Reconstruction of Trimmed and Faceted Vehicle Models for Isogeometric Analysis in LS-DYNA

Kendrick M. Shepherd[1], Xianfeng David Gu[2], Thomas J. R. Hughes[3]

[1]Department of Civil and Environmental Engineering, Brigham Young University, Engineering Building 430, Provo, UT, 84602-4081, USA
E-mail: kendrick.m.shepherd@byu.edu
[2]Department of Computer Science, Stony Brook University, New Computer Science Building, Stony Brook, NY, 11794-242, USA
[3]Oden Institute for Computational Engineering and Sciences, The University of Texas at Austin, 201 East 24th Street, C0200, Austin, TX, 78712-1229, USA

1 Introduction

The traditional engineering design-through-analysis process is inadequate for modern needs. In it, an engineering designer will create a model in a computer-aided design (CAD) software, after which an analyst takes this smooth CAD model, defeatures it, cleans up the model, and ultimately approximates the intended shape as a faceted, semi-structured mesh for subsequent engineering analysis. Analysis, thus, no longer operates on the intended object, but instead evaluates physics on a faceted approximation, which may lead to compromised results [1]. Furthermore, while design and analysis are the primary objects of interest in the design-through-analysis process, the intermediary steps of geometry cleanup and meshing consume over 70% of the time spent in the design-through-analysis process [2, 3]. Naturally, this leads to increased associated costs [4].

Seeking an alternative paradigm, isogeometric analysis was created to expedite the design-through-analysis process [5]. In it, the same functions used to represent CAD objects are employed in engineering analysis. Introducing these smooth functions for analysis increases analysis accuracy [6], mitigates numerical artifacts introduced in traditional modal analyses (and thus mitigates artifacts introduced for explicit dynamics) [7], and allows for the direct evaluation of CAD objects in engineering analysis without requiring an auxiliary mesh [5, 8]. Recognizing the value of this paradigm, commercial companies such as LSTC/Ansys and Coreform, support isogeometric techniques for shell and solid analysis.

Unfortunately, CAD models carry additional structure that greatly complicate their use in engineering analysis. Most CAD models are built as a combination of B-spline and NURBS surface patches, which are parametric rectangles mapped into a spatial domain using a curvilinear transformation. However, most CAD models are not curvilinear rectangles, but instead have complicated geometry and topology. To allow for more general shapes, Boolean (a.k.a. “trimming”) operations are employed to mask portions of a spline surface so that users only visualize part of the shape [9]. Though Boolean operations facilitate rapid design, they introduce topological and geometric ambiguities that cannot be exactly addressed computationally [10]. Instead, trimming operations are only approximately represented, leaving tiny gaps and overlaps between surface edges that should be coincident [9]. For this reason, CAD models without trimming are often called “watertight,” while trimmed models are frequently referred to as “leaky.”

Recent efforts seek to facilitate the direct use of trimmed CAD models in analysis using generalizations to the traditional cut cell method. These techniques have successfully been incorporated into LS-DYNA for explicit dynamics analyses in [11], but are still the subject of ongoing research. A more direct approach would be to instead simply reconstruct trimmed CAD models as a set of curvilinear rectangles occupying the same space as the original CAD object. A feature-aware, theory-based technique to perform such a decomposition was recently proposed in [12, 13]. In this paper, we will highlight the success to date of this technique by rebuilding trimmed shell-like members of the US Army’s Unclassified DEVCOM Generic Hull vehicle [14] into a watertight representation. Because the theory applies equally well for reconstructing faceted meshes, we also employ the technique in rebuilding the entire chassis of a 1996 Dodge Neon from a finite element mesh of the National Crash Analysis Center (NCAC) of George Washington University [15] into a set of watertight splines. The focus of this paper is the interface of this technique with commercial CAD tools and LS-DYNA; a reader interested in techniques and theory is referred to [12] for additional details.

2 Trimmed and Faceted Industrial Vehicles

The isogeometric reconstruction technique is evaluated on vehicles primarily for three reasons.

1. Vehicle models are featured, industrially-relevant, and comprised of multiple parts. Evaluation on a vehicle tests a gamut of geometries of practical relevance.
2. Vehicle models are subject to multiphysics events, and can test whether both the geometry and physics-based components of a simulation all work properly.
3. Experimental data is available for vehicles, allowing for the comparison of computational results against real data.

Of primary interest in improving the engineering design-through-analysis framework is a streamlined technique to convert trimmed CAD models into watertight ones. The US Army's Unclassified DEVCOM Generic Hull vehicle, which was developed to involve academia and industry in the research of under-vehicle blast events without needing security clearance, was used to evaluate the model reconstruction paradigm for trimmed CAD. The midsurfaces of its trimmed structural members are shown in Fig. 1, and an untrimmed representation of these (that visualizes the underlying computational representation of the vehicle) appears in Fig. 2.

