

Interdisciplinary Research (IDR) Origination Awards

Cover Page

Project Title

Addressing Computer-Aided Design (CAD) Deficiencies Using Next-Generation Spline Technologies

Principal Investigator(s) (full-time faculty)

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Track

Track one

Abstract

Computer-aided design (CAD) enables model exploration and characterization in industries ranging from automotive engineering to animation to jewelry. CAD modeling is essential prior to downstream processes including texturing and rendering in graphics, and analysis and manufacturing for engineering. Unfortunately, designers often lack desired control and/or precision to represent intended shapes due to limitations of current CAD software. Additionally, using CAD geometry in subsequent processes is far from streamlined: converting a CAD model into representations suitable for analyses consumes over 70% of the time spent in the engineering design-through-analysis process. This impedes model optimization, resulting in poorer products and higher costs. Though many alternative spline-based CAD modeling tools have been proposed to address outstanding CAD issues, few have been integrated into software. Industrial evaluation of these tools—including through a graphical user interface (GUI)—is limited.

This interdisciplinary research proposal (IDR) seeks to begin addressing deficiencies in the CAD modeling framework—including lack of control/precision of subdivision surfaces and poor ability to leverage CAD models in downstream processes—by (1) creating a data structure that subsumes each of the piecewise-polynomial spline-based CAD modeling techniques proposed in the last 50 years (including proposed alternatives), (2) integrating this data structure into a GUI for evaluation of various spline-based modeling techniques, and (3) evaluating the data structure, the GUI, and the various proposed and existing CAD representations expressible using this novel data structure. IDR results will generate software and publications that will facilitate future funding proposals to both industrial and government sources.

Summary of Plans for External Funding

IDR funding will lead to submissions in the following government and private competitions: NSF HCC (~\$300,000. Dec 2025, Oct 2026, Aug 2027); NSF EDSE (~\$300,000. Apr 2026, Feb 2027); NSF Expeditions in Computing (~\$15,000,000. Preliminary: July 2026, Final: March 2027); NSF POSE (~\$300,000. Aug 2027); Charles Pankow Foundation (\$120,000. Sep 2025, Aug 2026); Autodesk Foundation (~\$250,000. May 2026, May 2027).

Project Narrative

Introduction

“And now, behold, I say unto you, that these are the generations of the heaven and of the earth, when they were created, in the day that I, the Lord God, made the heaven and the earth, and every plant of the field before it was in the earth, and every herb of the field before it grew. For I, the Lord God, created all things, of which I have spoken, spiritually, before they were naturally upon the face of the earth.” (Moses 3:4-5)

The principle of design is critical in the process of creation. Particularly, three-dimensional characterization of intended shapes plays an essential role in understanding the product space well before production. Though prototypes are still created physically using techniques like clay modeling [44], the vast majority of modeling in engineering, gaming, and animation is performed using computer-aided design (CAD) software [9, 21]. CAD tools enable the rapid exploration of the design space through various gluing, stretching, disjoining, and masking operations. CAD models can be further enhanced by artistic colorations and texture mappings [26], and CAD models are typically rendered into realistic representations long before actual production [21]. In this sense, the CAD industry imitates the creative process that we understand God to use because of the Book of Moses.

Unfortunately, current CAD tools lack efficacy in both the design process and in downstream operations on the proposed designs. Particularly, the spline-based tools primarily employed for computer-aided design—subdivision surfaces, B-Reps based on non-uniform rational B-splines (NURBS), and piecewise linear surface meshes [2, 8]—struggle to simultaneously ensure flexibility, precision, and ease of modification [1, 2, 8, 45]. Depictions of each tool, including an enumeration of their strengths and limitations, are presented in Figure 1. The discrepancy in strengths and limitations of various modeling tools has led to siloing of different CAD industries depending on the needs of designers and of downstream users in the industry. For instance, animators, who require models that can be dynamically deformed, typically opt to use subdivision surfaces [9, 19, 30] because of their ability to produce organic shapes and because they do not yield gaps when computationally deformed. However, subdivision surfaces possess regions called “extraordinary-points” (EPs) or “star-points” which lack control and smoothness [15, 16, 35] (see Figure 2); these regions are frequently unsightly, and animators spend significant effort mitigating their effects [1, 24]. Conversely, engineering-based CAD typically employs NURBS-based B-Reps [21] because NURBS methods have much greater control and precision than subdivision surfaces [19, 45]. These characteristics are essential for engineering analysis and manufacturing. However, trimming operations are

