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Integrating Generative AI Into the Design Process: A Case Study on Space Haptic Boots

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ABSTRACT

Developing a product that satisfies certain standards follows a methodical approach known as the design process. It involves multiple phases of requirement elicitation, analysis, conceptualization, and evaluation. Generative Artificial Intelligence (AI) tools like ChatGPT have impacted the design process in various engineering fields, but there is limited research on how to integrate AI tools into the design process effectively. In a case study, we used ChatGPT to design an innovative object - a space boot with haptic technology. We explored various prompt methods and found that the process is iterative, requiring multiple adjustments to the prompts. This research paper highlights the design process and its evaluation methods, discusses its limitations, and provides a plan for future improvements.

Keywords: Prompt engineering, Design process

INTRODUCTION

The design process is a crucial and systematic procedure that aims to create a product, solution, or object that meets specific requirements and objectives in a creative and organized way. The approach to the design process varies depending on the designer and their preferences (Coyne, 1990). However, in general, it involves multiple phases of requirement elicitation, analysis, conceptualization, and evaluation (Slătineanu et al., 2021). The design process is highly iterative in engineering projects (Albert & Tullis, 2022; Yamada et al., 2022), meaning that it often involves repeating multiple phases before moving on to the next one. This iterative approach enhances the quality and functionality of the project by using feedback from the system as research for successive versions of the project.

The advent of generative Artificial Intelligence (AI) tools, such as ChatGPT, has impacted the design process in various engineering fields (Ahmad

et al., 2023; Ray & Majumder, 2023). Users of these tools engage in a process called "prompt engineering," which involves carefully crafting their prompts to achieve the desired output. Prompt engineering is a systematic procedure by which a user can refine their input parameters to attain their desired output (Shin et al., 2020). It is often used in conjunction with task descriptions to provide additional guidance to a specific AI model. Prompt engineering is essentially a way of instructing AI to perform specific tasks. The rise of generative AI tools and prompt engineering has led to concerns about their impact on the workforce. While AI tools have been found to increase productivity in complex tasks, they have also raised fears of job losses (Dell'Acqua et al., 2023).

Despite recent studies reviewing the use of AI in various disciplines such as civil, structural, and design (Thai, 2022; Aloisio et al., 2023; Yüksel et al., 2023), the question of how to actually integrate them into the engineering process effectively. In this case study, we embarked on a project to design an innovative object - a space shoe with haptic technology. We utilized the power of ChatGPT to assume diverse stakeholder roles and assist in the comprehensive haptic shoe design process, which included gathering requirements, creating prototypes, and executing a test plan. To evaluate the design space, we explored various prompt methods, such as zero-shot and super-prompt. Throughout the work, we found that the process is iterative in nature, requiring multiple adjustments to the prompt in order to effectively incorporate new contextual information and ensure its proper consideration. This research paper explores the specificities of the design process behind the creation of haptic shoes with ChatGPT and highlights the methods for evaluating the accuracy and effectiveness of the design. The study also discusses the limitations of our work and provides a plan for future improvements.

RELATED WORK

Historical Background on the Engineering Design Process

The engineering design process consists of various disciplines and methods, such as Agile, Waterfall, and Lean UX (Roy et al., 2008; Beitz et al., 1996). All these methods have steps or phases that describe, categorize, and timebox the tasks needed for project completion. As technology evolves, so do these methods. For instance, Agile methodology would not have made sense in software development before collaboration tools such as email, chat, version control systems, and more than one computer per team became available. Agile methodology is now the most popular method in software development (Cohen et al., 2004). Interestingly, Agile's origins lie in the hardware industry (Riby & Sutherland, 2016), showing how methodologies applied in one domain can be adopted and improved in other domains.

Generative AI

Generative AI uses deep learning models to create human-like content (Lin et al., 2023). Recently, thanks to tools like OpenAI's ChatGPT, powerful technology has gained popularity (Hu, 2023). Generative AI not only

presents a response but also creates content, surpassing Conversational AI in human-like interactions.