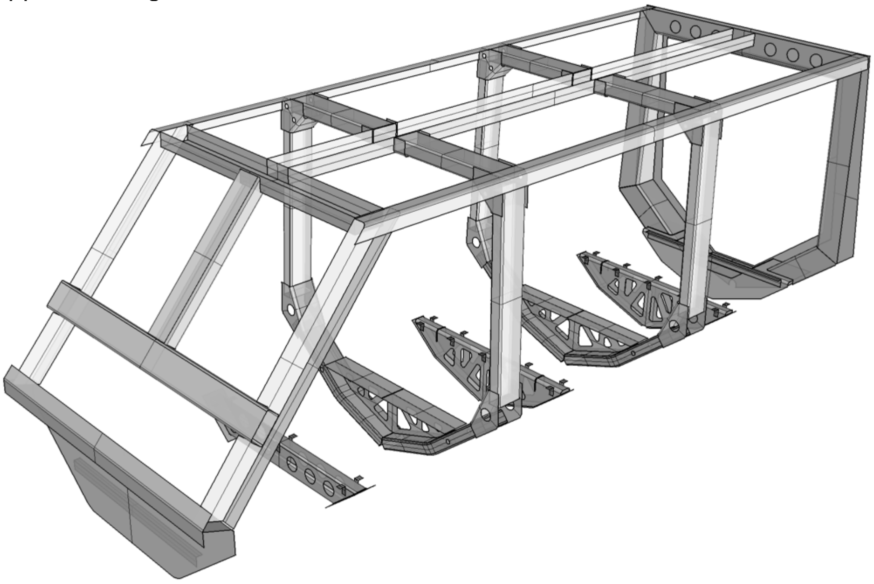

Fig.1: The trimmed structural components of the DEVCOM Generic Hull vehicle are shown. Compare this model to that of Fig. 5, after it has been reconstructed.

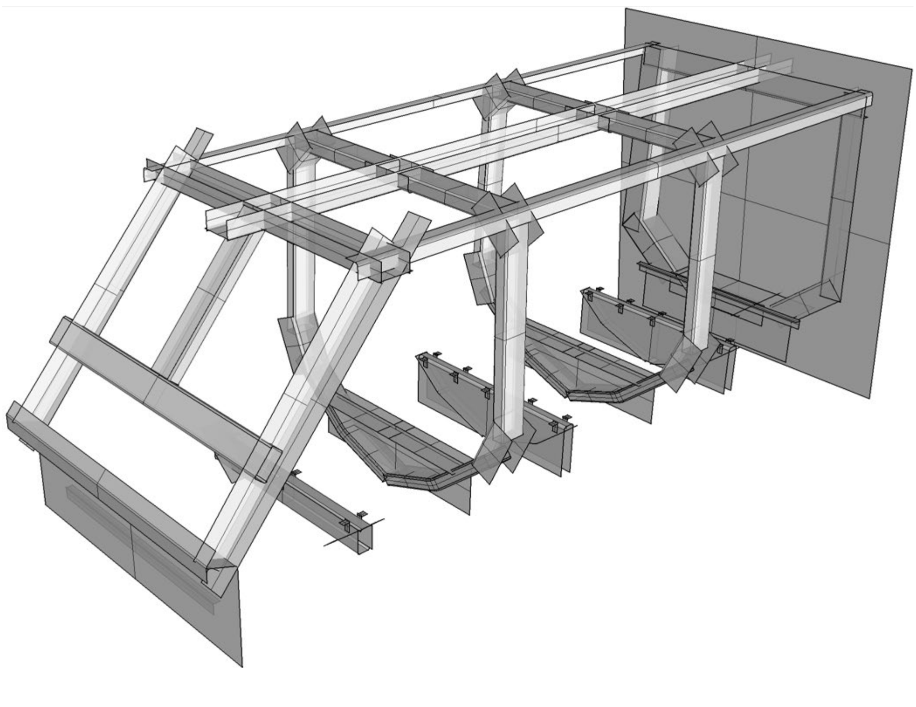

Fig.2: The untrimmed structural components of the DEVCOM Generic Hull vehicle are shown.

Of secondary interest is a technique able to convert faceted models into watertight isogeometric models (e.g. to reassess an archived representation of a previous design iteration for improved analysis). For this, and to evaluate the theory on a more complicated geometry than the DEVCOM vehicle, we reconstruct the chassis of the NCAC's 1996 Dodge Neon finite element model, shown in Fig. 3.

