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Guest Editorial

Special Issue: Artificial Intelligence and Engineering Design

Artificial intelligence (AI) has had a strong presence in engineering design for decades, and while theory, methods, and tools for engineering design have advanced significantly during this time, many grand challenges remain. Modern advancements in AI, including new strategies for capturing, storing, and analyzing data, have the potential to revolutionize engineering design processes in a variety of ways. The purpose of this special issue is to consolidate recent research activities that utilize existing or new AI methods to advance engineering design knowledge and capabilities.

During the conception of this special issue, we identified three core interfaces between the research domains of engineering design and AI: (1) leveraging AI methods directly in engineering design methods, (2) creating new AI capabilities that are inspired by unique challenges that arise in engineering design, and (3) creating and analyzing design methods that are tailored for the design of engineering systems where the systems themselves utilize AI, such as autonomous vehicles. The diverse body of research articles that now comprise this special issue gravitate toward the first of these themes: advancing engineering design capability through the use of AI. While these articles are an exciting contribution to the design research literature, significant opportunities exist for more fully exploring the remaining two interfaces, ideally through more unified interdisciplinary efforts. During the process of synthesizing this editorial, we recognized a fourth interface between engineering design and AI: specifically, investigating how AI could be used as an increasingly powerful tool for conducting engineering design research, such as AI tools that are used directly in research activities (e.g., experiment planning or gathering information from human designers) and that are not necessarily part of the designed system or the design method.

Two sets of clear themes have emerged from this special issue. The first set is expressed from the perspective of engineering design research and design processes. The second set is organized in terms of AI methods. We have organized these themes in this way in part to facilitate clearer communication across AI and Engineering Design research communities and to enable the productive collaboration that is needed to address open questions. Later, we discuss the relationship between AI and engineering design and then articulate the two sets of themes found in this special issue. Finally, a vision is presented for advancing interdisciplinary research in this area, including an initial outline of promising research topics.

Artificial Intelligence and Engineering Design

This special issue consolidates exciting new outcomes from recent research that focused on the application of modern AI methods to the creation and analysis of methods that advance engineering design capabilities. Design researchers have long recognized that AI tools can be used in many ways to advance how engineers perform design. For example, designers can now leverage AI to support more automatic and intelligent knowledge extraction and knowledge representation, support early design ideation, and even to discover design solutions to previously unsolved engineering problems. In addition, the capabilities of modern AI algorithms can enhance the efficacy of later-stage system design activities, such as those involving high-dimension and strongly interrelated detailed design decisions.

Tasks at early design stages, such as concept generation, have the potential to effect transformational change upon engineering system capabilities. Yet in practice, these early-stage tasks rely heavily upon designer experience and intuition. Human cognitive limits constrain such design processes, creating an opportunity for AI models to accelerate the ability of engineering to better meet the needs of humanity. Limitations of conventional methods and tools constrain the fidelity and scope of the design spaces that are tractable. AI methods are helping to solve problems where human intuition or human processing capabilities are insufficient, making it possible to expand the richness of design spaces that can be navigated successfully through AI support.

Some engineering functions may not even have known solutions, even via biological analogies; AI-based design strategies have the potential to aid in the discovery of design solutions to previously unrealized functions through nonobvious design configurations. Used as an identification tool, AI is enabling more efficient and higher-performance design solutions during design revision at the manufacturing and assembly level by screening and identifying part consolidation opportunities and multifunctional design potential.

More comprehensive investigation of the role of AI in engineering design methods and research appears to be reshaping how we think about design. AI methods that can transformatively restructure design spaces for various goals exist, such as more efficient navigation of design alternatives or insightful interrogation to extract design knowledge. Design spaces can be adaptable throughout design process stages. Less rigid formulations can produce more fluid design paradigms compared to established frameworks, such as design optimization. AI models can also serve as the design solution method without needing to be linked to iterative design optimization. Moreover, inverse design approaches fit well with AI tools, further bending our conception of design strategies. Publications at the interface of AI and engineering design have often been led by design research experts rather than AI experts, resulting in potential bias toward particular research questions and classes of AI methods. Approaching this interface from additional complementary directions could help us build a more complete understanding of how AI methods can further benefit society through advancements in engineering design.

