Department: Education

Using Computer Graphics to Make Science Visible in Engineering Education

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Abstract—Science plays a crucial role in engineering. But science tends to be obscure to students, especially when they are overwhelmed by complex engineering design challenges that involve many variables. This article shows how computer graphics can be used to visualize science concepts and operationalize inquiry practices in engineering design to support integrated learning and teaching of science and engineering. Based on these graphical capabilities, generative design driven by evolutionary computation can also be visually illustrated to give students a glimpse into how artificial intelligence is transforming engineering design. The article provides real-world examples in the field of sustainable energy engineering based on Aladdin, an open-source design and analysis Web app. It also presents evidence of learning from pilot tests at culturally diverse high schools. Science educators interested in incorporating engineering design into their lesson plans may find this article helpful.

The Next Generation Science Standards (NGSS) mandated by many states in the U.S. has elevated the importance of engineering design in K-12 education to the same level as scientific inquiry.[1] However, a decade after the official launch of NGSS, the educational technologies for engineering design still lag far behind those for scientific inquiry. For instance, there exist numerous visual simulations that use computer graphics to bring science concepts to life for students to explore,[2] but there are many fewer options when it comes to supporting engineering design in K-12 schools. The lack of technologies for enhancing engineering education does not reflect the close relationship between engineering and technology in the workplace.

Part of this disparity may have stemmed from the weak linkage between science and engineering in many existing educational software intended for K-12 students and teachers. On the one hand, a scientific inquiry tool that supports students to investigate certain science questions may not be equipped with design capabilities for solving highly open-ended engineering problems in the real world. On the other hand, an engineering design tool that enables students to draw three-dimensional computer models of structures and forms may not provide meaningful and explicit connections to specific science content that teachers need to cover, thereby reducing their interest in adopting it in a science class.

At this decennial milestone of NGSS, celebrated by many educators for the incorporation of engineering into major education standards for the first time in the history of American education, we review our work on bringing science education and engineering education closer together using computer graphics as a connective tissue. Allowing a significant part of engineering, such as construction, testing, and analysis, to be virtualized with visually appealing effects and details, computer graphics creates opportunities for science teachers to realistically include engineering design in their lesson plans when their classroom time and budget are limited—as an alternative to traditional engineering projects based on building and testing physical prototypes that may take more time and resources to prepare and implement.

SCIENCE IN ENGINEERING

In general, what distinguishes engineering design from other types of design such as architectural design is the extent to which science is applied. Engineering is inspired and guided by science extensively and deeply, but it cannot violate any fundamental laws in science—no matter how hard we try to design a machine, it simply will not run perpetually without power. Educators must convey this nature of engineering to students.

In educational practice, engineering design can be used as a pedagogy to teach basic concepts in science[3] or a method to teach engineering as an application of science[4] (or a combination of both). In any case, students face two steep cognitive barriers. First, science concepts are far less evident than other design variables such as shapes and costs in most engineering problems. Second, the ability to apply a science concept to improving a design rests not only on the understanding of the concept *per se*, but also on the understanding of its interplay with all the other factors that may affect the overall function of the system. The latter is related to systems thinking and essential to core design practices such as making tradeoffs that satisfy multiple criteria under multiple constraints.

FIGURE 1. An overlay of the daily total solar irradiance (shown as heatmaps) and heat fluxes (shown as arrows) on top of a house (upper) designed in Aladdin.

VISUALIZE SCIENCE IN DESIGN

Based on computational tools capable of calculating the effects of the underlying science concepts on a design solution, we can use computer graphics to generate visual representations of the concepts from the computed results and superimpose them onto students' own design artifacts to help them overcome the two cognitive barriers. Figure 1 provides an example from a sustainability engineering project that aims to minimize the energy consumption of a house under design using the Aladdin app that we developed based on WebGL and React.[5] The example shows the spatial distributions of solar radiation on the building envelope of the house and the net heat transfer across it over a 24-hour cycle. Scientific visualizations such as these can create learning opportunities for students to see science concepts at work individually or concertedly in their own designs, thereby fostering the integration of different concepts and the linkage between science and engineering. This affordance is expounded below using cool roofs[6] as an example.