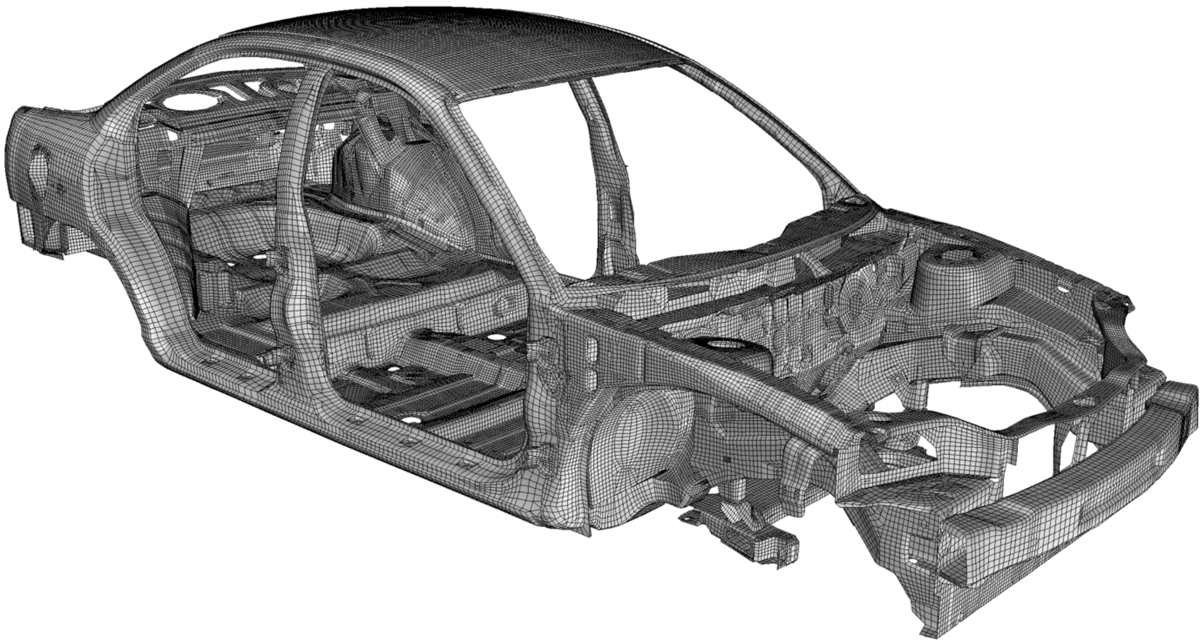

Fig.3: The NCAC's finite element mesh of a 1996 Dodge Neon chassis, from [15], is shown for reference. Compare this mesh to the reconstructed model shown in Fig. 6.

3 Reconstruction of Model Geometries

Reconstruction of CAD models takes place in a series of steps, including

1. Define the features on the original model to be preserved in the reconstruction process,
2. Triangulate the model for a valid computational domain while preserving feature data,
3. Compute/Define singular (a.k.a. extraordinary) points and cut the surface mesh into a topological disk with cuts to singularities,
4. Minimize discrete surface Ricci energy,
5. Computationally modify the Ricci parameterization to induce a quadrilateral layout,
6. Extract the quadrilateral layout, and
7. Fit watertight splines to the computed layout.

The process is visually depicted on a bracket of the DEVCOM Generic Hull vehicle in Fig. 4. Step 1 is currently accomplished manually, while all other steps are completed automatically or semi-automatically. Computation of singular points for the Dodge Neon also involved some manual component because the theoretical guarantees of configuration validity presented in [8, 16] do not yet hold for these highly-featured models.

For rebuilding meshes, the process is identical to that of rebuilding a trimmed CAD object except the triangulation procedure may simply involve dividing quadrilaterals into two triangles. A more thorough discussion of these points, including mathematical motivation, is given in [12].

