Reconstruction of CAD Models into Single Trimmed Surfaces Research Note

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Abstract

Classical methods by which computer-aided design (CAD) geometries are represented for both design and analysis involve meshing. This poses problems, as the meshing process takes a significant amount of time and labor, results in an approximate representation of the geometry of interest, and typically generates models capable only of low-order analyses. This research focuses on accurately and efficiently rebuilding given CAD surfaces or meshes into single trimmed surfaces (rather than a piecewise-linear approximation/representation), making them suitable for use in isogeometric analysis.

1 Introduction

Over 60% of simulation effort performed by the automotive industry is related to crash and safety simulations [11]. These analyses range in scope from evaluations of individual components to complete assemblies to entire vehicles, and leverage both shell and solid elements. Unfortunately, the process of converting a computer-aided design model into an analysis-ready form, a process typically called meshing, accounts for approximately 70% of the entire time spent in the design-through-analysis process [1, 4] and involves a significant amount of manual labor. The requirements for automotive meshes are particularly stringent, requiring well-structured, feature-aligned, quadrilateral/hexahedral meshes of uniform element size suitable for explicit dynamics [9]. Resulting analyses almost exclusively employ low-order finite element methods to facilitate larger explicit time steps [2].

In this work, we develop a method to partially bypass this labor-intensive meshing process by reconstructing shell components of a vehicle into trimmed single-surface spline patches suitable for isogeometric analysis. Trimmed spline patches have been used by both Honda and BMW to perform isogeometric body-in-white crash analyses [7]. However, the techniques to rebuild these surfaces are proprietary, and current single-surface reconstruction methods fail on geometries with rapidly changing normals [15]. The method presented here is simple, theory-driven, and demonstrated to work on geometries similar to those that are problematic for current methods. A schematic of the method's workflow is shown in Figure 1. Here, the original CAD geometry or its representative mesh is first converted into a feature-aware approximating triangulation, which is then flattened using theory from conformal or differential geometry to define the parametric domain and trimming curves of the intended spline. Subsequently, the bijection between this flattened geometry and its original spatial representation is then used to inform a mapping of a B-spline back into the spatial domain. Once the spatial surface is achieved, it is trimmed using the boundary of the original geometry, thereby reconstructing the intended geometry as a single trimmed B-spline surface. Resulting spline geometries are then used in LS-DYNA to demonstrate their suitability for analysis.

2 Creating the Single Trimmed Surface

The following describes the method by which a CAD model is converted into a single trimmed spline surface.

2.1 Triangulation and Flattening Many automotive structural analyses require use of a well-structured quadrilateral mesh, which can be expensive to create. For the purposes of geometry reconstruction, however, a triangulation can be used, which is significantly easier to compute. The triangulation should be of sufficient integrity to accurately approximate the geometry (e.g., include features) and to also be used in subsequent analyses.

Using this triangulation, the surface is flattened to the plane. In this work, the shell surface is temporarily cut into a topological disk using Dijkstra's algorithm [3], after which the surface is flattened via a Tutte embedding [16] and optimized by a Dirichlet-like energy us-