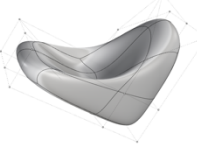
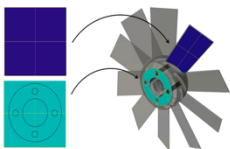
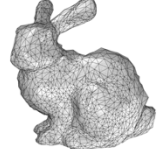

<u>Current CAD Methodologies</u>			<u>Improved Techniques</u>
SubD Surfaces	B-Splines/B-Reps	Meshes	
			
<ul style="list-style-type: none"> + Flexible/Rapid Design + Dynamic Deformation + Used in Animation + Organic/Smooth Shapes - Lack Precision - Not Suitable for Analysis - No Topology Altering - EP Definitions - Challenging with Sharp Features 	<ul style="list-style-type: none"> + Precise Design + Topology Modification + Used in Engineering + Featured Shapes - Typically Trimmed - Not Suitable for Analysis - No Dynamic Deformation - Slower Design Process - Agglomeration of Disjoint Pieces 	<ul style="list-style-type: none"> + Easy Texture Mapping + Suitable for Analysis + Dynamic Deformation + Topology Modification - Faceted/Not Smooth - Too Many Design Points - No Active Modification - Lack of User Control 	<ul style="list-style-type: none"> + Combine SubD and B-Rep Strengths + Topology Modification + Suitable for Analysis + Local Refinement/Modifying - EPs are Still Being Studied - No Existing GUI to Interact - Merits of Alternatives Not Yet Studied from Design and User Perspective

Figure 1: The predominant data structures currently used in CAD and their strengths/weaknesses are shown, as well as a comparison with alternative improved CAD methodologies.

ubiquitous in B-Reps [6]; these operations introduce tiny gaps and overlaps in models that make them unsuitable for animation [22, 29]. Furthermore, these trimming operations impede computer-aided analysis and computer-aided manufacturing processes because the underlying data structure is frequently intractable [22] (see Figure 3). Indeed, the process of converting from a CAD object into an analysis-suitable representation frequently consumes over 70% of the time spent in the engineering design-through-analysis process [4, 11, 23] and leads to billions of dollars in losses in the automotive industry alone [5].

Research over the last two decades aiming to address these issues in CAD has coalesced around the need for smooth spline-based CAD tools that mimic the flexibility of subdivision surfaces while also providing the precision of NURBS-based B-Reps. Much of the recent work in this area has been spearheaded by engineers aiming to enable accurate and high-speed engineering analyses using techniques called “isogeometric” methods [14], which must cope with outstanding shortcomings of both subdivision surfaces and B-Reps to be successful [22, 31, 32, 33, 39, 41]. However, despite a variety of proposed alternatives with mathematical behavior similar to the desired behavior of both subdivision surfaces and NURBS [10, 31, 38, 39, 43], neither researchers nor designers have the ability to graphically and interactively evaluate most of these tools. Consequently, the design community lacks the ability to assess proposed alternatives and make meaningful steps towards addressing its outstanding issues. **The purpose of this proposal is to create an extensible user-friendly framework by which to evaluate the various proposed CAD tools that seek to address the limitations of meshes, subdivision surfaces, and B-Reps.** This will be accomplished by developing a flexible data structure that describes spline-based geometry (including piecewise-linear meshes, NURBS, and subdivision surfaces, in addition to a variety of alternative techniques) and can readily adopt alternative representations at EPs. This data structure will then be