Roof materials can affect the energy consumption of a building significantly. The solar radiation on a roof decreases the heat loss of the house in the winter because it raises the temperature of the exterior surface of the roof and thereby slows down the heat flow through the roof as per Fourier's Law of Thermal Conduction. On the other hand, the solar radiation on the roof increases the heat gain of the house in the summer because heat flows from the outside to the inside during the day and a higher exterior temperature of the roof caused by solar radiation results in a higher rate of thermal conduction into the house through the roof. To the house, this effect decreases the heating cost in the winter but increases the cooling cost in the summer. Exactly what material to choose for the roof depends also on the aesthetic consideration, the climate of the location, and the insulation of the roof. In this case, students must understand these science concepts, as well as their intricate interactions that result in opposite outcomes in different seasons, in order to make an appropriate choice. Although we can introduce the scientific knowledge to students at the beginning of a design project, there is no guarantee that they will be able to assimilate all the concepts right away and apply them to their own designs later. To remind students of those concepts in action, Aladdin renders a picture of their effects just at the time when students are analyzing their own designs (see the lower image of Figure 1). The visual cues in the picture may draw students' attention to the scientific attributes of their designs that may otherwise be hidden from them.

ENHANCE INQUIRY IN DESIGN

Although NGSS separates scientific inquiry and engineering design, the two practices are often intertwined in engineering education projects. On the one hand, inquiry provides an effective way to help students develop a deeper understanding of the related science concepts needed to undertake design tasks on a rational basis. On the other hand, design creates opportunities for students to encounter authentic science problems in their own engineering projects that need to be investigated and understood through inquiry. In this section, we will discuss how computer graphics can be used to generate visual feedback to facilitate inquiry practices in a design environment. We will continue with the cool roof example introduced previously and then provide another example from a different engineering field.

Inquiry in Sustainable Building Design

Suppose we would like students to conduct an experiment to investigate the effect of roof color on building energy usage so that they can better understand the essential science concepts before making a design decision. In such an experiment, the roof color is treated as the independent variable—the only property to be changed. The energy usage is treated as a dependent variable that is affected by the roof color. Everything else should be a controlled variable that remains the same in the experiment.

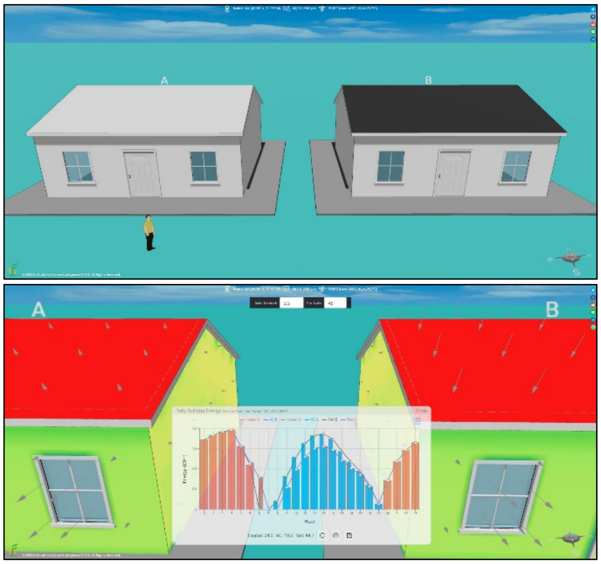

FIGURE 2. An experiment in Aladdin for investigating the effect of roof color on building energy usage with two houses that are identical except the roof color (Location: Natick, Massachusetts, USA; Date: June 10; Thermostat setpoint: 20°C). The inset combination chart compares their hourly heating (red bars), cooling (blue bars), and total energy (lines) use in a 24-hour cycle.

Let us first create a simple house in Aladdin (with the location, date, and thermostat settings described in the caption of Figure 2). One inquiry approach is to choose a roof color, run a building physics simulation, record the calculated energy usage of the house, repeat this process a few times, and then analyze the recorded data to draw a conclusion. As this approach repeats the above steps in sequential order, we call it a *serial experimentation*. Since Aladdin is a graphically rich app, students can also use a *parallel experimentation* approach. They can copy the house to a different position to create two identical houses (see the upper image in Figure 2). Then students change the roof color of one of them so that one roof is light-colored and the other dark-colored. In this way, students only need to run a single simulation and the results for the two houses can be analyzed in parallel and compared side by side. The results suggest that the house with the dark-colored roof consumes more energy for air conditioning as it *gains* net energy from the outside through its roof in the 24-hour cycle, as opposed to the other one that *loses* net energy to the outside. The visual contrast posed by the opposite directions of heat flux arrows drawn on the two roofs in the lower image of Figure 2 highlights this difference. The comparison of the hourly results between the two houses is also shown in a combination chart consisting of two bar charts and a line chart that represent heating, cooling, and total energy usage for each house (see the inset in Figure 2).