AI has had a profound impact on organizations, societies, and individuals. It excels in systematic reasoning, learning from input variations, predicting, and adapting to changes in its environment. In its early stages, AI primarily focused on supervised and unsupervised learning, drawing inspiration from nature and biology to computationally solve data-intensive problems. Traditional AI algorithms, including neural networks, genetic algorithms, decision trees, random forests, support vector machines, and k-means clustering, were limited by their dependence on structured data for both model building and information processing (Duan et al., 2019). Newer AI algorithms now handle unstructured data, emphasizing deep learning and reinforcement learning. Algorithms like convolutional and recurrent neural networks excel in analyzing diverse data, while industry demand has spawned Natural Language Processing (NLP) algorithms like BERT, LSTM, and language models for automation (Kushwaha and Kar, 2021). These algorithms initially required abundant data and significant computational resources, posing challenges for real-world applications. However, newer AI models like federated learning and tiny machine learning have addressed these issues and found adoption in industrial applications. They've tackled the "cold start problem," where data for initial training is lacking. Additionally, reinforcement learning has gained prominence in marketing and financial management applications (Singh et al., 2022).

Generative AI, a new generation of AI, plays a vital role in various fields, with two notable examples being StyleGAN (Karras et al., 2019) and OpenAI's GPT. StyleGAN, developed by NVIDIA, excels in generating diverse and highly realistic images through a style-based approach, expanding possibilities for digital art. OpenAI's GPT series, particularly GPT-3, has revolutionized natural language processing by producing human-like text with exceptional fluency and coherence, advancing tasks like question answering, essay writing, and conversation (Brown et al., 2020). These instances highlight generative AI's transformative potential in creative industries, content creation, and human-machine interaction, paving the way for further progress in image synthesis and text generation.

Generative AI offers potential applications in a variety of industries, including business, education, healthcare, and content generation. Generative AI solutions offer a wide array of applications for businesses, spanning marketing and sales, operational processes, IT and engineering tasks, risk management, legal functions, human resources, financial operations, as well as employee optimization in utility settings (Chui et al., 2022). Generative AI has diverse roles in education and research. It assists students with information retrieval, subject-related queries, and multilingual writing. For educators, it generates teaching materials, grades assignments, and creates lesson plans. It also creates personalized educational content, enhancing engagement and learning outcomes (Kasneci et al., 2023). In the realm of academic research, it serves as a valuable resource for self-learners in open education by providing tailored guidance and feedback (Firat, 2023). Generative AI can also revolutionize the healthcare sector. With ChatGPT's ability

to pass medical licensing exams (Kung et al., 2023), it is evident that generative AI can play a significant role in patient interaction, clinical diagnosis support, telehealth services, health education, advice, and promotion, thus reshaping healthcare in various ways. Generative AI can be used to develop new drugs and treatments.

Bilgram & Laarmann (Bilgram and Laarmann, 2023) discuss how generative AI models can enhance the early stages of innovation, including exploration, ideation, and digital prototyping, based on six months of experimentation in innovation projects. Their experimentation provides real-world examples of AI-assisted approaches for tasks such as user journey mapping, idea generation, and prototyping. It suggests that generative AI has the potential to revolutionize early prototyping by delegating tasks to AI agents, resulting in quicker iterations and cost savings.

METHOD

Design Process

This section showcases the use of prompt engineering to design a haptic boot for space exploration, particularly tailored for extravehicular activities (EVAs) on celestial bodies like Mars. Prompts are used to generate innovative design concepts based on stakeholder perspectives and system requirements. Safety and ethics standards are adhered to during the design process. The following are the elements of the design process:

- *Zero-shot Prompt:* We used an initial, basic prompt to design a haptic boot, but it lacked specificity and essential details.
- *Super-prompt:* As a second step, we used a super-prompt, simulating a NASA design engineer's role. It yielded a comprehensive design that included technical details and relevant components, although certain parts were impractical due to their size and weight.
- *Iterative Design Process:* We continued the design process by identifying stakeholders with ChatGPT, then developing use cases, collecting requirements, and integrating safety and ethics standards.
- *Initial Design:* ChatGPT, in the role of a NASA engineer, proposed a design for haptic boots after analyzing the use cases, user stories, and shall-style requirements gathered in the previous stage. The proposal included sensor models and components as placeholders and highlighted the significance of collaboration and validation with NASA's engineering team.
- *Design Refinement:* Adopting the role of a safety engineer, chatGPT evaluated the design, suggesting improvements across multiple aspects and ensuring safety standards and requirements were met.
- *Design Evaluation Plan:* As a test engineer, chatGPT outlined a comprehensive testing plan, covering various aspects and emphasizing radiation-hardened components, astronaut comfort, and iterative improvements.
- *Design Evaluation Criteria:* Test protocols and cases were provided by the test engineer persona of chatGPT, addressing mechanical, sensor, communication, power, ergonomics, safety, environmental, and data storage testing.

- *Design Verification:* To ensure compliance, we evaluated the final design against the requirements that were gathered.

The development of a haptic shoe using prompt engineering involves a series of steps, as illustrated in Figure 1. The first step is information collection, where data on the intended design is gathered and analyzed. The second step involves testing and refining prompts, which are the signals sent to the shoe to produce haptic feedback.

The third step is to consider safety and ethical guidelines, ensuring that the shoe meets the necessary standards. Once this is done, the design and evaluation phase begins. This phase includes creating a prototype, which is a preliminary version of the shoe that allows for further testing and refining.

The next step is to develop test plans and protocols, which will be used to evaluate the shoe. These test plans include assessing test cases, which are scenarios designed to test the shoe's functionality in various situations. Finally, the design is verified against the requirements, ensuring that it meets the necessary specifications.

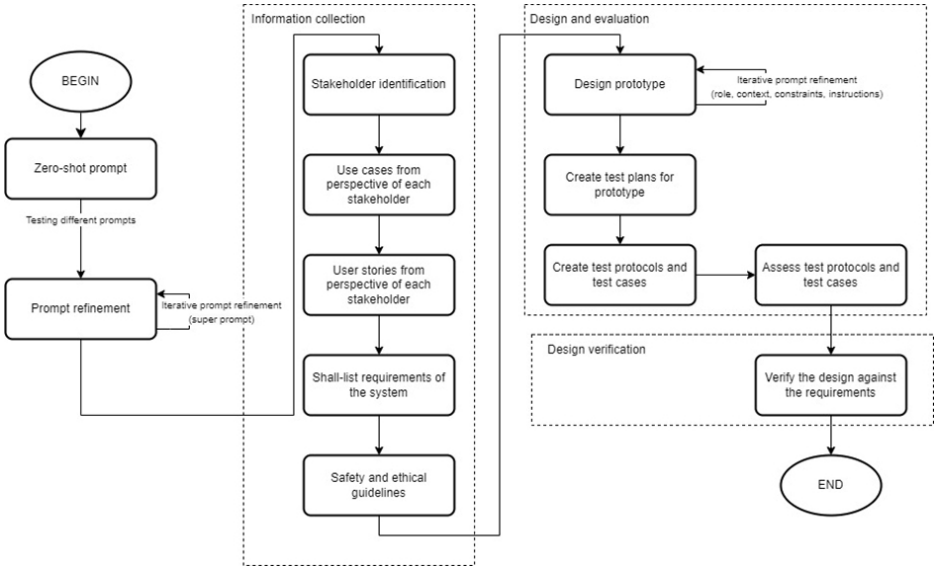

Figure 1: Prompt engineering design process.

Results and Preliminary Evaluation

In Figure 2, there's an example use case generated by ChatGPT from the perspective of an astronaut. This use case outlines the requirements for how the haptic shoe should function on the Martian surface. It should be able to detect obstacles and provide tactical cues to alert the astronauts of any potential dangers. Additionally, it should give feedback about the location and size of the obstacles, which will help the astronaut navigate accordingly.

Use Case: Obstacle Detection and Navigation
Goal: To assist the astronaut in detecting and navigating around obstacles on the Martian surface.
Precondition: The astronaut is wearing the haptic shoe and is exploring the Martian environment.
Main Success Scenario: 1. The haptic shoe senses the presence of obstacles, such as large rocks or depressions, in the astronaut's path. 2. The haptic shoe provides tactile cues to alert the astronaut about the obstacle's location and size. 3. The astronaut modifies their route or takes appropriate steps to navigate around the obstacle based on the haptic feedback.

