EXPLORING THE USABILITY OF AI PROMPTS FOR MECHANICAL ENGINEERING DESIGN DEVELOPMENT

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ABSTRACT

Computational support for concept exploration has been a research development in the last two decades, and the ascent of AI tools such as Chat GPT and generative design is further expanding it. Mechanical engineering tends to focus on more stringent functional requirements and compliance with regulation, and while the potential of AI developments to support it exists, it also likely requires significant oversight by the human. Exploring the use of AI in mechanical engineering design and the level of trust placed on its outcomes is an important question for future engineering design development, especially since AI and machine learning are improving exponentially. This paper explores the levels of helpfulness/need for oversight and checks by humans in terms of where AI could be beneficial in the mechanical engineering design process, how this could be supported, and how reliable can it be. Exploration of students' perception of AI and its objective usefulness was contrasted, by performing a comparison between designs conducted with and without AI support. AI tools used focused on product design specification generation, concept image generation and generative design. Then recommendations were given on tools that are currently considered to be helpful for mechanical design development, highlighting the positives and negatives of the approach using AI and potential for adoption of AI in engineering design education.

Keywords: Mechanical engineering design; education; AI; generative design

1 INTRODUCTION

AI scenarios are being discussed with possible futures envisaged ranging from the, worst case scenario, collapse of the society in which education would be necessary to adapt and survive, to fully automated AI luxury scenario where machines take over human work but the outcomes are positive for the society, requiring educational focus on other productive endeavours [1]. The history shows us that technological progress is rarely stopped, and that AI developments will likely continue regardless of societal concerns. A good example is writing, we have gone from quill to pencil to pen, to typewriters to computers. Each jump in technology has been met with apprehension and concerns about its effect on the future, but ultimately, we have devised ways to use that technology reliably, responsibly and in ways that improves our activities - no one is using typewriters these days. Regardless of the scenario that the future ends up resembling the most, our ability to use AI effectively and efficiently will be crucial for mechanical design of the future. Instead of fighting progress, a more productive approach would be to establish ways to support learning in AI mediated environments [2]. Utilising pedagogical practices that include collaboration between educators and learners to re-imagine education futures and further enhance them to include more creativity, complex problem solving, and critical thinking are a step towards this [2].
To explore pedagogical practices in utilising AI in the context of mechanical engineering design, this paper explored the AI tools' potential to support product design specification (PDS) and concept design generation. It reports the outcomes of a student project focusing on a mechanical design of a Formula 1 (F1) wheel nut, first independently and then using AI. Challenges they have encountered throughout that process were analysed and recommendations are given for pedagogical approaches to use of AI in similar student projects in the future.

2 ADVANTAGES AND CHALLENGES OF AI FOR MECHANICAL DESIGN

Mechanical design is a highly regulated field, in terms of the need to comply with safety requirements, risk assessments and standards guiding final product certification procedures. Therefore, even if we approach AI optimistically, as a tool that can help improve our design process, we need to ensure that we fully understand what kind of outputs it is able to provide and how we could validate them.

AI has the potential to improve many aspects of a mechanical design process:

- AI does not draw from designers' prior experience so it would not be limited to designers' preconceived notions of functionality, which can lead to fixation or bounded ideation [3, 4]. Ideas that might not have worked in the past, might be feasible with advances in technology and AI suggesting them for consideration may re-introduce them, while experienced designers would potentially overlook them.
- AI is able to rapidly provide summaries of information available to it, and in some cases (e.g. PDS development) this could be highly beneficial to a designer [5].
- AI produces fast, high quality, visual representations. In mechanical design, visualisation, whether in a form of a sketch or an image, can often convey the problem or the solution far more effectively than a written description [6].
- AI can provide shape optimisation based on loading requirements and limitations on space usage defined by designers [7]. This combined with new manufacturing processes can lead to significant advances in part performance.

