Towards Modeling for Design: Aspects of Multi-fidelity Geometry using CAPS

Nitin Bhagat[1]
University of Dayton Research Institute, Dayton, OH 45469, USA

Ryan Durscher[2] and Dean Bryson[3]
Air Force Research Laboratory, WPAFB, OH, 45433, USA

Multi-fidelity approaches to air vehicle design provide opportunities to leverage both the accuracy of high-fidelity performance predictions as well as the reduced cost and improved speed of less accurate, low-fidelity predictions. However, the implementation of multiple analyses brings the burden of creating multiple analysis models (geometry, meshes, and analysis inputs) that are generally different, yet must be consistent. Multiple facets comprise the fidelity of a particular analysis model. These include the single discipline physics models and assumptions implemented, the geometric features and representation, interdisciplinary couplings, and the level of numerical error in the solution. The objective of this paper is to demonstrate how the Computational Aircraft Prototype Syntheses (CAPS) exposes these modeling aspects to perform multi-fidelity design studies. This paper provides examples to demonstrate configuration variations and discusses results exploring various multi-fidelity aspects facilitated using CAPS.

I. Abbreviations

CAPS = Computational Aircraft Prototype Synthesis
AIM = analysis interface module
OML = outer mold line
IML = inner mold line
VLM = vortex lattice method

II. Introduction

Multi-fidelity modeling is currently seen as an approach to enable bringing higher-fidelity data earlier in the aircraft design process. Here, the *fidelity* of a model is described as its accuracy or faithfulness in representing reality from the viewpoint of the model's intended use. The goal of variable- or multi-fidelity methods is to balance the realism of predicting vehicle performance with the associated cost, which generally increases with realism. By improving the fidelity of predictions in the conceptual to preliminary design stages, the hope is to overcome limitations of the traditional early-design tools, which may lead to late design defects or missed opportunities.

As the *multi-fidelity* modeling community has expanded ---both in users and developers--- there seems to be no consensus on what constitutes a change in the level of *fidelity*. Indeed, the gamut of engineering analyses available provide a multidimensional spectrum by which to assess model fidelity. At the same time, to be useful in a design process, these tools must be readily automated to enable designers the flexibility to evaluate a potentially large number of configurations. The Computational Aircraft Prototype Syntheses (CAPS)[1] modeling for design program attempts to provide automated meshing and analysis preprocessing linked to parametric, attributed, differentiated geometry

---

[1] Research Engineer, Air Vehicle Optimization Group (AMD), Senior Member AIAA.
[2] Research Aerospace Engineer, Design and Analysis Branch (AFRL/RQVC), Senior Member AIAA
[3] Research Aerospace Engineer, Design and Analysis Branch (AFRL/RQVC), Senior Member AIAA.

models. In this manuscript, we highlight various aspects of multi-fidelity, parametric modeling that are readily available using CAPS.

III. Aspects of Multi-fidelity Modeling

From the perspective of computational simulations, there are different types of modeling decisions that need to be addressed: Geometric Representation, Physics Modeling, Interdisciplinary Coupling, and control of numerical error (e.g., grid and residual convergence levels) to balance solution accuracy and cost. While we believe this list broadly captures variations on fidelity found in the literature, other aspects of fidelity may almost certainly be encountered; particularly when considering experimental tests as a method of performance prediction. These aspects frequently confound with each other. For example, the level of physics modeled may necessitate a change in geometric representation, such as the condensation of structural properties into a beam representation, or the details used to describe a flap deflection. Similarly, they also underscore that model fidelity levels often do not fit neatly into a hierarchy. One could consider a tightly coupled aeroelasticity simulation using low-order structures and aerodynamics, or a loosely coupled simulation using high-order physics.

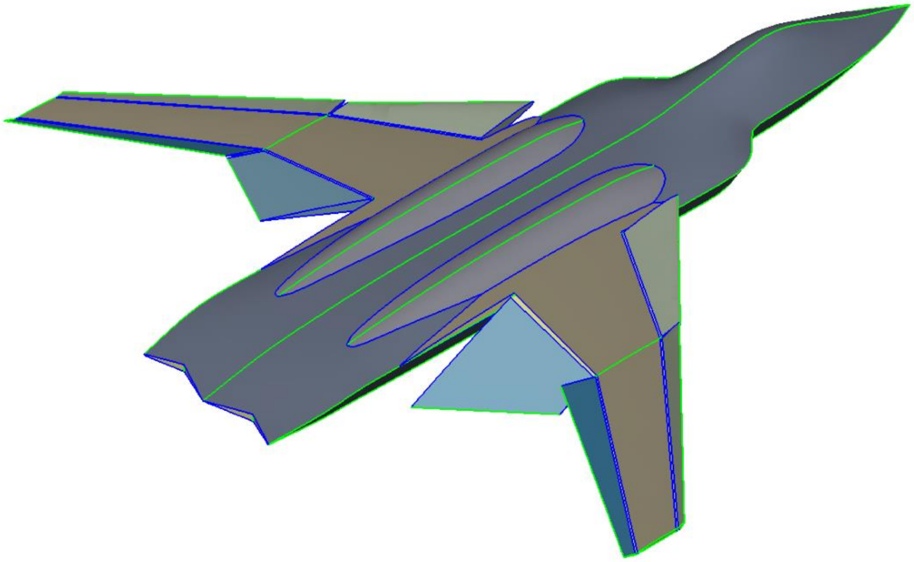


Figure 1: Conceptual view of a representative geometric model.

Figure 1 shows a conceptual representation, that typically comes out of a geometry package. This representation provides a designer just a visual clue of the model, and may not be a suitable representation for various analyses and fidelities that a design process demands. In CAPS, this representation is used as a template to derive/construct various configurations, components features, and views to serve them for analysis as needed. This concept is further described through examples in the following sections.

A. Geometric Representation

The geometric representation within a multi-fidelity model can either be parametric or direct (statically defined). The advantage of parametric modeling over direct, is that it allows a designer to achieve simple changes within a component, as well as complex changes at the component level resulting in a desired configuration. Additionally, parametric modeling can also eliminate repetitive, laborious geometric tasks during design iterations. Once the designer provides appropriate switches, the recipe script can take care of slicing, dicing, and assembling the configuration into an appropriate representation suitable for the preferred analysis or multiple representations (and possibly linked to each other) for different analyses.

