CAD-integrated Untrimmed Body-fit Unstructured Spline LS-DYNA Preprocessing for Isogeometric Analysis and Digital Twins

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1 Introduction

Isogeometric Analysis (IGA) has emerged as a next generation advancement in the field of Computer-Aided Engineering (CAE) and simulation thanks to its ability to utilize geometric representations native to Computer-Aided Design (CAD) models. Ansys *LS-DYNA*®'s proven capabilities for IGA have made it the premier solver for the technology. While the direct benefits for analysis are well documented, industrial adoption has been hampered by the difficulty in producing IGA-ready models from CAD data. Trimmed multi-patch IGA preprocessing approaches have seen advances at the industrial level but the desire for untrimmed body-fit unstructured splines has remained an unsolved approach in IGA preprocessing. In this paper, we discuss an IGA preprocessor for Ansys *LS-DYNA*® that not only produces untrimmed body-fit unstructured splines but does so in a process that is integrated directly into a CAD application. This allows for a direct coupling between CAD and IGA alleviating the intersections between surfaces in the native CAD model consisting of approximations represented by curves rather than explicit surface-to-surface continuity, resulting in what is referred to as a geometrically non-watertight model. nVariate's technology creates a watertight spline CAD model in such a way that the intersections between surfaces are defined without gaps. We are able to retain all of the product and manufacturing information (PMI) associated with the original CAD model as well as provide a two-way link to the original design model. In addition, our unique watertight technology allows for model integration and a direct link to CAE from currently disparate domains such as Computer-Aided Inspection (CAI) and Computer-Aided Manufacturing (CAM). We show that not only is there a utility for IGA preprocessing in providing a CAD-integrated untrimmed body-fit unstructured spline technology for Ansys *LS-DYNA*® but beyond preprocessing there are benefits for the synchronization of data across the digital thread in providing a representation for digital twins.

2 Background

Computational simulation requires increasingly accurate model descriptions and discretizations in order to provide more predictive and reliable results for CAE models. The conventional process for both finite element analysis (FEA) and IGA modeling is one-way and lossy as there is no formal relationship or traceability between the CAD design model and the translated analysis models, necessitating redundant work and inefficiencies in single-use model processing. This paper describes development by nVariate of an application to produce IGA capabilities utilizing watertight spline models. These capabilities are for producing shell models for analysis applications. The technology demonstrated herein helps fill the current critical void in the simulation of manufactured parts and tightly couples the currently disparate engineering workflows of CAD, CAI, CAE, in which as-designed, as-inspected, and as-simulated models are formally related.

Conventional FEA modeling and simulation relies on faceted mesh-based models derived from CAD models based on meshing techniques. Meshing discretizes the models for analysis, but more importantly creates gap-free watertight descriptions of the geometry that do not exist in the native CAD format but are necessary for using in FEA solvers. Creating the mesh-based FEA models is one of the biggest pain points in the current standard simulation workflow – it is a frustrating, error prone, and time-consuming process that limits the computational accuracy and rate at which design iteration can occur. IGA promises enhanced computational analysis aspects, but still necessitates a watertight spline representation.

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The conventional process for both FEA and IGA modeling is one-way and lossy as there is no formal relationship or traceability between the CAD design model and the translated analysis models, necessitating redundant work and inefficiencies in single-use model processing. The built-in healer in meshing and healing software is often not effective in fixing or identifying what specifically needs to be fixed, and analyst's solutions for dealing with this issue include trying to import the file in a different format or cutting out sections of problematic geometry and rebuilding them using the drawing tools in the meshing software. In some cases, removing and re-building problematic geometry has a higher success rate than manually healing the model or allowing the software to automatically heal the model. All of this is very time-consuming and has the potential to decrease accuracy of the simulation results, as well removing the modeling data for use in other domains (e.g., design, inspection, manufacturing, etc.).

nVariate's initial IGA shell preprocessing application is in the form of a fully integrated extension in PTC *Creo*®. We implemented the use of authoritative watertight spline CAD models establishing a linked model between the simulation/analysis and design/product definition domains using watertight spline technology, enabling the possibility to construct a two-way link between the WatertightCAD design geometry sent to the analysis software, and the deformed geometry resulting from the analysis process. This capability addresses a workflow for IGA data exchange (i.e., automated *Basis Transform* workflow), as well as linking integrated inspection data into the workflow through complimentary morphed digital twin capabilities. The application is intended to integrate into the current and planned data exchange workflows using both native and neutral data exchange formats.