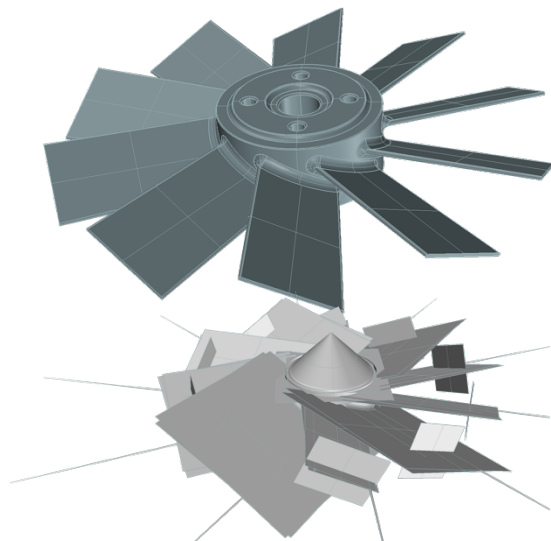


Figure 3: A CAD B-Rep of a Rolls Royce engine turbine is shown above. Below is a visualization of the underlying data. This discrepancy between the visualization and the CAD data impedes use of the model in downstream analysis and manufacturing.

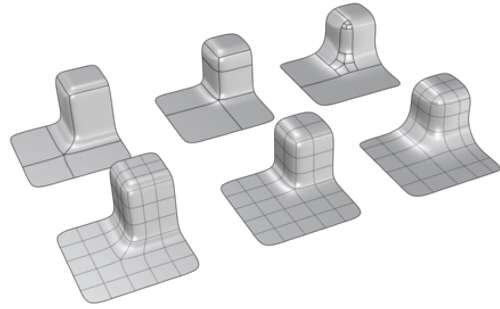


Figure 2: Various CAD spline structures are shown for a simple surface extrusion, with EPs at locations with 3 or 5 edges (but not 4) emanating from a single vertex [27]. Note that EPs and faces with more than four edges have poor smoothness in regions with high curvature, as seen from the poor light reflections in these regions.

integrated into a user-focused graphical-user interface (GUI) to help in the evaluation of the proposed alternatives. Studies will then be performed to evaluate the flexibility of the data structure (e.g. for extensibility to future methods), the GUI, and the actual spline-based CAD alternatives. **Ultimately, the research will enable exploration of the next generation of CAD software that overcomes existing challenges of CAD, including poor behavior around EPs and inefficiencies in downstream operations including engineering analysis.**

Proposed Plan

Though a variety of tools are being proposed to address outstanding issues in computer-aided design (e.g. [15, 16, 22, 38, 41, 42]), there is currently no means for designers to dynamically and interactively evaluate these tools. The work of this proposal will create a data structure capable of characterizing these alternative methods, will develop a GUI suitable for representing them, and will begin the process of evaluating these

suggested improvements. Detailed descriptions of activities are presented in what follows, and a timeline for various milestones is given in Table 1, on the final page of the project narrative.

(1) *Data Structure Creation*. The research team will develop a novel data structure that is flexible enough to represent both existing and proposed design tools, as well as future methods. The framework will combine the combinatorial map data structure for topology [17] with Bezier extraction [3, 28] methods for geometry. Bezier extraction is currently used by the engineering analysis community to leverage various spline spaces for finite element analysis [20] but lacks necessary topological information for its use in CAD software. Through Bezier extraction, polynomial-based splines are represented as a combination of simple building blocks, with distinct CAD/splines tools defined by different combinations of these building blocks. Combinatorial maps (and their simplification to oriented surfaces called the half-edge data structure) will provide additional topological details, have strong theoretical guarantees of flexibility, and are the current workhorse in surface processing. Efforts in this IDR will focus on locally tensor-produce splines (including those with EPs) whose control cages are described using quadrilateral meshes because these are currently the most important tools in CAD. Extensions to triangulations [36, 37] and mixed quad/triangle spaces [40], locally refined spaces [12, 13, 18], and non-polynomial spaces [25] will be evaluated in subsequent funding. K. Shepherd will primarily be responsible for this task and will be assisted by a PhD student mentee.

