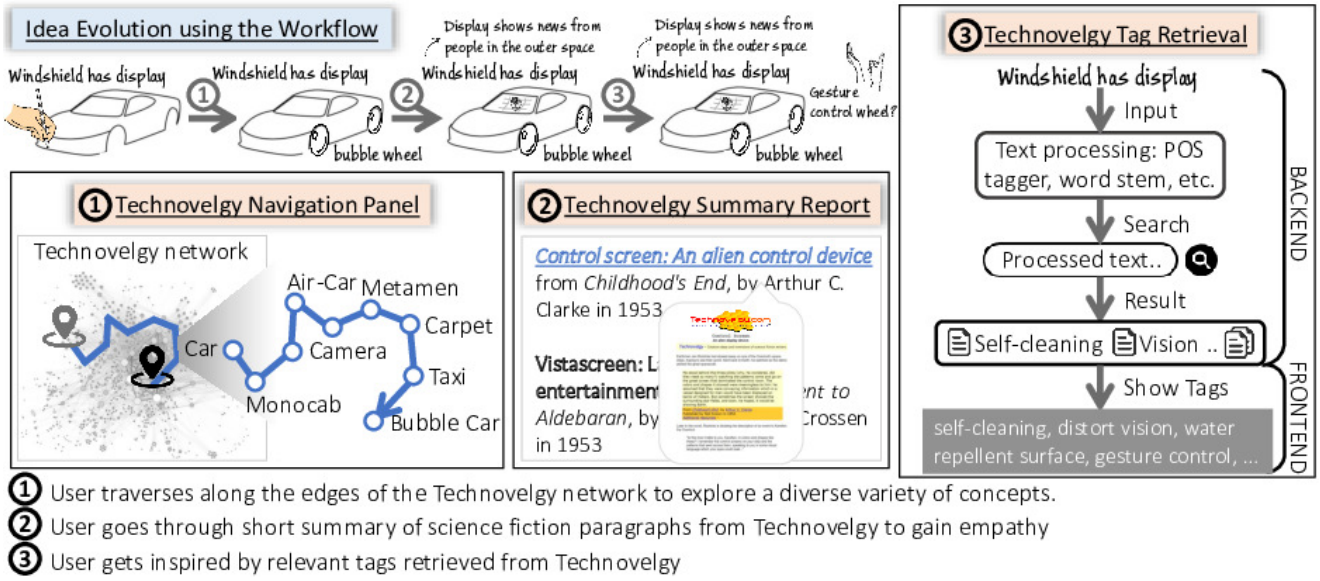

Fig. 9: This scenario shows how to integrate *technovelgy* within a automotive-UI design conceptualization workflow to provide stimulation. While the designer is sketching out some design concepts, the workflow may provide (1) a navigation panel for allowing them to explore different clusters of information in *technovelgy*, (2) short summary of science fiction paragraphs from *technovelgy* for allowing the designer to gain insights of the story, and (3) automatic tag retrieval mechanism that shows words/phrases that are relevant to the current design. Appropriate science fiction references were chosen for each of the textual stimuli shown here. Most of these references appeared in fiction books, several years before their realization. We also show a few novel ideas previously mentioned in sci-fi literature that are extracted from the *technovelgy* website and are not of everyday use as of today.

8 Speculative Fiction for Design Ideation: An Interactive Framework

8.1 A General Workflow for Design Ideation

We first note that a comprehensive user-driven workflow for ideation with speculative fiction should integrate textual data, text-inference models based on NLP, and the user interactions in an iterative loop (Figure 8). Additionally, we also propose that this iterative loop be available to the user at all possible stages, including problem discovery and refinement, sub-problem determination, and solution concept generation.

Design research is filled with several examples of new ideation workflows that were developed and evaluated to support creative idea synthesis. Here, we aim to identify workflows that could be particularly useful in exploring speculative fiction as an idea generation framework. Recently, several works have explored text-based stimuli in mind-mapping for ideation. In their article on mind-mapping via contextual query expansion, Chen et al. [94] presented a novel algorithm for creating mind-maps based on ConceptNet, a commonsense semantic network. In their work, they carried out user-studies to study Human-Human and Human-Computer interactions while using their mind-mapping program for different topics. They found that computers can generate semantic and subjective metrics comparable to human collaborative interactions. In another article by Chen et al. [95], they have dug into the topology of collaborative mind-maps and the temporal evolution of the maps during the whole process, which

provides a deeper understanding of how the human brain behaves while collaboratively working on a new topic. We believe that a data-set such as *technovelgy* could be directly integrated with these types of workflows to enable new types of mind-mapping tools allowing for exploring ideation methodologies based on speculative fiction.