3 WatertightCAD technology

The design and manufacturing industry is in the process of transitioning from human-centric workflows to automated digital workflows. In the digital paradigm, the goal of a model-based enterprise (MBE) is to develop a computer-based three-dimensional digital model which can be used to define the shape and performance characteristics of a part, assembly, or product in a machine-readable format [1]. Human-interpretable two-dimensional drawings, three-dimensional renderings annotation, notes, etc. are replaced with entities, properties, and attributes described in a format that can be directly consumed and utilized by the computer or machine requiring the information.

The digitized product model utilized in computer-aided (CAx) applications is divided into two primary components, the model-based definition (MBD) which is the geometric model representing the spatial description of the data, and the product and manufacturing information (PMI) which is the metadata describing all of the non-geometric attributes or properties of the model [2]. While PMI is related to the geometry described in the MBD, it is not information that defines the actual geometric model itself (i.e., the information used in the spatial description of the model) [3].

Modern CAD software packages that are used to generate MBD geometry were originally developed to allow drafters and designers to convey design intent in the human-centric paradigm. By design the architecture and data structure of almost all CAD software used by industry today is optimized for visualization on screen or paper. As a result, in most use cases CAD models are not fit-for-purpose machine-readable MBD models which can be directly consumed by computers and machines in the other domains of a digital-centric MBE paradigm.

What a designer sees on the computer screen, the graphical human-based interpretation of the geometry, is not the same as the geometry stored within the CAD software at the database level. The majority of CAD models are constructed from basic shapes and surfaces called primitives, or analytic geometry (e.g., cubes, spheres, planes, cones), NURBS surfaces, and procedural geometry (e.g., extrusions, lofts, sweeps, blends, etc.), which are combined using operations called Booleans to create compound shapes. By adding and subtracting pieces of these basic shapes the user is able to construct a more complex geometry. The resulting model is referred to as a Boundary-Representation or B-rep, as it defines the representation of a solid volume by a collection of its bounding surfaces.

To understand why the data stored in the CAD system is not directly usable by computers and machines in the other domains of a digital-centric MBE paradigm, consider the *QIF Bracket* model shown in Fig.1. When viewed on the user's screen the rendered model appears smooth and continuous – essentially as it is meant to appear post-manufacturing (Fig.1.1). What is stored inside the CAD model at the

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semantic data level; however, is over 1000 independent unbounded geometric surfaces and curves (Fig.1.2).

The extent of the shapes and surfaces rendered on the screen of the CAD workstation is defined by trim curves, which designate which portions of the unbounded domain of the geometry should be rendered visible by the graphics card and which portions should be hidden to display the design-intent geometry on the user's computer screen. Due to mathematical limitations, the trim curves shared by adjacent surfaces do not actually align with each other, and instead are located within a tolerance of one another such that the resulting gap is not visible in the rendered object. As a result, the geometry stored in the CAD database is geometrically non-watertight, meaning that none of the independent geometric objects making up the *QIF Bracket* are mathematically joined to one another (i.e., the adjacent surfaces lack $G^0 = C^0$ surface continuity).

In an exploded view, it is possible to see the hundreds of trimmed parts that make up the model, and the associated gaps that lie between the intersections of every part (Fig.1.3). The gaps are hugely problematic if the model is to be used for downstream applications, in particular simulation or additive manufacturing (AM) workflows that do not tolerate non-watertight representations.