The geometry template and associated parameterization used for illustration purposes within this paper and created within the CAPS infrastructure, has three major components: wing, fuselage, and inlet. Variations at the configuration level are shown in **Figure 2**; whereas component level variations are shown in **Figure 3**. As seen from the two figures (**Figure 2** and **Figure 3)**, there are additional sub-components and features that may be dictated either by the designer or desired by the type of analysis. For example, flaps are considered as a sub-component and whether the wing tip is sharp or rounded, is considered as a feature. Similarly, the inlet is considered as sub-component of fuselage. These relations, dictated by designer, facilitate global and relative parameterization required for the analysis and design process.

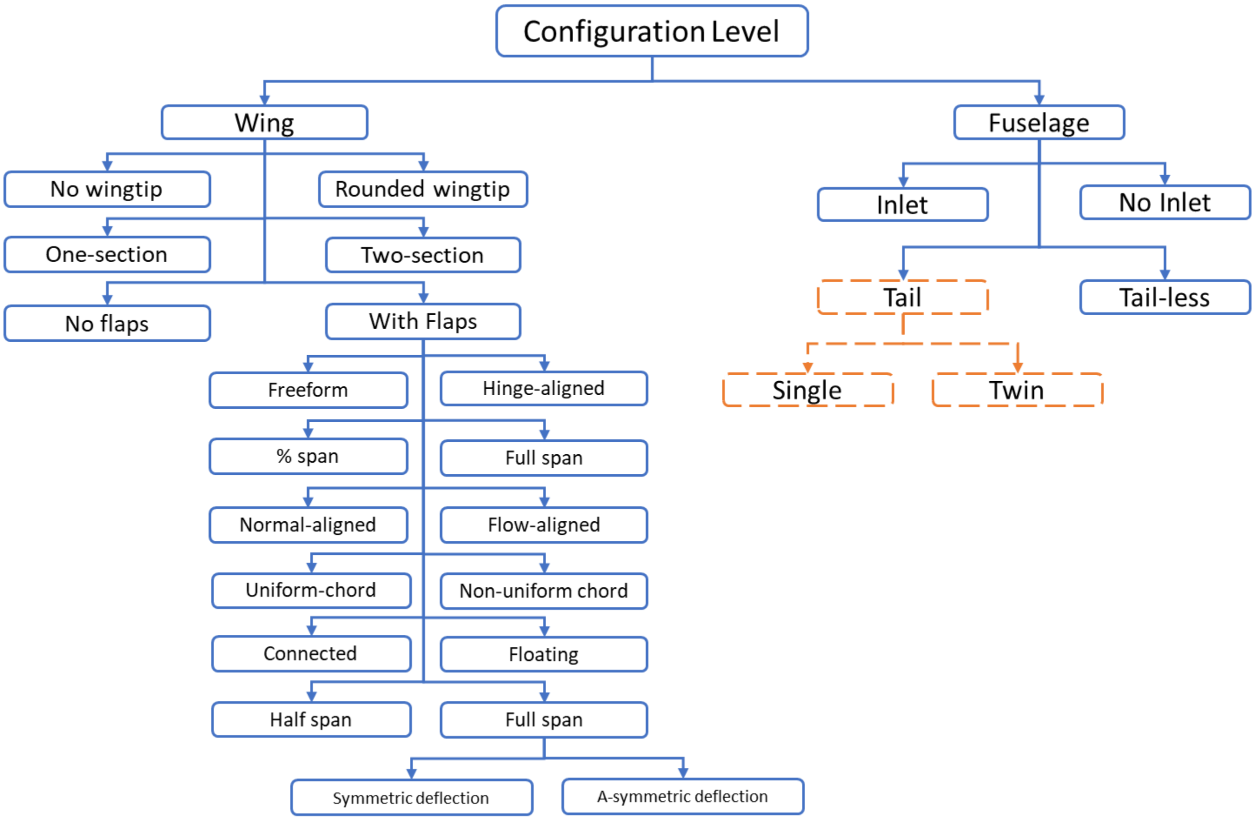


Figure 2: Parametric variations - Configuration Level

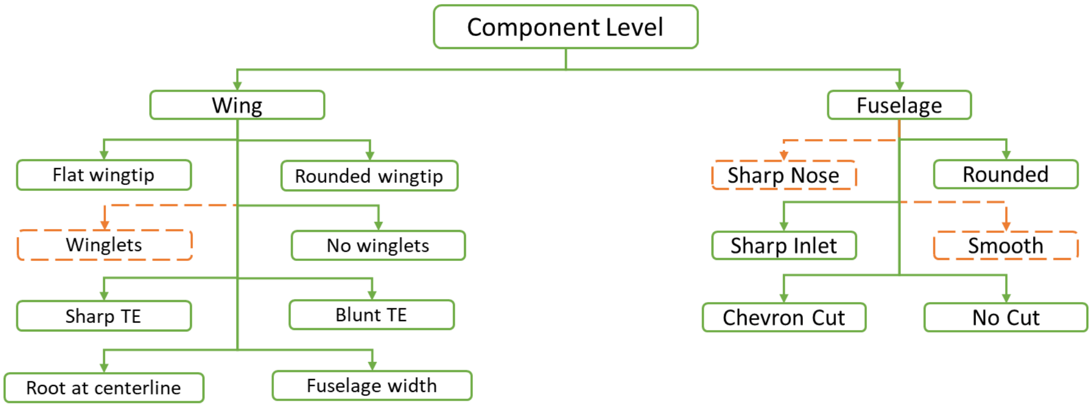
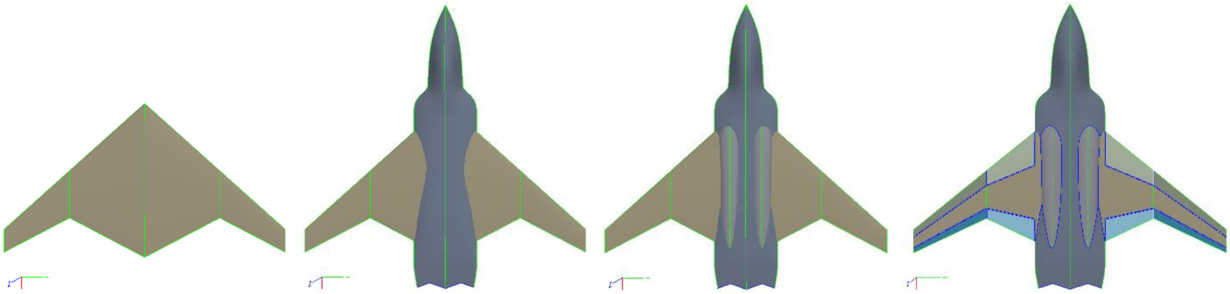


Figure 3: Parametric variations - Component Level.