AI also has, potentially significant, drawbacks that need to be controlled:

- It is difficult to establish if AI suggestions comply with standards and regulations for a specific context, as AI often is not transparent about data sources, leading to a lack of trustworthiness [8]. More concerningly, AI may indicate it complies with standards and regulations whereas in reality its decision making is based on inaccurate data, which could subsequently lead to costly late-stage design changes likely unacceptable for the designers [9].
- Scientific principles and emerging requirements those place on mechanical designs can occasionally be too complex for AI to integrate in concept generation contexts [10].
- All solutions AI suggests are limited to information it has access to, and therefore can lead to a very specific type of fixation (e.g. "naturalistic" shapes too expensive to manufacture) [11, 12].
- Users typically do not know where the data they are inputting into the AI system is stored and who may have access to, leading to potential IP issues for both parties [10].
- It is difficult to access the information about, and potentially even understand, the approaches AI takes, making it difficult to evaluate the proposed solutions (i.e. black box approach) [10].

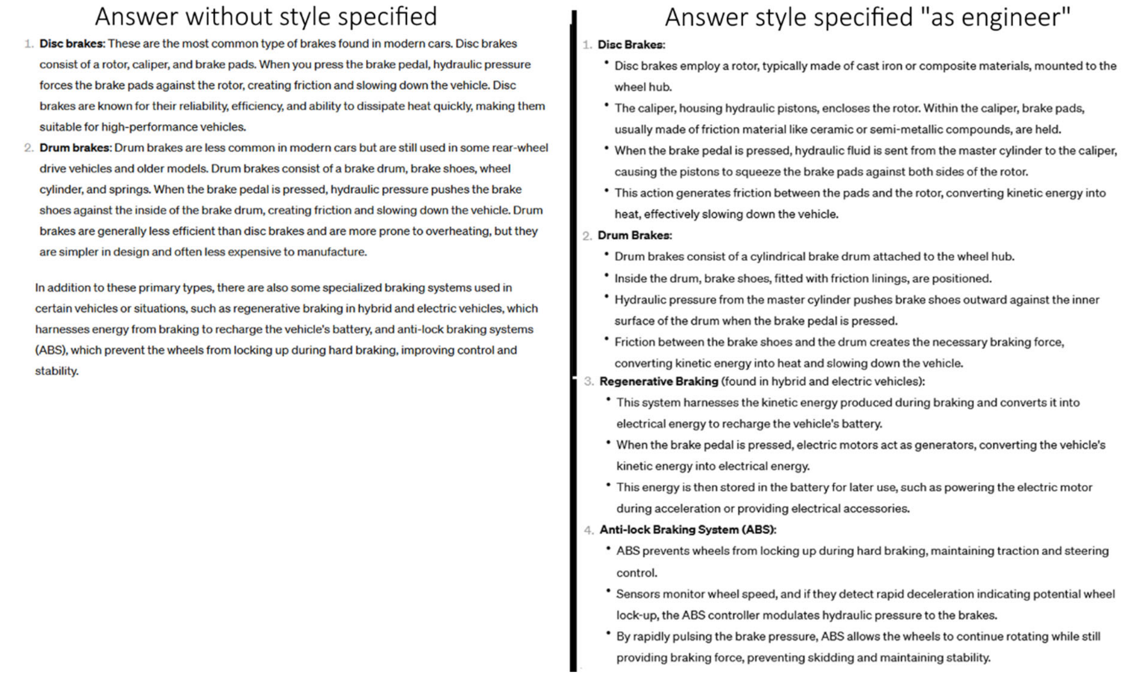
In other highly regulated fields, medical for example, similar challenges have been identified and concerns have been risen regarding AI reproducibility and generalisability [13]. Despite the high number of models published for running of mechanical ventilators (12,422 in 2019), only 130 models received approval for clinical practice from the FDA in 2020, due to lack of validation [14].

3 EXISTING AI OPTIONS AND HOW THEY COULD BE USED

Three types of AI applications are explored in the context of mechanical design in this paper: (1) natural language models, (2) image generation models using chat prompts, and (3) generative design models. All three types rely on machine learning and probability models, however from a user perspective they have very different uses and applications.

Natural Language Models provide written answers to questions or prompts given to them by the user. They can be a useful tool for high level questions users are seeking answers to such as "What are the types of brake mechanisms typically used in a car?". The quality of the response is subject to the prompt wording (e.g. specifying the tone of the Chat GPT to "as if I'm an engineer" improves response detail and complexity of answer), as shown in Figure 1. This approach could be used to explore the PDS and potentially gather useful data in the early conceptual design stages.