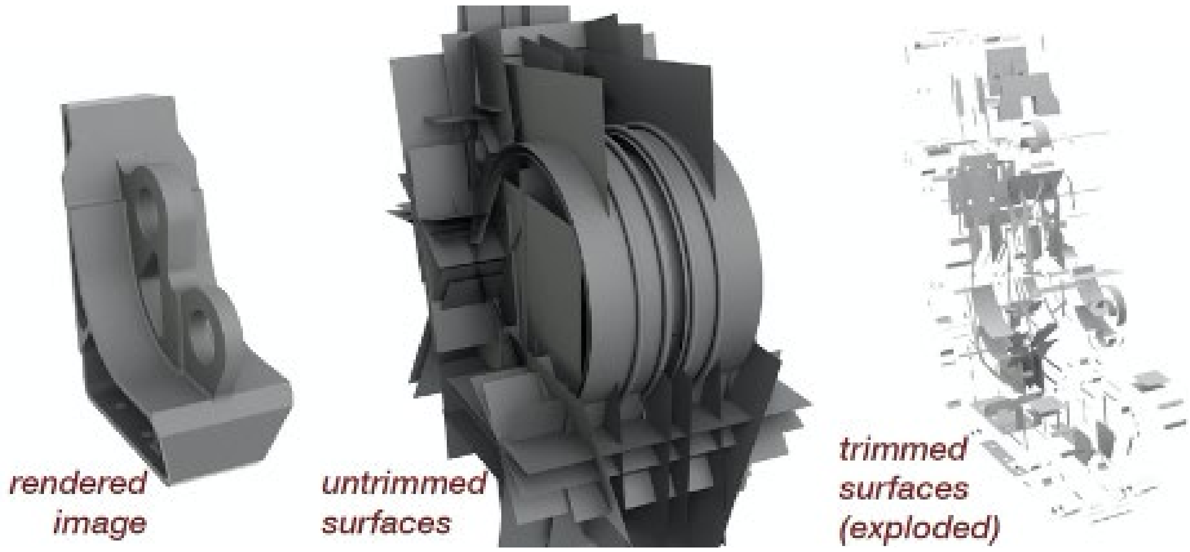

Fig.1: QIF bracket B-rep form; 1.1) rendering most familiar to CAD users; 1.2) untrimmed surfaces of the solid model; 1.3) exploded trimmed view.

In addition, because the underlying geometry in the CAD data structure is never updated to reflect the actual design intent – surface domains are only bounded by trim curves – the underlying geometry defined by Booleans is locked in place. In order to modify or update the MBD geometry, the model must be procedurally rebuilt using modified primitive objects with Boolean operations reapplied to reflect the desired change. The implications of this are profound, because PMI data generated during the lifecycle of a product cannot be used to automatically update or morph the CAD geometry that defines the as-designed part. Any updates to the MBD geometry based on lifecycle PMI to create domain specific ("as-x") digital twins must be made manually through human intervention (essentially re-creating the CAD geometry using the PMI as input), or via automated processes which rely on first deforming meshed approximations of the CAD geometry and then backing out a parametric CAD representation. Model updates via meshed approximations break the associativity and traceability links between the original design MBD and its PMI and the updated digital twin model and its PMI. All of this leads to a paradigm where digital twins are not updated or *morphed* versions of the design MBD, rather they are a collection of disconnected CAD models, data models, or tessellation which describe the underlying object but have no formal mathematical relationships between one another.

To address the issues associated with geometrically non-watertight CAD models in a digital-centric MBE paradigm, nVariate developed its unique WatertightCAD technology [4], [5], [6], originally invented and patented by researchers at The University of Texas at Austin [7], [8], [9], [10], [11] and exclusively licensed by nVariate. Our WatertightCAD technology creates a ready-to-use watertight CAD model

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using native CAD shape representations inside the CAD environment by constructing the model in such a way that the intersections between geometric shapes and surfaces are defined without gaps. We achieve this by utilizing our five-step process which performs a mapping from the non-watertight CAD model to a watertight CAD model, as illustrated in Fig.2.

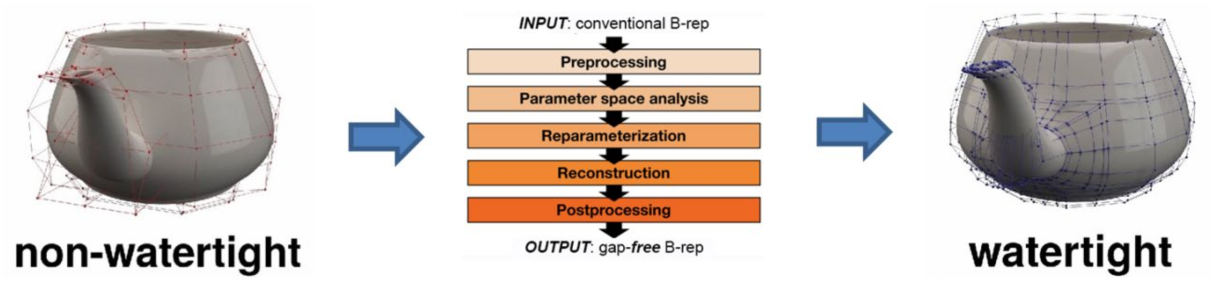

Fig.2: A non-watertight CAD model converted to a watertight CAD model using nVariate's technology.