The next logical step is to consider visual modalities augmented with textual stimuli. One of the seminal workflows, C-Sketch, was developed by Shah et al. [96]. C-Sketch structured creativity in engineering design and proved that it has clear advantages to other existing methods for the provocation of creativity with the help of extensive experimental studies. Other approaches, such as infusing speculative fictional text for inspiring the design team, could also prove to be a highly potent mode of collaborative creativity. We are also interested in tools that could effectively integrate speculative text stimuli with visual modalities, such as sketching based on new neural-network-based approaches. For example, Borgianni et al. [66] studied multiple modalities of external stimuli (textual and pictorial) in the design idea generation process. They observed that the presence of pictorial stimuli resulted in increased rarity and non-obviousness of ideas, whereas other metrics such as quality, quantity, and originality were unaffected. Thus, having a tool that offers a means to provide mixed-modality stimuli for idea generation could potentially offer better results for multiple metrics. Ha and Eck [97] used thousands of human-drawn images representing hundreds of classes to train their model to generate stroke-based drawings of the objects. Such models could be enriched with textual excerpts during the training phase to identify visual stimuli along with textual stimuli. We can integrate similar approaches with the work by Benjamin et al. [98] who explored image-based assistance for the designers where the authors converted user-drawn skeletons into images and used them to query the image-repository for design ideas.

8.2 Example: A storyboard on Automotive-UI Display

In this section, our goal is to describe an example of automotive-UI design to illustrate how a simple database such as *technovelgy* could be operationalized in the future by using the conceptual framework developed earlier. In general, the broad problem of UI (user interface) design begins simply with the input and output modalities. Input modalities are the actions that the user can take through physical (e.g., a button press), verbal (e.g., speech input), physiological (e.g., EEG, ECG), and several other modes. Output modalities are essentially those through which the user is receiving information from a system such as visual (e.g., a blinking light), verbal (e.g., the car talks to the driver), or even kinesthetic and tactile feedback (e.g., the steering wheel vibrates asking the driver to turn to avoid an accident). Therefore, for different functions, the designer of this automotive-UI system would need to consider a large variety of combinations of the input/output devices and related software. For example, an auto-translation task requires machine-translation software, a microphone as an input device, and a speaker or headphone as an output device of the computer. For its human counterpart, ears and mouth are required as sensory

and actuating organs, respectively.

Suppose the designer is currently exploring the idea of augmenting the car's windshield with an advanced display (Figure 9). The designer provides a simple textual input based on which several types of stimuli can be generated. For instance, a set of tags can be retrieved to help the designer explore a broad set of possibilities in terms of the functionality associated with a wind-shield display. The designer could choose to focus on one of these tags (say "*projection*") and deeply explore the selected functionality. On a different tool-view, a broader navigation panel may provide the designer with a large space of car concepts mined from *technovelgy* that may allude to technology similar to the one the designer is conceptualizing. Based on our study, directly providing textual excerpts itself would be potentially valuable. In many cases, the text is not merely a container for the engineering aspects of the design problem, but also a means to provide some social and cultural context to the problem. This is where, direct excerpts could be best suited. Quoting an example from our user studies, in a design task on 'workout in space', some of the users thought of having special provisions for different age groups as well as for persons with disabilities. Thus, the contextual passage-based stimuli have the potential to provide social and cultural means to design. Apart from the direct usage, the designer can also think of modifying the flow of the processes as well as combining more than one function into a single platform. For instance, one of the participants from our user study designed a back-mounted bag for food & water supply and the oxygen tank for the 'underwater camping' design task.

By integrating existing text visualization techniques, one can thus envisage a feature-rich design tool wherein the designer can get stimulation or inspiration at different levels of detail (a direct excerpt from a book, a tag-cloud, a topic navigation panel, and several other visual representations) to build up on their ideas.