Figure 2: An example of a use case generated by ChatGPT from an astronaut's perspective.

Figure 3 shows the overview of the design generated by ChatGPT. The sensors collect data about the user's environment, such as the force applied to the shoe, the texture of the ground, the incline of the ground, the presence of obstacles, and a 3D map of the surroundings. The microcontroller processes this data and generates control signals for the actuators. The actuators then vibrate the shoe to provide haptic feedback to the user. The system is powered by a battery.

During our preliminary meeting with a subject matter expert, we conducted an assessment to gather the necessary requirements that would determine the functionalities of haptic shoes for space exploration. We explored various use cases to determine the most crucial functionalities that haptic shoes must possess, such as providing feedback on the surface of an unknown planet or alerting astronauts of potential hazards. The use cases are apparently useful and form a basis for brainstorming, but the stakeholders must be engaged to ensure that all necessary functionalities are included. Assessing the requirements generated by ChatGPT against some of IEEE 830 quality standards, the provided requirements fall short. For instance, the requirements are not traceable as we do not their actual source. In assessing the design overview, we discovered that apart from two components, the haptic shoe design generated by ChatGPT comprises components that are not currently available in reality. These components are essentially placeholders that were generated by the language model. However, we observed that there are two actuators capable of providing the desired haptic feedback effect, namely the precision Microdrives Pico Haptic Feedback Kit and Nidec Copal Electronics' vibration motors. Hence, the rest of the components in the design are inconsequential as they are not available in real life and are solely generated by the language model.

DISCUSSION AND FUTURE WORK

We used a haptic boot for space exploration to showcase the practical potential but also the limitations of AI-driven design. The iterative design process used incorporated various personas such as a NASA engineer and a safety

engineer. This allowed for a comprehensive approach to the design, addressing technical, safety, and ethical aspects. In our opinion is a cost-effective way to identify major blind spots in a project.

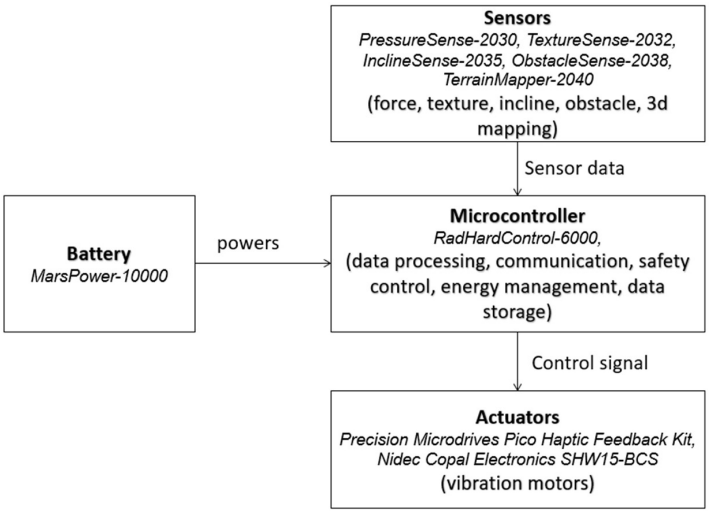

Figure 3: Overview of the system generated.

However, we also noted that some AI-generated components do not exist in reality (hallucination). This underscores the importance of human-in-the-loop, oversight and validation in the design process. The generated use cases, particularly from the astronaut's perspective, provided valuable insights into the potential functionalities and challenges of the haptic boot on celestial bodies like Mars. While the AI model was able to brainstorm innovative concepts, the need for stakeholder engagement beyond the AI-generated personas became evident to ensure the practicality and relevance of the design. We highlight, the identification of two suitable real-life actuators capable of providing the desired haptic feedback. Moving forward, our focus using notebooks such as Semantic Kernels to codify the process. Additionally, a more in-depth evaluation using established standards, such as the IEEE 830 quality criteria, will be incorporated.

In the future, we plan to evaluate solutions using established standards such as IEEE 830 quality criteria and by checking the suggested components against the market.

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