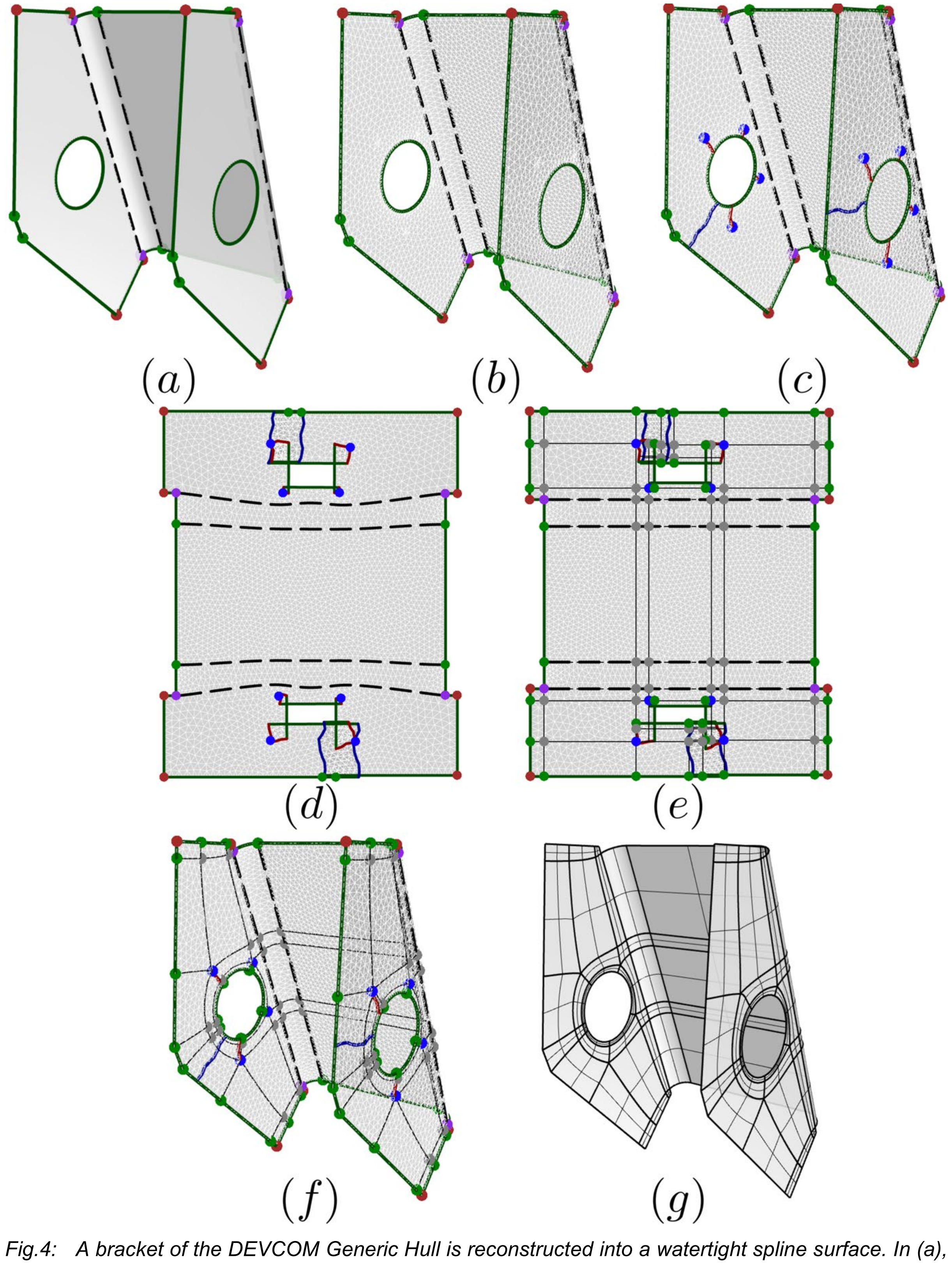

Fig.4: A bracket of the DEVCOM Generic Hull is reconstructed into a watertight spline surface. In (a), features are extracted from the trimmed CAD geometry, after which a feature-aware triangulation is computed in (b). Next, singular points that will be so-called "extraordinary points" are computed and the surface is cut to a topological disk with cuts to singularities in (c). Discrete surface Ricci flow defines the parameterization of (d), and this parameterization is modified to yield a quadrilateral layout-inducing parameterization in (e). The induced quadrilateral layout on the triangulation is visualized in (f), and bi-cubic splines are fit to the layout in (g) to yield a watertight surface reconstruction suitable for subsequent design and analysis operations.

4 Integration with CAD and LS-DYNA

Because this work is highly geometric in nature, the pipeline for geometry reconstruction is carefully integrated with CAD for a graphical user interface. Here, we chose Rhinoceros 3D because of its simplicity in incorporating user-defined plugins and because intermediary objects can be readily visualized in its visual programming language, Grasshopper. These together provide a separate but structured interface in Rhino through which operations can be performed, and affords a simple venue for debugging.

Both CAD and faceted models are loaded into Rhinoceros, after which feature extraction and triangulation of the objects occur. C# plugins for Grasshopper are employed in Rhino for relatively inexpensive computations, such as selection of singular points and extraction of a quadrilateral decomposition from a parameterization. The parameterization, however, involves solving for minima of nonlinear energies, and thus is addressed in C++ code for more rapid computation. After a quadrilateral decomposition is computed on a surface, Coons patches are used to rebuild the entire surface into a set of watertight splines, which utilize the traditional NURBS-based B-Rep data structure. As such, the entire model reconstruction workflow fits into the existing CAD framework.

Watertight reconstructed structural members of the DEVCOM Generic Hull vehicle (corresponding to the trimmed images in Fig. 1 and Fig. 2) are shown in Fig. 5. Similarly, a watertight reconstruction of the entire 1996 Dodge Neon chassis is shown in Fig. 6, and is generated from the mesh displayed in Fig. 3.

After watertight spline spaces are computed, the watertight B-Reps are then output to LS-DYNA for isogeometric analysis. For models composed of only one B-Rep midsurface, output is completely defined using a Grasshopper plugin. Similarly, for relatively simple models coupling few midsurfaces together using edge ties, output is defined using an in-house Grasshopper plugin. Isogeometric modal analyses on some of the proposed spline spaces are shown in Fig. 7 and Fig. 8.