Inquiry in Renewable Energy Design

In many renewable energy projects, the goal is to design solutions that maximize the energy output within a given space and budget. However, the output depends on many design variables that may appear to be esoteric to students at the beginning. As such, students must develop a basic understanding of these variables in order to design effectively. In an educational environment like Aladdin, students can use an inquiry approach to examine how these variables affect the energy output and thereby learn operational knowledge about them.

One type of renewable energy design supported in Aladdin is solar power towers. This is a type of concentrated solar power that features a tall tower surrounded by many mirrors controlled by computers, called heliostats. As the sun moves across the sky, these heliostats are rotated to reflect sunlight to a central receiver installed at the top of the tower. The design involves setting the positions of the heliostats and the height of the tower, among other variables. In an optimal design, the heliostats should not cast too much shadow on one another or block the light reflected by others from reaching the central receiver.

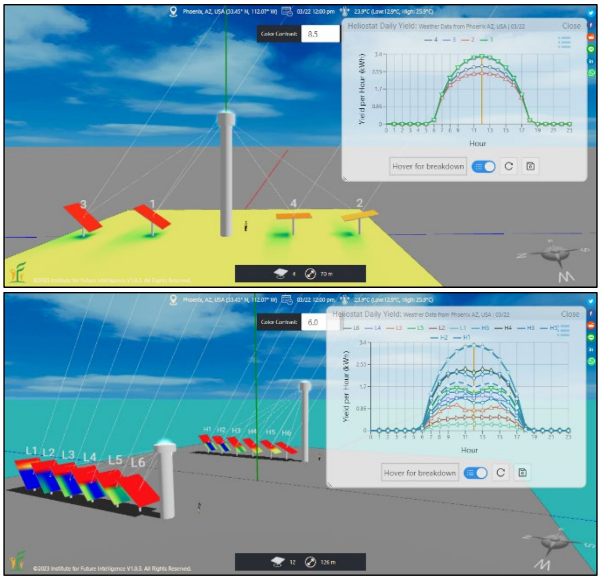

FIGURE 3. Experiments in Aladdin for investigating the cosine efficiency of the heliostats around a solar power tower and the effect of the tower height on the output (Location: Phoenix, Arizona, USA; Date: March 22). The inset graphs show the hourly outputs of each heliostat.

Figure 3 shows how Aladdin can help students learn two variables key to a solar power tower (in the following explanation, we assume that the power tower in question is in the northern hemisphere). The first is known as the cosine efficiency. For sunlight to be reflected to the central receiver, a heliostat must be rotated to face the bisector of the angle between the line connecting it to the sun and the line connecting it to the receiver. For a heliostat to the south of the tower, this angle is larger than that for a heliostat to the north. As a result, the angle of incidence of sunlight that strikes the former is larger. Due to the projection effect, the solar irradiance on a surface is proportional to the cosine value of the angle of incidence. The larger the angle, the weaker the solar irradiance. Hence, less solar energy is reflected by a heliostat to the south of the tower than by a heliostat to the north. This is why many solar power towers do not use a simple layout in the form of concentric circles for their heliostat fields (which has equal numbers of heliostats to the north and south of the tower). The optical paths from the sun to the receiver reflected by the heliostats and the solar radiation heatmaps on their surfaces in the upper image of Figure 3 provide a graphic explanation.

The second design variable for students to explore is the height of the tower. The taller the tower is, the more solar energy the heliostats reflect. This may be less obvious to students than the cosine efficiency explained above and can use some help from computer graphics. The lower image of Figure 3 shows an experiment with two equally-spaced arrays of heliostats lining up respectively to the north of two towers with different heights. The heatmaps on the heliostats indicate that the shadowing and blocking losses are greater in the case of a shorter tower. This is why engineers have built very tall towers for large power plants. For example, the Crescent Dunes Solar Energy Project in Nevada, USA, which consists of 10,347 heliostats on a land area of 6.5 km², has a tower as tall as 200 meters.

