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Saikat Dey, Romain M. Aubry, B. Kaan Karamete, and Eric L. Mestreau

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14. ABSTRACT
Capstone is a geometry-centric platform for a unified representation of the geometry, mesh and attribution needed for engineering analyses with varying fidelity. Meshes and the attributes are both associated with a robust mathematical model of the geometry enabling any change in the geometry to be automatically propagated to the meshes and attributes needed for analyses. It provides a software platform with well abstracted and compact interfaces to create, modify and query geometry, mesh and attribution information for a model. This forms a foundation for geometry-based design environments and solvers that access geometry at runtime for scalable and accurate a-posteriori mesh adaptation.

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Capstone: A geometry-centric platform to enable physics-based simulation and design of systems

Saikat Dey, Romain M. Aubry, B. Kaan Karamete, and Eric L. Mestreau

Abstract—We have developed *Capstone* as a geometry-centric platform for a unified representation of the geometry, mesh and attribution needed for engineering analyses with varying fidelity. Meshes and the attributes are both associated with a robust mathematical model of the geometry enabling any change in the geometry to be automatically propagated to the meshes and attributes needed for analyses. It provides a software platform with well abstracted and compact interfaces to create, modify and query geometry, mesh and attribution information for a model. This forms a foundation for geometry-based design environments and solvers that access geometry at runtime for scalable and accurate *a-posteriori* mesh adaptation. *Capstone* provides a graphical frontend for computational fluid dynamics, electromagnetic as well as ship/submarine shock-damage analyses modeling. It is being used and evaluated by several DoD organizations as part of the DoD HPCMP CREATE™ Program [6].

Index Terms—Geometric modeling, mesh generation, computer-aided-engineering, engineered resilient system, product lifecycle management.

1. Introduction

PHYSICS-based computational approaches have steadily gained acceptance and usage in engineering design and analyses for both civilian and military applications [1], [2]. A fundamental aspect of these approaches involves the ability to accurately simulate the response or performance of engineering systems, ranging from ships, aircrafts and submarines, to micro-electro-mechanical devices, on a computer. Such a virtual prototyping capability offers significant advantages over traditional empirical design approaches based purely on building physical prototypes and experimental testing [3]. Computationally-based approaches are now part of a broader push to streamline and make the defense acquisition process more cost effective. One such effort is the Computational Research and Engineering Acquisition Tools and Environments (CREATE™) program [6] aimed at developing a suite of high-performance physics-based computational tools addressing the needs of the air- vehicle, ships and radio-frequency antenna community. The goal is to enable generation of high-fidelity design and decision data earlier in the acquisition process by using carefully validated and scalable physics-based computational tools combined with high-performance computing platforms. This enables more systematic evaluation of the design space for more optimal design(s) while at the same time reducing the overall cost of development.

Physics-based simulation of engineering systems is underpinned by model(s) of mathematical-physics comprising of one or more partial differential equation(s). Computational model(s), derived from the mathematical model(s), consisting of the discretized representation of the differential equations, are solved as part of the simulation. A core component of the computational model consists of what we refer to as the *analyzable representation*. It encapsulates three main pieces of information: (1) a mathematical description of the geometry of the system, possibly including the operational environment, called the *geometry model*, (2) a spatial discretization of the geometry model often called the *mesh model*, and (3) information besides the geometry and the mesh that completes the description of problem from an analysis solver's standpoint, such as, boundary and initial conditions, material parameters needed as part of constitutive laws and the like, collectively known as the *analysis attribution* information.

The effectiveness of physics-based computational tools (solvers) in the engineering acquisition process depends on the maturity of tools and capabilities for generating the *analyzable-representations* needed by

- *S. Dey is with Code 7131, U.S. Naval Research Laboratory, Washington, DC 20375*
- *Email: saikat.dey@nrl.navy.mil*
- *R. Aubry, B.K. Karamete, and E.L. Mestreau are with Sotera Defense Solutions, Herndon, VA 20171*
- *Email: romain.aubry.ctr.fr@nrl.navy.mil, kaan.karamete.ctr@nrl.navy.mil, eric.mestreau.ctr@nrl.navy.mil*

the solvers. In the conceptual and early phases of the design, the need is rapid and automatic creation of analyzable representations from parametric system models. These representations are used in analyses with varying levels of fidelity. In the more detailed analyses of the design, or for evaluations of existing systems, one needs the ability to create analyzable representations that have analysis-suitable geometry with the requisite geometric accuracy and meshes that meet the accuracy needs based on the physics and the requirements of the discretization approach used.