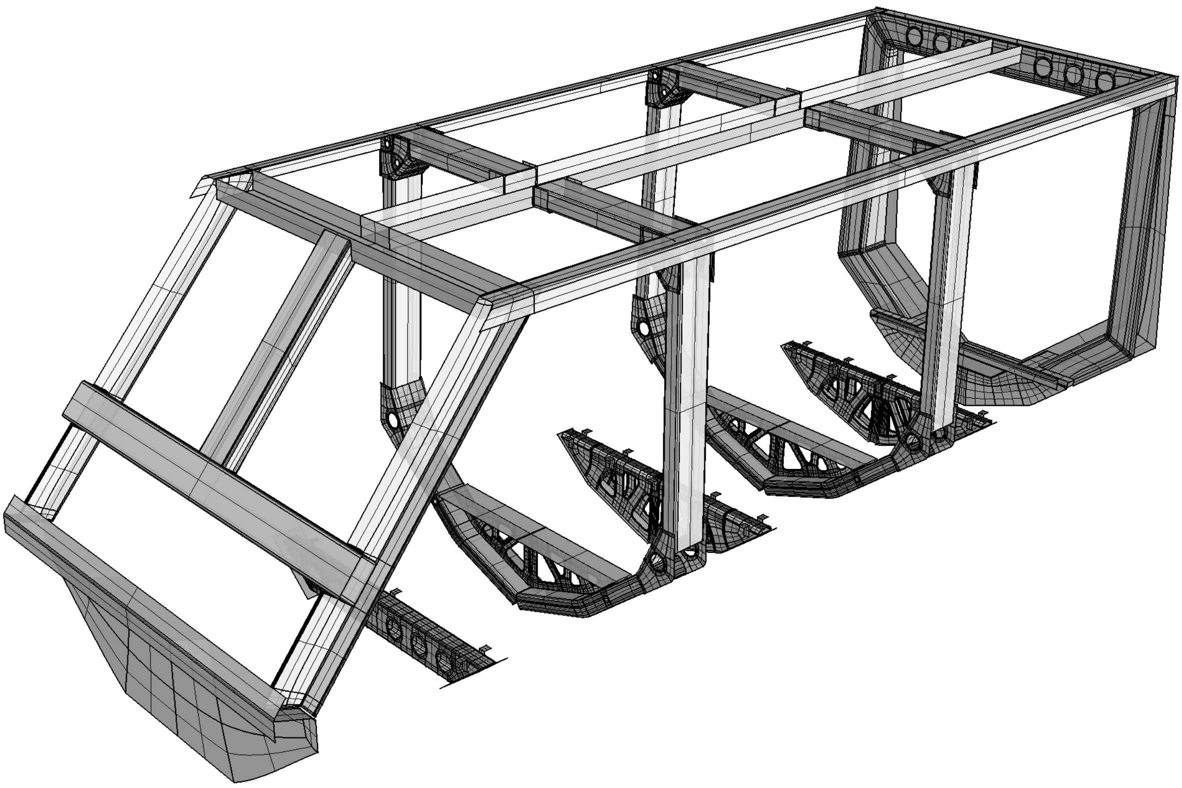

Fig.5: Rebuilt smooth Beziér patches the US Army's DEVCOM Generic Hull vehicle constructed using the proposed method are shown. Splines were computed using the trimmed CAD geometry of Fig. 1 as input.

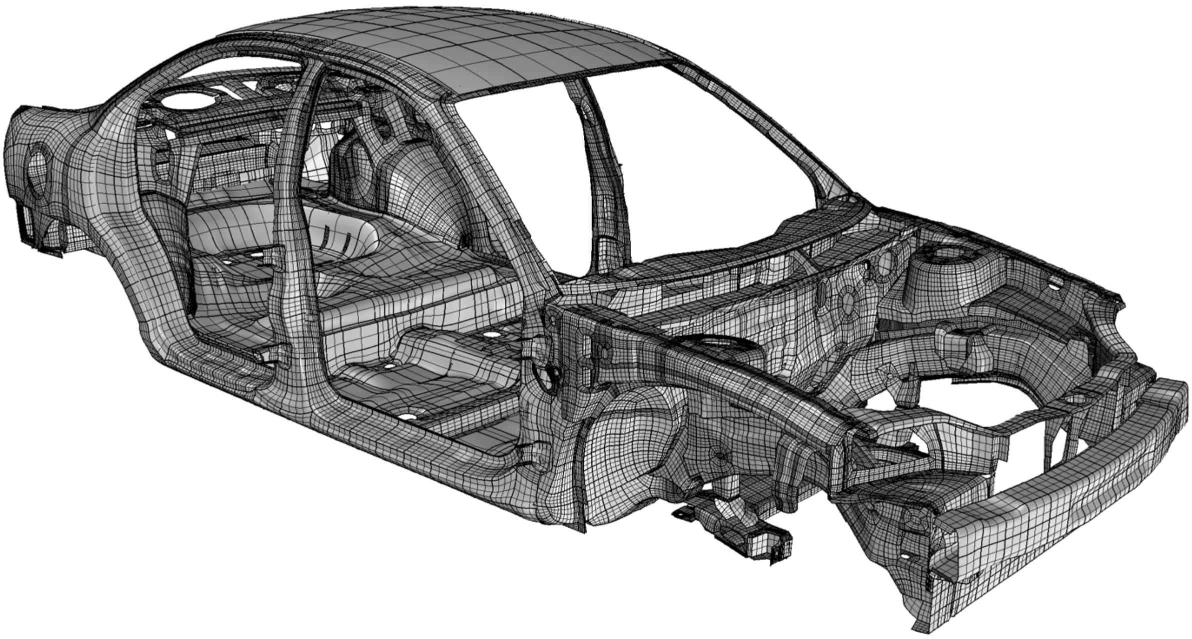

Fig.6: Rebuilt smooth B-spline surfaces of the NCAC's 1996 Dodge Neon constructed using the proposed method are shown. Splines were computed using the mesh of Fig. 3 as input.

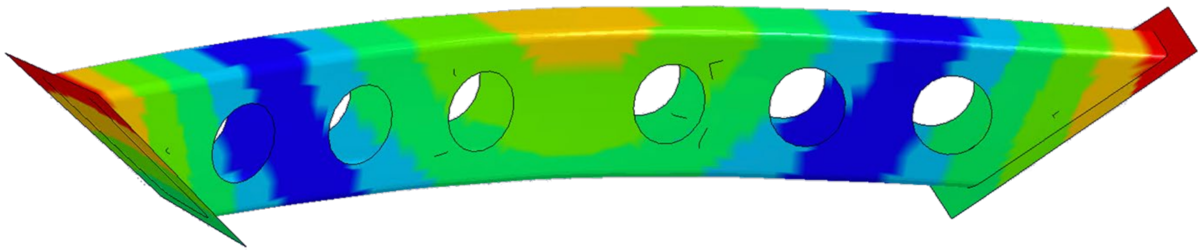

Fig.7: The seventh mode (first non-rigid body mode) of an isogeometric, boundary-fit beam assembly in the DEVCOM Generic Hull is shown, defined using cubic NURBS patches.