SUPPORT CITIZEN SCIENCE

Computer graphics is important to citizen science[7] that provides a pathway of informal education because it can be used to create visually appealing presentations of science that entice learners. To some extent, all the graphical capabilities described above pave the road for Aladdin to grow into a platform for citizen science in the fields of energy and sustainability.

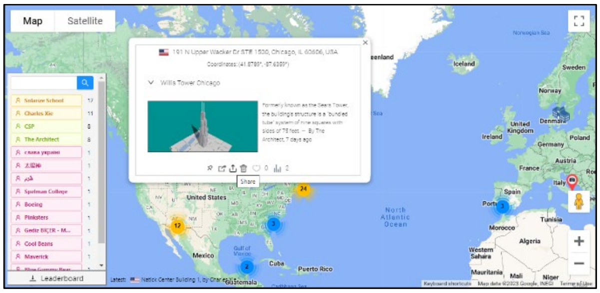

FIGURE 4. Maps embedded in Aladdin show models for projects in the real world contributed by users. These models are represented by markers anchored at their geocoordinates. When hovered, a marker opens an information window with a brief description about the model and buttons to open, share, or like it.

Maps are an ideal visual organizer for citizen science projects that depend on geolocations (Figure 4). They provide a public forum for citizen scientists to propose and share their ideas about renewable energy projects that may impact their own neighborhoods. Unlike other types of social networks in which participants present ideas in text, images, or videos, Aladdin allows users to turn ideas into visual, interactive, and analyzable models that can be found on the map by anyone concerned about their own communities. These models can also be displayed on top of satellite images for users to get a sense about how the ideas may fit into the local environments. They can be analyzed using the numerical simulations provided in Aladdin to evaluate their costs and benefits.

Figure 5 shows four Aladdin models of different types of real-world projects in different parts of the world. Whether it is a rooftop solar panel project, a utility-scale solar power plant, or a public building, users can create a design solution with Aladdin, publish it to the map to share with the world, and draw public interest in crowdsourcing further development of the design and even its eventual construction.

FIGURE 5. Aladdin as a citizen science platform for modeling and/or designing real-world projects. From top to bottom: The PS20 solar power tower in Seville, Spain; The Solar Strand at the University of Buffalo, New York, USA; Solar panel arrays on the roof of Terminal A, Logan International Airport, Boston, USA; The BILSEM science education center in Mersin, Türkiye.

VISUALIZE AI IN DESIGN

Generative design is a new genre of design technology based on artificial intelligence (AI).[8] Once the design criteria and constraints of a product are specified, generative design starts an evolutionary computation process that efficiently explores the entire parameter space supported by the software to find optimal solutions. During the iterative search for feasible solutions, the software automatically constructs a vast number of forms at each step, tests their functions using numerical simulations, evaluates their quality based on the given criteria and constraints, and then selects those that are closer to the goal for the next step. By repeating these computational routines many times, a variety of designs that meet the goal eventually emerge. Engineers then review these outputs, often with the aid of interactive visual analytics for intuitive appraisal and comparison across the board and choose one or more designs for prototyping. This paradigm shift in design methods entails a fundamental change of mindset for design thinking that must be addressed in the engineering education of future workforce.

A problem in teaching generative design is that AI appears to students as a black box that, while capable of recommending useful solutions, does not give any explicit clues about why and how they are chosen. This opacity is a recognized problem that has been driving the research and development of explainable AI, or XAI.[9] As an example of XAI, Aladdin opens the black box of AI by visualizing how it uses science to drive design.

Design Space Exploration

For starters, consider the design of a small solar farm comprising four rows of solar panels, each of which is allowed to have a different tilt angle (Figure 6). The goal is to find the values of these angles that result in maximal total output of electricity for the whole year from all the solar panels. You may have seen solar panel rows in the real world that typically tilt at the same angle. This makes sense when the inter-row spacing is sufficiently large such that a row does not cast shadow on the one behind it. But when the rows are more close-packed in order to use land more efficiently, conventional wisdom may not lead to the best solution. The comparison between a solution designed using a conventional rule of thumb and a solution suggested by AI in Figure 6 shows that AI manages to avoid significant shadowing losses. Let us observe how AI solves this problem by visualizing its trajectory in the design space (Figure 7). To this end, we use genetic algorithms (GA) implemented in Aladdin to mimic "AI thinking" since the rationale of GA is easier to understand due to its similarity to Darwinism.

