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OPERATOR 4.0 FOR HYBRID MANUFACTURING

Fillingim, Kenton Blane;
Feldhausen, Thomas

Oak Ridge National Laboratory

ABSTRACT

Hybrid manufacturing, a combination of additive and subtractive manufacturing capabilities in one system, has recently become a more viable production option across several industries. Although current hybrid manufacturing research covers a broad range of topics, there is a lack of focus on how this new technology impacts both the designer and the operator of hybrid systems. This paper identifies areas of literature across design theory and Industry/Operator 4.0 research efforts and presents a path for applying this research to hybrid manufacturing users. The unique relationship between operator and designer is highlighted as they learn new strategies and develop new intuitive judgements over time to become the first experienced/expert users of hybrid manufacturing. The potential impact of excessive cognitive workload due to the novel combination of processes is discussed. This paper begins a critical discussion about proper knowledge transfer to other hybrid designers and operators, as well as towards efforts of monitoring, inspecting, and automating hybrid manufacturing processes.

Keywords: Knowledge management, Additive Manufacturing, Human behaviour in design, Hybrid Manufacturing, Operator 4.0

Contact:
Fillingim, Kenton Blane
Oak Ridge National Laboratory
United States of America
fillingimkb@ornl.gov

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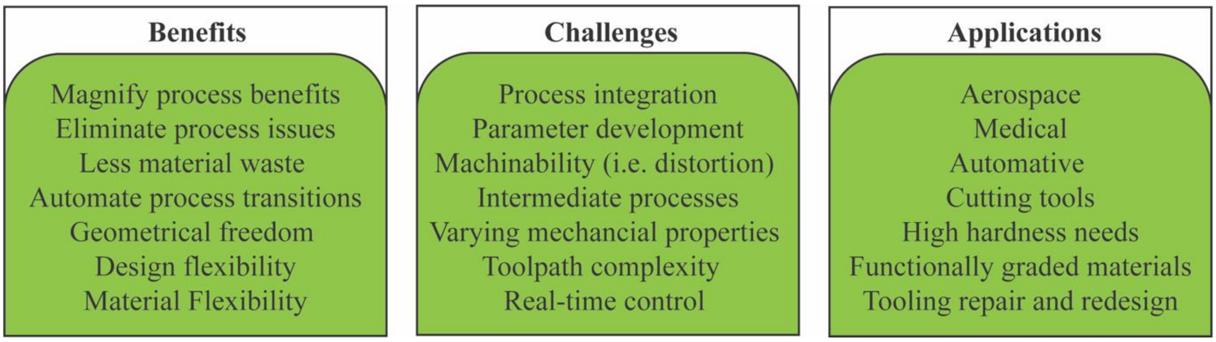
1 INTRODUCTION

Advanced manufacturing developments over the last few decades have made manufacturing technology more efficient and powerful than ever. However, it has also become more complex than ever. Industry 4.0 can be described as advanced digitalization through sensors, Internet of Things (IoT), security efforts and more, applied to manufacturing contexts (Kaasinen *et al.* 2020; Feldhausen *et al.* 2021). Industry 4.0 has also been referred to as smart manufacturing or cognitive manufacturing (Corporation 2017). These cyber-physical systems (CPS) are now being reassessed to include the operator as human-cyber-physical systems (H-CPS), a direction being termed Operator 4.0 (Ruppert *et al.* 2018). Operator 4.0 has been broken into eight distinct aspects which apply different purposes towards operator assistance (Romero *et al.* 2016). These eight phases are the Super-Strength, Augmented, Virtual, Healthy, Smarter, Collaborative, Social, and Analytical Operators. These eight sectors have been seen as beneficial to consider alongside the Industry 4.0 advancement. Operators have shown desires to be involved with Operator 4.0 design processes, and they have highlighted the need for knowledge sharing and adaptive learning technology that promotes personal efficacy while on the job (Kaasinen *et al.* 2020).