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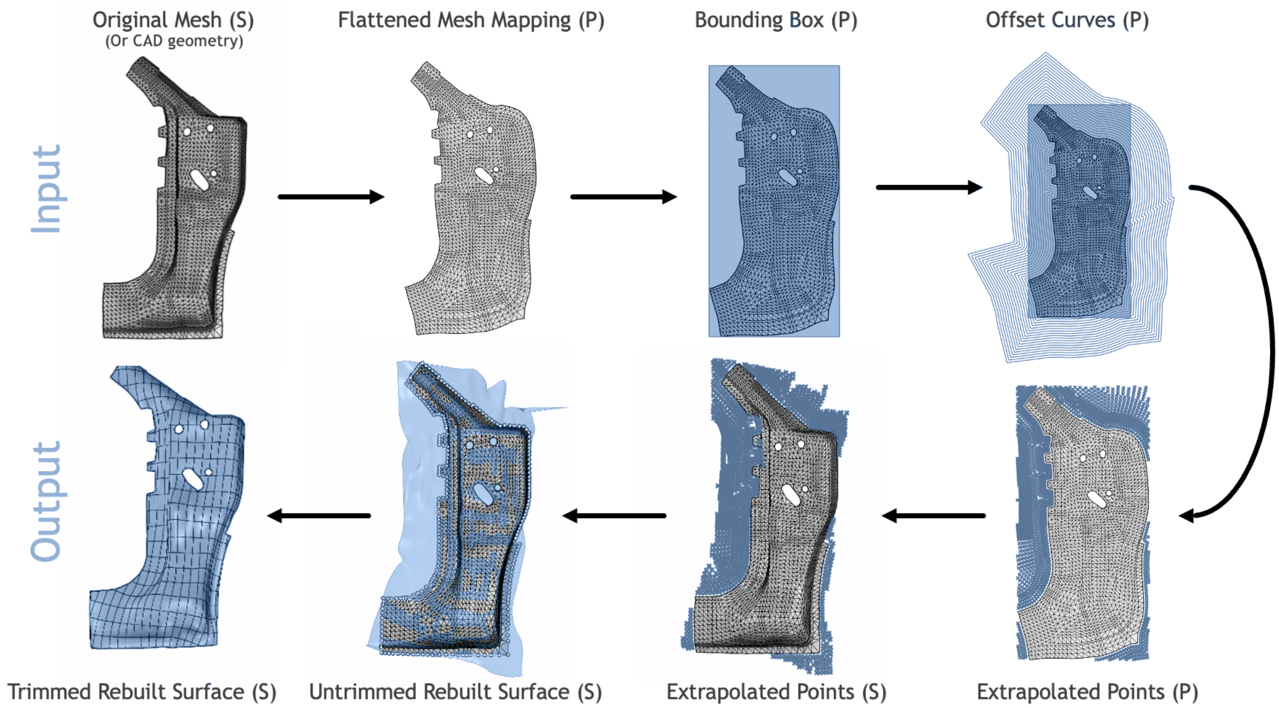

Figure 1: The process by which a single trimmed surface is created from an original CAD geometry (or its mesh) is displayed. Spatial and parametric domains are denoted by (S) and (P), respectively. The geometry of interest for this graphic is a component of a 1996 Dodge Neon A-pillar [5], whose biquadratic reconstruction is made using 484 control points.

ing progressive parameterizations [8]. Cuts introduced are then removed using constraints similar to those prescribed in [12, 13]. Alternatively, slit maps [18] and Ricci flow [6, 17] could be used to guarantee the validity and topology of the embedding, after which optimization could be performed for geometrical fidelity [8, 12]. The flattened representation should have as little distortion as possible (i.e., be close to an isometry).

Upon flattening, a bounding box is computed to define a u- and v-coordinate system that will act as the parametric domain of the reconstructed surface. Here, a principal component analysis may be used to align the bounding box with predominant feature directions to produce a better representation.

2.2 Mapping Back into the Spatial Domain

Once the triangulation and its flattening have been computed, points on the flattened geometry in the parametric domain are sampled and mapped back into the spatial domain by solving a surface fitting problem. In this work, fitting is performed by solving a simple least squares problem to define the control points of the intended spline surface [10].

When the span of each B-spline basis function intersects the flattened geometry, a least squares solution can be found that is of full rank and can be easily solved. However, when the system of equations is rank deficient, control points may be associated with basis functions for which there is no geometric fitting data. This rank deficiency must be addressed to define a valid mapping.

A visual representation of this rank deficiency can be seen in Figure 2. The grid overlaying the flattened geometry is defined by user-chosen knot vectors in the u- and v-directions (that subdivide the predetermined bounding box) and defines the Bézier mesh for the spline. Potential problems arise when the flattened geometry does not intersect a Bézier mesh cell. This is because the spatial mapping of the control point of a basis function whose support overlaps this cell is uninformed by the cell's data. If a basis function evaluates to zero (or near zero) for all sampled parametric coordinates of the flattened mesh, the final geometry is not well defined, the positioning of associated control points may be spurious, and the resulting geometry will be ill-behaved—particularly near the boundary of the original surface.

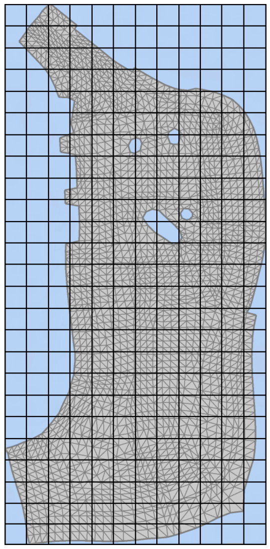

Figure 2: A possible Beziér mesh for fitting a 1996 Dodge Neon A-pillar component [5] is shown, as would be defined by knot vectors in the u- and v-directions.