Articles in this issue link to a diverse set of approaches used in AI and utilize various neural network architectures to develop surrogate models. These surrogate models typically learn abstract representations to understand the underlying processes, which can be then explained to gain further insight. Several approaches also assist the designer through human augmentation and increased automation, while also expanding design spaces through transfer learning. These approaches are applied to many

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aspects of the design process including systems design, conceptual design, generative design, and several detailed design applications in areas including supply chains, medical devices, and aeronautics.

Readers may be keenly aware that the guest editors have not attempted to define AI. While some excellent definitions exist, conflicts in (sometimes evolving) AI definitions held by such a diverse set of potential authors are likely. We opted to consider submissions that utilized AI as defined by the authors, as long as the definition is justifiable, and if the submission makes a notable contribution to the body of engineering design knowledge. As a result of this inclusive approach, some readers may not consider some methods appearing in this issue to be AI. The definition of AI will not be settled here; rather, we hope that one of the primary contributions of this special issue is a helpful step toward more successful integration of AI and engineering design research.

This special issue incorporates a variety of topics that represent the state of the art in how AI is changing how we do engineering design today. Articles solicited represent intellectual contributions to engineering design research at the intersection of unmet engineering challenges, advances in AI, and design-relevant contexts. Articles published in this issue fall largely within the general area of AI being utilized as an enabling tool for advancing engineering design capabilities. In particular, many articles focus on enhancing early-stage design capabilities. Previous special issues exist for related topics, including Machine Learning for Engineering Design and Data-Driven Design. This special issue has provided an opportunity to publish design research linking to the broad area of AI that may not have fit well with these previous special issues. For example, one article (Gyory et al.) utilizes an AI agent to perform dynamic design team management based on predefined logical rules.

The guest editors have identified significant themes that have emerged from this collection of articles, organized first into topics that are presented from an engineering design research perspective and second into topics that are articulated from an AI method perspective. Please note that the distinctions between these themes can be fuzzy; some studies lie at the intersection between two or more themes. The following two sections introduce these themes and point readers to relevant articles in this special issue. This editorial then concludes with remarks on open research questions at the interface of AI and engineering design.

Engineering Design Research Themes

When viewed through the lens of engineering design research, four broad themes emerge from this special issue, each of which is discussed here.

Design Theme 1: Conceptual Design and Design Synthesis. Several articles involve advances in utilizing AI for more expansive and comprehensive yet practical exploration of complex design configuration spaces, including topological changes, design synthesis, and support for enhanced human creativity. Methods are either automated or involve a partnership between AI and human designers. More conventional design paradigms induce a different constraining of design spaces than might be possible with this class of AI-based design methods. Natural language processing (NLP) is utilized in several studies presented here as a key interface with the human creative process (T. Chen et al., Han et al., and Lee et al.). Two survey papers also provide context and future directions for utilizing the AI-based methods for this and other design needs (Han et al. and Jiang et al.). The article by Song et al. presents a study of the influence that AI tools have on strategies followed by designers during engineering design processes. As noted earlier, several articles link to two or more themes. For example, Behzadi et al., Q. Chen et al., Nobari et al., Quigley et al., and Raina et al. all link to both methods for conceptual design and Design Theme 2: Accelerating Design Processes.

Design Theme 2: Accelerating Design Processes. Multiple contributions in this special issue utilize AI tools to reduce the time, computational iterations, or other resources required to obtain a good design solution. Two key AI-based strategies employed to accelerate iterative design processes include (1) transfer and representation learning (Behzadi et al., Herzog et al., and Whalen et al.) and (2) invertible neural networks for optimization (Ghosh et al. and Oddiraju et al.). While many current AI-related research efforts outside of engineering design research focus on training models from scratch for maximum accuracy with large datasets, many articles in this special issue (and other design research publications) gravitate toward pretrained networks, such as used in transfer learning, to enhance accuracy with limited datasets (Ferrero et al. and Yuan et al.). This observation links to the Transfer Learning AI theme discussed later. In addition, AI methods that better support generation of design solutions that are substantially distinct from previous designs, such as transfer learning methods that are successful in design domains that are more distant from the training data, may be particularly valuable.

Design Theme 3: AI-Based Direct Estimation and Tuning. In addition to accelerating iterative design processes, some methods proposed AI-based tools that reduce or eliminate the need for iterative design. Articles by Burge et al., Dachowicz et al., and Li et al. used neural networks to design solutions for given initial conditions. The article by Raina et al. used learning by demonstration to provide design solutions, and the article by Caputo et al. utilized deep reinforcement learning to achieve adaptive responses to changing environmental conditions without the need for any new design iterations.

