Covert, Re-usable and Multi-role (CRaM) UAV

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Presently at Composite Engineering Inc. (CEi), an initial design study has been completed on a covert re-usable and multi-role (CRaM) unmanned aerial vehicle (UAV). The configuration is based on the concept that next-generation military aircraft systems for re-supplying troops in the field, will replace the older propeller airplanes with jet-engine airplanes. As a result, to maintain airplane flight efficiency and optimum range, aerial drops of material and supplies must now be performed at altitudes up to 30,000 feet. Consequently, current parachute-equipped re-supply systems are no longer feasible from such altitudes. To address this, the new system requires that it may be deployed at altitude, and covertly cruise and/or descend to the drop location. In addition, this new system requires that the descent vehicle is either destroyed after deployment of a supplies canister, such that no traceability exists, or the system must be capable of deploying the supplies canister and return, via flight under its own power, to a safe zone for recovery. CEi has addressed this need by first employing a multi-disciplinary optimization (MDO) code which couples aerodynamic vortex lattice based methodologies with an MDO solver, followed by higher fidelity computational fluid dynamic (CFD) analysis of the near-optimized configuration, for further refinement and characterization.

I. Introduction and Historical Significance

A. Historical Case for a New Design

Aerial re-supply to front line troops has been a war-fighter/planner method of re-supply since World War I and the dawn of the airplane. During World War II, aerial parachute-equipped re-supply containers were a routine method for re-supply of food, ammunition, medical supplies and general goods. Since that time, the methods of re-supplying front line troops has seen little change; airplanes and supplies have changed and evolved, but the use of propeller powered airplanes has been a mainstay in the military. Propeller powered airplanes are well-matched to this mission where the propeller remains at or near optimum operating efficiency at lower altitudes and airspeeds. However, with the onset of a military fleet upgrade to jet-powered airplanes, the ability no longer exists to remain efficient at low altitude. Thus the methodology for troop re-supply must also be updated with a system which is capable of being released at higher speeds and altitudes. Additionally, due to the time in which it requires to descend from high-altitude release to arrival at ground-level, the vehicle needs to be capable of maintaining low visibility, such that the supplies canister can reach its destination undetected.

The CRaM UAV system seeks to meet the above listed mission requirements of safely delivering a canister filled with troop supplies, un-detected from deployment to insertion, by means of engineering design using an MDO routine. The *primary requirement* is therefore to develop a vehicle which can be either destroyed after deployment of a supplies canister, such that no traceability exists, or the system must be capable of deploying the supplies canister and return, via flight under its own power, to a safe zone for recovery.

The *secondary requirement(s)* of the multi-role CRaM UAV is the capability to carry alternative payload(s) for the purposes of reconnaissance, or aerial radio frequency (RF) relay. While these secondary requirements are important, they do not provide the same aerodynamic or mass property stress to the analysis, of high enough magnitude, on which to base the MDO routine and design study. This is primarily

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because these payloads remain attached and the aerodynamics and mass properties remain nearly constant throughout the mission — not including fuel burn.

B. The CRaM Argument

The CRaM vehicle presents an interesting design study, wherein the integral-vehicle (IV) — descent vehicle (DV) plus a supplies canister (SC) — requires a propulsion system which is capable of range extension, but not climb; whereas the DV, post canister deployment, must to be capable of continued flight, including climb and possibly minimal advanced maneuvering, see figure 1. Additionally, upon deployment of the SC, the DV experiences a large shift in the X and Z center of gravity (CG) locations and mass moments of inertia (MOI). Therefore the flight system must be capable of large transients in CG and MOI, yet remain stable and controllable until recovery.

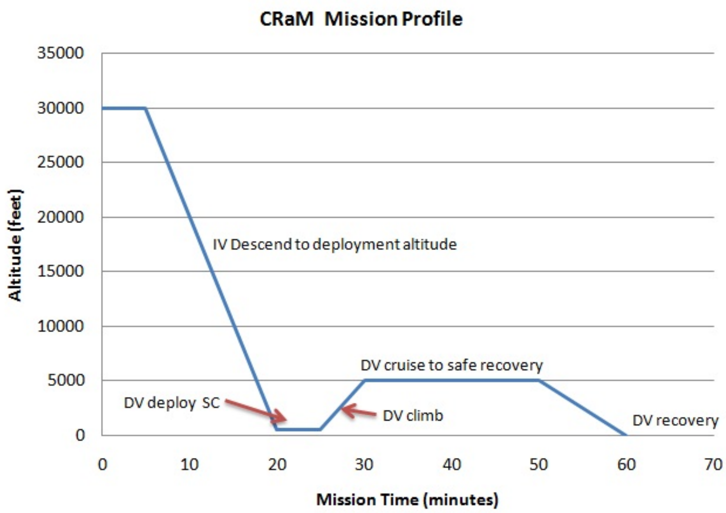


Figure 1. CRaM Mission Profile.