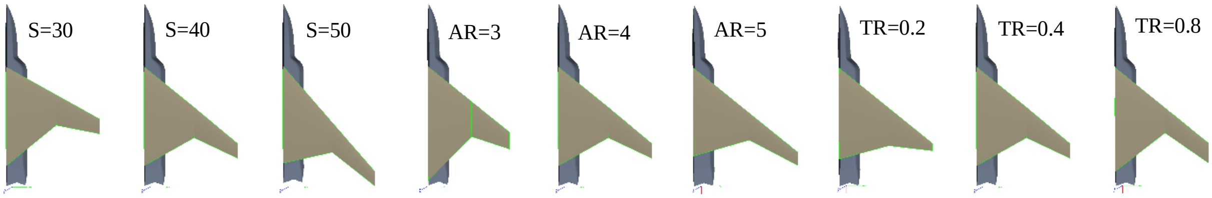
At the configuration level, individual components can be turned on and off as desired. An interface to these complex variations is possible via a simple switch parameter. Each view shown in **Figure 4** has a single switch/parameter associated with each component. The resulting outer mold line version from each variation is a watertight representation and is suitable for various analyses, such as computational fluid dynamics.



Wing +Fuselage +Engine bump-outs Complete configuration

Figure 4: Componentized, parametric configurations demonstrating multiple levels of geometric detail.

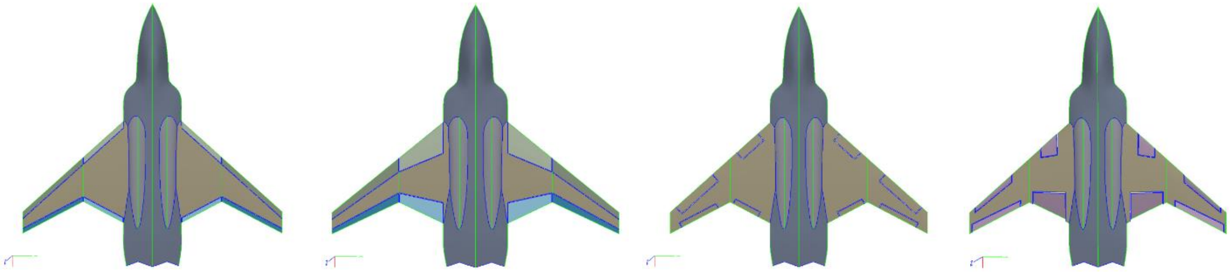
The parametric variations at individual component level can be achieved in similar way. A parameterized wing is shown in **Figure 5a-c**. Three parametric changes are shown, varying wing sweep angle in **Figure 5a**, aspect ratio in **Figure 4b**, and taper ratio in **Figure 4c**. Here, the configuration with Wing Sweep=40, Aspect Ratio=4 and Taper=4 is considered as a baseline. In addition, other parametric variations are possible, such as area ratios between inboard and outboard sections, dihedral angle, and location of the root of wing with respect to vehicle centerline.



(a) Wing Sweep (b) Aspect Ratio (c) Taper

Figure 5: Example parameterizations for an individual component wing.

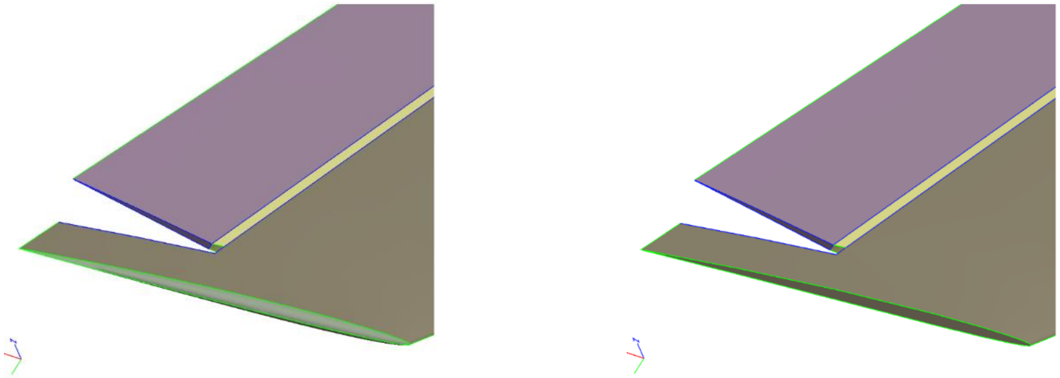
Several variations in the control effectors (i.e., flaps) have been implemented. A sampling of different flap configurations is shown in **Figure 6**. A small subset of parameters can be used to define inboard and outboard flaps. As an example, if the chord of all flaps is desired to be same, specifying a uniform chord (in terms of percentage of the tip chord) is sufficient. Flaps can have full-span (**Figure 6a,b**), or partial span (**Figure 6c,d**). For a more flexible configuration, individual flaps can be generated by providing a hinge line that identifies location, span and chord for each flap (**Figure 6d**). In addition, there is an option of whether flaps need to be flow-aligned (**Figure 6a,b**), sweep-aligned (**Figure 6c**) or hinge-aligned (**Figure 6d**). The flap deflections on the mirrored side can be symmetric or anti-symmetric with respect to the main side.



(a) Flow-aligned, uniform (b) Flow-aligned, variable (c) Sweep-aligned, uniform (d) Hinge- aligned, flap

Figure 6: Variations in control effectors layouts.

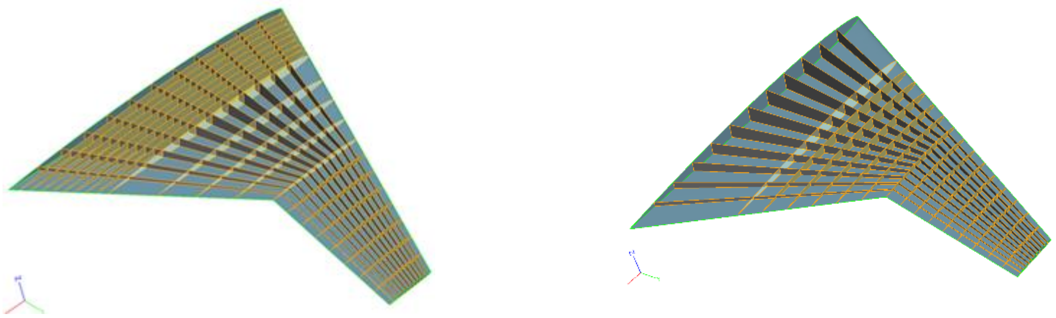
Other component level variations may be dictated by an analysis fidelity or discipline. For example, a rounded wing tip as shown in **Figure 7a** may be desired for a high-speed flow as opposed to blunt/sharp wing tip as shown in **Figure 7b**. A similar geometry smoothening may be needed at the fuselage-engine bump junction which is not shown here.