Because our process relies on a mapping of the trimmed non-watertight geometry to the watertight version rather than a translation or re-casting, we retain all of the PMI metadata associated with the original CAD model as well as provide a two-way link to the original non-watertight design model. Construction of the watertight model is automated, runs in the background of the CAD application, and occurs in real-time during model generation or on the order of minutes for an existing model. The watertight model has no geometric gaps, represents the MBD geometry using a spline-based geometric description, and maintains the original model tolerance. The watertight version of the QIF bracket created using nVariate's WatertightCAD technology is shown in Fig.3. Note that what is rendered on the user's screen is now identical to the geometry stored inside the CAD model at the semantic data level.

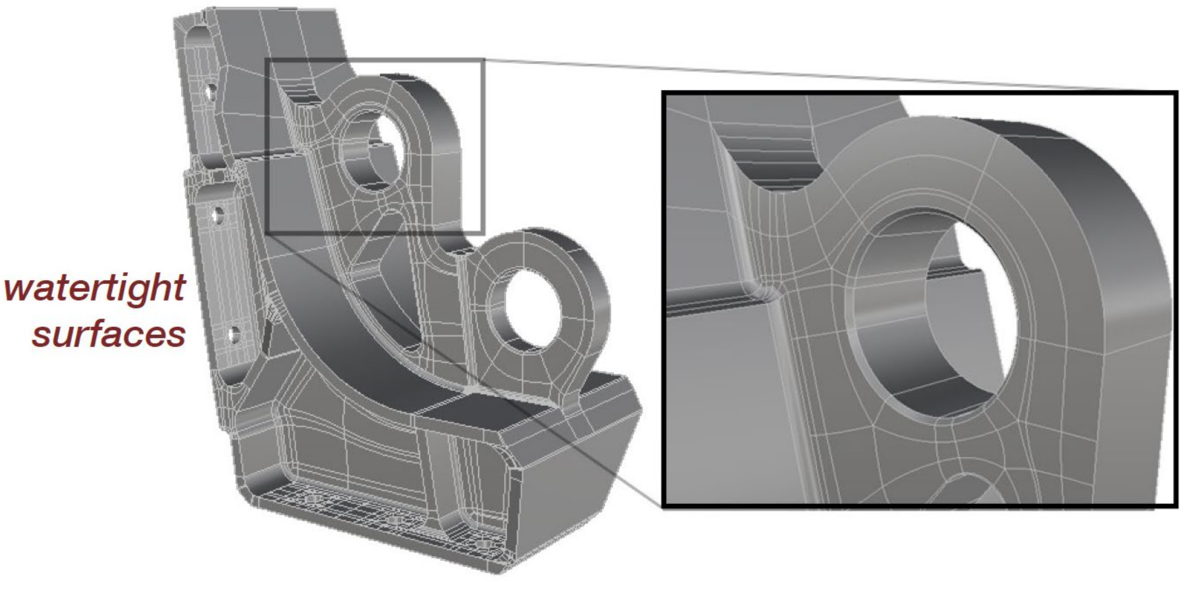

Fig.3: Watertight QIF bracket. Note the smooth continuous spline definitions of the surface. The hole is defined by a perfect circle, rather than a faceted approximation as would be expected with a mesh representation.

Since our WatertightCAD process utilizes existing geometric data stored in CAD software and maps the data to a format that is usable by downstream CAx applications, we do not create a proprietary data format for our WatertightCAD model. Data is stored in the native CAD format (e.g., PTC *Creo*® .prt file), and is compatible with all CAx neutral standards such as STEP, QIF, etc. [12], [13], [14], [15], [16].