Now, leading researchers are looking even beyond the 4.0 movement. The European commission pushes an Industry 5.0 effort which focuses on a more human-centric approach to designing industrial systems (Müller 2020). The covid-19 pandemic, exposing weaknesses in current manufacturing processes, pushed the advancement of Operator 5.0, based on more resilient manufacturing capabilities (Romero and Stahre 2021). Operator 5.0 hopes to avoid disruptions, withstand disruptions, adapt to change, and recover and proactively learn from the unexpected. Although still in development, hybrid manufacturing is becoming a more noticeable and viable option for design and manufacturing in the 4.0/5.0 movements. Hybrid manufacturing technology combines additive and subtractive processes into one system, allowing users to perform these processes interleaved as desired. This new space of increased design freedom, which in turn produces increased planning and production complexity, has mostly been unexplored from a human factors standpoint to date. Designers are learning how to design for hybrid systems, while operators are learning how to operate such systems. Both are developing heuristic and intuitive responses to the technology without much external cognitive assistance, as the literature is relatively young and not well documented. However, in order for this technology to be better adopted into industry, research toward better understanding and equipping hybrid designers and operators should be pushed forward. This paper provides an overview of hybrid manufacturing, the research gaps in the current design for hybrid manufacturing landscape, and direction for research areas which should be addressed moving forward.

2 HYBRID MANUFACTURING



Benefits

- Magnify process benefits
- Eliminate process issues
- Less material waste
- Automate process transitions
- Geometrical freedom
- Design flexibility
- Material Flexibility

Challenges

- Process integration
- Parameter development
- Machinability (i.e. distortion)
- Intermediate processes
- Varying mechancial properties
- Toolpath complexity
- Real-time control

Applications

- Aerospace
- Medical
- Automative
- Cutting tools
- High hardness needs
- Functionally graded materials
- Tooling repair and redesign

Figure 1: Summary of hybrid manufacturing benefits, challenges, and applications

As hybrid systems have recently been the focus of heavy research efforts, many researchers have provided review papers to consolidate the current state of the art (Zhu *et al.* 2013; Lorenz *et al.* 2015; Dávila *et al.* 2020; Jiménez *et al.* 2021; Pragana *et al.* 2021; Dezaki *et al.* 2022). Highlights of the benefits, challenges and applications found across these sources have been summarized in Figure 1. By combining subtractive and additive processes into a single cell, many of the disadvantages of the singular processes can be eliminated. For example, rough surface finishes from additive processes disappear by means of machining. Excessive material waste from machining bulk stock is mitigated by only printing the minimum amount of material required. Hybrid systems provide some progress of automation by allowing several processes without the part having to be manually moved and reset in new systems. For designers, hybrid systems provide new, creative, and complex design flexibilities, as well as material flexibilities. Hybrid systems with directed energy deposition (DED) additive processes include the benefits of functionally graded materials (FGM) (Jiménez *et al.* 2021). Alloying can be performed by combing two materials at once, or one part can have two different materials deposited in separate features (Dávila *et al.* 2020). Yamazaki shows an oil industry example of multi-material by using higher performing materials in critical performance areas and cheaper steels elsewhere, drastically reducing material cost while keeping comparable cycle times (Yamazaki 2016). Others have also considered hybrid for multi-material products (Reichler *et al.* 2019; Weflen and Frank 2021).

With these new benefits come new challenges, some of which have not been accounted for in traditional systems. Integrating the hardware and software as one system is not easily accomplished. Process and parameter development is nontrivial, often machine specific, and requires prior experience or intuition to refine (Lorenz *et al.* 2015). Intermediate steps like heat treatments to reduce residual stresses can be difficult, forcing users to make their parameters as optimal as possible to minimize the number of processes (Dávila *et al.* 2020). Machinability becomes an issue with distortion that might take place during additive phases (Jiménez *et al.* 2021). Factors such as humidity from machining coolant must be studied to see if they impact additively manufactured parts (Kannan *et al.* 2022). Interleaved processes can present unique mechanical properties and microstructures that must considered. New build angles without supports can impact part strength (Dezaki *et al.* 2022). There is difficulty creating efficient 5-axis toolpath strategies and collision avoidance due to the new complex geometries (Dávila *et al.* 2020; Jiménez *et al.* 2021). New CAM strategies must be explored to account for accuracy with both additive and subtractive processes, which CAM software has not traditionally been designed for (Zhang *et al.* 2020; Feldhausen *et al.* 2022a). Tool accessibility requires much planning and design considerations. Lastly, although inspection and monitoring efforts have been put forth in hybrid systems, real-time control has not yet been reached (Zhu 2013; Thien *et al.* 2020; Feldhausen *et al.* 2021).