While computer-aided-design (CAD) systems have been used extensively for producing design geometry, it is often done in a manner that is not suitable for analyses relevant to evaluate system performance. For instance, considerable effort has to be expended to make a CAD representation of the geometry for manufacturing purposes suitable for a specific analysis. Manufacturing details of the geometry such as rivet holes are often not relevant for many engineering analyses and may in fact lead to poor mesh quality thus impacting the accuracy of the simulation. In addition, many legacy approaches where meshes are not associated with a valid geometric model and attribution is done in an ad-hoc manner tied to the mesh model. This defeats automation and increases the cycle time whenever a mesh is changed for the same design geometry.

Early in the *CREATE™* program it was realized that filling the gaps in the capabilities to generate analyzable representations was a critical need. As part of the *CREATE™ Meshing and Geometry (MG)* project, we have developed a software platform called *Capstone* to enable the generation of analyzable representations suitable for physics-based analyses of engineering systems at different stages of the design process.

Key attributes of *Capstone* are:

- Geometry of the system described based on an abstract geometry model with the ability to create geometry from scratch as well as import and modify existing geometry. *Capstone*'s geometric representation is agnostic of the actual CAD or geometry system being used. This enables *Capstone* to be useful in existing workflows that use different geometry systems including the case when the geometry is only available in a legacy discrete form.
- Careful classification of the topological entities in the mesh model against the topological entities in the geometry model. This is critical to ensure validity of the mesh model and robustness of the mesh generation process [4].
- Association of analysis attributes directly with the geometric model definition [5]. This ensures that any meshes generated from a given geometric model automatically inherit the needed analysis attributes.

The rest of this article is organized as follows: Section 2 describes the overall architecture of *Capstone* and its intended usage scenarios. This is followed by a description of example uses and impact on different stages of the acquisition process in Section 3. Section 4 presents concluding remarks.

2. THE *Capstone* PLATFORM

The design of *Capstone* was influenced by some key requirements that include:

1) Providing a common infrastructure (platform) for standalone and runtime access to geometry, mesh and attribution for all the tools being developed as part of the CREATE™ Program.
2) Ability to operate in the geometry-kernel (CAD system) agnostic manner and handle discrete geometry representations.
3) Modular infrastructure that is easy to maintain.
4) Provide extensibility including the ability to leverage/use existing algorithms and technology and enable addition of new capabilities by other developers.
5) Support multiple platforms including Linux®, Windows®, and Mac OS®.

Capstone is not a monolithic software tool. It has a layered architecture. At its core, it is a compact set of well-abstracted function-driven *application programming interfaces* (API) that address three fundamental components:

1) Three-dimensional geometry.
2) Mesh generation and adaptation.
3) Attribution.

Each component comprises a database to house a robust representation of the information associated with it and a set of operators (API) to create, modify and query the information. These APIs are abstracted to enable applications using them to be independent of the underlying implementation of a specific database. This is a key to having the platform work in a CAD system agnostic manner because the implementation details of the database do not affect the algorithms that use the abstract definitions. For instance, meshing algorithms work on geometry independent of the kernel (database) that houses it as shown in Figure 1.

All the high-level functionality in *Capstone* is provided through a *plugin* approach. A *plugin* is a dynamically loaded library that provides a runtime capability. *Capstone* uses *plugin* pervasively to provide capabilities that include concrete database implementation(s), user-interface dialogs, 3D renderers, mesh generators, data importers and exporters, and specialized functions for geometry handling and attribution.

Based on requirements to serve the needs of enduser analysts and designers, as well as, providing a foundation for other tools to be built on top of it, *Capstone* platform is designed to be accessed in different ways:

- as a *software development kit* (SDK) to link with its APIs and functions and leverage them at runtime, and
- as a standalone application with a *graphical user interface* (GUI) to generate analyzable representations.