Image generation models produce an image based on a prompt from the user. They can often be trained by supplying reference images different weights can be assigned to different elements of the prompt. Exclusion criteria can also be added. Most current image generation programs are used for generating artwork and allow the style of art to be specified (e.g. animated or painting). Some developments aiming to support engineering design specifically are evident, such as Leo (www.getleo.ai) where the user would be able to provide a description of a design from which the software generates CAD that is editable by the user. However, this solution is still at relatively early stages of development and currently only provides image generation, as can be seen in Figure 2. Image generation could be used during brainstorming, while the basic visualisation of shapes and their associated functions are being explored.


Answer without style specified

1. **Disc brakes:** These are the most common type of brakes found in modern cars. Disc brakes consist of a rotor, caliper, and brake pads. When you press the brake pedal, hydraulic pressure forces the brake pads against the rotor, creating friction and slowing down the vehicle. Disc brakes are known for their reliability, efficiency, and ability to dissipate heat quickly, making them suitable for high-performance vehicles.
2. **Drum brakes:** Drum brakes are less common in modern cars but are still used in some rear-wheel drive vehicles and older models. Drum brakes consist of a brake drum, brake shoes, wheel cylinder, and springs. When the brake pedal is pressed, hydraulic pressure pushes the brake shoes against the inside of the brake drum, creating friction and slowing down the vehicle. Drum brakes are generally less efficient than disc brakes and are more prone to overheating, but they are simpler in design and often less expensive to manufacture.

In addition to these primary types, there are also some specialized braking systems used in certain vehicles or situations, such as regenerative braking in hybrid and electric vehicles, which harnesses energy from braking to recharge the vehicle's battery, and anti-lock braking systems (ABS), which prevent the wheels from locking up during hard braking, improving control and stability.

Answer style specified "as engineer"

1. **Disc Brakes:**
   - Disc brakes employ a rotor, typically made of cast iron or composite materials, mounted to the wheel hub.
   - The caliper, housing hydraulic pistons, encloses the rotor. Within the caliper, brake pads, usually made of friction material like ceramic or semi-metallic compounds, are held.
   - When the brake pedal is pressed, hydraulic fluid is sent from the master cylinder to the caliper, causing the pistons to squeeze the brake pads against both sides of the rotor.
   - This action generates friction between the pads and the rotor, converting kinetic energy into heat, effectively slowing down the vehicle.
2. **Drum Brakes:**
   - Drum brakes consist of a cylindrical brake drum attached to the wheel hub.
   - Inside the drum, brake shoes, fitted with friction linings, are positioned.
   - Hydraulic pressure from the master cylinder pushes brake shoes outward against the inner surface of the drum when the brake pedal is pressed.
   - Friction between the brake shoes and the drum creates the necessary braking force, converting kinetic energy into heat and slowing down the vehicle.
3. **Regenerative Braking** (found in hybrid and electric vehicles):
   - This system harnesses the kinetic energy produced during braking and converts it into electrical energy to recharge the vehicle's battery.
   - When the brake pedal is pressed, electric motors act as generators, converting the vehicle's kinetic energy into electrical energy.
   - This energy is then stored in the battery for later use, such as powering the electric motor during acceleration or providing electrical accessories.
4. **Anti-lock Braking System (ABS):**
   - ABS prevents wheels from locking up during hard braking, maintaining traction and steering control.
   - Sensors monitor wheel speed, and if they detect rapid deceleration indicating potential wheel lock-up, the ABS controller modulates hydraulic pressure to the brakes.
   - By rapidly pulsing the brake pressure, ABS allows the wheels to continue rotating while still providing braking force, preventing skidding and maintaining stability.