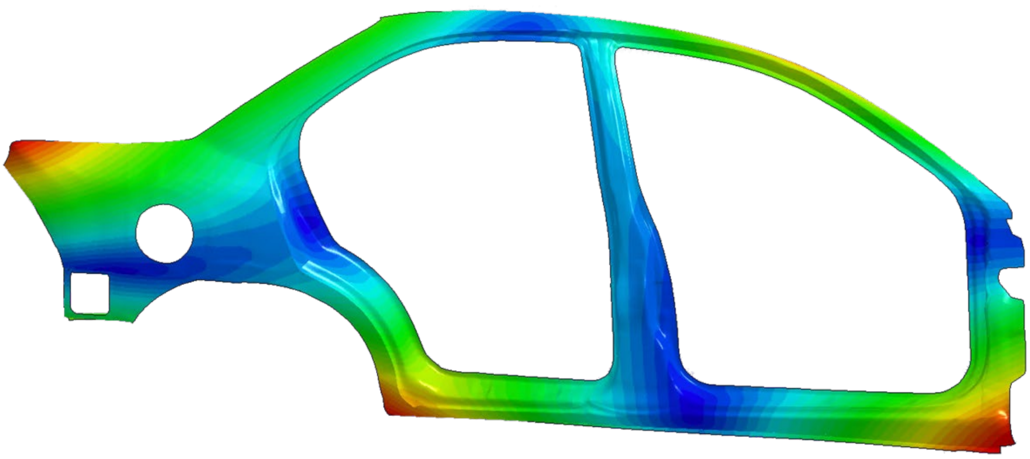

Fig.8: The seventh mode (first non-rigid body mode) of an isogeometric, boundary-fit shell of the outer-right portion of the chassis of a 1996 Dodge Neon defined using cubic NURBS patches is shown.

5 Mixed FEM/IGA Crash Event of a 1996 Dodge Neon

Understanding the viability of the proposed isogeometric spline spaces for industrial crash analysis is of particular interest. As a preliminary evaluation of these splines, we re-ran the frontal crash model of [15], but instead replaced the outer-right mesh of the vehicle chassis with a rebuilt cubic spline geometry, whose modal analysis is shown in Fig. 8. To accomplish this more extensive model modification, we used Beta-CAE's ANSA preprocessor, rather than our basic in-house pre-processor. Spot welds were used to connect the isogeometric portion of the model to the mixed finite-element mesh. Results of the original finite element crash model are shown in Fig. 9 for reference. Because the mesh size of the original model has elements around 15mm to 20mm in size, but the industry standard for large plastic deformation is presently around 2mm to 4mm, we also ran crash analysis with the outer-right shell of Fig. 8 refined to ~2mm mesh elements, but all other elements of the mesh the same as the original model, shown in Fig. 9. Finally, a mixed IGA/FEA model is shown in Fig. 10, with all components of the original model the same, but the outer-right shell component replaced with an isogeometric bicubic spline representation, computed by the method of [12, 13].

These results show that the original coarse finite element simulation tends to be stiffer than both the isogeometric and the refined model, as is expected. Particularly, the original model has fairly little deformation near the A-pillar, and the roof only slightly deforms directly above the B-pillar. However, both the isogeometric and the refined mesh simulation show much larger deformation in the A-pillar and in the roof above the B-pillar. These results indicate that the plastic deformation of interest is more accurately captured by the isogeometric spline shells as expected.

All models were run using 8 SMP threads on an Intel(R) Xeon(R) W-2145 CPU @ 3.70 GHz with 64.0 GB of RAM. In terms of clock speeds for the models, the original, coarse crash model took 1 hour and 59, while the refined FEM model took 3 hours and 52 minutes. For the mixed IGA/FEA model, compute time took 3 hours and 54 minutes, showing that runtimes are comparable, even with unoptimized isogeometric code. It is expected, however, that as additional research is performed in efficiently implementing large-scale spline-based computations, the runtimes for the isogeometric techniques will decrease considerably.

6 Conclusions and Outlook

In this work, we leveraged the spline reconstruction methods of [12, 13] to reconstruct two industrial vehicles: the trimmed DEVCOM Generic Hull vehicle [14] and a mixed finite element model of a 1996 Dodge Neon [15]. These models are then output for analysis using LS-DYNA. The work culminates with a mixed finite element/isogeometric crash analysis using boundary-fitted splines from the aforementioned reconstruction technique. It exhibits a pipeline with potential for automation that can take a trimmed or faceted model and convert it into an isogeometric spline model suitable for CAD and analysis operations. The paper demonstrates through commercial tools that the existing design-through-analysis pipeline has potential for speedup through a semi-automated model reconstruction process.

In addition to the aforementioned contributions, this work demonstrates that isogeometric techniques can be used in LS-DYNA in conjunction with mixed finite element techniques. Such a paradigm could be of value when regions of high interest and requiring particular accuracy are modelled using splines, while those of less interest are modelled using finite element meshes. This strategy may be useful until analysis runtimes for splines in LS-DYNA are faster than those of traditional finite-element techniques.

Continued efforts are needed for isogeometric model reconstruction in a variety of forms. First, this work has focused on open shells, which are predominantly used for vehicle analysis. Additional research needs to determine how to rebuild closed CAD models for purposes like boundary element analysis. Efforts here may be able to exploit the theory recently described in [17] in this process. Next, more research needs to focus on how to automate and improve feature-extraction and singularity placement for models. Beyond the scope of shells, robust and semi-automatic isogeometric model generation for volumetric models needs significant study. Finally, though splines defining both the DEVCOM and the NCAC models are computed in this work, additional research needs to focus on expediting the preprocessing steps necessary to take these models from CAD to analysis, including connection definition, constraint prescription, and preclusion of penetration between distinct components of an assembly. A full crash analysis of the vehicle will then follow.