9 Conclusions and Future Directions

Our objective was to position speculative fiction based stimuli as a new research direction in engineering design ideation. We provided the grounds for our proposition of using science fiction-based stimuli for creative idea generation in engineering design through a comprehensive literature review. To further support our proposed framework, we studied how science-fiction narratives could stimulate the designers' thinking process during ideation. This study resulted in a set of directives that can be useful for future research in this direction. Specifically, our observations helped bring out certain key research questions that could be interesting for the design community to pursue. To make our case for this framework, we presented a concrete example of how a future ideation tool could utilize speculative fiction and finally.

Our first set of immediate goals is to devise new studies that could provide statistically significant quantitative insights in speculative fictional design inspiration. In particular, we plan to study the effect of different types

of speculative fiction based stimuli (e.g., words, narratives, images) on different types of design problems (e.g., day-to-day design, novel challenges), and find out what in science fiction makes a 'good stimulus'. We further plan to expand our study analysis to include a thorough intent analysis of the participants' actions. We believe this is crucial for a better understanding of when and what type of stimulus should be provided to the designer. The intent analysis will relate each of the actions of the designer to one or multiple intents such as problem exploration and solution presentation.

Our review of the technological enablers (such as text mining and NLP) paves a path forward for some immediate research activities. For instance, it would be an important step to explore text mining and natural language processing methodologies in the context of our knowledge of speculative fiction and its relevance to engineering design and create a multi-level-of-detail data-set from *technovelgy*. The idea is to enable a sophisticated environment for the designers that offer various textual stimuli catering to several types of design problems. To conclude, we believe that speculative fiction could provide a strong basis for a powerful line of inquiry within the rich research domain of creative design ideation.

Acknowledgements

This work was supported in part by DARPA under contract number HR00111910006 and by NSF Award Number 2013612 from NSF-DUE (IUSE Program). The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsors.

References

[1] Adams, D., 1980. *The hitchhiker's guide to the galaxy*. Harmony Books, New York, USA.

[2] Vinayak, and Ramani, K., 2015. "A gesture-free geometric approach for mid-air expression of design intent in 3d virtual pottery". *Computer-Aided Design,* **69**, pp. 11 – 24.

[3] Zheng, J., Chan, K., and Gibson, I., 1999. "Real time gesture based 3d graphics user interface for cad modeling system". In TWLT, Vol. 15, p. 234.

[4] Vinayak, F., Liu, H., Ramani, K., and Jasti, R., 2016. Methods and systems for interactively producing shapes in three-dimensional space, July 5. US Patent 9,383,895.

[5] Mohanty, R. R., Castillo, R. M., Ragan, E. D., and Krishnamurthy, V. R., 2019. "Investigating Force-Feedback in Mid-Air Sketching of Multi-Planar Three-Dimensional Curve-Soups". *Journal of Computing and Information Science in Engineering,* **20**(1), 10. 011010.

[6] Bakker, S., Antle, A. N., and van den Hoven, E., 2012. "Embodied metaphors in tangible interaction design". *Personal and Ubiquitous Computing,* **16**(4), Apr, pp. 433–449.

[7] Piya, C., Vinayak, F., and Ramani, K., 2015. Manipulating virtual environment using non-instrumented physical object, Nov. 19. US Patent App. 14/712,695.

[8] Tu, X., 1999. "Perception modeling". *Artificial Animals for Computer Animation: Biomechanics, Locomotion, Perception, and Behavior*, pp. 65–83.

[9] Purdy, P., 2013. "From science fiction to science fact: How design can influence the future". *User Experience Magazine,* **13**(2).

[10] Clarke, R., 1994. "Asimov's laws of robotics: Implications for information technology. 2". *Computer,* **27**(1), pp. 57–66.

[11] Idier, D., 2000. "Science fiction and technology scenarios: comparing asimov's robots and gibson's cyberspace". *Technology in Society,* **22**(2), pp. 255–272.

[12] Garrett, L. K., 2006. Beyond the wall: an investigation into the relationship between industrial design and science fiction.

[13] Wilson, A. D., 2004. "Touchlight: An imaging touch screen and display for gesture-based interaction". In Proceedings of the 6th International Conference on Multimodal Interfaces, ICMI '04, Association for Computing Machinery, p. 69–76.

[14] Underkoffler, J. S., 1999. "The i/o bulb and the luminous room". PhD thesis, Massachusetts Institute of Technology.

[15] Ward, T. B., 1994. "Structured imagination: The role of category structure in exemplar generation". *Cognitive psychology,* **27**(1), pp. 1–40.