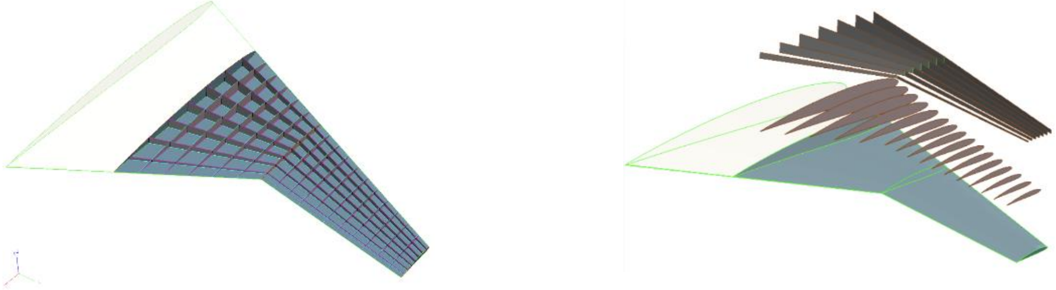
(a) Wing with rounded tip (b) Wing with flat tip

Figure 7: Visual comparisons of wingtip treatments.

While an aerodynamic analysis typically requires just the outer mold line (OML), a structural analysis often demands complex, internal geometry representations referred within as the inner mold line (IML). Structural layouts, for a wing, implemented in our representative geometric model here, are shown in **Figure 8**. These variations in the IML layout are parametrically defined and control the skin, ribs, and spars design. The ribs-spars layout can be conventional or novel.



(a) Layout from root (b) Spars extened to root, rib at wing-fuse junction



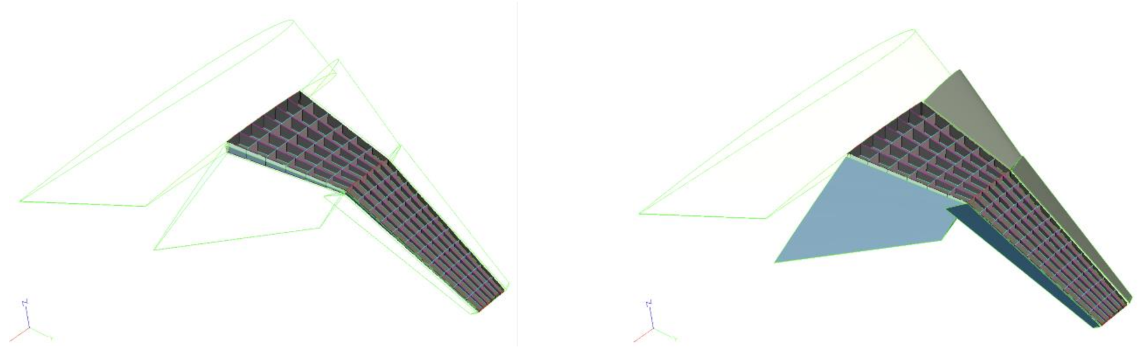
(c) Stitched layout (d) Unstitched layout (exploded view)

(e) Cartesian-style, one-section wing (f) Cartesian-style, two-section wing

Figure 8: Variation of the internal structural layout of the wing.

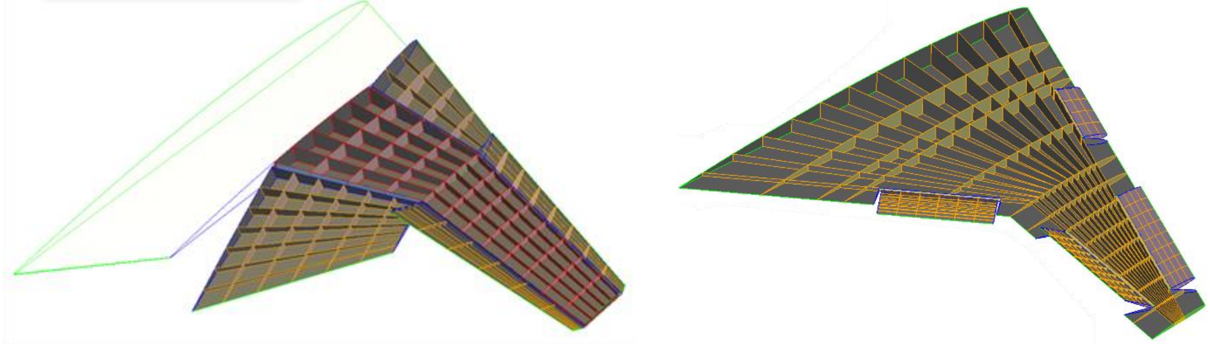
At the component level, a set of local parameters may be required for a component feature, that ties with (global) component parameterization. The layout may need to consider the presence of adjoining components as dictated by either designer or analysis capability. For example, one may desire to analyze the wing only and turn off the fuselage, thus requiring ribs starting from vehicle centerline or root of the wing. Such a representation is shown in **Figure 8a**. In another instance, the designer may wish to represent wing-fuselage junction as a rib, as illustrated in **Figure 8b.** If a designer wishes to perform comparative analysis for the effects of having a layout where ribs, spars skin are fused together vs. individual ribs, spars and skin that analysis software can assemble; views shown in **Figure 8c,d** can be used for such studies. The last two layouts shown in **Figure 8e,f** are unique cartesian style layouts that may be dictated by the design/optimization process.

Parametric variations of conventional as well as novel IML layouts for a wing with flap configurations are illustrated in **Figure 9.** The wing layout, especially ribs, accommodate the presence of (deflected) flaps and can preserve connection between the wing and flaps, if desired. The structural representation for flaps can either be a point load, flap skin, or have their own riblets and sparlets. For the case with flaps with their own structural layout, an individual flap is set to have a defined number of riblets and sparlets, based on local parameters specific to each flap.



(a) Wing IML, flap cutouts

(b) Wing IML, flaps skin only



(c) Wing + flaps IML

(d) Wing + flaps (uniformchord, hinge-aligned) IML

Figure 9: Variations of the internal structural layout of the wing with control surfaces.