Figure 1. Chat GPR output; left - basic question prompt, right -"as an engineer" prompt

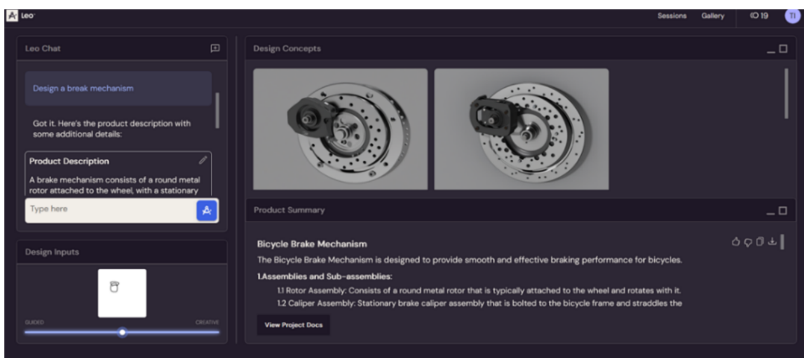


Figure 2. LEO brake mechanism created from text prompt and basic sketch prompt

Generative design requires the user to input the location of forces on a predesigned 3D model, limit areas where material should not be placed, choose a manufacturing process to be used, and then uses finite element analysis to find the best mechanical structure optimising for mass reduction and strength requirements. Generative design is used during detailed design, when the key design decisions were already made, and the shape is being optimised for strength and weight enhancement.

4 CASE STUDY OF F1 NUT DESIGN

Potential for use of AI in mechanical design education was explored on an example of an F1 wheel nut development. A final year mechanical engineering student was given a task to "explore where in the design process AI could be beneficial, how they would use it, and how reliable they think it can it be". F1 wheel nut was chosen as it was simple enough to design twice in the time frame given, but complex and regulated enough to consider key mechanical engineering challenges that are making use of AI difficult during the design process. Its design and the forces it must be capable of withstanding are bounded by the FIA regulations and physical constraints of materials used. At the same time as F1 is a popular sport and AI software was expected to have a range of resources at its disposal. The student had expertise based on their past internship with an F1 team and could make informed judgements when key decisions needed to be made. Performing this project allowed the student to improve their design skills and learn about maintaining robustness of design while incorporating AI developments in their design process. It also enabled them to critically evaluate it and learn how to incorporate new tools in their processes only when they are certain their outputs can be trusted. Student was given a list of potential tools to use in all three AI application types described in Section 3. They were also given the option to add new tools they discovered independently. They created one design on their own, without the use of AI. Then they used AI to create a different design. Two outcomes were then compared.

4.1 Use of Natural Language Models

Chat GPT was used to create a PDS of a final design including secondary locking feature and thread size. Chat GPT, Perplexity AI and Bing AI Chat (Copilot) were used for concept design generation.
It was found that increasing the complexity of the prompt in Chat GPT had a significant impact on the PDS created. Requesting a PDS for "a wheel nut" resulted in a "hexagonal" shape of maximum outer diameter of "50 mm". Neither was applicable within FIA regulations. Increasing the complexity of the prompt by requesting references the AI stated that "size and thread are to be compatible with current F1 standards" but did not specify what these were. This meant that the student still needed to check the outcomes and add crucial relevant data. Despite the complex prompt, the Chat GPT generated PDS still specified incorrect values, e.g. specifying the maximum weight of the wheel nut to be 60g (too low). On the other hand, some values were over specified such as consistently setting the material as "lightweight titanium alloy with corrosion protection"- unnecessary as the alloy would not corrode anyway and the protection would add undesirable cost and mass. Using Chat GPT function to create an initial PDS and then editing it to better align with requirements still took 10 minutes less than it took the student to create the PDS on their own. However, the student had already performed all the research allowing them to make those judgements during their independent PDS creation, and if that time was added the total time required to fully complete the activity was not shorter. AI does automate some repetitive activities, which may be beneficial regardless.
For concept generation Chat GPT produced verbal descriptions of the concepts that were more creative and had a wider scope than those designed by the student. The student primarily considered factors such as reliability, low mass and adherence to FIA regulations. However, AI lacked engineering knowledge and often suggested unrealistic outputs such as: (1) use of magnets to aid quick snapping or release (This increases complexity of the operation while not adding much benefit); (2) use of composites for ultra-light construction (Composite manufacturing is extremely time intensive and due to the short lifespan and large quantity of wheel nuts required it would significantly increase the cost of the wheel nut production, that due to unidirectional strength would not be capable to withstand rotational force); or (3) adding "smart" elements including sensors to prevent over-tightening or under-tightening (FIA requires passive sensors. Proposed location of sensors would mean they could get damaged and battery powering them would create chemically unstable environment. The sensors already exist in the wheel gun.). Word descriptions suggested by AI were often vague and difficult to translate into usable concepts as they were not compliant with the technical requirements or always follow the scientific principles.
Ultimately, there were few credible sources regarding wheel nut features, e.g. material used or the forces exerted on it (such as the tightening force produced by braking). But even when credible sources were available, such as the technical datasheet for the Dino Pauli wheel gun, the AI used more popular but less reliable sources instead. It was unable to reference peer reviewed publications and books, as they were not freely available online. In general, the information produced roughly agreed with that produced by the student, but references by Bing AI required checks to assess their reliability.