[16] Barlowe, W. D., Summers, I., and Meacham, B., 1979. *Barlowe's Guide to Extraterrestrials: Great Aliens from Science Fiction Literature*. Workman Publishing Company.

[17] Marsh, R. L., Ward, T. B., and Landau, J. D., 1999. "The inadvertent use of prior knowledge in a generative cognitive task". *Memory cognition,* **27**(1), pp. 94–105.

[18] Shah, J. J., Vargas-Hernandez, N., and Smith, S. M., 2003. "Metrics for measuring ideation effectiveness". *Design Studies,* **24**(2), pp. 111–134.

[19] Daly, S. R., Seifert, C., Yilmaz, S., and Gonzalez, R., 2016. "Comparing ideation techniques for beginning designers". *Journal of Mechanical Design,* **138**, pp. 101–108.

[20] Sarica, S., Luo, J., and Wood, K. L., 2020. "Technet: Technology semantic network based on patent data". *Expert Systems with Applications,* **142**, p. 112995.

[21] Han, J., Shi, F., Chen, L., and Childs, P. R., 2018. "A computational tool for creative idea generation based

on analogical reasoning and ontology". *AI EDAM,* **32**(4), pp. 462–477.

[22] Brown, A. S., and Logan, B., 2015. "How fiction puts the science in engineering". *Mechanical Engineering,* **137**(02), pp. 32–39.

[23] Logsdon, J. M., Lear, L. J., and Launius, R. D., 1995. *Exploring the Unknown: Selected Documents in the History of the US Civil Space Program*, Vol. 1. NASA.

[24] Gold, H. L., 1954. "Ready, aim-extrapolate". *Galaxy*, May 1954, p. 4.

[25] Engelbart, D. C., 2001. "Augmenting human intellect: a conceptual framework (1962)". *PACKER, Randall and JORDAN, Ken. Multimedia. From Wagner to Virtual Reality. New York: WW Norton & Company*, pp. 64–90.

[26] Heinlein, R. A., 1947. "On the writing of speculative fiction". *Of Worlds Beyond,(Chicago, 1964)*, p. 17.

[27] Johnson, B. D., 2011. "Science fiction prototyping: Designing the future with science fiction". *Synthesis Lectures on Computer Science,* **3**(1), pp. 1–190.

[28] Grimshaw, P., and Burgess, T., 2014. "The emergence of 'zygotics': using science fiction to examine the future of design prototyping". *Technological Forecasting and Social Change,* **84**, pp. 5–14.

[29] Kirby, D., 2010. "The future is now: Diegetic prototypes and the role of popular films in generating real-world technological development". *Social Studies of Science,* **40**(1), pp. 41–70.

[30] Lindley, J., and Coulton, P., 2015. "Back to the future: 10 years of design fiction". In Proceedings of the 2015 British HCI Conference, pp. 210–211.

[31] Elsden, C., Chatting, D., Durrant, A. C., Garbett, A., Nissen, B., Vines, J., and Kirk, D. S., 2017. "On speculative enactments". In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, CHI '17, Association for Computing Machinery, p. 5386–5399.

[32] Mankoff, J., Rode, J. A., and Faste, H., 2013. "Looking past yesterday's tomorrow: using futures studies methods to extend the research horizon". In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 1629–1638.

[33] Popper, A., 2015. "Transforming business through science fiction prototyping". *Computer,* **48**(1), pp. 70–72.

[34] Johnson, L., Levine, A., Smith, R., and Smythe, T., 2009. "The 2009 horizon report, austin". *Texas: The New Media Consortium*.

[35] Higgins, D. M., and O'Connell, H. C., 2019. "Introduction: Speculative finance/speculative fiction". *CR: The New Centennial Review,* **19**(1), pp. 1–9.

[36] Dunne, A., and Raby, F., 2013. *Speculative everything: design, fiction, and social dreaming*. MIT press.

[37] Johnson, B. D., 2011. "Science fiction prototyping: Designing the future with science fiction". *Synthesis*

Lectures on Computer Science, **3**(1), pp. 1–190.

[38] Isenson, R. S., 1966. "Technological forecasting in perspective". *Management Science,* **13**(2), pp. B70–B83.

[39] Graham, G., and Mehmood, R., 2014. "The strategic prototype "crime-sourcing" and the science/science fiction behind it". *Technological Forecasting and Social Change,* **84**, pp. 86–92.