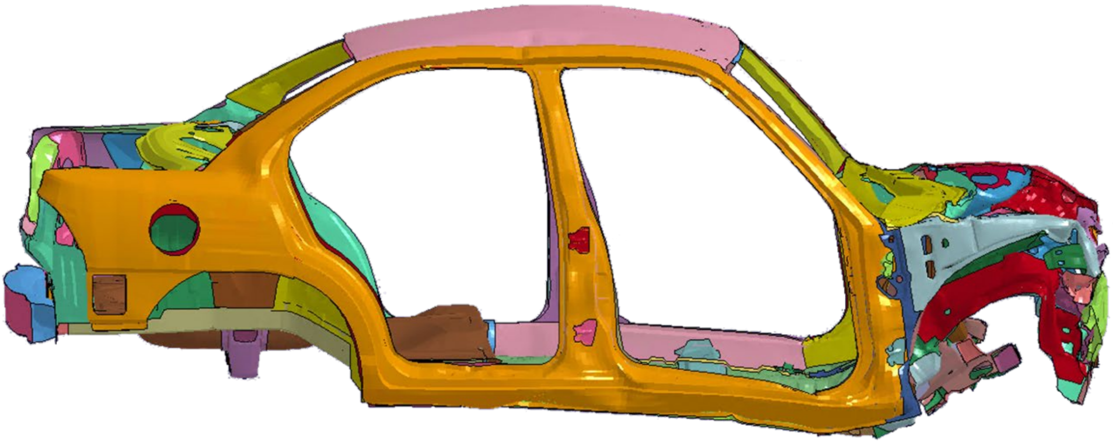

Fig.9: The chassis of the 1996 Dodge Neon crash model reproduced from [15] after frontal crash loading using traditional linear triangle and bilinear quadrilaterals elements is shown above.

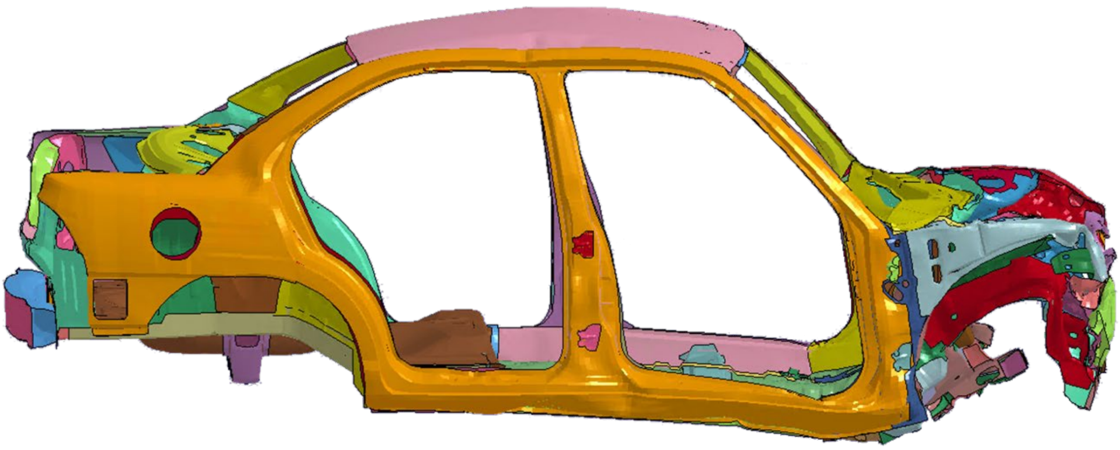

Fig.10: The chassis of the 1996 Dodge Neon crash model with outer-right shell (in orange) is refined to ~2mm resolution based on the original model of [15] and then subjected to frontal crash loading using traditional linear triangle and bilinear quadrilateral elements, as shown above.

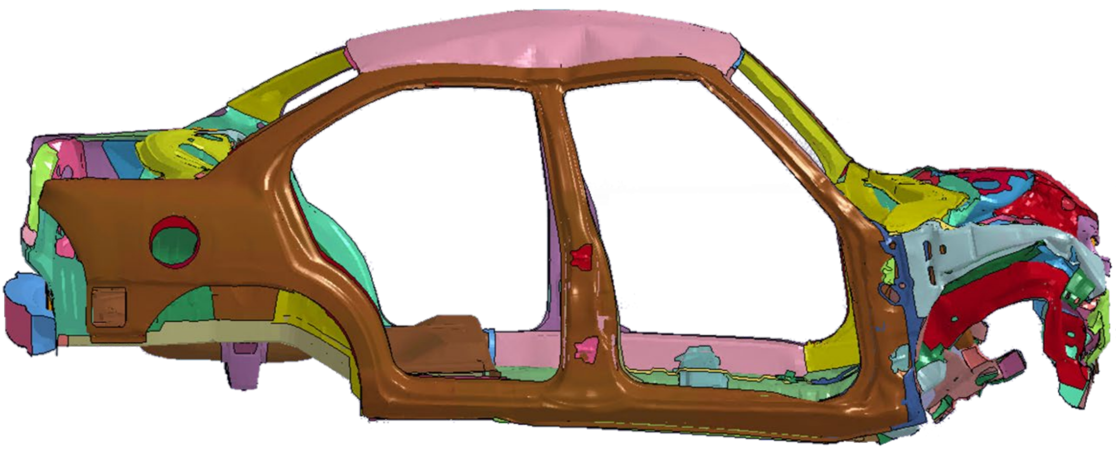

Fig.11: After replacing the outer-right shell of the vehicle chassis (in brown, replacing the orange shell of Fig. 9, and shown in Fig. 8) with an isogeometric bicubic shell, the chassis of the 1996 Dodge Neon crash model from [15] is shown after frontal crash loading. This model uses a single isogeometric component, with all others being the mesh elements from [15].