4.2 Use of Image Generation Models

Leo, Dream Studio, Alpaca, Starry AI and Microsoft Bing AI were explored for concept generation.
Most are trained for artwork and did not respond well to engineering descriptions, even when reference images were provided. Figure 3 illustrates the response of Microsoft Bing AI image generator to the prompt "a side mirror for a Formula One team which is aerodynamic", displaying a solution that is not particularly aerodynamic, nor displaying an F1 car.
It was difficult to create a prompt (detailed or generalised) to be accepted by Leo. Further development of the software may change that, but at this stage it did not meet the requirements of the problem explored. Overall, the outcomes of image generation were not usable. They were either highly artistic

or very simple, mechanically, did not consider function of the product in any way and often included unnecessarily complex forms e.g. turbine on the side of the car in Figure 3 that serves no purpose.

Figure 3. Microsoft Bing AI image generation

4.3 Use of Generative Design

Generative design was performed in Fusion360 for three commonly used materials (Aluminium 2014 T6, Stainless Steel 17-4-PH and Titanium 6Al-4V). Its outcomes, shown in Figure 4, allowed the designer to compare them - an improvement to traditional way of working. Five-axis CNC was specified as it is a common manufacturing method in F1 teams. Additive manufacturing was allowed for greater freedom with shape optimisation (although it would often not be used, due to high cost). The outcomes of generative design were interesting, although not entirely applicable. Some suggested elements were taken on and merged with the design student created on their own, to create a medium range solution that could potentially be functional, pending further testing. Using thin ribs to connect two parts of the wheel nut reduces the mass but could be a safety hazard in high-speed environments.

Figure 4. Generative design shape optimisation (top - Fusion360 generative design, middle – modified by student to comply with regulation, bottom – standard wheel nut design)

4.4 Students' Perception of AI and Objective Usefulness

Student performing the case study has shown high ability to evaluate the outcomes of AI at the appropriate stages of the development process. They suggested that AI may be useful for PDS creation and generative design, with intervention from the designer, and only as inspiration otherwise. This agreed with the educators' perspective. However, this is likely significantly influenced by the student's work experience with an F1 team, which is not common across the cohort. Overall, in the teaching practices outside of this case study AI was occasionally perceived by students as trusted source, even when its outcomes were vague and unjustified by peer reviewed sources. An exercise similar to the one performed in the reported case study would likely be beneficial to include in the curriculum.

5 RECOMMENDATIONS FOR AI USE IN EDUCATION

It is likely that future AI will be adapted for the needs of specific fields and that data sources the algorithms have access to will allow curation, increasing the reliability and robustness of the proposed solutions. However, in their current form they should be used with caution. Discussion of AI abilities and validity of the outcomes they generate should be prioritised with students early in the process. Following recommendations are made, based on the outcomes of the study described in this paper:

- AI use in appropriate contexts can be encouraged, but the validity of its outcomes should always be questioned.
- Discussion should be engaged in with the students to establish what the novelty of the AI solution is and how they can assess if the problem is genuinely being solved.
- All AI outputs should be evaluated against engineering standards and engineering principles.
- All AI outputs should be compared with outcomes of other experimental or analytical methods.
- AI limitations in the specific context should be explored and fully understood by the designer.

These agree with the existing suggestions, found in the literature, to encourage learners to be critical consumers by questioning AI intelligence and trustworthiness [15], AI can be used with problems it excels at but human skills need to supplement it. It should not be seen as the ultimate solution. Instead, it needs to be managed, if its sources and general principles it employs are validated, students can learn to use it and generate reliable outputs.

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