[40] Linehan, C., Kirman, B. J., Reeves, S., Blythe, M. A., Tanenbaum, J. G., Desjardins, A., and Wakkary, R., 2014. "Alternate endings: using fiction to explore design futures". In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*. pp. 45–48.

[41] Callaghan, V., Clarke, G., and Chin, J., 2009. "Some socio-technical aspects of intelligent buildings and pervasive computing research". *Intelligent Buildings International,* **1**(1), pp. 56–74.

[42] Chin, J., Callaghan, V., Clarke, G., Hagras, H., and Colley, M., 2004. "Pervasive computing and urban development issues for the individual and society".

[43] Lukens, J., and DiSalvo, C., 2012. "Speculative design and technological fluency". *International Journal of Learning and Media,* **3**(4).

[44] Blythe, M., 2014. "Research through design fiction: Narrative in real and imaginary abstracts". In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '14, Association for Computing Machinery, p. 703–712.

[45] Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., and Wood, K., 2017. "Design prototyping methods: state of the art in strategies, techniques, and guidelines". *Design Science,* **3**, p. e13.

[46] Liedtka, J., 2014. "Innovative ways companies are using design thinking". *Strategy and Leadership,* **42**(2), pp. 40–45.

[47] Zheng, X., and Miller, S. R., 2019. "Should it Stay or Should it Go?: A Case Study of Concept Screening in Engineering Design Industry". Vol. Volume 7: 31st International Conference on Design Theory and Methodology of *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. V007T06A014.

[48] Roberts, J. P., and Middleton, A., 2014. "Evolving products: from human design to self-organisation via science fiction prototyping". *Technological Forecasting and Social Change,* **84**, pp. 15–28.

[49] Raven, P. G., 2017. "Telling tomorrows: Science fiction as an energy futures research tool". *Energy research & social science,* **31**, pp. 164–169.

[50] Sterling, B., 2009. "Cover story design fiction". *interactions,* **16**(3), pp. 20–24.

[51] Jansson, D. G., and Smith, S. M., 1991. "Design fixation". *Design Studies,* **12**(1), pp. 3 – 11.

[52] Maier, N. R., 1931. "Reasoning in humans. ii. the solution of a problem and its appearance in consciousness". *Journal of comparative Psychology,* **12**(2), p. 181.

[53] Kohn, N. W., and Smith, S. M., 2011. "Collaborative fixation: Effects of others' ideas on brainstorming". *Applied Cognitive Psychology,* **25**(3), pp. 359–371.

[54] McAdams, D., and Wood, K., 2000. "Quantitative measures for design by analogy". *Proceedings of DETC2000*.

[55] Linsey, J. S., Wood, K. L., and Markman, A. B., 2008. "Increasing innovation: presentation and evaluation of the wordtree design-by-analogy method". In ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection, pp. 21–32.

[56] Linsey, J., Markman, A., and Wood, K., 2012. "Design by analogy: A study of the wordtree method for problem re-representation". *Journal of Mechanical Design,* **134**(4).

[57] McAdams, D. A., and Wood, K. L., 2002. "A Quantitative Similarity Metric for Design-by-Analogy ". *Journal of Mechanical Design,* **124**(2), 05, pp. 173–182.

[58] Goel, A. K., 1997. "Design, analogy, and creativity". *IEEE expert,* **12**(3), pp. 62–70.

[59] Moreno, D. P., Hernandez, A. A., Yang, M. C., Otto, K. N., Hölttä-Otto, K., Linsey, J. S., Wood, K. L., and Linden, A., 2014. "Fundamental studies in design-by-analogy: A focus on domain-knowledge experts and applications to transactional design problems". *Design Studies,* **35**(3), pp. 232–272.

[60] Zhang, C., Mcadams, D. A., and Grunlan, J. C., 2016. "Nano/micro-manufacturing of bioinspired materials: a review of methods to mimic natural structures". *Advanced Materials,* **28**(30), pp. 6292–6321.

[61] Helms, M., Vattam, S. S., and Goel, A. K., 2009. "Biologically inspired design: process and products". *Design studies,* **30**(5), pp. 606–622.

[62] Shu, L., Ueda, K., Chiu, I., and Cheong, H., 2011. "Biologically inspired design". *CIRP annals,* **60**(2), pp. 673–693.

