# Overview of the Airdrop Systems Modeling Project within the Collaborative Simulation and Test (CST) Common High Performance Computing Software Support Initiative (CHSSI) Portfolio

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**The US Department of Defense High Performance Computing Modernization Program Office (DoD HPCMPO) is attempting to address the current lack of a standardized numerical toolset to model and simulate the performance of a typical aerodynamic decelerator system (ADS). No such tool or system of tools exists that can simulate with high fidelity the performance of an ADS throughout its operational envelope. Within the Collaborative Simulation and Test (CST) Common High Performance Computing Software Support Initiative (CHSSI) portfolio, the HPCMPO is funding the Airdrop Systems Modeling (ASM) project to deal with this need. A collaborative group has been formed to produce a generic Simulation Control Module (SCM) that will serve as a software breadboard on which to connect and combine such analysis tools. The SCM will provide a framework within which an airdrop design engineer or analyst may combine appropriate groupings of analysis and simulation capabilities. In addition, through the interaction of this module and the portfolio's integration software, simulation and test results will be able to be pooled, compared, and used to form a coherent view of the predicted system's operational characteristics.**

## I. Introduction

THE operation of a typical aerodynamic decelerator system (ADS) entails a transition from horizontal to vertical motion with an associated deceleration and reduction of the system speed by an order of magnitude. As the system transitions to steady descent it also undergoes an inflation phase where the system encounters elevated stress levels in its structural components. Various analytical, semi-empirical, and numerical simulation tools have been developed to address the various phases of the decelerator system's operational profile. These tools tend to be very idiosyncratic to the developer of the tool and not generally applicable across all phases of the operation of the decelerator system. One obstacle standing in the way of a generally applicable tool or methodology is the current lack of a standardized infrastructure that defines the coordinated operation of the various analysis tools. This coordinated operation could be required to perform a tightly-coupled fluid-structure interaction (FSI) simulation or



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could be part of a scenario where the researcher desires to use one or more computational fluid dynamics (CFD) analysis tools in the simulation, tailoring the optimum tool to the appropriate regime of flight for the system. (Within this paper, *CFD* is used to refer to the field of Computational Fluid Dynamics, *CSM* is used to refer to Computational Structural Mechanics - although this field can alternatively be referred to as *CSD* (Computational Structural Dynamics), and *FSI* refers to the combined solution of a coupled fluid and structural system where Fluid-Structure Interactions are significant.) An impediment to evaluating and refining the quality of the numerical simulation is the difficulty inherent in relating the simulation results quantitatively to the test data beyond isolated points of comparison.

An ongoing portfolio funded by the US Department of Defense High Performance Computing Modernization Program Office (DoD HPCMPO) has been initiated to address these two issues. The airdrop FSI analysis code developed by the modeling team led by U.S. Army Natick Soldier Center has been used as the starting point for creating a generic Simulation Control Module (SCM). The SCM will provide a framework within which an airdrop design engineer or analyst may combine appropriate groupings of analysis and simulation capabilities. In addition through the interaction of this module and the portfolio's integration software, simulation and test results will be able to be pooled, compared, and used to form a coherent view of the predicted system's operational characteristics.

## II. Current State of the Art

Early innovative work applied the finite element methodology to problems involving moving boundaries and interfaces[1,2]. Building upon this work, the modeling team led by the Natick Soldier Center performed pioneering work in applying FSI techniques to the ADS problem[3-9]. More recently the modeling team has been applying an iteratively-coupled finite element-based FSI methodology to various additional ADS challenges[10-12]. The fluid dynamics portion of this methodology is based upon the Deforming-Spatial-Domain/Stabilized Space-Time (DSD/SST) formulation that was developed for flows with moving boundaries and interfaces. The structural mechanics portion of the methodology is based upon the principle of virtual work for a cable-membrane structure under tension. In recent years several other investigators have also applied different FSI techniques to the ADS problem. Strickland and his colleagues[13-14] have modeled the vorticity transport equation and have applied it to flexible structures and bodies. The coupling between the fluids code and the structural dynamics code is accomplished by using an added mass term in the fluids code that reflects the influence of the structure on the fluid. Lingard,[15] and Taylor and his analysis team,[16-18] have applied the commercial code LS-DYNA with its Arbitrary Lagrangian-Eulerian (ALE) formulation to parachute systems. In this approach, the fluid mesh is alternately allowed to move and distort as the simulation progresses and then is reset back to its original configuration at a user-defined frequency. During the reset process mass balances and transport processes are conserved in an "advective" correction.