2.1 Users and Usage Scenarios

Capstone users may be broadly classified into the following categories:

1) *Analysis Data Modeler:* Represents users who generate an analysis-suitable mesh from a given source geometry. Individual expertize varies from novices to those well-versed with the issues associated with geometric modeling and meshing. The key needs is for tools that enhance productivity by reducing cycle time. Although geometry may be recreated based on provided data, normally the source of geometry is a representation within a CAD-system or geometric modeling kernel or legacy discrete data. Typical examples of such a user would be someone doing an analysis of an existing aircrafts' ability to perform a given maneuver; someone doing shock damage analysis for a detailed ship model; or someone evaluating the performance of a complex antenna as integrated into a complex structure.

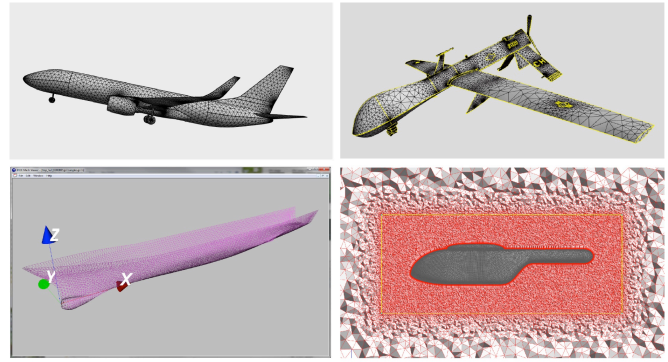

Fig. 1. *Capstone* algorithms work in a geometry-system-agnostic manner. For instance, the same meshing algorithms work seamlessly for the geometries in SMLib™ kernel [27] (top right), LEAPS database [29] (bottom left) and discrete geometry (bottom right)

2) *Design Tool Creator:* The users in this category aim to develop a vertically integrated, and highly automated process for conceptual to early design. They have intimate knowledge about the process and workflow associated with specific acquisition activities. Their main concerns are focused on how quickly they can design, build and deploy custom-environments and tools to support early design, as far as meshing and geometry are concerned. They will usually have complete control of the geometry generation / design process. We can assume they need all the tools needed by the Analysis Modeler at their disposal. The customers for this category of users are design engineers who need tools to rapidly develop, and qualify design concepts based on high-level mission requirements without a high-degree of expertise in geometric modeling and/or meshing. Typical examples of users in this category would be the other development teams engaged in the creation of parametric design tools and environments for conceptual-early design.
3) *Analysis Code Developer:* This group includes developers of physics-based solvers who need programming-access to underlying geometry and meshing infrastructure for spatial adaptivity, ray-tracing, in/out categorizations, and other geometry related queries based on needs of the solver technology and algorithms. Their solvers are often deployed on massively parallel computing platforms and therefore require geometry access/query to be scalable on these platforms. Typical examples of users in this category would

be the developers of complex analysis codes and solvers.

Analysis Data Modelers predominantly use the GUI-based frontend of *Capstone* whereas other two groups primarily used the SDK to integrate or embed *Capstone's* functionality into their specific applications.

3 Impacting the DoD Acquisition Process

A key goal of the CREATE™ Program is to significantly improve the effectiveness of the DoD acquisition process by enabling more physics-based analyses earlier in the design process where it can have the most impact in reducing cost and assessing the design against the requirements. *Capstone* is impacting all stages of the acquisition process as well as helping in the maturation and transition of several new technologies that require specialized analyzable representations.

3.1 Early design stages

The *Capstone* SDK provides a common building block for early-stage design tools and environments by providing the geometry, meshing and attribution based on the desired level of fidelity of analysis needed by the designers. It is the foundation for the air-vehicle early design tool *DaVinci* being developed by CREATE™-AV project to enable development of associative models of air-vehicles comprised of parametric geometry components. The geometry, meshes and attributes needed for simple empirical to high-fidelity physics-based analyses is then available automatically and seamlessly. Figure 2 shows a case where a design geometry can be piped straight to the *Kestrel* solver to determine the hi-fidelity aerodynamic performance characteristics. In a similar manner, the CREATE™-Ships and the CREATE™-RF projects are embedding the *Capstone SDK* in their respective design environments and tools.

There are two key capabilities that *Capstone* platform enables here:

1) The seamless transition to a solver enables automated optimization of the design where geometry or other design parameter may be varied , and
2) The use of abstract APIs and the kernel-agnostic nature of the platform implies that design evaluations may be performed independent of geometry system.