(2) *Graphical User Interface (GUI)*. Exploration of the design space using various existing, proposed, and potential CAD methodologies will be accomplished by creating a user-aware GUI built upon the spline data structure described above. The GUI will allow users to dynamically assess functionality, ease of use, and graphical representation of various spline and EP treatments. This GUI is a critical component missing for evaluating proposed CAD alternatives. S. Holladay will primarily be responsible for this task. He will be assisted by a computer science student whom he mentors. The GUI itself will be created using a software called Houdini [34] due to its flexibility, its importance in the design community, and Holladay's expertise.

(3) *Perform User Experience (UX) Investigation*. Given designers' inability to access novel CAD techniques, there is a dearth of knowledge about how these methods compare against current methods, including their strengths and shortcomings. The most recent academic study comparing CAD methods from a UX perspective appears to be from two decades ago [45], which was prior to the definition of any of the proposed alternative spline-based CAD techniques. While a variety of mathematical properties have been proved indicating potential for these methods, little to no evaluation has been performed by users. Using the data structure and the GUI created within the scope of this proposal, we will begin a user-focused evaluation of various proposed design tools, including simple NURBS-based B-Reps [22], subdivision surfaces [7], T-splines [29], and Almost C1 splines [38], in addition to various EP treatments (e.g. [15, 15, 38]). S. Christensen will lead these efforts, assisted by an undergraduate student mentee. To help ensure that the GUI itself does not adversely affect the perception of the proposed tools, Christensen will additionally perform studies prior to GUI development to understand the desired UX for computer-aided design; this information and subsequent studies will then inform the development of the GUI tools.

(4) *Publish Findings and Propose Additional Funding*. Findings from this research will lead to top-tier publications including one in *Computer-Aided Design (CAD)* describing the data structure, one at SIGCHI 2027 discussing UX with current CAD, one in *CAD* regarding the UX findings of proposed CAD alternatives, and one at SIGGRAPH 2027 regarding the integrated data structure and GUI. These publications and the software itself will demonstrate the value and viability of the IDR research and will help with proposing additional funding from both private and government sources, as discussed hereafter.

Why This Research Team?

Shepherd studies isogeometric analysis, splines, and CAD from the engineering perspective. His research has addressed deficiencies of the B-Rep based computer-aided design-through-analysis pipeline. He has also helped create novel spline techniques for hierarchical splines and unstructured splines. He will create the data structure, help with its integration into the GUI, and ensure that the proposed tools add value to the design process from the perspective of the engineering community.

Holladay works in animation and has years of experience as an animator at Pixar. He is also proficient in the use of Houdini. His strengths lie in graphics and interactions with GUIs. He will oversee the creation of the GUI and ensure the value of the proposed methods from the animation and graphics communities.

Christensen works in UX and design, including years of practical experience outside of BYU. He will help oversee the entire process from a user experience perspective, including that the GUI meets necessary criteria for its successful use and in determining the merits and shortcomings of various proposed spline methods. Christensen will then work with Shepherd and Holladay to find initial users to evaluate the tools and provide feedback, which Christensen will study. Shepherd will use the findings of Christensen's studies to mathematically characterize the strengths and shortcomings of these alternative CAD tools, which will then inform whether proposed alternatives address current shortcomings of CAD.

Obtaining Future Research Funding

Completion of this work will result in a flexible data structure, a user-informed GUI, and compelling user-informed data that will demonstrate potential to future funders, as discussed in the "Plans for External Funding" portion of this proposal. Results for unstructured tensor product splines from this work will inform inquiries into additional design spaces, including triangulations, locally refined spaces, and non-polynomial methods, which are of interest in computational design and in engineering analyses. With this research in place, we can gain support from organizations interested in engineering design, engineering analysis, graphics, animation, and human-computer interaction—communities which each share interest in these CAD issues, but for which our team must overcome a threshold of preliminary results prior to having a competitive proposal. With result established from IDR funding, it will be significantly easier to demonstrate the applicability of our research to these communities, whereas without IDR support it will be extremely challenging to convince sponsors to invest into an unproven data structure and GUI, despite their potential merits.