[63] Morris, E., McAdams, D. A., and Malak, R., 2016. "The state of the art of origami-inspired products: A review". In ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection.

[64] McAdams, D., and Li, W., 2014. "A novel method to design and optimize flat-foldable origami structures through a genetic algorithm". *Journal of Computing and Information Science in Engineering,* **14**, p. 031008.

[65] Malaga, R. A., 2000. "The effect of stimulus modes and associative distance in individual creativity support systems". *Decision Support Systems,* **29**(2), pp. 125–141.

[66] Borgianni, Y., Maccioni, L., Fiorineschi, L., and Rotini, F., 2020. "Forms of stimuli and their effects on idea generation in terms of creativity metrics and non-obviousness". *International Journal of Design Creativity and Innovation,* **8**(3), pp. 147–164.

[67] Goldschmidt, G., and Sever, A. L., 2011. "Inspiring design ideas with texts". *Design Studies,* **32**(2), pp. 139 – 155.

[68] Chan, J., Dow, S. P., and Schunn, C. D., 2015. "Do the best design ideas (really) come from conceptually distant sources of inspiration?". *Design Studies,* **36**, pp. 31 – 58.

[69] Christensen, B., 2020. www.technovelgy.com.

[70] Lewis, C., 1982. *Using the "thinking-aloud" method in cognitive interface design*. IBM TJ Watson Research Center Yorktown Heights, NY.

[71] Chandrasegaran, S., Ramanujan, D., and Elmqvist, N., 2018. "How do sketching and non-sketching actions convey design intent?". In Proceedings of the 2018 Designing Interactive Systems Conference, DIS '18, Association for Computing Machinery, p. 373–385.

[72] Goucher-Lambert, K., Gyory, J. T., Kotovsky, K., and Cagan, J., 2020. "Adaptive Inspirational Design Stimuli: Using Design Output to Computationally Search for Stimuli That Impact Concept Generation". *Journal of Mechanical Design,* **142**(9), 03. 091401.

[73] Gilon, K., Chan, J., Ng, F. Y., Liifshitz-Assaf, H., Kittur, A., and Shahaf, D., 2018. "Analogy mining for specific design needs". In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, pp. 1–11.

[74] Blei, D., Ng, A., and Jordan, M., 2003. "Latent dirichlet allocation". *Journal of Machine Learning Research,* **3**, pp. 993–1022.

[75] Yan, X., Guo, J., Lan, Y., and Cheng, X., 2013. "A biterm topic model for short texts". In Proceedings of the 22nd International Conference on World Wide Web, WWW '13, Association for Computing Machinery, p. 1445–1456.

[76] Sridhar, V. K. R., 2015. "Unsupervised topic modeling for short texts using distributed representations of words". In Proceedings of the 1st workshop on vector space modeling for natural language processing, pp. 192–200.

[77] Zuo, Y., Wu, J., Zhang, H., Lin, H., Wang, F., Xu, K., and Xiong, H., 2016. "Topic modeling of short texts: A pseudo-document view". In Proceedings of the 22nd ACM SIGKDD international conference on knowledge discovery and data mining, pp. 2105–2114.

[78] Lin, T., Zhang, S., and Cheng, H., 2016. "Understanding sparse topical structure of short text via stochastic variational-gibbs inference". In Proceedings of the 25th ACM International on Conference on Information

and Knowledge Management, pp. 407–416.

[79] Kiros, R., Zhu, Y., Salakhutdinov, R. R., Zemel, R., Urtasun, R., Torralba, A., and Fidler, S., 2015. "Skip-thought vectors". In Advances in neural information processing systems, pp. 3294–3302.

[80] Yao, W., and Huang, R., 2018. "Temporal event knowledge acquisition via identifying narratives". In Proceedings of the 56th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers), Association for Computational Linguistics, pp. 537–547.

[81] Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., and Wood, K. L., 2002. "A functional basis for engineering design: reconciling and evolving previous efforts". *Research in engineering Design,* **13**(2), pp. 65–82.

[82] Miller, G. A., 1995. "Wordnet: A lexical database for english". *Commun. ACM,* **38**(11), Nov., p. 39–41.

[83] Mikolov, T., Chen, K., Corrado, G., and Dean, J., 2013. "Efficient estimation of word representations in vector space". In 1st International Conference on Learning Representations, ICLR 2013, Scottsdale, Arizona, USA, May 2-4, 2013, Workshop Track Proceedings, Y. Bengio and Y. LeCun, eds.