The use of a rank-deficient solver was attempted in order to combat this mapping problem. However, it was discovered that rank-deficient solvers work well on the interior, poorly on the boundary, and very poorly for unsampled areas outside of the geometry. Because these purely algebraic approaches lacked control in the regularity and quality of the surface, geometric techniques were instead employed.

The first portion of the geometric approach to solving the least squares problem is an additional sampling of the original geometry (i.e., refinement through interpolation). This provides more control points from which a mapping from the parametric domain back into the spatial domain can be achieved, which can help when a highly refined B-spline is prescribed for a comparatively coarse mesh.

The second portion of the geometric approach involves sampling parametric points outside the boundary of the flattened geometry (but contained in the bounding box) and then defining a corresponding spatial coordinate for each of these parametric points. Such points will be referred to as pseudo-points. Pseudo-points are chosen to be of sufficient density in each of the empty (or near-empty) Bézier cells to remove the rank deficiency. Spatial positioning of each of these pseudo-points is determined by extrapolation of the spatial boundary using a spatial distance proportional to the parametric distance of the pseudo-point from the flattened surface. Currently, the point of extrapolation is coplanar with the closest geometric face. Upon completion of this extrapolation process, a least squares problem that is no longer rank deficient results and leads to a much better-behaved geometric fit.

2.3 Trimming The surface resulting from solving the least squares problem is a curvilinear quadrilateral that contains extraneous portions resulting from the pseudo-point mapping. Consequently, the surface must be trimmed in order to properly account for the outer boundary and internal holes of the original geometry. The boundaries of interest are selected (and must be projected, when necessary) and used for trimming purposes. It should be noted that rebuilt boundaries may be chosen to only be a subset of those on the actual geometry (due to defeaturing, a poor quality mesh, a poor quality CAD representation, etc.).

3 Results

The proposed fitting framework was developed as a plugin to the CAD software, Rhinoceros 3D. Upon extracting the single trimmed spline surface of the geometry of interest, the reconstructed surface is input to LS-DYNA for modal analysis, thereby demonstrating its suitability for isogeometric analysis. Here, three rebuilt automotive components are highlighted.

Dodge Neon Floorboard: Figure 3 depicts a reconstruction of a Dodge Neon floorboard [5], which involves significant curvature, featuring, and topological complexity. This rendering was configured using bicubic splines and 1,089 control points.

Dodge Neon Cabin Side Panel: The side panel of a Dodge Neon [5] is also analyzed, as is shown in Figure 4. Existing methods on comparable geometries require use of multiple trimmed spline patches, forc-

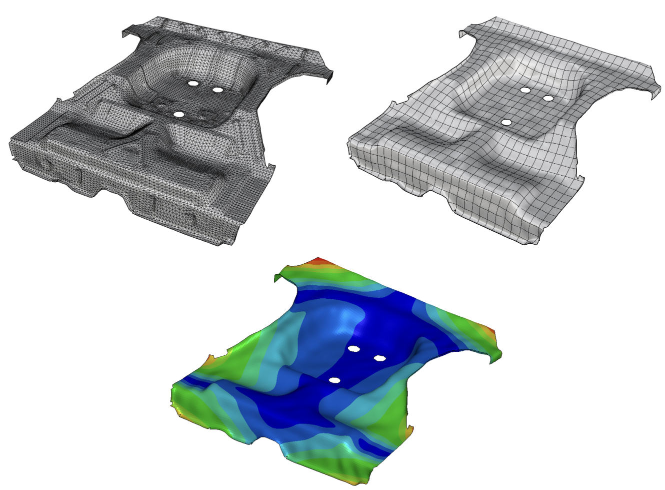

Figure 3: A Dodge Neon floorboard mesh [5], rebuilt geometry, and modal analysis are shown.