As mentioned two years ago in [18], “how to effectively perform simulations on large-scale NURBS geometries,” is still a learning process. As more robust tools to generate these models become available, our common vision of how to best implement high-fidelity isogeometric analyses will also improve. We anticipate that these model reconstruction techniques will help generate the spline geometries that can then be evaluated to improve isogeometric simulation and streamline the design-through-analysis experience.

7 Acknowledgements

We would like to thank the team at LS-DYNA for their collaboration in executing the isogeometric analyses in LS-DYNA. We also want to thank the team at Beta-CAE for their assistance in replacing faceted portions and connections of the 1996 Dodge Neon model with the defined isogeometric components for the mixed IGA/FEA analysis.

Thomas J. R. Hughes and Kendrick M. Shepherd were partially supported by United States Department of Defense Contract N6833518C0014 through a subcontract with Coreform, LLC, which is gratefully acknowledged.

8 Literature

[1] Luo, X., Shephard, M., Remacle, J.-F.: "Influence of geometric approximation on the accuracy of higher order methods", Technical Report, Scientific Computation Research Center, Rensselaer Polytechnic Institute, 2001.

[2] Boggs, P.T., Althsuler, A., Larzelere, A.R., Walsh, E.J., Clay, R.L., Hardwick, M.F.: “DART system analysis”, Report, Sandia National Laboratories, 2005.

[3] Farouki, R.T.: “Closing the gap between CAD model and downstream application”, SIAM News, Vol. 32, No. 5, 1999, 1–3.

[4] Brunnermeier, S.B., Martin, S.A.: “Interoperability cost analysis of the US automotive supply chain,” Supply Chain Management, Vol. 7, No. 2, 2002, 71–82.

[5] Hughes, T.J.R., Cottrell, J.A., Bazilevs, Y.: “Isogeometric analysis: CAD, finite elements, NURBS, exact geometry, and mesh refinement”, Computer Methods in Applied Mechanics and Engineering, Vol. 194, No. 39–41, 2005, 4135–4195.

[6] Evans, J.A., Bazilevs, Y., Babuška, I., Hughes, T.J.R.: “*n*-widths, sup-infs, and optimality ratios for the *k*-version of the isogeometric finite element method”, Computer Methods in Applied Mechanics and Engineering, Vol. 198, No. 21–26, 2009, 1726–1741.

[7] Hughes, T.J.R., Reali, A., Sangalli, G.: “Duality and unified analysis of discrete approximations in structural dynamics and wave propagation: Comparison of *p*-method finite elements with *k*-method NURBS”, Computer Methods in Applied Mechanics and Engineering, Vol. 197, No. 49–50, 2008, 4104–4124.

[8] Hiemstra, R.R., Shepherd, K.M., Johnson, M.J., Quan, L., Hughes, T.J.R.: “Towards untrimmed NURBS: CAD embedded reparameterization of trimmed B-rep geometry using frame-field guided global parameterization”, Computer Methods in Applied Mechanics and Engineering, Vol. 369, 2020, 113227.

[9] Marussig, B., Hughes, T.J.R.: “A review of trimming in isogeometric analysis: Challenges, data exchange, and simulation aspects”, Archives of Computational Methods in Engineering, Vol. 25, 2017, 1–69.

[10] Sederberg, T.W., Anderson, D.C., Goldman, R.N.: “Implicit representation of parametric curves and surfaces”, Computer Vision, Graphics and Image Processing, Vol. 28, No. 1, 1984, 72–84.

[11] Leidinger, L., Breitenberger, M., Bauer, A.M., Hartmann, S., Wüchner, R., Bletzinger, K.-U., Duddeck, F., Song, L.: “Explicit dynamic isogeometric B-Rep analysis of penalty-coupled trimmed NURBS shells”, Computer Methods in Appliced Mechanics and Engineering, Vol. 351, 2019, 891–927.

[12] Shepherd, K.M.: “Isogeometric analysis-suitable geometry: Rebuilding CAD surface geometries via quadrilateral layouts”, PhD thesis, The University of Texas at Austin, 2021.

[13] Shepherd, K.M., Gu, X.D., Hughes, T.J.R.: “Isogeometric Model Reconstruction of Open Shells Via Ricci Flow and Quadrilateral Layout-Inducing Energies”, submitted for review, 2021.

[14] Dooge, D., Dwarampudi, R., Schaffner, G., Miller, A., Thyagarajan, R., Madanmohan, V., Babu, V.: “Evolution of occupant survivability simulation framework using FEM-SPH coupling”, 2011

NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), Dearborn, MI, 2011.
[15] George Washington University. “Finite element model of Dodge Neon”, Technical report, George Washington University, Virginia Campus, 2006.
[16] Knöppel, F., Crane, K., Pinkall, U., Schröder, P.: “Globally optimal direction fields”, ACM Transactions on Graphics, Vol. 32, 2013, 59:1–59:10.
[17] Zheng, X., Zhu, Y., Lei, N., Luo, Z., Gu, X.: “Quadrilateral mesh generation III: Optimizing singularity configuration based on Abel-Jacobi Theory”, arXiv preprint, arXiv:2007.07334, 2020.
[18] Leidinger, L.F., Breitenberger, M., Bauer, A.M., Oberbichler, T. Hargmann, S., Wüchner, R., Bletzinger, K.-U., Duddeck, F., Song, L.: “Explicit isogeometric B-Rep analysis on trimmed NURBS-based multi-patch CAD models in LS-DYNA”, 12th European LS-DYNA Conference, Koblenz, Germany, 2019.