[84] Pennington, J., Socher, R., and Manning, C. D., 2014. "Glove: Global vectors for word representation". In Proceedings of the 2014 conference on empirical methods in natural language processing (EMNLP), pp. 1532–1543.

[85] Salle, A., Villavicencio, A., and Idiart, M., 2016. "Matrix factorization using window sampling and negative sampling for improved word representations". In Proceedings of the 54th Annual Meeting of the Association for Computational Linguistics (Volume 2: Short Papers), Association for Computational Linguistics, pp. 419–424.

[86] Speer, R., Chin, J., and Havasi, C., 2017. "Conceptnet 5.5: An open multilingual graph of general knowledge". In Proceedings of the Thirty-First AAAI Conference on Artificial Intelligence, AAAI'17, AAAI Press, p. 4444–4451.

[87] Brown, T. B., Mann, B., Ryder, N., Subbiah, M., Kaplan, J., Dhariwal, P., Neelakantan, A., Shyam, P., Sastry, G., Askell, A., et al., 2020. "Language models are few-shot learners". *arXiv preprint arXiv:2005.14165*.

[88] Turc, I., Chang, M.-W., Lee, K., and Toutanova, K., 2019. "Well-read students learn better: On the importance of pre-training compact models". *arXiv preprint arXiv:1908.08962v2*.

[89] Howard, J., and Ruder, S., 2018. "Universal language model fine-tuning for text classification". *arXiv preprint arXiv:1801.06146*.

[90] Ranjan, B., Siddharth, L., and Chakrabarti, A., 2018. "A systematic approach to assessing novelty, requirement satisfaction, and creativity". *AI EDAM,* **32**(4), pp. 390–414.

[91] Sarkar, P., and Chakrabarti, A., 2011. "Assessing design creativity". *Design studies,* **32**(4), pp. 348–383.

[92] Siddharth, L., Madhusudanan, N., and Chakrabarti, A., 2019. "Toward Automatically Assessing the Novelty of Engineering Design Solutions". *Journal of Computing and Information Science in Engineering,* **20**(1), 09. 011001.

[93] Kershaw, T. C., Bhowmick, S., Seepersad, C. C., and Hölttä-Otto, K., 2019. "A decision tree based methodology for evaluating creativity in engineering design". *Frontiers in psychology,* **10**, p. 32.

[94] Chen, T.-J., and Krishnamurthy, V. R., 2020. "Investigating a Mixed-Initiative Workflow for Digital Mind-Mapping". *Journal of Mechanical Design,* **142**(10), 06. 101404.

[95] Chen, T.-J., Mohanty, R. R., Hoffmann Rodriguez, M. A., and Krishnamurthy, V. R., 2019. "Collaborative Mind-Mapping: A Study of Patterns, Strategies, and Evolution of Maps Created by Peer-Pairs". Vol. Volume 7: 31st International Conference on Design Theory and Methodology of *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. V007T06A039.

[96] Shah, J. J., Vargas, H. N., Summers, J. D., and Kulkarni, S., 2001. "Collaborative sketching (c-sketch) — an idea generation technique for engineering design". *The Journal of Creative Behavior,* **35**(3), pp. 168–198.

[97] Ha, D., and Eck, D., 2018. "A neural representation of sketch drawings". In International Conference on Learning Representations.

[98] Benjamin, W., Chandrasegaran, S., Ramanujan, D., Elmqvist, N., Vishwanathan, S., and Ramani, K., 2014. "Juxtapoze: Supporting serendipity and creative expression in clipart compositions". In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '14, Association for Computing Machinery, p. 341–350.

[99] Christensen, B., 2020. Bubble city: Underwater domes provide living space for large communities.

[100] Christensen, B., 2020. Bubble: An undersea elevator.

[101] Christensen, B., 2020. Exoskeleton: Fighting suit.

[102] Christensen, B., 2020. Gravity-simulator harness: Device that simulates gravity's effect on muscles to keep in shape while in space.

[103] Christensen, B., 2020. King's free park: A park in which anarchy reigned; a very long, narrow park.

[104] Christensen, B., 2020. Sprung-samser treatment a medical treatment to extend human life.

Appendix A: Design statements and sample text stimuli provided to the designers

We asked the designers to work on the following two design statements.