Design Theme 4: Broader Design Process Support. A few articles make broader contributions that cannot be strictly classified along a specific theme mentioned earlier. The article by Wang et al. makes a theoretical contribution involving the use of Gaussian processes in a scalable manner to represent complex spaces. The article by Kim et al. utilizes AI-based tools to perform sentiment analysis on product listings and how they evolve. The article by Gyory et al. proposes and tests an AI-based team management system against a human-based management system; an overall increase in productivity and content is realized through the AI system. The article by Caputo et al. proposes a new approach to conceptualize real options and flexibility analysis in engineering systems design, building upon principles from deep reinforcement learning. This supports the view that more work is needed to develop new AI and data-driven methods to design complex engineered systems so that they can better deal with uncertainty and risks—which is much needed, especially given ongoing threats from climate change and global healthcare emergencies.

AI Method Themes

When viewed from the perspective of identifying specific AI methods that are shown to be useful for advancing engineering design capabilities, five themes materialize. An exposition of these themes is provided below.

AI Theme 1: Natural Language Processing. Natural language processing has been used in several papers included in this special issue. NLP serves as a human-interpretable way to interact with many AI-based systems, and so improvements to NLP methods can benefit the tools adapted to engineering design problems (T. Chen et al., Han et al., Kim et al., Lee et al., and Yuan et al.).

AI Theme 2: Graph (Neural) Networks. Many design representations may be represented as graphs (e.g., assemblies (Ferrero et al.) and structures (Whalen et al.)). In future work, it would be beneficial to see more studies that address remaining challenges in applying graph networks to engineering design, such as invariance/equivariance properties, explainability, and transferability.

AI Theme 3: Generative Models. Use of generative models continues as a demonstrated AI-based design strategy (Behzadi et al., Q. Chen et al., Nobari et al., Oddiraju et al., Quigley et al., Yuan et al.); one potential benefit is the ability for these models to produce solutions without iterative optimization. Within the set of

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articles utilizing generative models, articles by Behzadi et al. and Nobari et al. address the challenges with small data set sizes, which is an important characteristic of many data-driven design strategies. To enhance what can be done using small data sets, the article by Nobari et al. introduces a label-aware self-augmentation training approach, and the article by Behzadi et al. uses knowledge transfer.

AI Theme 4: Transfer Learning. Transfer learning is emerging as an important tool for dealing effectively with the small data sets that are common in engineering design. The article by Whalen et al. explores the transferability of a learned graph network on a variety of structural design problems. The article by Herzog et al. presents a study of the effectiveness of knowledge transfer in the context of semi-supervised learning of labels on 3D geometries.

AI Theme 5: Representation Learning. The article by Raina et al. introduces new ways of representing design policies (e.g., sequences of design decisions) when the action space structurally changes during the design process. Gaussian process (GP) models that learn latent categorical representations are presented in the article by Wang et al., and the scalability issue of GP models is investigated.

Future Opportunities for AI and Engineering Design Research

This special issue offers a partial snapshot of the current research results in AI and engineering design. The previous sections summarize some aspects that were addressed in the special issue; here, we articulate what appears to be missing, and what could serve as the basis for rich future collaborations in interdisciplinary research between AI and engineering design researchers. We identify both AI methods that need further study as elements in engineering design methods, as well as ways AI could be addressed differently in the context of engineering design (e.g., new AI contributions motivated by design, design of AI-based systems, and AI methods as tools in engineering design research).

The collection of articles utilizes several well-established model-free AI methods for the purpose of accelerating engineering design processes, but leaves open the opportunity to investigate the use of model-based learning techniques in these contexts. This may be because most of the applications studied here do not have clear associated dynamics. The solutions obtained from these methods can be used not only as solutions to engineering design problems but also model-based strategies that leverage assumptions about the form of the system being modeled (e.g., physics-based phenomena or distributions) could lead to a deeper qualitative design understanding. Model- and dynamics-based learning methods could be exciting and insightful avenues for engineering design research.