B. Physics Modeling

Within the context of multi-fidelity design, a geometric model must fully account for various levels of desired fidelity within an analysis. This is readily apparent in aerodynamics. For example, various low-order models that one might consider include lifting line theory, vortex lattice, and panel methods. These approaches could also be augmented with estimates of skin friction and wave drag to increase their realism. Including additional physical effects in the representative model, one might consider the Euler or Navier-Stokes equations. Aerodynamic simulations may also be assumed to be (quasi-) static or transient. With an intelligent parameterization and attribution scheme, different analysis views can be generated for each fidelity and discipline bound by related parameters with CAPS. For the current template, various views available are listed in **Figure 10.** In addition, these views can interact with each other by enabling data transfer between different analyses, for example a data exchange between fluid and structural analysis.

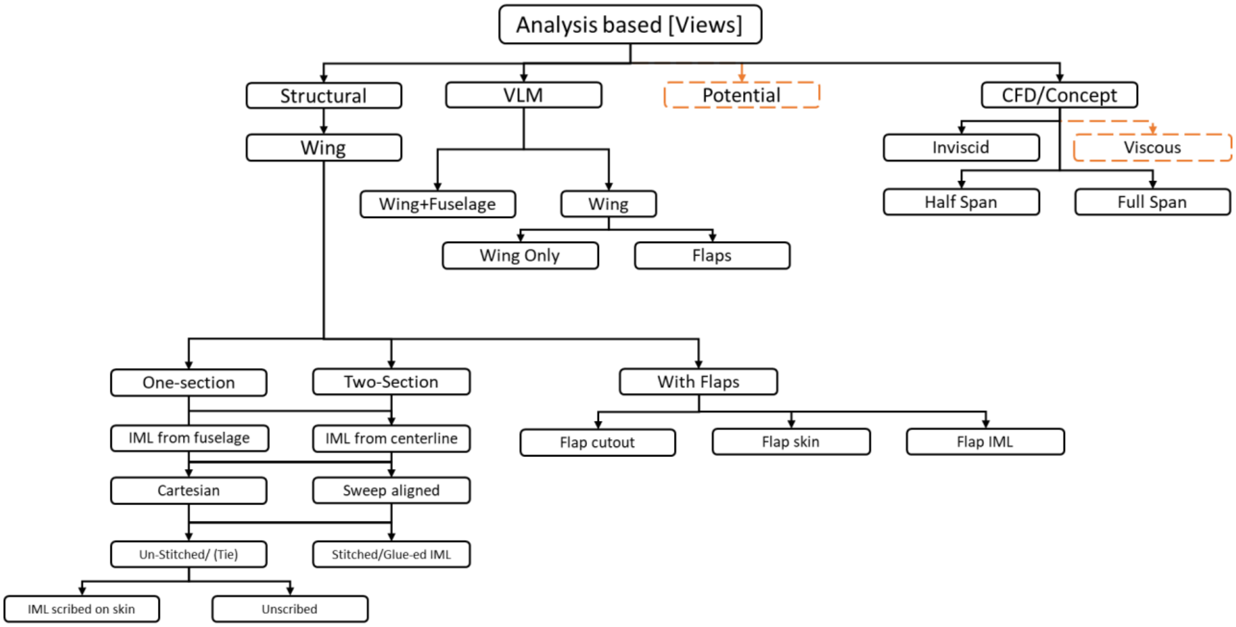


Figure 10: Hierarchy of analysis VIEWs

Figure 11 shows various views that are suitable for a specific discipline and/or fidelity. The first three views can be used for fluid analysis with an incremental level of fidelity, whereas the Structural view can be used to for structural analysis. A common set of the parameters and appropriate attributes enables these views to be generated from the same template, thus maintaining geometry shape, size and specific features.

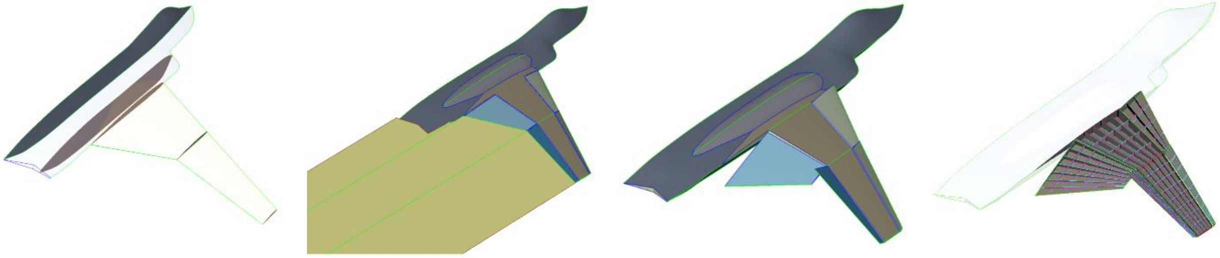

(a) VLM (b) Potential (c) CFD (d) Structural

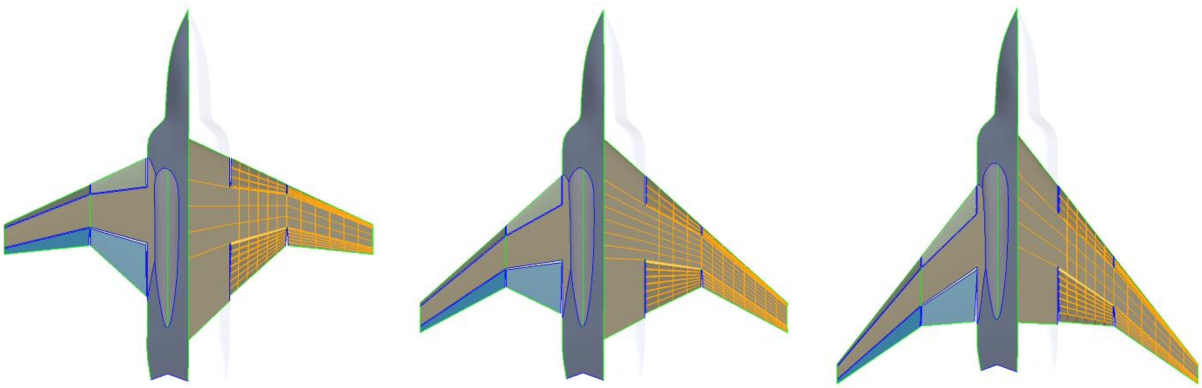
Figure 11: Analysis VIEWS spanning multiple-fidelities and disciplines.