1. **Underwater camping**

   Camping is an activity which can bring thrilling experience as well as can be enjoyable as a leisure activity. Florida adventures, a water-sports entertainment company, has several branches across the world and is planning to start a novel experience for their existing and new customers - camping underwater. They want to offer underwater camping experiences ranges from a couple of days to a month. Please provide a design solution for the above problem in the form of annotated sketches.

2. **Work-out in space**

   To maintain health, exercise is a necessity for the astronauts. Virgin Atlantic is planning to send passengers to space for recreational purposes. Maintaining the health routines for the space-passengers is one of the prime concerns for Virgin Atlantic and they are looking for novel design solutions for "working-out in space". Please provide a design solution for the above problem in the form of annotated sketches.

A few of the text stimuli provided to the users related to 'Underwater camping' are shown below.

(a) **Underwater domes provide living space for large communities [99]**

Bubbles... there is one down in the Caribbean called New Eden. Depth, approximately 175 fathoms. As of the most recent census, it was home to over 100,000 people. A huge, illuminated geodesic dome it is, providing an overhead view with which Euclid would have been pleased. For great distances about this dome, strung lights like street lamps line avenues among rocks, bridges over canyons, thoroughfares through mountains. The bottom-going seamobiles move like tanks along these ways; minisubs hover or pass at various altitudes; slick-seeming swimmers in tight and colorful garb come and go, entering and departing the bubble or working about it.

(b) **An undersea Elevator [100]**

His class took one of the dozen bubbles back to the surface: slow-moving pressurized elevators that traveled up and down Xanadu's gigantic tether chains, ferrying work crews, researchers, and students. Each was large enough for ten people to lounge comfortably, with food processors, entertainment centers, Napcaps, and linking facilities. They had spent less than four hours down on the floor; the trip back would be a leisurely lunch.

Some of the text stimuli related to the design topic 'Work-out in space'

(a) **An exoskeleton [101]**

The Lieutenant Colonel was extremely dead. He'd come down from the heavens in his full NAFTA military power-armor, a leaping, brick-busting, lightning-spewing exoskeleton, all acronyms and input jacks. It was powerful, elaborate gear, of an entirely different order than the gooey and fibrous street tech of the two urban intrusion freaks. But the high-impact crash had not been kind to the armored suit. It had been crueler still to the bone, blood, and tendon housed inside.

(b) **Device that simulates gravity's effect on muscles to keep in shape while in space [102]**

"When we got back," Joe told Brown, "we were practically invalids. No exercise up here. This time we've brought some harness to wear. We've some for you, too..." Joe got out the gravity-simulator harnesses. He showed Brent how they worked. Brown hadn't official instructions to order their use, but Joe put one on himself, set for full Earth-gravity simulation. He couldn't imitate actual gravity, of course. Only the effect of gravity on one's muscles. There were springs and elastic webbing pulling one's shoulders and feet together, so that it was as much effort to stand extended—with one's legs straight out—as to stand upright on Earth. Joe felt better with a pull on his body. Brent was upset when he found that to him more than a tenth of normal gravity was unbearable. But he kept it on at that. If he increased the pull a very little every day, he might be able to return to Earth, in time. Now it would be a very dangerous business indeed. He went off to put the other members of the crew in the same sort of harness.

Sample text stimuli unrelated to 'Underwater camping' or 'Work-out in space' are shown below.

(a) **A park in which anarchy reigned [103]**

"The modern transportation systems cleaned the air and made traffic jams archaic and left the nation with an embarrassing problem. What to do with ten thousand miles of unsightly abandoned freeways? King's Free Park had been part of the San Diego Freeway, the section between Sunset and the Santa Monica interchange. Decades ago the concrete had been covered with topsoil. The borders had been landscaped from the start. Within King's Free Park was an orderly approximation of anarchy."

(b) **A medical treatment to extend human life [104]**

"Eighty or ninety or more, looking about forty, [Hasan] could still act thirty. the Sprung-Samser treatments had found highly responsive material. It's not often that way. Almost never, in fact. They put some people into accelerated anaphylactic shock for no apparent reason, and even an intracardial blast of adrenalin won't haul them back; others, most others, they freeze at five or six decades. But some rare ones actually grow younger when they take the series - about one in a hundred thousand. It struck me as odd that in destiny's big shooting gallery this one should make it, in such a big way."

List of Figures

List of Tables