In addition, having created both the spline data structure and the GUI will put this team in a strong position for collaboration. Other researchers that want to dynamically and graphically visualize their tools will either need to create their own product or will want to piggyback off our GUI using our flexible data structure. As a result, funding going to those researchers will likely filter into BYU for development and support of additional tools.

Expected Research Outcomes

The following are a brief enumeration of expected research outcomes:

1. Creation of a new data structure for spline-based methods on unstructured tensor-product domains (with and without EPs) and its integration into a new GUI, resulting in two peer-reviewed publications and discussions with BYU's Technology Transfer Office about how to disseminate this product;
2. Training of one CCE PhD student, one UX undergraduate student, and one CS student;
3. Completion of a preliminary study comparing various splines from a user interaction perspective and then characterizing these results mathematically, resulting in two more peer-reviewed publications;
4. Exploration of adaptive/locally-refined spline technologies from a UX perspective, which will not be entirely completed during this proposal, but will lead to future funding and a publication later;
5. Proposals for funding from various government and private organizations.

Put in a more qualitative light, the proposed work will enable the active exploration of dozens of CAD technologies that build on the strengths of existing CAD frameworks while minimizing the weaknesses, including the ability to locally modify a model without affecting its representation globally. By placing these tools in the hands of designers, the design community will inform the merits of these proposed frameworks and help identify merits and weaknesses of the proposed technologies compared to existing ones. As designers begin investigating, employing, and providing feedback on these alternative tools, this will concomitantly lead to a more effective design infrastructure, both during the actual design process and during the use of created CAD models in the downstream processes in which the models must operate.

Table 1: Milestones of the IDR are presented below. Items with a “C,” “H,” or “S” indicate that Seth Christensen, Seth Holladay, or Kendrick Shepherd, respectively, will primarily be responsible for the task. Items with an “X” indicate equal responsibility between all investigators.

	Sep-25	Oct-25	Nov-25	Dec-25	Jan-26	Feb-26	Mar-26	Apr-26	May-26	Jun-26	Jul-26	Aug-26	Sep-26	Oct-26	Nov-26	Dec-26	Jan-27	Feb-27	Mar-27	Apr-27	May-27	Jun-27	Jul-27	Aug-27
Research Milestones																								
Perform Preliminary UX Studies	C	C	C	C																				
Create Basic Data Structure (DS) for Quads	S	S	S	S																				
Develop Basic Interface with Houdini	H	H	H	H																				
Extend GUI for Quad-Based Splines			H	S	H	S																		
Develop Input/Output File Format				S	S	S																		
Evaluate GUI Based on Findings of Studies					C	C	C	C	C	C	C	C	C	C										
Extend DS for Extraordinary Points						S	S	S	S	S	S	S	S											
Extend the GUI for Extraordinary Points						H	H	H	H	H	H	H	H	H	H	H							H	H
Gather Community Data for Evaluation												S	S	S										
Evaluate Design Tools from UX Perspective																C	C	C	C	C	C	C		
Enhance DS for Local Refinement															S	S	S	S	S	S	S	S		
Implement Local Refinement for Testing															S	S	S	S	S	S	S	S		
Integrate Local Refinement into GUI																H	H	H	H	H	H	H	H	H
Assess DS Extensions for Future Funding																			S	S	S	S	S	S
Preliminary UX on Locally Refined Spaces																						C	C	C
Documentation Milestones																								
BYU/Simmons Endowment Report												X												X
Submit to SIGCHI/SIGGRAPH													X				X							
Submit to Computer-Aided Design Journal																	X					X		
Additional Funding Milestones																								
Charles Pankow Foundation Proposal	X											X												
NSF Human Centered Computing Proposal				X										X										X
NSF Eng. Design & Systems Eng. Proposal								X										X						
Autodesk Foundation Proposal									X													X		
NSF Expeditions in Computing Proposal										X									X					
Explore/Submit NSF POSE Proposal																X	X	X						X