Once the trimmed as-designed CAD MBD (or an MBD in any CAx domain) is mapped to a watertight spline-based representation, we can rapidly and computationally efficiently perform unlimited refinement of the geometry via the well know technique of knot insertion. This allows for obtaining the desired element discretization for simulation. Once knots are inserted into the splines defining the MBD

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geometry, PMI data can be associated with those knots and then used to inform a displacement of the knots, resulting in a *morph* or deformation of the MBD geometry as shown in Fig.4, in this case obtained from CAI data during a quality engineering review. This technique is described in greater detail in [17] and [18].

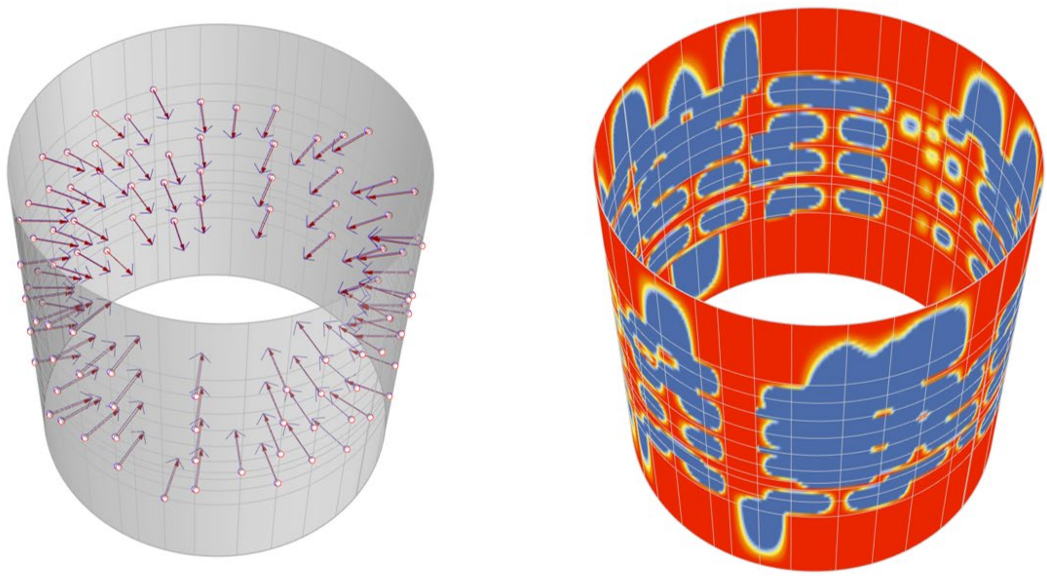

Fig.4: In the image on the left, knots are inserted in the splines defining the geometry of the watertight MBD cylinder, resulting in the updated MBD geometry shown in the image on the right. Deviations from the original geometry are highlighted in blue.

The association of the PMI data to the watertight spline model via knot insertion, and the subsequent resolution of that data via our morphing process, creates a domain-specific MBD as-x digital twin model that has a formal mathematical relationship to the original design MBD as well as the PMI used to generate it.

4 Development of IGA preprocessing digital twin applications to create shell input files for use in Ansys LS-DYNA® from a PTC Creo® CAD design model

nVariate has been developing an IGA preprocessing digital twin application to create an IGA shell input file for use in Ansys *LS-DYNA*® from a PTC *Creo*® CAD design model. This is in direct support of the Ansys *LS-DYNA*® IGA shell keyword (i.e., *.k) file write capabilities integrated into a PTC *Creo*® extension, utilizing the latest `*IGA` keyword model published by Ansys (see Fig.6). Additional LSDA binary write capability has been under development along with the ASCII formatted *Basis Transform* (previously Bézier EXTraction or BEXT) writer using the Ansys *LS-DYNA*® LSDA API for native efficient large model data exchange integration.

The IGA features have been integrated into nVariate's WatertightCAD_CAE application as part of the WatertightCAD PTC *Creo*® extension. The CAE menu provides the user interface for the WatertightCAD_CAE application. Clicking on the *Save LS-DYNA* File button shown in Fig.5 opens a separate pop-up window which provides the functionality for writing Ansys *LS-DYNA*® files. This function provides the ability to write Ansys *LS-DYNA*® IGA files from watertight B-reps generated from the WatertightCAD for PTC *Creo*® application. Prior to utilizing the *Save LS-DYNA* File function, a CAD model must first be opened in PTC *Creo*® and reconstructed using the Watertight Model function from the WatertightCAD submenu. Pressing the *Save LS-DYNA* File button opens a pop-up menu titled "*Save LS-DYNA* Keyword File" as shown in Fig.8. The Element Type and Part ID fields of this pop-up have drop-down menus allowing for additional feature selections.