C. Interdisciplinary Coupling

While fidelity level may be varied within individual disciplines, the level of coupling between them also introduces variation in realism. Taking aero-structural design as an example, a unidirectional coupling could consider structural deformations under aerodynamic loading without considering the feedback of the deflections into the loads. In a loosely coupled sense, bi-directional coupling may iteratively transfer the aerodynamic loads and structural displacements until some level of convergence is achieved. In a tightly coupled sense, the equations of all disciplines are solved simultaneously. An example of this is in NASTRAN, where linearized aerodynamics and structural finite element models are solved in aeroelastic trim and flutter solutions.

With CAPS, when interdisciplinary couplings are considered within a unitized analysis, they are typically managed within the AIMs[1]. However, when analyses do not provide for couplings, CAPS provides methods to facilitate the communication of data between different models when they share common geometry. **Figure 12** shows analysis views where parameterization of the structural layout (IML) is tied with the wetted surface OML. Hence, any change in the

OML view, that affects the structural layout, gets reflected in the IML view. In addition, as these views are derived from the same template, all common features, parameters and attributes can be easily linked. This linking provides a means to exchange of analysis data via common representation.



(a) Sweep=30 (b) Sweep = 40 (c) Sweep=50

Figure 12: Coupling of parameterization with VIEWs.

D. Time Estimates for Multi-fidelity, Parametric Model Creation

While we do not address the numerical error (e.g., grid and residual convergence levels) associated with solution accuracies here, as the scope of that is relative to the particular analysis being executed, we do consider the cost of developing the multi-fidelity, parametric model itself. The script for the representative geometry detailed in previous sections was developed over a period of time. As with any design process, not all requirements were available when the project was started. As the model's script evolved and results were demonstrated, various components, features and views were revised based on the feedback from researchers who intended to perform analysis and design studies specific to their needs. This prompted additional development work to support the implementation of desired geometry features. The following table shows approximate time required to create the script with various features of this representative geometry.

Table 1: Creation times for script components and views.

Configuration			**Approximate Scripting Time**
Setup			6 hours
Components	Wing		9 hours
	Flaps		16 hours
	Fuselage		4 hours
	Inlet		5 hours
Views	Concept		2 hours (assembly)
	CFD	Wing	2 hours
		Flaps	6 hours
		Fuselage	1 hour
		Inlet	1 hour
	VLM	Wing	1 hour
		Fuselage	1 hour
	FEA	Wing	16 hours
		Flaps	18 hours

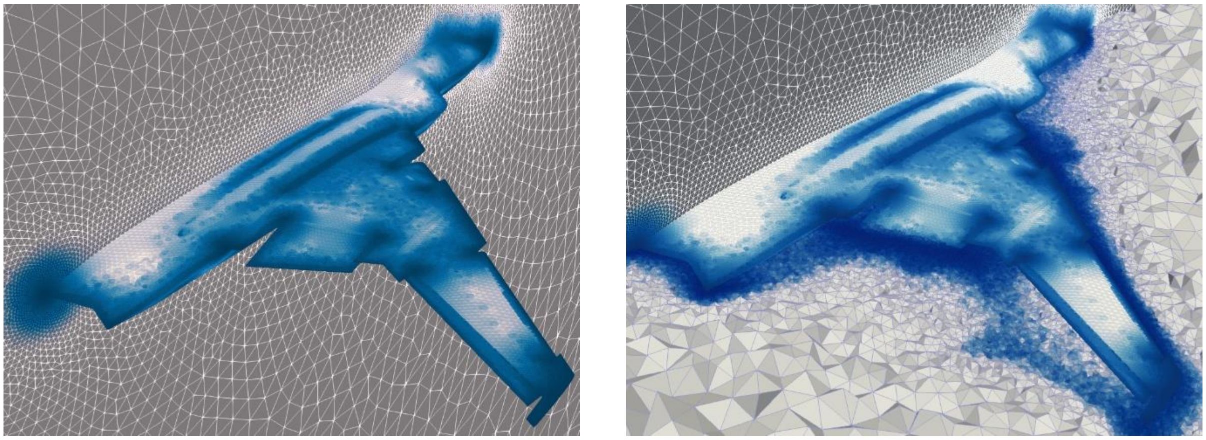
At times, while the script was being developed, this prompted adding as well as updating certain features inside CAPS by the CAPS developers, and testing of those features on a simplified use-case. These efforts are excluded from above estimates. The initial setup includes time spent in creating configuration parameter, design parameters, organizing the components and sub-scripts to establish a driver script. The time spent in implementing the components includes development of conceptual views of each component. The time spent in implementing the Views includes updating and sometimes modifying the conceptual views to accommodate analysis requirements. In addition, the time also includes implementing specific attribution schemes to aid analysis views.

IV. Representative Analysis Examples for a Multi-fidelity Model

The example script and the resulting geometry representation discussed so far is intended to be distributable, rebuildable, customizable such that the representations can be updated to satisfy as the design process evolves. This section describes how the current template of parametric geometry has been used for analysis and design using CAPS.

A few examples in which the geometric model has been updated by researchers to add more components, features, and views, as well as applied for various analyses and design studies are: Lickenbrock et al. [3] have reported additions to the wing component defined by a different set of parameters to perform multifidelity and multidisciplinary analysis; Rumpfkeil et al. [4] updated the IML to apply the geometry representation for aeroelastic optimization with control deflectors; Thelen et al.[5] have reported an addition of panel (OML) view and a modified IML view specific to their needs to perform flutter analysis; Additionally, the geometry model was used to illustrate CAPS capabilities at the NATO Science and Technology Organization meeting[6].