There has already been a push for hybrid systems in several application spaces including aerospace, medical, and automotive industries, as well as areas requiring high hardness materials (die and molds, energy, and petrochemical) (Dávila *et al.* 2020). There is interest in FGM applications such as cutting tools, optics, and biomedical parts (Jiménez *et al.* 2021). Tooling is one of the most common end uses considered when discussing hybrid manufacturing. Hybrid provides flexibility with tooling design and production, specifically in casting applications, injection molding tools and mold inserts (Jeng and Lin 2001; Boivie *et al.* 2011; Abdillah and Ulikaryani 2020; Soffel *et al.* 2021). It can also provide a new opportunity for retooling, where additive and subtractive processes can be performed on existing tooling to replace worn sections or add entirely new features (Saleeby *et al.* 2020; Feldhausen *et al.* 2022b). Ren et al. has proposed this with common die damages (Ren *et al.* 2006). Outside of tooling, others have also shown redesign considerations from a broader context (Newman *et al.* 2015). Gas turbine part production and blade repairs have been shown as well (Nowotny *et al.* 2010; Jones *et al.* 2012). In summary, most complex geometries that would benefit from easier means of production or repair are a main target of hybrid systems.

To fully utilize hybrid systems, it is possible to rely on lessons learned from previous attempts to integrate new technology into workspaces, or to introduce a new workforce into existing systems. For example, Schmitz recognized that online CNC training programs can allow for distracted learners (Schmitz *et al.* 2022). Virtual reality-based CNC training work should work towards varying the degree of support based on user needs and understanding the degree of help needed to complete the task (Ryan 2022). Hsieh pushes for aspects such as video or simulations to improve visualization of abstract CNC concepts (Hsieh and Li 2018). Duffy saw that repeated CNC training can lower workloads, but study participants still struggled between choosing “safe” versus “efficient” operations (Duffy 1999). Lastly, Mogessie makes the case for training modes which can become modularized and generalized, such that training can be redesigned and repurposed for multiple metal additive manufacturing machines as needed (Mogessie *et al.* 2020).

Hybrid manufacturing has an extensive future work space; however, the authors see a human factors element to the process that remains unexplored. From the designer perspective, hybrid systems present more opportunities in the design space, and design creativity must be fully engaged in order to maximize these opportunities. Designers and operators must carefully and intentionally communicate to understand how proposed designs are performing during production, so that the correct iterations can take place. As shown in Figure 2, hybrid operators are charged with performing at a level requiring higher cognitive workloads and knowledge of several different facets of manufacturing, rather than being extremely skilled at just one facet of manufacturing. With attached monitoring and inspection technologies, they may attend to several process aspects at once. Hybrid operators are the first to develop an intuition for how these systems behave collectively, how far the capabilities can be pushed, and how to judge part quality, successes, and failures. This serves as the basis for three new research areas worth exploring alongside the technical development of hybrid systems, in order to accelerate and improve the use these systems across industries: design strategies, intuition development, and cognitive loads. The following sections will discuss the state of research across each area and provide future directions in more detail.

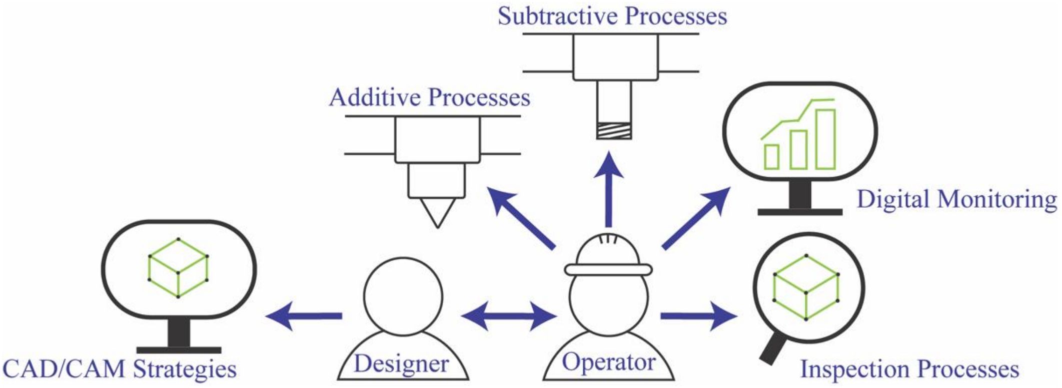


Figure 2: Hybrid manufacturing designer – operator – system relationships.