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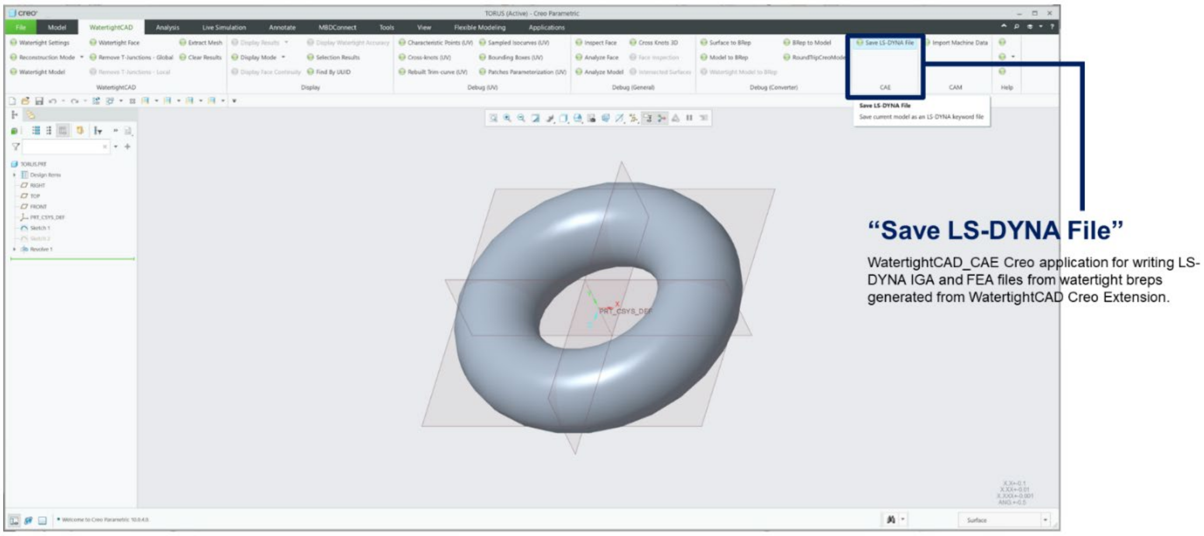
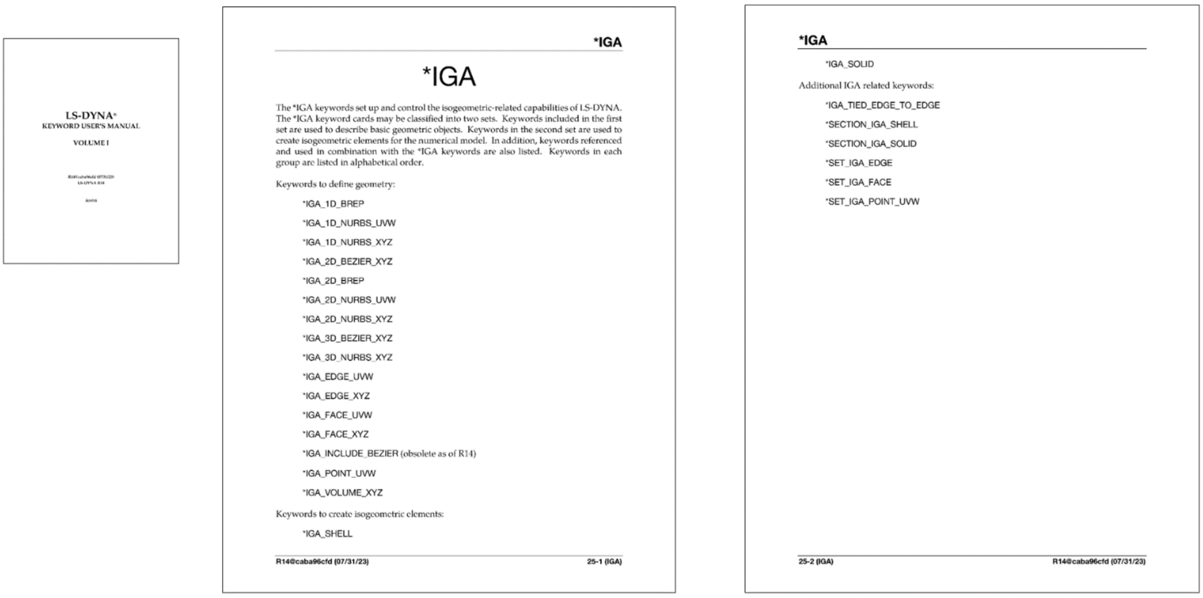