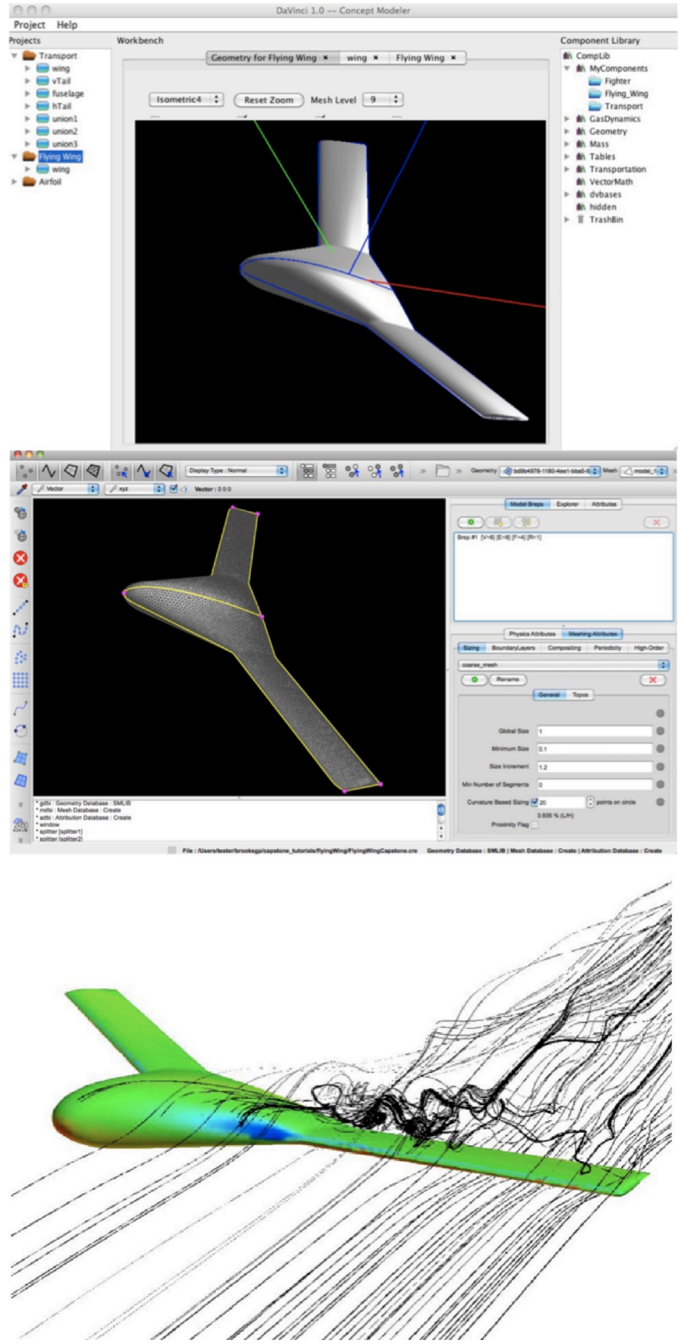

Fig. 2. *Capstone SDK* enables the generation of associative system models consisting of parametric geometry components that may be analyzed based on the accuracy needs of the design phase. This example [10] shows an instance of an early-stage parametric model of a wind-body configuration created in CREATE™-AV *DaVinci* (top), meshed and attributed by Capstone (middle) and then pushed seamlessly into CREATE™-AV *Kestrel* for physics based analysis (bottom) of aerodynamic performance.