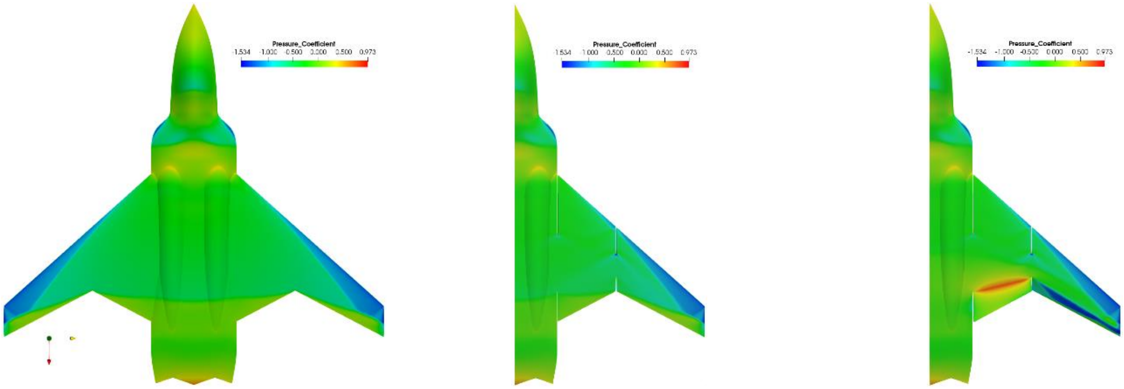
Adding to the above referenced examples, the following outlines some additional executions of single-analysis processes of creating geometry, generating mesh, and performing fluid analysis in an effort to stress the parametrics of this representative geometry with CAPS. These stress tests involved creating Python scripts using the pyCAPS[2] module and using CAPS to link meshing and analysis software to the parametric geometry. In our examples here, SU2[7] and AVL[8] were used to test two different levels of the aerodynamic fidelity within the model. For meshing, AFLR4[9,10] was used to generate surface meshes and AFLR3 was used to generated volume meshes. ParaView[11,12] was used to visualize the analysis data and generate snapshots.


(a) Surface Mesh

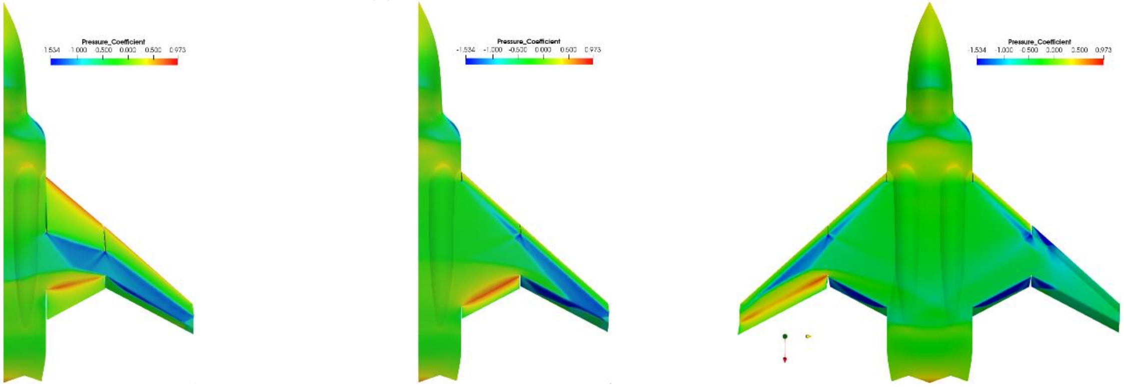
(b) Volume mesh through a cut plane

Figure 13: Representative meshes used for fluid analysis

A representative set of meshes are shown in **Figure 13** for CFD level analysis, while **Figure 14** shows a comparison of pressure contours for variations in flap configurations and associated deflections. The results are shown for a mix of half-span and full-span models. The full-span model is used when flow is not symmetric based on flap configuration. Two sets of plots for normalized lift coefficient vs drag coefficient with sweep angles and AR over a range of sub- and transonic Mach numbers are shown in **Figure 15.** Furthermore, to further stress the parametrics, a design of experiments varying the sweep and aspect ratio of the lower order aerodynamic model is shown in **Figure 16**, using AVL[8] as the analysis code.

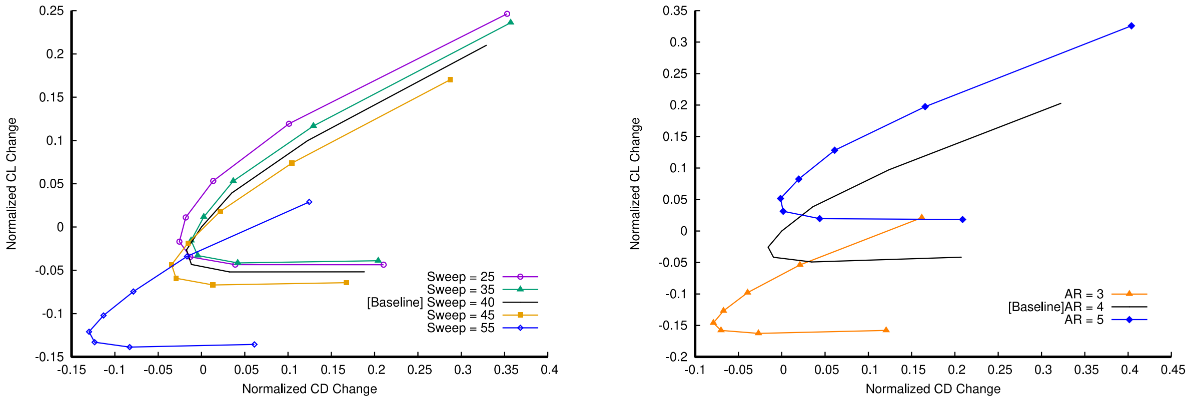


(a) No Flaps (b) Flaps with zero deflections (c) Trailing edge flaps deflected



(d) All flaps deflected (e) Flaps with uniform chord Fullspan, antisymmetric flap deflections

Figure 14: Fluid analyses on parametric variations: pressure contours.



(a) Normalized plot for sweep Noramlized plot for AR

Figure 15: Drag polar plots over a range of Mach numbers.