3 DESIGN KNOWLEDGE AND STRATEGIES

As knowledge towards designing for and operating hybrid manufacturing systems continues to grow, it is necessary to understand how to document and transfer this knowledge in an efficient manner. Heuristics have been highlighted in prior work as a common mode for transferring design rules (Fu *et al.* 2016). In manufacturing, much recent work has focused on Design for Additive Manufacturing (DfAM) knowledge. For example, Blösch-Paidosh and Shea derived 29 “high-level, process independent” DfAM heuristics by studying 275 design artifacts (Blösch-Paidosh and Shea 2017). Others target more process-dependent (such as SLM or FDM) or feature-specific (such as rapid tooling or design for assembly) application of design rules (Adam and Zimmer 2014; Urbanic and Hedrick 2016). Some studies focus less on the knowledge itself but rather how to best present this information to others. When presenting information to assembly workers, Thorvald suggests batched information rather than sequential information, symbols rather than traditional article numbers, and mobile information rather than stationary (Thorvald 2011). Blösch-Paidosh and Shea used a redesign scenario with students to show the benefits of heuristics as a lecture assistance tool (Blösch-Paidosh and Shea 2019). DfAM heuristics have been studied for effectiveness (such as design quality, design novelty, or self-efficacy) when comparing modalities of presentation and the timing in which they are provided in one’s design process (Fillingim *et al.* 2020; Schauer *et al.* 2022a; Schauer *et al.* 2022b).
Studying design for hybrid manufacturing may not only involve transferring good strategies but avoiding negative design traits as well, such as design fixation. Design fixation can be a negative result of learning new advanced manufacturing techniques in several ways. First, studies show signs of design fixation when additive manufacturing is a part of the process (such as prototyping), but conventional methods are ultimately used for larger production (Abdelall *et al.* 2018b). This series of work promotes software to mitigate fixation when moving between the two methods (Abdelall *et al.* 2018a). Designers have also shown a tendency to fixate on manufacturing constraints that have limited past designs when learning new manufacturing capabilities, a concept coined Manufacturing Fixation in Design (MFD) (Bracken Brennan *et al.* 2021). Therefore, dispersing knowledge of new and emerging technology can help broaden one’s design thinking. Leahy et al. showed that initial concepts – both self-generated and provided by example, can drive design fixation, but tools such as design heuristics can limit fixation in idea generation phases (Leahy *et al.* 2020). Moreno et al. had similar success with design by analogy methods that aid eliminating design fixation and increasing creativity (Moreno *et al.* 2016). Schauer et al. saw success in heuristic use as well, but warns that the timing of heuristic presentation may matter in regards to fixation (Schauer *et al.* 2022a; Schauer *et al.* 2022b).

For hybrid manufacturing, designers should begin applying strategies that help reduce design fixation, so that the newly formed hybrid design space can be explored to its full potential. Dispersing hybrid design strategy knowledge as it emerges should also help broaden design thinking, although few studies have looked into decision making in hybrid manufacturing holistically. Fillingim and Fu have documented learned heuristics for hybrid manufacturing, although this work focused mostly on extraction methods and statistical correlations of perception (such as self-perceived heuristic reliability and frequency of use) (Fillingim and Fu 2022). Feldhausen et al. presented a review of CAM strategies tailored towards hybrid manufacturing (Feldhausen *et al.* 2022a). Joshi and Anand used factors representing (a) geometric complexity and (b) manufacturing time to assess practical implementation of hybrid methods compared to additive or subtractive methods only (Joshi and Anand 2017). Operators should understand design intents and understand the new strategies being employed to reach those goals. As combining processes increases the complexity and quantity of content transferred from designer to operator (and vice versa), future work should explore the efficiency in documentation and transferral between the two as well.