In each effort, the results and models are distinct to the software being used. Data-sharing between the analysis packages is difficult or impossible. For a member of one research team to take advantage of a technological innovation from another group's software essentially requires a reformulation of the problem in the other's software environment. There is obviously a need for a mechanism or environment that can facilitate multiple approaches to the ADS modeling challenge.

## III. Coupling Strategies

An FSI simulation is typically characterized by the way in which the fluid and structural components of the system are coupled numerically. Where the response of the fluid and structural components are calculated separately, the approach can be referred to as *partitioned, iteratively-coupled,* or *block-iterative.* Depending upon the degree of fidelity to which the mutual influence of the two components is modeled, the *partitioned* approach may also be referred to as *weakly-* or *strongly-coupled*. Where the response of both of the fluid and structural components are solved together simultaneously, the simulation approach is often referred to as a *monolithic* or *direct* solution.

Although the *partitioned* approach is more modular, allowing for more freedom in defining the degree of coupling between the fluid and structural components of the system, it's primary drawback is that this freedom can result in an inability to satisfy conservation principles across the interface. For systems where the fluid mass or density is comparable to that of the structural component the *partitioned* approach can tend to go *unstable*. The monolithic approach tends to produce stable solutions for such problems. Another potential advantage of using a *partitioned* approach is the ability to optimize the time-scales used for the temporal evolution of each component of

the system. The *monolithic* approach, on the other hand, typically evolves the simulation with a system-wide constant time-step. The historical wisdom is that the *partitioned* approach is computationally faster than the *monolithic* methodology. But in some instances where the *monolithic* approach more accurately accounts for the coupling between the two components of the system, the overall cost of the *monolithic* approach might be less due to the fact that although each iteration step takes more computational effort, the method converges in fewer steps. It is unclear for the general ADS FSI application as to which method is more computationally efficient and choosing a particular approach to modeling an ADS application tends to be based more upon concerns of accuracy and solution stability.

Since the SCM might be required to support either *partitioned* or *monolithic* approaches, a quick review of the current work in this area is informative. Causin, et al.,[19] provide an interesting study relating the stability of *weakly-coupled* and *strongly-coupled partitioned* schemes to physical parameters. A simple linear FSI system is used to analytically determine stability and convergence criteria. The same criteria appear to apply to complex nonlinear FSI problems. Stability and convergence are shown to strongly depend on the structural mass to fluid mass ratio and on geometric properties of the solution domain (namely, stability and convergence decrease as structural mass decreases). Even if a *strongly-coupled partitioned* scheme is stable, its convergence may be very slow depending on this mass ratio. Fernandez and Moubachir[20] determine the exact jacobian matrix in conjunction with a *partitioned* scheme and find that using it significantly improves the convergence rate. Hübner, et al.,[21] present a *monolithic* formulation where both the CSM and CFD are formulated as space-time finite elements. They are not able to obtain the jacobian matrix needed for Newton-Raphson and discuss the difficulties encountered in solving the resulting system using linear algebraic equation solvers (LAEs). Heil[23] deals with development of a LAE solver for *monolithic* schemes. Michler, et al.,[23] state that energy conservation (and therefore, stability) is only trivially maintained under restrictive interface compatibility conditions for *monolithic* schemes based on results from a simplified prototype FSI problem. They propose a modified spatial discretization to correct this. Heil[22] and Michler, et al.,[23] deal with *strongly-coupled partitioned* schemes and the use of block Newton iteration to improve stability. Tezduyar, et al.,[24] examine the use of coupled CFD, CSM, and mesh-moving. They present three FSI coupling schemes: *block-iterative*; *quasi-direct*; and *direct* schemes. The *block-iterative* is a *partitioned* scheme. The *quasi-direct* allows the system (made up of the fluid and structural components) to be solved directly while the mesh movement is treated separately. In the *direct* coupling case, the fluid, structure, and mesh movement components are addressed simultaneously. In the two examples presented, the *block-iterative* scheme is used to simulate a T-10 soft landing while the lightness of the flag material in the flapping flag case requires the use of the *quasi-direct* scheme.