Several articles in this issue utilize pretrained networks, which are either adapted to identify/classify design models or to develop a framework for explaining engineering design related processes. While the pretraining approach has been discussed in AI under the names of transfer and curriculum learning, its deeper understanding is particularly important to engineering design due to frequent scenarios where data are limited or expensive, e.g., during the exploration of new material systems. In such scenarios, it would be valuable to be able to learn effective representations, rules, or solution search strategies from one set of design problems and apply that knowledge to a different (or more complicated) set of problems. While empirical evidence has been reported where such transfer has potential, we expect deeper investigation into the theoretical conditions for certifiable performance of pretrained models, and more comprehensive ontologies that define knowledge transfer within the broad context of engineering design. The tendency toward pretraining approaches in engineering design methods exemplifies the deeper underlying needs that are unique to engineering design and motivate additional fundamental AI investigations. This observation is representative of the second interface between AI and engineering design research, as identified in the second paragraph of this editorial, and is an opportunity for productive interdisciplinary discussion.

An interesting future direction for this effort would be to solve engineering design problems using both the pretraining and from scratch strategies for neural networks and then to compare the abstractions learned using both approaches. It would also be valuable to evaluate hybrid methods, where certain layers are allowed to mutate to adapt to the given problem. Alternately, networks trained from one paradigm can be used as the initialization for the other, and optimal abstractions can be learned for the given problem sets. As observed earlier, many articles in this issue concentrated on new AI-enabled design methods to better support early-stage design tasks. Research topics that are notably absent from a design methods research perspective include those that investigate AI-based methods intended for more comprehensive late-stage design (e.g., AI agents that aid automation of fully detailed design specifications required for the production).

In addition to the outputs of AI research benefitting design research, the converse is also possible. For example, tools from current engineering design research, such as design automation methods, could be used to rapidly generate rich and tailored data sets that amplify the impact of AI methods. Furthermore, engineering design challenges and knowledge from design research could help inform new advancements in AI, presenting a new opportunity for interdisciplinary collaboration and motivation for enhanced communication across research disciplines. Another class of open research questions involves the creation of design methods that are tailored to meet the needs that are unique to design systems where AI is part of the system being designed and not necessarily part of the design method. Finally, AI methods could be used as a tool in engineering design research, which is distinct from use as part of a design method. For example, many design research studies involve human components; AI could play a significant role as a research tool in interfacing with human designers, users of designed systems, and other stakeholders. It could also transform planning of research experiments and data collection.

Addressing these questions is distinct from fundamental advances in AI theory and algorithms alone; generation of new knowledge that is relevant to engineering design and that links to AI requires scientific rigor in both domains and motivates deeper collaboration between design research and AI research experts. Completely new AI concepts may take engineering design capabilities in unexpected directions, and vice versa. Many important open questions remain, and only a few have been highlighted here. We encourage readers to apply their own unique perspective and expertise to distill and identify additional scientific questions at the intersection of AI and engineering design research, especially those that may benefit from deep interdisciplinary collaboration. We hope to work collectively toward more impactful research at the interface of AI and engineering design. Achieving this will require extensive future efforts. Existing work does involve independent forays into adjacent disciplines (e.g., design researchers gaining AI expertise), but, on the whole, studies at this interface are still performed in a largely siloed manner. Perhaps the fundamental differences in language, perspectives, and goals between the AI and engineering design research communities add to the underlying difficulties. A significant investment across disciplines would be required to realize this vision of intrinsic interdisciplinarity for research at the interface of AI and engineering design.

James T. Allison
University of Illinois at Urbana-Champaign,
Urbana, IL 61801
e-mail: jtalliso@illinois.edu

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Michel-Alexandre Cardin
Imperial College London,
South Kensington,
London SW7 2DB, UK
e-mail: m.cardin@imperial.ac.uk

Chris McComb
Carnegie Mellon University,
Pittsburgh, PA 15213
e-mail: ccm@andrew.cmu.edu

Max Yi Ren
Arizona State University,
Tempe, AZ 85226
e-mail: yiren@asu.edu

Daniel Selva
Texas A&M University,
College Station, TX 77845
e-mail: dselva@tamu.edu

Conrad Tucker
Carnegie Mellon University,
Pittsburgh, PA 15213
e-mail: conradt@andrew.cmu.edu

Paul Witherell
National Institute of Standards and Technology,
Gaithersburg, MD 20899
e-mail: paul.witherell@nist.gov

Yaoyao Fiona Zhao
McGill University,
Montreal, QC, H3A 0C3, Canada
e-mail: yaoyao.zhao@mcgill.ca

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