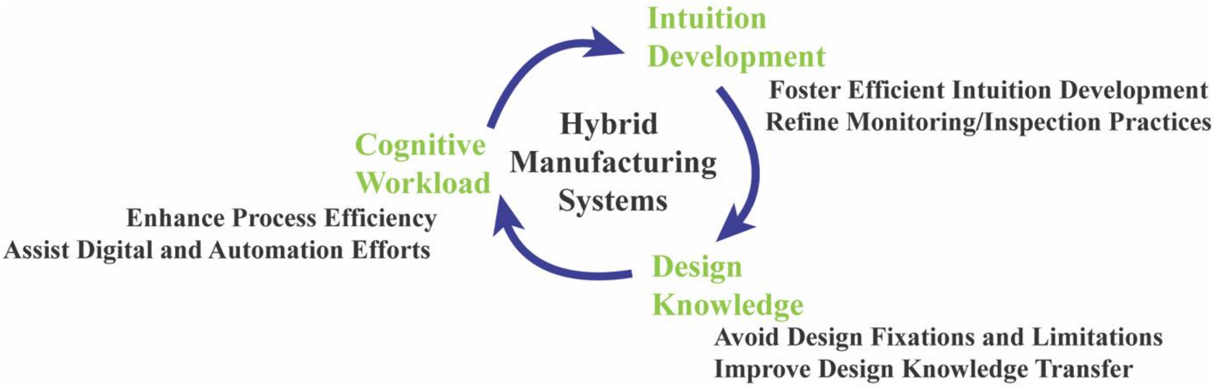


Figure 3: Proposed research directions for hybrid manufacturing

4 INTUITION DEVELOPMENT

The most common studies of intuition in manufacturing have come from a management perspective (Elbanna *et al.* 2013; Fantini *et al.* 2015; Liebowitz *et al.* 2019; Korherr *et al.* 2022). There have been specific pushes towards intuition for factory physics, a term defining the behavior of manufacturing systems, again for management purposes (Hopp and Spearman 2011). This intuition does not help just a human decision-maker on their own, but simulation-based assessments as well. Gershwin shows how a lack of intuition in general software packages can lead to trouble, such as simulations that leave out critical knowledge or include non-critical factors (Gershwin 2018). This means factory technology that excludes aspects of human intuition may never reach its full potential. Standridge has also shown that behavioral insight from factory physics can provide more accurate simulation models (Standridge 2004). As such, manufacturing systems research is needed to understand which data is relevant and how it should be put to use. To develop intuition in factory physics, simulations have been performed alongside coursework to shorten learning curves while on the job (Gómez 2007).

To perform research on intuition development in hybrid manufacturing will require an understanding of several human factors surrounding intuition. Sinclair speaks on affect across all phases of the intuitive process: as antecedent (such as mood), as a process component, and as a confirmation (feeling-charged judgement) (Sinclair 2010). They also warn of misguided participant experience levels, as experience does not mean expertise, and “semi-experts” may still produce poor decision-making because they are stuck between being cautious and being intuitive. Novices may default towards heuristic and biased decision-making. Intuition does not always emerge into consciousness instantaneously; there are cases where intuition incubates and surfaces at a later time during unrelated tasks (such as while walking). Studies on incubated vs non-incubated intuition, as well as mood, on design quality have been performed (Paige *et al.* 2021). Participant decision-making under time pressure versus a deliberation period has produced results consistent with the Social Heuristic Hypothesis (SHH), meaning that under time constraints people will default towards heuristic strategies that have worked for them in the past, if the situation looks similar to one encountered in the past (Capraro and Cococcioni 2015). When given deliberation time, one may gather more details and knowledge and choose to override the heuristic response. Therefore, the SHH perspective gives weight to one's learning from personal experiences to their behavior in new experiences (Rand *et al.* 2014).

In summary, intuition in manufacturing environments have often focused on higher-level employees and not in those in direct operation of the systems. Hybrid operators may be working on new and unfamiliar designs and processes due to the youth of the technology. As operators move from novice to experienced to expert users, capturing how intuition is discussed, processed, and relayed in new situations and to new users would actively influence better process monitoring and inspection efforts. It would also help CAD/CAM designers, as they should understand how their decisions impact other decisions. For example, a product design of several hole sizes impacts manufacturing decisions significantly compared to one using equal sized holes (Gershwin 2018).

5 COGNITIVE WORKLOAD

Alongside Industry 4.0 and Operator 4.0, there have been efforts towards reducing cognitive load in manufacturing. In a survey on the feasibility of cognitively aware safety systems (CASS), operator support was highlighted by participants as one of the most important innovation areas of their respective fields moving forward (Mangler *et al.* 2021). The cognitive manufacturing umbrella term is now being used to include tools that aim to reduce cognitive load in manufacturing (Carvalho *et al.* 2020). A literature review from Carvalho et al. shows several main causes of overload in manufacturing: interruptions, training/instructional situations, manual assembly, maintenance activities, order picking, and visual inspection/quality inspection. Outlines have been made for decision-making towards automating these cognitively challenging aspects of manufacturing (Torn *et al.* 2021). This starts with clustering then characterizing tasks to understand the automation value in terms of cognitive load reduction and other human factors.