Since there are a variety of possible approaches to the FSI simulation problem, each with its own strengths and weaknesses, and applications where one approach might be more relevant than another, it makes sense to formulate the computational infrastructure to accommodate a wide variety of methodologies. The approach taken in designing the SCM was to build upon an already working FSI strategy, a *block-iterative partitioned* methodology; generalize it; and then extract the elements required from the generalized model to form the SCM.

The *block-iterative* solution strategy as it is applied to the parachute problem is shown schematically in Fig. 1. First one performs a Newton-Raphson step for the fluid system. The appropriate pressures are then transferred to the structural system through the fluid-structure interface. Next, a Newton-Raphson step is performed for the structural system. The displacements and velocities of the surface mesh are transferred back to the interface. The necessary mesh movement is determined and applied in an update to the fluid system. The process is repeated for a predetermined number of iterations or until a desired level of nonlinear-iteration convergence is reached, and process is applied to the next time-step.

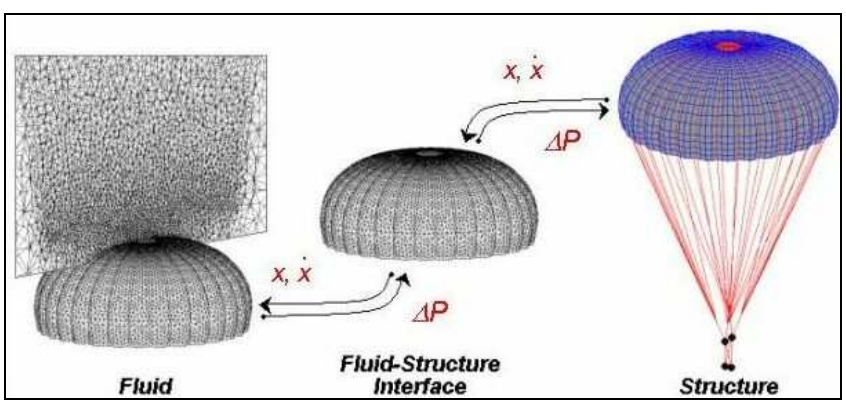

**Figure 1. Current Fluid-Structure Interaction (FSI) execution methodology.**

## IV. CHSSI Technical Approach

The development of the Simulation Control Module (SCM) requires starting with the existing FSI system and then generalizing it so that the structure of the components and the interconnection between the components can then form a generic FSI infrastructure. A current version of the software analysis code used by the modeling group was frozen and termed the *FSIBASELINE*. The sequence of its operation is given in Fig. 2. The functional interconnectivity was then generalized into a generic SCM (see Fig. 3). Excluding the required pre- and post-processing, the module is equipped with an internal data structure that accommodates the physical description of the system being simulated (its discretization, such as the computational grid) as well as the state of the model (such as the current values of the flow variables in the flow regions and stress states of the structural components). The functional operation of the simulation is then broken into separate modules that have interface software to facilitate communication between the modules and the data structure that represents the state of the simulation solution.