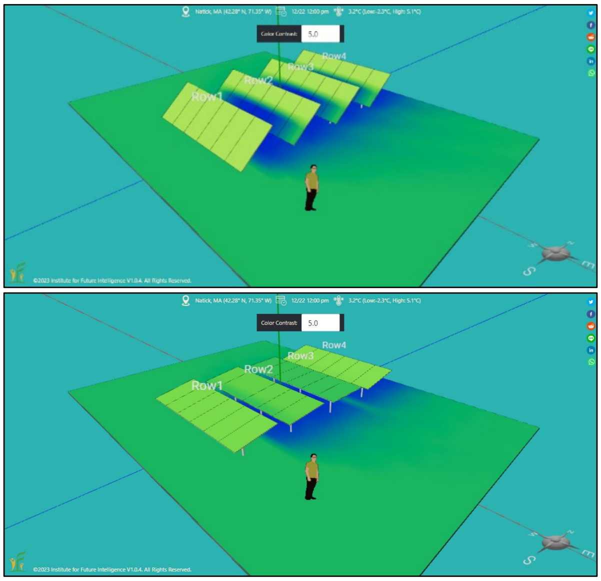

FIGURE 6. A design problem in Aladdin for finding the tilt angles of four rows of solar panels that result in maximal annual output. Upper: The heatmaps of the rows that tilt at the same angle equal to the latitude (a conventional rule) show significant shadowing losses in the winter; Lower: The heatmaps of a solution recommended by AI show it avoids inter-row shadowing.

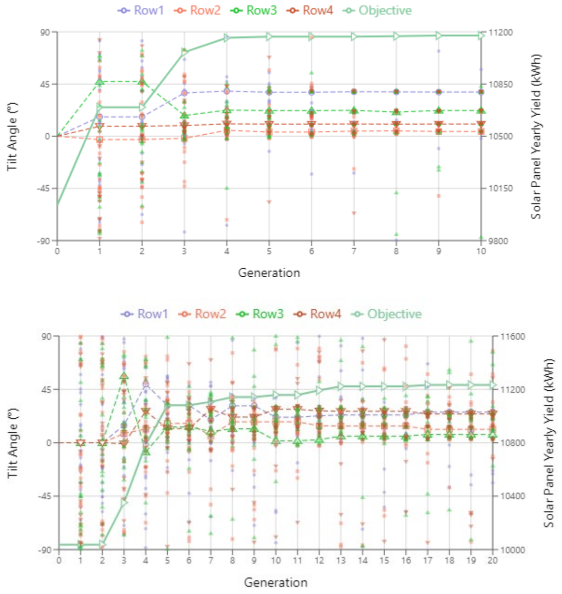

FIGURE 7. Aladdin visualizes the design space explored by GA with a mutation rate of 30% (upper graph) and 70% (lower graph), mimicking different degrees of divergent design thinking of humans. The legend is “Row1, Row2, Row3, Row4, Objective” in both biaxial graphs, with the text color matching the line color.

In design theories and practices, design space exploration is a key concept. As humans, we tend to fixate on certain areas in the design space that seem familiar to us. However, our experience is a double-edged sword—while it allows us to do our job quickly, it also limits our ability to see beyond what we already know. AI has a similar creativity problem—an algorithm may be self-reassured to stick to a local optimum due to its interpolative nature in machine learning. To overcome this trap, GA uses a mutation operator that randomizes the “genes” during the process of evolution. Figure 7 shows the effect of this mutation operator in sampling the design space. The small dots in each biaxial plot represent all the individual solutions that have been generated at each step of evolution. Their distribution in the vertical direction at each step represents their “genetic” diversity. As you can see from these graphs, when the mutation rate is low, the “genes” tend to concentrate on a few spots after a few generations. But when the mutation rate is high, they become more scattered (though a higher degree of diversity does not improve the results significantly in these runs, possibly because the fitness landscape is relatively flat in the given design space).