Fig.5: WatertightCAD_CAE as a PTC Creo® Extension - CAE::Save LS-DYNA File menu option.

The Template Keyword File is an optional field that provides additional analysis-relevant information not currently available for direct user input in PTC *Creo*®. Examples would be parameters such as global properties, constraints, and loads. The command copies the information from the selected template file into the output keyword file. The Output Keyword File field allows the user to specify the file that will be created. The **`*IGA_SHELL`** (Basis Transform) option creates IGA elements by performing a Bézier transform operation on the continuous watertight surface created by our WatertightCAD application. Continuity is embedded in the *Basis Transform* (previously Bézier EXTraction or BEXT) file.



LS-DYNA®
KEYWORD USER'S MANUAL
VOLUME I

*IGA

*IGA

The *IGA keywords set up and control the isogeometric-related capabilities of LS-DYNA. The *IGA keyword cards may be classified into two sets. Keywords included in the first set are used to describe basic geometric objects. Keywords in the second set are used to create isogeometric elements for the numerical model. In addition, keywords referenced and used in combination with the *IGA keywords are also listed. Keywords in each group are listed in alphabetical order.

Keywords to define geometry:

*IGA_1D_BREP
*IGA_1D_NURBS_UVW
*IGA_1D_NURBS_XYZ
*IGA_2D_BEZIER_XYZ
*IGA_2D_BREP
*IGA_2D_NURBS_UVW
*IGA_2D_NURBS_XYZ
*IGA_3D_BEZIER_XYZ
*IGA_3D_NURBS_XYZ
*IGA_EDGE_UVW
*IGA_EDGE_XYZ
*IGA_FACE_UVW
*IGA_FACE_XYZ
*IGA_INCLUDE_BEZIER (obsolete as of R14)
*IGA_POINT_UVW
*IGA_VOLUME_XYZ

Keywords to create isogeometric elements:

*IGA_SHELL

R14@caba96cfd (07/31/23) 25-1 (IGA)

*IGA

*IGA_SOLID

Additional IGA related keywords:

*IGA_TIED_EDGE_TO_EDGE
*SECTION_IGA_SHELL
*SECTION_IGA_SOLID
*SET_IGA_EDGE
*SET_IGA_FACE
*SET_IGA_POINT_UVW

25-2 (IGA) R14@caba96cfd (07/31/23)

Fig.6: Ansys LS-DYNA® IGA Keywords.