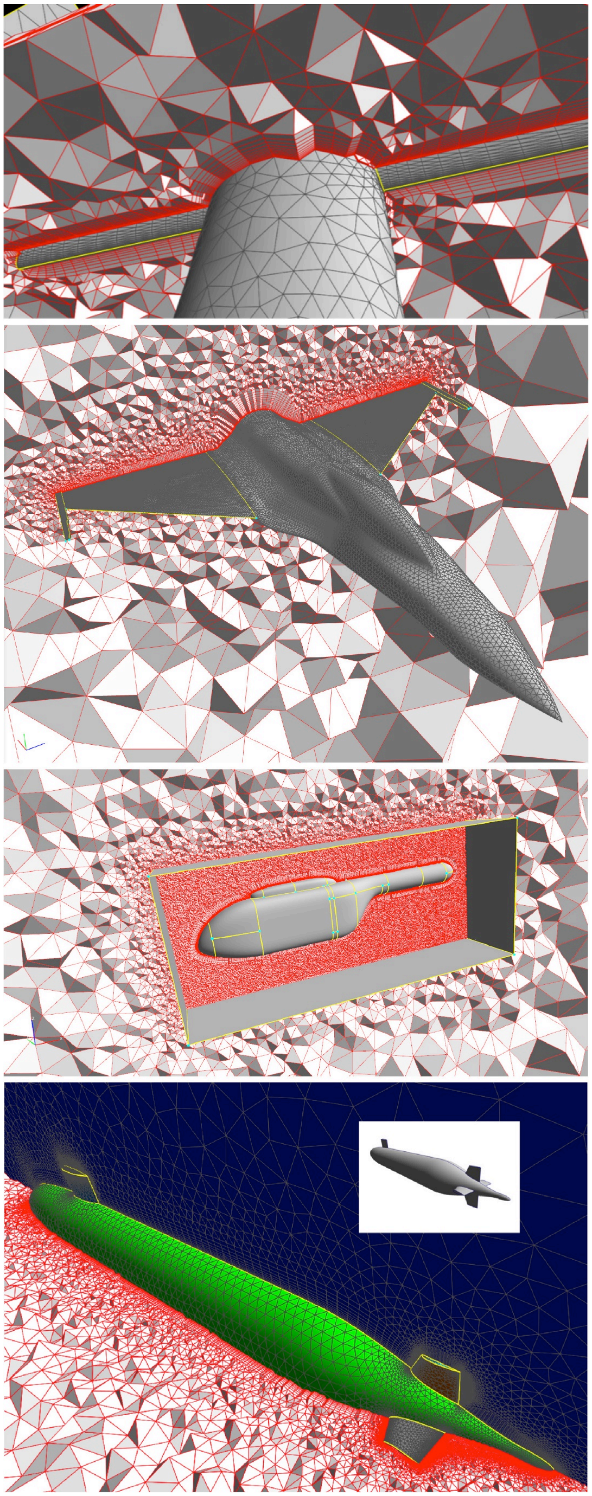

Fig. 3. *Capstone* includes the ability to generate meshes for resolving the flow around complex structures. It has incorporated existing 3rd-party meshing technology [8] as well as developed its own surface and volume meshing algorithms with a novel unified approach to robustly handle mesh anisotropy simultaneously for surface and volume meshing [12],[15].

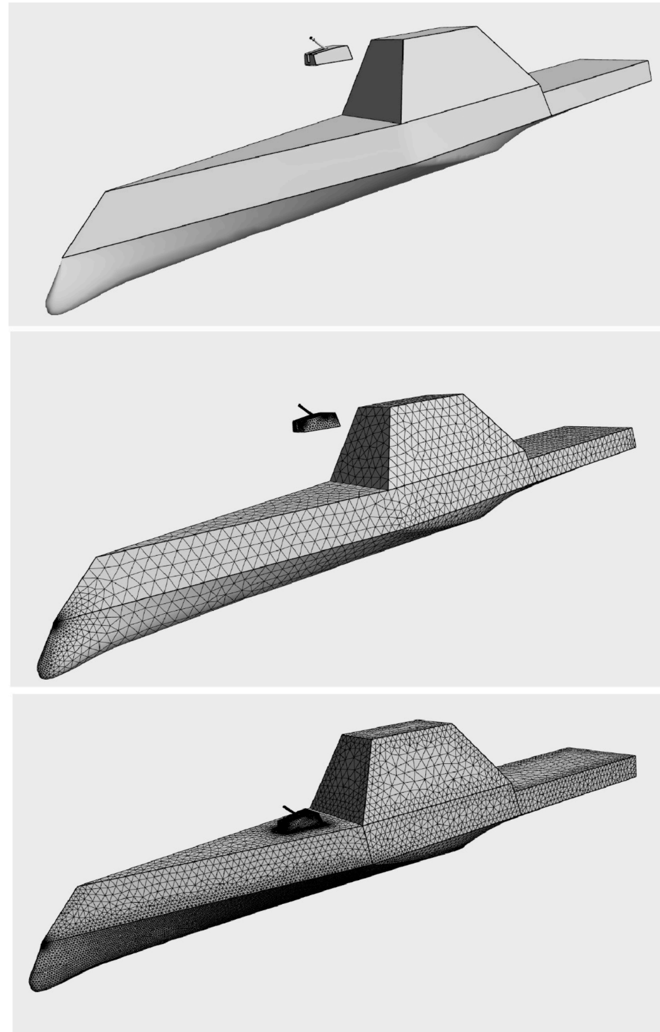

Fig. 4. *Capstone* includes robust Boolean algorithms [7] for discrete geometry to enable rapid and automated preparation of analyzable representations for ship shock-damage analyses when some of the component may only exist in legacy discrete data. This example shows the mesh of a legacy component (gun) being implanted in the mesh of a ship structure.