To meet the above objectives, the MDO code will seek to maximize the Breguet Range Equation while minimizing the total IV weight plus payload ($W_{airplane}$ + 250 lbs.):

$$Range = \int_{w_i}^{w_f} \frac{V(L/D)}{-CW} dW = \frac{V}{C}\frac{L}{D}\ln(\frac{W_i}{W_f}) \qquad (1)$$

where the range can be manipulated into terms of velocity, lift coefficient (C_L), and drag:

$$V_{best\ range} = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{3K}{C_{Do}}}} \qquad (2)$$

$$C_{L\ best\ range} = \sqrt{\frac{C_{Do}}{3K}} \qquad (3)$$

$$D_{best\ range} = qS(C_{Do} + \frac{C_{Do}}{3}) \qquad (4)$$

where W is the weight of the vehicle, ρ is the density of air, S is the wing reference area, K is the drag-due-to-lift factor,

$$K = \frac{1}{C_{L\alpha}} \qquad (5)$$

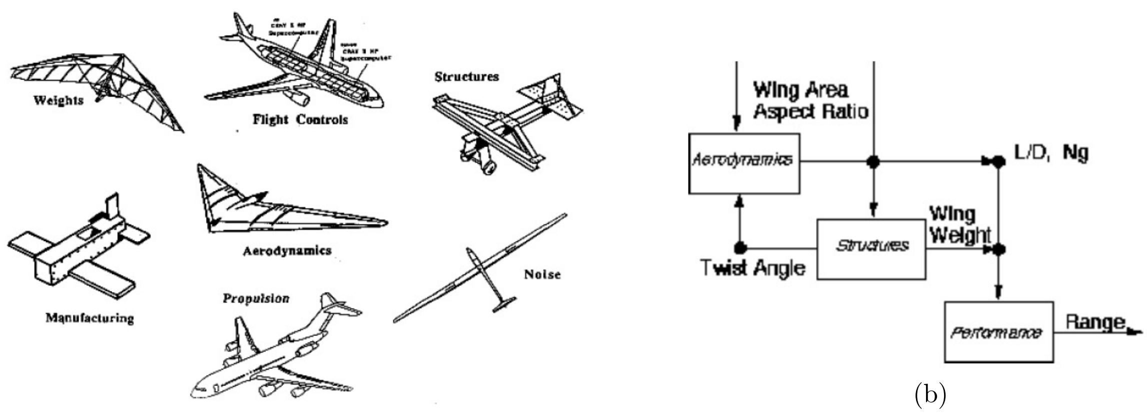
and C_{Do} is the drag coefficient of the vehicle at zero α. While the IV is in descent, it will be assumed that power (thrust) nearly equals drag, while the post-deployment DV thrust is slightly greater than drag, allowing the vehicle to climb:

$$
\begin{aligned}
T_{IV} &\leq D_{IV} = qS(C_{Do} + KC_L^2) && (6)\\
T_{DV} &\geq D_{DV} = qS(C_{Do} + KC_L^2) && (7)\\
L_{IV} &\leq W_{IV} = qSC_L && (8)\\
L_{DV} &\leq W_{DV} = qSC_L && (9)\\
V &= \sqrt{\frac{2}{\rho C_L}(\frac{W}{S})} && (10)
\end{aligned}
$$

The MDO routine will also seek to maximize the payload volumetric area, while minimizing the vehicle mass, and thereby affecting the structural characteristics. Mass properties equations will be employed in the analysis, based on historical data and airplane design methodologies for fighter aircraft.[11] While structural calculations will be made using CEi internal empirically derived values for composite laminate thickness versus strength and density.

II. Modeling Strategies

The CRaM design philosophy was influenced by the low observable (radar cross section) aircraft designs of the F-22 and F-35, as well as the carbon-composite manufacturing capabilities of companies like Composite Engineering Inc.,[1] and CEi's experience in unmanned aerial targets. The initial investigation into the CRaM design was first to determine an IV planform which was statically-stable, with aerodynamic characteristics similar to literature[8,13] and applying the literature results as a basis from which to start a multidisciplinary-optimization, varying: inboard-to-outboard planform area, wing-sweep, wing-twist, airfoil-family, airfoil-thickness and chord length, see figure 2b. Upon obtaining a preliminary design, a study was performed on the entire angle-of-attack (α) and angle-of-side-slip (β) envelope, with special interest in the longitudinal stability characteristics as a function of center of gravity variation.



(a) (b)

Figure 2. MDO in Airplane Design[9] (a), MDO flow diagram[4] (b).

Comparing the stability coefficient results to literature data available in stability and control,[3,5] further investigation was made, and an initial 6DOF simulator was developed in MatLab & Simulink. By employing a basic attitude hold autopilot block and performing simple pitch-up maneuvers and roll maneuvers, the simulation provided a benchmark from which to test the vehicle dynamics for further optimization. Later, tuning of the aerodynamic properties would be obtained with higher-order methods, and 6DOF results could be obtained with higher fidelity.