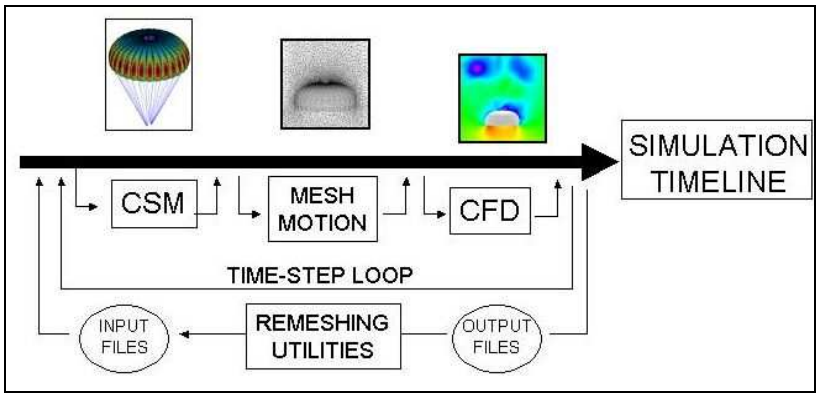


**Figure 2. Current simulation *FSIBASELINE* execution timeline.**

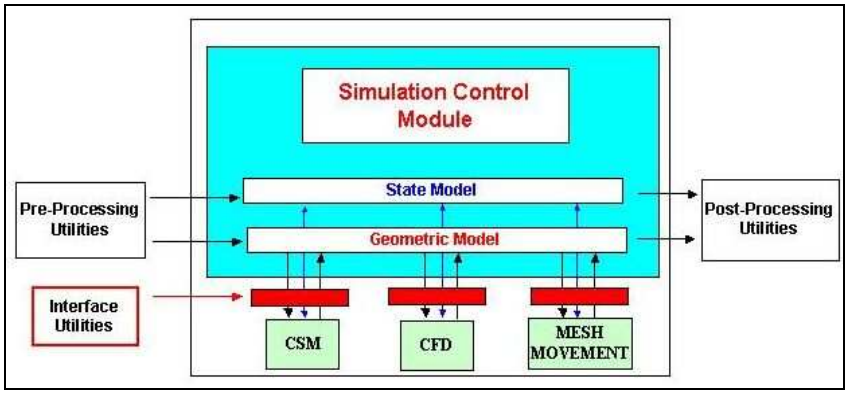


**Figure 3. Generalization of FSI simulation procedure with modularity of solution function.**

The definition of the SCM can be further delineated to accommodate an even more generic functionality (see Fig. 4). The SCM now controls the initial setup of a *FSI DATA Kernel* (the requisite data structure to carry out the simulation), the execution logic of the simulation modules (which reside in a generic *"Solver Space"*), the interaction between the modules and the *FSI Data Kernel*, and final post-processing and output. Conceptually the *FSI Data Kernel* is the data-structure and amount of computer memory required to store the geometry and state information for the total system – the fluid and structural components as well as the additional coupling terms or

data that might be used when comparing results. The *"Solution Space"* is at this point merely a conceptual placeholder for a variety of operations that can be performed within the execution loop.

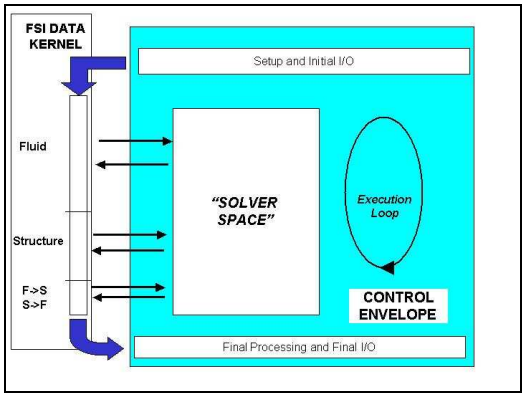


**Figure 4. Generic Simulation Control Module (SCM) configuration.**

Figure 5 shows a representation of the functionality of the *FSIBASELINE* software in terms of the SCM formulation. Within the iteration loop, the *CSD*, *CSM*, and *Mesh Motion* modules are invoked in turn. The *CFD* module executes and stores both the updated fluid state and the $\Delta P$ values for the interface into the *FSI Data Kernel*. This interface pressure data as well as the current structure state provide input for the *CSM* module execution. The *CSM* returns an updated structural model and deformations and velocities of the interface elements. The new interface information is used by the *Mesh Motion* module to create a new configuration for the fluid component of the system. The execution process is then repeated for a user-specified number of iterations with periodic data storage of iteration results.

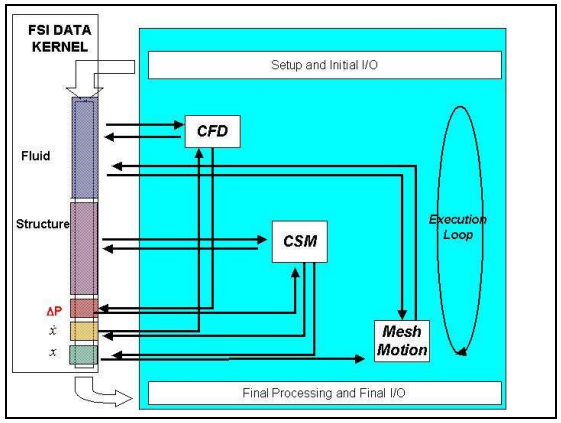


**Figure 5. *FSIBASELINE* operation formulated within the SCM Model.**

It is the intent of the project to construct the SCM so that it can be used in several different ways. The following cases represent non-exhaustive list of possible scenarios where the SCM might be used to perform FSI simulations, used to compare the results of such simulations with experimental databases, or used to interact with reduced order modeling (ROM) of ADS platforms.