Recent manufacturing-focused cognitive load research has been directed towards assembly workers. The Cognitive Load Assessment for Manufacturing (CLAM) survey tool uses five task-based factors and six workstation-based factors (Thorvald *et al.* 2017; Thorvald *et al.* 2019). This work emphasized understanding environmental impacts on assembly workers. Others document mental effort and stress levels using human motion tracking devices at assembly workstations (Lagomarsino *et al.* 2022). Eye tracking has been used alongside the NASA Task Load Index (TLX), a widely accepted cognitive load metric in several application spaces, to show that increased cognitive load leads to increased task time in automotive manufacturing assembly task times, demonstrating the negative impacts of workload on manufacturing (Hart 2006; Biondi *et al.* 2023). Several studies have also looked at human-robot interactions and collaborations. Guidelines have been developed using case studies for reducing operator load while improving trust and awareness with collaborative assembly systems (CAS) (Gualtieri *et al.* 2021). Fabroni et al. conclude that robots should tailor their behavior to the needs of the one who is using it (Fraboni *et al.* 2021). Operator control of robots has been tested using NASA TLX from both local and remote locations (Zimmer *et al.* 2022). Lastly, virtual reality has been used alongside surveys to assess operator workloads by simulating work environments (Khamaisi *et al.* 2022). For operator-robot collaborations, virtual reality studies have shown that less robot autonomy and multi-modal feedback (audio and visual) reduced operator task distraction and workload impact (Kaufeld and Nickel 2019).

For hybrid manufacturing, designers are learning to develop models and CAM strategies that include novel, interleaved processes. These are methods that software has not initially considered for its users. Operators are similarly learning to facilitate novel, interleaved processes in one job while simultaneously observing inspection/monitoring technologies being added to manufacturing technology. These combinations can lead to large numbers of errors, failures, and production iterations. Identifying the specific workload pain points will allow hybrid technology to be more efficiently incorporated into industry and provide direction for automation and cognitive assisting technologies. It may benefit the hybrid process to differentiate factors that determine instantaneous (specific time points) and overall (across the entire process) cognitive loads (Lagomarsino *et al.* 2022). Tong and Nie emphasized that high designer load could relate to their need for knowledge, which impacts knowing when to push new knowledge towards designers (Tong and Nie 2022). Therefore, studying cognitive load has relevance towards the previous design section discussed as well.

6 CONCLUSION

A review has been presented seeking to connect hybrid manufacturing systems to the Industry and Operator 4.0/5.0 efforts in current literature. While there are many benefits to hybrid manufacturing, with applications that will improve costs and expand design opportunities, understanding how humans might best interact with this technology requires attention. Design strategy development and documentation are needed to understand how we are and how we might better design for hybrid technology. Operator intuition and workloads can be understood to modify workstations and aid automation or digital technology collaborations that optimize operator performance. This paper contributes to this effort by identifying avenues to build upon, rather than replacing, the existing literature provided. For example, the cognitive load review provides a variety of settings and factors which might contribute to excessive operator workloads. These metrics may serve as a baseline for understanding how hybrid systems might heighten some factors more than others. Similarly, it was shown that prior work has studied the modalities in which one might discover, document, and present DfAM knowledge. The same methods and theory can provide a starting point for understanding hybrid design and manufacturing.

This review sets the stage for several case study avenues in hybrid manufacturing. One might advance hybrid design knowledge and strategies by comparing how new strategies differ and have commonalities with recent work pushed in DfAM or DFMA (Design for Manufacture and Assembly). Assessments can be formed to understand differences in workload when one considers additive and subtractive processes for a single design and a synthesized manufacturing session. Lastly, hybrid intuition assessments may be checked for deviations from CNC or DED intuition in separate settings, may help advance our understanding of best hybrid training and documentation practices. Overall, this work provides a more holistic approach to hybrid systems development to equip industry with the tools needed to successfully integrate these systems into their work environments.

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