The second point is very significant because it enables one to treat the design specifications like a recipe that may be evaluated in organizations with completely different geometry (CAD) systems.

3.2 Detailed design stages

Capstone enables the generation of models needed for sophisticated physics-based analyses of several critical problem domains including, flow around air-vehicles, ships and submarines, ship and submarine shock-damage analysis and evaluation of radio-frequency antennas and their integration into different platforms. Figure 3 depicts several examples of *Capstone* meshing capabilities for complex flow analyses.

3.3 Improving turnaround time

Capstone has significantly improved the ability to rapidly produce analyzable representations and reduce the overall cycle-time for the preparation of complex models for ship shock damage analyses. In many instances, such analyses require the integration of dozens or more components into the ship structure. While the ship main structure may have a well-defined clean geometry in a CAD-like system, many of the components are legacy designs whose geometry is only available in some discrete form. This precludes the ability to utilize the Boolean operations available as part of a CAD system or geometry kernel. A longstanding issue was the manual and tedious process of integrating the discrete geometry representations of such components into the main ship structure to get a final model that is suitable for analysis. For large and complex ships this could take up to one year with legacy tools. On top of that, the resulting model may be invalid due to the user error in the manual process which may not be evident before actual analysis is preformed and the results analyzed by subject matter experts. *Capstone* has developed capabilities to bridge this gap by developing a robust algorithm to do discrete Boolean operations (just like the kernel does for CAD-based representations) that enables the automated integration of components. Figure 4 shows an example. The process takes a matter of seconds-to-minutes for each component and it ensures that the resulting model meets the validity requirements of the intended analyses.

Capstone also enables generation of analyzable representations to support complex fluid-structure interaction scenarios such as those involving moving control surfaces, or rotating parts and evaluation of store-separation for flight certifications as depicted in Figure 5.

3.4 A foundation to build other computational tools

The *Capstone SDK* is being used by several tools that are impacting the acquisition community. It provides scalable runtime access to the geometry as well as *strand meshing* [19] capability for