One way of achieving Verification and Validation of the solvers used within an FSI simulation is to compare the results for the same configuration obtained from different simulation codes. An example of such an effort is the simulation portion of the *Airflow Influence on Airdrop (AIA)* effort being performed by U.S. and German researchers.[25] A possible application of the SCM in this context is schematically represented in Fig. 6.

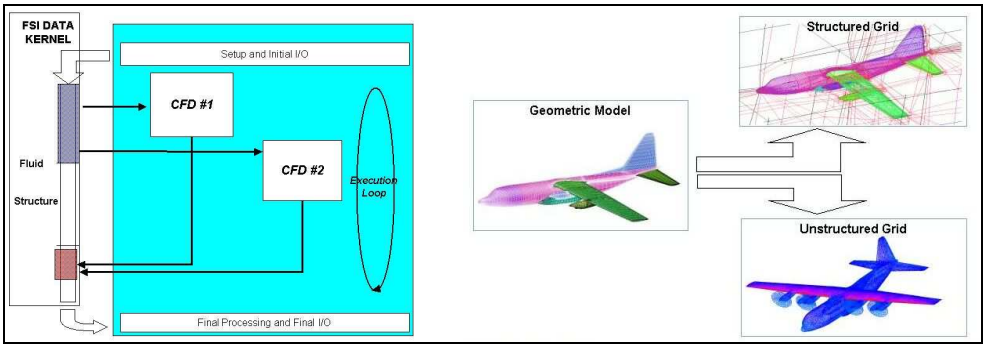


**Figure 6. Computation and comparison of a flow-field using the same model but different CFD solvers.**

It might also be desirable, as illustrated in Fig. 7 using the multi-domain concept[8], to use different flow solvers in different portions of the flow domain. In this case the solvers access portions of the fluid data structure intrinsic to them as well as regions of the flow that overlap with those influenced by other CFD solvers. Another variant of this problem might be the situation where an *overset* solver is being used to solve the flow-field local to an ADS system as it moves through a larger flow environment. The SCM can also be applied to the *submodeling* of a structural system as well. (*Submodeling* is a practice in CSM where a detailed model of a portion of a mechanical system is executed in conjunction with a coarser model for the whole device, quite similar in practice to the use of the *overset* methodology in CFD.)

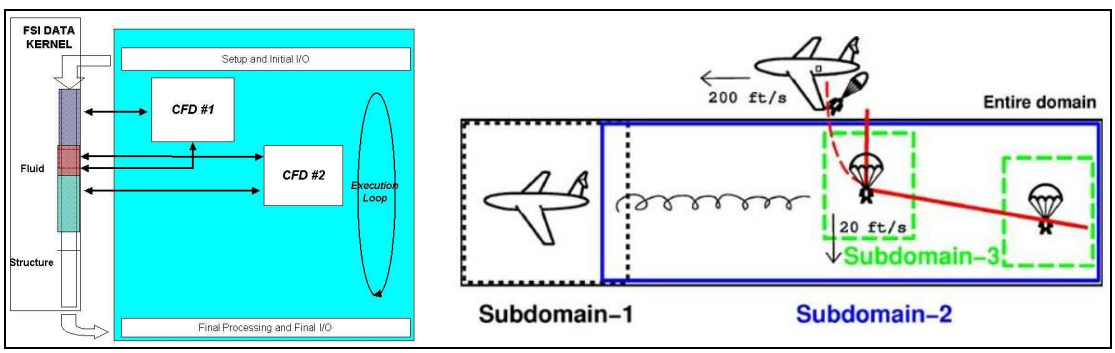


**Figure 7. The use of different flow solvers for different portions of the flow domain.**

For the situation where the fluid and structural components have a comparable mass, some form of *monolithic* solver is most likely required to accurately and realistically model the physical system. Such a system has been experimentally characterized by Desabrais and Johari[26] and is schematically represented in Fig. 8. The solver in this case influences both the fluid and structural part of the *FSI Data Kernel.* It also interacts with a secondary part of the *FSI Data Kernel* relating to movement of the interface that is used as input for the mesh movement calculations.