Human-AI Collaboration

An implication of our work on using computer graphics to visualize AI’s actions in engineering design is that the design capabilities of AI can then be turned into instructional power to guide students. We envision Aladdin as a “design buddy” to students that uses “visual contact” to enable close human-AI collaboration, an emerging skill that many believe is important to the future of work as AI is reshaping our industries.

In Aladdin, students can always create or revise their own designs manually with the drawing tools provided on its 3D graphical user interface. When students are not sure about the performance level of their designs, they can then employ AI to assess, refine, or even change their designs—as if they asked an expert for assistance. When students invoke AI in this capacity, their current designs will be automatically included in the first generation to start the evolution. In such a way, students’ current design ideas are taken into consideration by AI. Unless the current design is already optimal, AI can always generate better solutions. By comparing their current designs and AI’s improvements, students can learn from AI. For example, when AI generates a solution that surprises students, it effectively creates a cognitive dissonance that spurs students to learn and integrate new ideas and concepts with their existing knowledge.

RESULTS FROM SCHOOLS

In this section, we report preliminary results from our most recent studies. In May 2022, we conducted pilot studies with 142 students from two Midwestern high schools in the USA. In both schools, the students completed a week-long Aladdin curriculum that included a Solar Energy Science unit and an AI-assisted Solar Farm Design unit. They were challenged to design an array of photovoltaic solar panels that generates maximal annual profit or achieves the shortest payback period for an investor while meeting a set of constraints such as a limit for the total construction budget and a field in a fixed shape. A post-survey was administered to collect student feedback on their learning experiences. Figure 8 shows their responses. Among the students of these two schools, 34 out of 87 respondents with valid responses liked the visualizations in Aladdin. In addition, more than half of those respondents (49) liked the ability to test different design ideas on their own in Aladdin. This epistemic agency would not have been possible without using computer graphics to render the results of student designs so that they can immediately see how their ideas play out in the design environment. More results from these studies will be published elsewhere.[10]

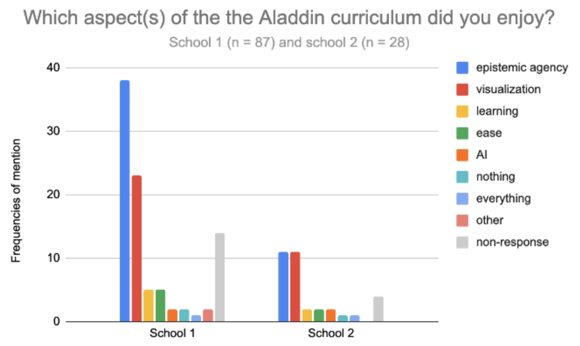

FIGURE 8. The exit survey results from two high schools about students' reactions to various aspects of the curriculum modules based on Aladdin. The majority of the students from both schools were positive about the visualization and epistemic agency provided by the tool.

The design artifacts created and published by students can also be visually examined by teachers and researchers to assess their design performance. Figure 9 provides two examples published by students in two other small-scale pilot studies (that are still unfolding at the time of writing), one in a tribally-controlled high school in southwestern USA and another in a public high school in Türkiye. In the former study, students are challenged to design a solar energy system to power their school. In the latter study, students are encouraged to explore creative solutions to integrate renewable energy into the infrastructure of their community. Both examples illustrate the pivotal role of computer graphics in igniting students' imagination in engineering design.

FIGURE 9. Two original designs proposed by high school students to promote renewable energy. Upper: Rooftop solar panel arrays for a high school; Lower: Solar updraft towers in unused space of a highway ramp.

CONCLUSION

This article demonstrates that computer graphics can be used in an engineering design environment to highlight the role of science and generate visual feedback about students' own designs. This affordance allows students to test a design idea on a scientific basis, develop a deeper understanding of a science concept through inquiry, and learn the application of science to engineering.

We also show that generative design can be animated such that students can observe closely how AI can be used to sift through many design options step by step and zero in on a few leads. Such a visualization vividly reveals AI at work to students with concrete pictures, rather than abstruse formalism or computer code, about science concepts and engineering principles that determine the effectiveness of a potential design solution. It is through witnessing how AI "thinks" to find solutions that students start to appreciate its power, question its limitations, and evaluate its trustworthiness as a scientific inquiry and engineering design tool. Our future work will focus on developing innovative technologies and pedagogies that help students cultivate this ability to harness the power of AI in engineering design and thus be prepared to join the AI revolution in the industry.

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