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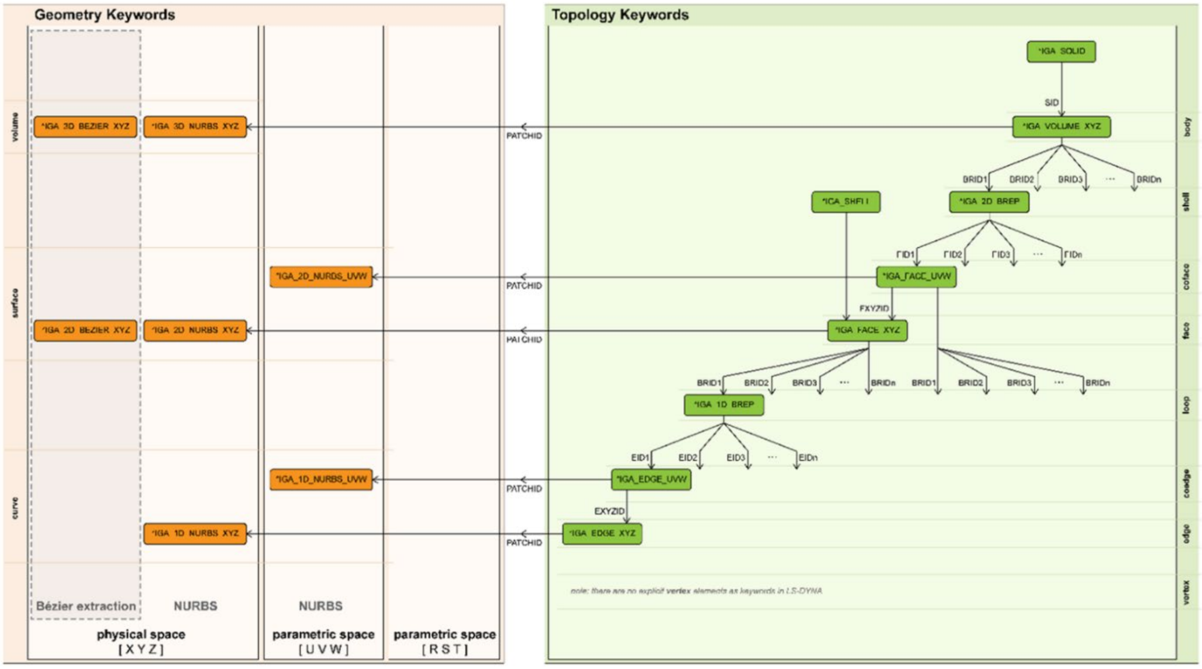

Fig.7: Diagram of Ansys LS-DYNA® IGA Keyword relationships.

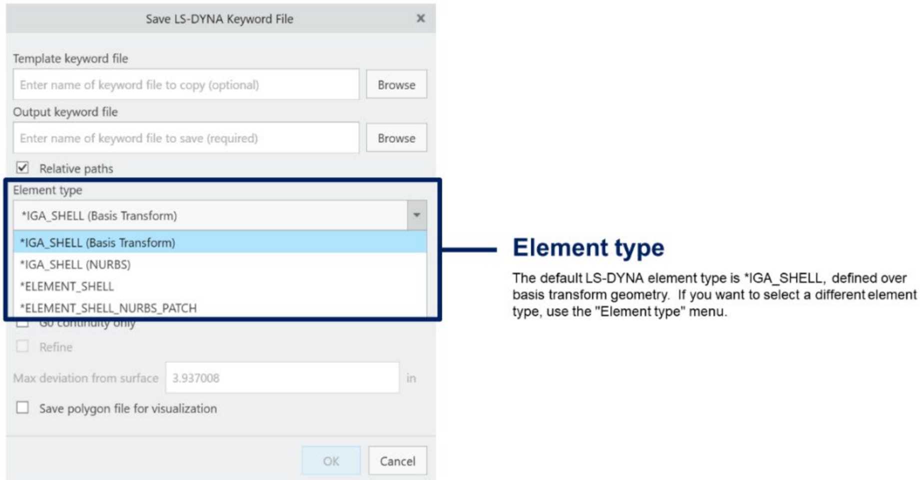

Fig.8: WatertightCAD_CAE as a PTC Creo® Extension - functions available in the CAE sub-menu of the WatertightCAD ribbon menu, with the pop-up menu which appears after selecting “Save LS-DYNA File” Element type function.

5 Summary

While IGA is a promising technology well supported by Ansys *LS-DYNA*®, preprocessing CAD models has long remained a problem for wide-spread industrial adoption. In this paper, we outlined the development of our CAD-integrated IGA preprocessor for Ansys *LS-DYNA*® that not only produces untrimmed body-fit unstructured splines but does so in a process that is integrated directly into a CAD application (PTC *Creo*®). This allows for a direct coupling between CAD and IGA alleviating the intersections between surfaces in the native CAD model consisting of approximations represented by curves rather than explicit surface-to-surface continuity, resulting in what is referred to as a geometrically non-watertight model. nVariate's unique watertight technology allows for model integration and a direct link to CAE from currently disparate domains such as CAI and CAM. Not only is there a utility for IGA preprocessing in providing a CAD-integrated untrimmed body-fit unstructured spline technology for Ansys *LS-DYNA*® but beyond preprocessing there are benefits for the synchronization of data across the digital thread in providing a representation for digital twins.

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