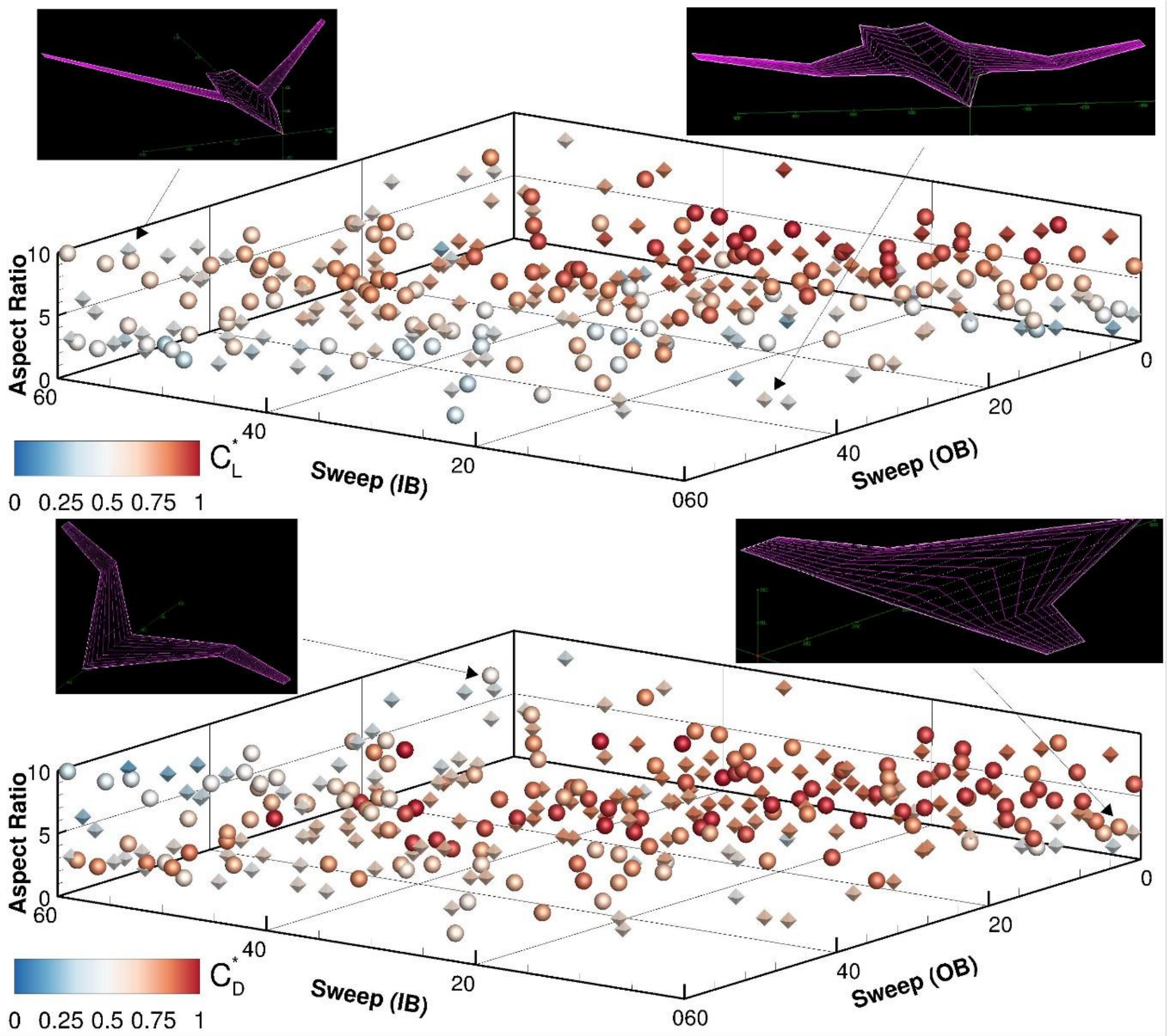


Figure 16: Design of experiment results using AVL using two geometry fuselage representations within the analysis.

V. Conclusion

The efforts reported in this manuscript highlight various multi-fidelity modeling considerations made accessible to designers using CAPS. Discussion and examples on how these different aspects are considered and managed are provided. Results from aerodynamic analysis and a design of experiment studies are provided to demonstrate the application and stress test the parametrics of the representative geometry. In addition, adoption and application of this geometry model by other designers demonstrates collaborative aspect of the geometry developed in CAPS.

Acknowledgments

First author acknowledges the support of the Air Force Research Laboratory, Aerospace Systems Directorate. This work has been cleared for public release, distribution unlimited, case number: AFRL-2021-3941

References

[1] Bryson, D. E., Haimes, R., and Dannenhoffer, J. F., III, “Toward the Realization of a Highly Integrated, Multidisciplinary, Multifidelity Design Environment,” AIAA SciTech Forum, American Institute of Aeronautics and Astronautics, San Diego, CA, 2019.

[2] Durscher R., Reedy, D., “pyCAPS: A Python Interface to the Computational Aircraft Prototype Syntheses”, AIAA SciTech Forum, American Institute of Aeronautics and Astronautics, San Diego, CA, 2019.

[3] Lickenbrock, M., Rumpfkeil M., Beran, P., Kolonay, R., “Multi-fidelity, Multidisciplinary Analysis of an Efficient Supersonic Air Vehicle”, AIAA SciTech Forum, American Institute of Aeronautics and Astronautics, Orlando, FL, 2020.

[4] Rumpfkeil, M., Lickenbrock, M., Beran, P., Kolonay, R., “Multi-fidelity, Aeroelastic Analysis and Optimization with Control Surface Deflections of an Efficient Supersonic Air Vehicle”, AIAA SciTech Forum, American Institute of Aeronautics and Astronautics, 2021.

[5] Thelen, A., Rumpfkeil, M., Beran, P., “Multi-fidelity Flutter Analysis of an Efficient Supersonic Air Vehicle”, AIAA AVIATION Forum, American Institute of Aeronautics and Astronautics, 2020.

[6] Bryson, D., Bhagat, N., Haimes, R., Dannenhoffer III, J., “Automated, Multifidelity Aero-Structural Modeling for Design of Military Aircraft”, AVT-324 Specialists’ Meeting on Multidisciplinary Design Approaches and Performance Assessment of Future Combat Aircraft, 2020.

[7] Economon, T., Palacios, F., Copeland, S., Lukaczyk, T., and Alonso, J., “SU2: An Open-Source Suite for Multiphysics Simulation and Design,” AIAA Journal, Vol. 54, No. 3, 2016, pp. 828–846.

[8] Drela, M., and Youngren, H., “AVL,”, 2017. URL http://web.mit.edu/drela/Public/web/avl/.

[9] Marcum, D., and Weatherill, N., “Unstructured Grid Generation Using Iterative Point Insertion and Local Reconnection,” AIAA Journal, Vol. 33, No. 9, 1995, pp. 1619–1625. doi:10.2514/3.12701.

[10] Marcum, D., “Unstructured Grid Generation Using Automated Point Insertion and Local Reconnection,” The Handbook of Grid Generation, edited by J. F. Thompson, B. Soni, and N. P. Weatherill, CRC Press, 1998, pp. 18–1.

[11] Ahrens, James, Geveci, Berk, Law, Charles, “ParaView: An End-User Tool for Large Data Visualization, Visualization Handbook”, Elsevier, 2005, ISBN-13: 978-0123875822.

[12] Ayachit, U., “The ParaView Guide: A Parallel Visualization Application, Kitware”, 2015, ISBN 978-1930934306.