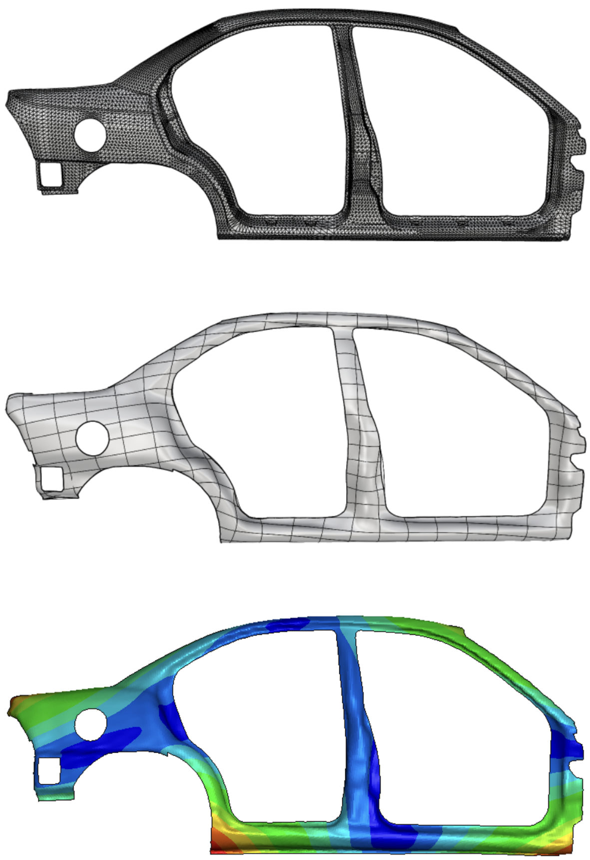

Figure 4: A Dodge Neon cabin side panel mesh [5], rebuilt geometry, and modal analysis are shown.

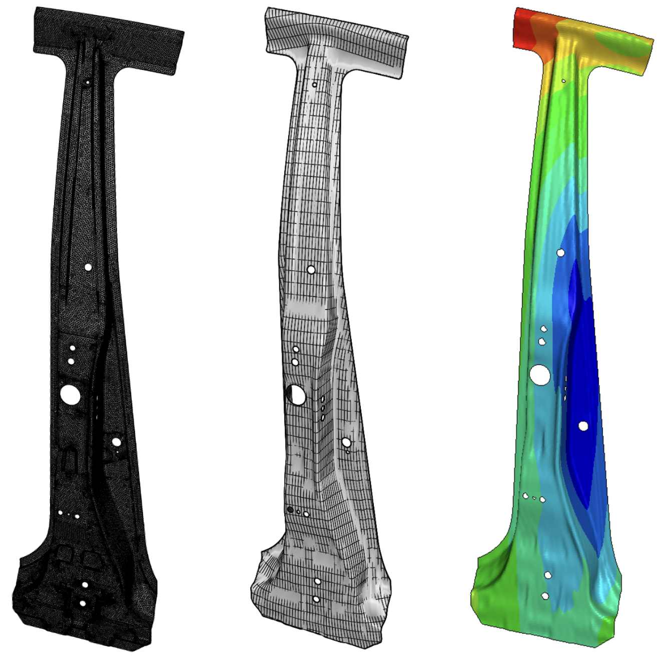

Figure 5: A Honda B-pillar geometry [14], rebuilt geometry, and modal analysis are shown.

ing weak continuity between parts that should be completely conforming [15]. Such weak coupling leads to poor analysis results [15]. Our method uses a single trimmed spline surface, which is superior from an analysis perspective. The fitting depicted in Figure 4 employs biquadratic splines with 484 control points.

Honda B-Pillar: Previous examples involve analyses on meshed and defeatured geometries (as the original CAD representations were unavailable), but the Honda B-Pillar of Figure 5 was provided directly by Honda [14] as a boundary representation CAD geometry. It has 845 trimmed spline surfaces, which are rebuilt as a valid triangulation. After surface fitting, trimming operations are performed using the original spline surface (rather than its approximating mesh). A visual representation is given in Figure 5, where the rebuilt bicubic surface has 3969 control points.

4 Conclusions

This work proposes a technique to rebuild CAD and mesh geometries as single-surface trimmed splines. Results demonstrate that these rebuilt splines are suitable for analysis and have potential for both coarse and fine spline surface reconstructions. Improvement to the splines can be made by the user through adding additional knots in the knot vector, stipulating use of higher degree polynomials, and/or prescribing additional sampling through interpolation.

Though the fitting method described in this work yields results suitable for analysis, future research should involve more advanced techniques aimed to improve accuracy and robustness. These techniques may include localization of the problem, better accounting for curvature near the boundaries, and feature preservation.

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