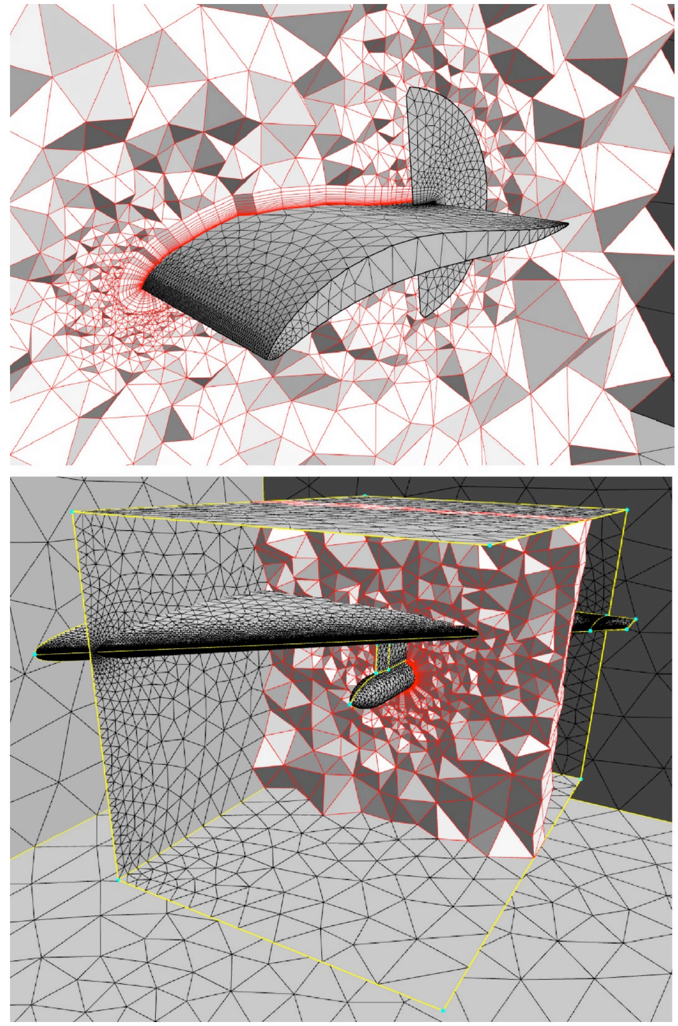

Fig. 5. *Capstone* has several specialized capabilities for complex-flow configurations. It automatically generates the geometry and mesh constructs for including the effects of moving control-surfaces using the sliding-plane approach (top) as well as the overset-based approach (bottom) to do store-separation studies for flight-certification.

CREATE™-AV solvers *Kestrel* [11] and *Helios* [16,17]. Furthermore, it is the foundation for the CREATE™-AV's *DaVinci* [9] tool that provides a design environment for conceptual-to-early design of air-vehicle platforms. CREATE™-RF's *Sentri* [20] solver is embedding the SDK to provide seamless access to geometry, meshing and attribution for antenna design and evaluation. Similarly, the CREATE™-Ships *RSDE* and *IHDE* [18] tools are embedding the SDK for access to its meshing algorithm for design and evaluation of ship and submarine structures.

4 CONCLUSION

Computationally based approaches that use physics-based solvers and leverage the advances in high performance computing platforms are becoming an important way to improve the efficiency of the acquisition process. *Capstone* is proving to be a key enabler of this approach by reducing the cycle time in the generation of analyzable representations as well as enabling hi-fidelity physics-based solutions that rely on *a-postetriori* error analysis and mesh adaptation [25,26]

In the longer term, one can see *Capstone* platform becoming a core component in defense system lifecycle management by providing a common reference for geometry, meshing and attribution for design information. Ongoing activities such as the Air Force's *digital thread* [21] and *digital twin* [22] initiatives and the DoD *Engineered resilient systems* [23,24] program are steps in that direction and *Capstone* is poised to play an important role. One can imagine a scenario where conceptual designs for ships and air-vehicles based on the *Capstone* platform being propagated through preliminary and detailed design stages and used for system enhancements and sustainment. With its use of abstract functional APIs, the platform ensures that the generation of analyzable representations can be treated like a recipe that can be realized seamlessly during any stage of the design process. More importantly, the same recipe may be invoked much after the system is fielded, with potentially different geometry system and meshing algorithms realizing it, to evaluate possible enhancements and other operational issues.

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AUTHOR BIOGRAPHIES

Dr. Saikat Dey's is a Mechanical Engineer with the US Naval Research Laboratory and the Meshing and Geometry Project Manager for the DoD HPCMP CREATE Program. He has a PhD in Civil Engineering (Computational Mechanics). His research interests cover geometry-based high-order methods with applications to structural-acoustics and wave-dependent problems, mesh generation and a-posteriori adaptation. Dr. Dey is a member of AIAA and the USACM.

Dr. Romain M. Aubry is a Research Scientist with Sotera Defense Solution on contract to the US Naval Research Laboratory as part of the DoD HPCMP CREATE Meshing and Geometry Project. He holds a PhD in Civil Engineering specializing in flow problems. His research interests span numerical solution of incompressible and compressible flow problems, mesh generation and iterative solvers. He is a member of AIAA and USACM.

Dr. B. Kaan Karamete is a Scientific Researcher with Sotera Defense Solutions on contract to the US Naval Research Laboratory as part of the DoD HPCMP CREATE Meshing and Geometry Project. He holds a PhD in Mechanical and Engineering Sciences. His area of expertise is in the field of computational numerical simulations especially unstructured meshing, modeling and bio-mechanics.

Mr. Eric L. Mestreau is a Scientific Researcher with Sotera Defense Solutions on contract to the US Naval Research Laboratory as part of the DoD HPCMP CREATE Meshing and Geometry Project. He holds a M.Sc. in Mechanical Engineering (Diplome d'Ingenieur) and Diplome d'Etudes Approfondies (Equivalent to Ph.D. Classes) in Structural Mechanics. His area of expertise covers computational fluid dynamics, structural dynamics, finite element analysis, pre- and post-processing and computer graphics.

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