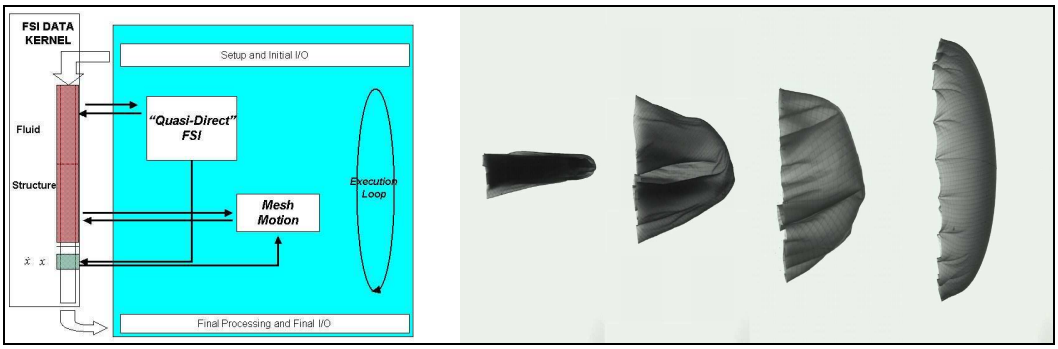


**Figure 8. The use of the SCM to model a *monolithic* formulation.**

The final example potential application of the SCM is to use it as a means to connect the simulation to external information. This connection might merely entail bringing the information in from an external data source (such as an experimental database) and then comparing the results to this database. This is another objective of the AIA effort[25] and this process is shown schematically in Fig. 9. The utilization of the SCM might also involve using a database or empirically-derived reduced order model (ROM) to drive the motion of the structure. This type of application is different from a full FSI calculation because the motion or deformation of the structure is proscribed and not a function of the fluid component response. The ability of the SCM to allow high fidelity simulations to interact with experimental databases or ROMs as it is the first step in creating a bridge between the high-performance computing (HPC) and Test and Evaluation (T&E) communities on a quantitative level.

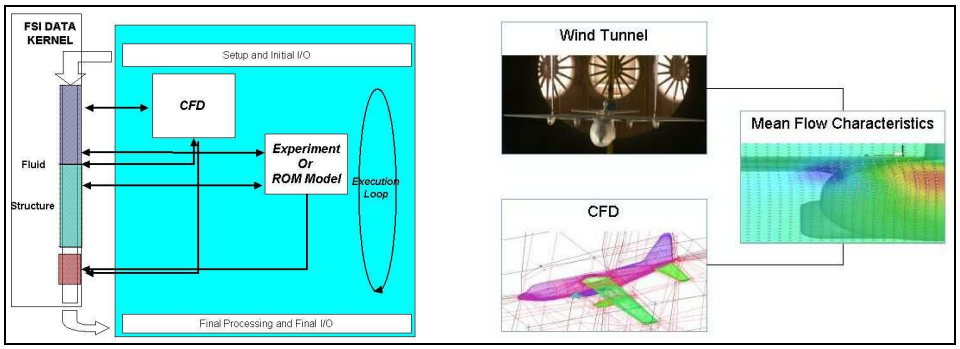


**Figure 9. Interconnecting HPC simulations and experimental databases and empirically-derived models.**

## V. Conclusion

The Airdrop Systems Modeling project within the CST CHSSI portfolio is approaching the half-way point in the three-year program. Excellent progress has been made in laying the conceptual groundwork for the definition of the Simulation Control Module (SCM) as well as writing the software required for its operation. Benchmark problems have been identified and run as part of the Verification process for the operation of the *FSIBASELINE* code, and will be used as the SCM is developed to ensure accurate and efficient operation of the SCM-based simulation methodology. The end product of the project is meant to be a software tool that can be used to advance the state of the art in ADS simulation technology. Involvement and interest is solicited from the technical community as input to make the SCM and its operation more capable and attractive to use by the design, analysis, and test and evaluation communities.

## Acknowledgments

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