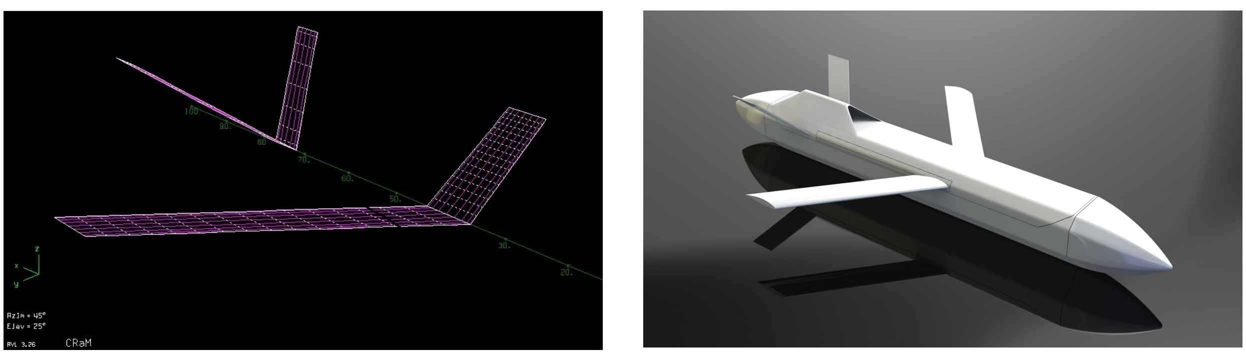
A. Low-Order Methods

The initial investigation managed the pitch moment in two ways; first by creating pitch stability through wing sweep, and second by applying lower cambered airfoils on the inboard regions of the CRaM wing and higher cambered airfoil sections on the outboard regions of the CRaM wing. The cambered airfoil creates two things: first, the restoring pitch-moment common to cambered profiles, creates pitch stability, and second, the cambered profile, when combined with proper wing twist and airfoil thickness, creates the optimal lift distribution over the wing, which increases the efficiency of the wing, and ultimately increases the maximum range. Additionally, by varying the airfoil camber over the span of the wing, effective dihedral is produced, without geometrically cranking the wing. The virtual dihedral creates roll stability, which is simultaneously enhanced by the IV being a high-wing design, which also increases roll stability.

The optimized stability and range maximization was obtained by applying a gradient-based multi-disciplinary design optimization (MDO) routine, coupling MatLab with Athena Vortex Lattice (AVL),[2] a vortex-lattice-method code. The MatLab-AVL optimization obtained a compromise of airfoil-family, airfoil thickness, wing sweep and wing twist, and ultimately the MDO results compare well with the findings of.[4,6,7,10,15,18] Figure 3a presents the final version of the VLM model. During the initial optimization study, the control surfaces were assumed "locked" at zero degrees deflection, until a statically stable airplane met the requirements of the IV. Following this study, the control surfaces were engaged and movable, to determine the control surface effectiveness against maneuvering requirements for both the IV as well as the DV.

By applying the MatLab-AVL routine in a batch-mode, an analysis was performed throughout the flight envelope with sweeps of the α and β envelope at various velocities. The result is a complete 6DOF aero-database for the simulation, as well as a series of surface plots which provide a quick-look reference of the aircraft force and moment coefficients over the entire design space, see figures 6 & 7.

Based on the VLM results, a 3D parametric CAD model was created for CFD analysis. The CAD model, is linked to a design table which provides general sizing information for wing size, airfoil shape and thickness, fuselage shape, etc.. Figure 3b presents the resulting model geometry from this initial investigation, with some shape enhancement post-processing, the same geometry which was used in the CFD analysis.



(a) (b)

Figure 3. CRaM vortex lattice model (a), CRaM preliminary CAD model (b).

B. High-Order Methods

1. Mesh

A systematic approach was taken for the investigation of the CRaM vehicle using CFD, first to determine grid dependencies on the results, and second to provide the "tuning" values needed for the Low-Order database. A full model was used, because of the need to model yaw-moment, and an initial mesh was created using engineering experience in CD-Adapco STAR-CCM+ for aircraft profiles of similar size.

The initial mesh resulted in a structured-mesh domain which contained 10.4 million elements, followed by progressively coarser domains with 8.4, 6.2 and 3.4 million elements. To capture the boundary layer, six prismatic layered cells were used, and were varied in thickness throughout the grid dependency study. Ultimately, the study revealed that a domain of 6.2 million cells provided nearly equal accuracy, similar convergence and with good computational time, when compared to the finer mesh domains. At low α and β – Lift, Pitch Moment, Yaw Moment and Roll Moment were within 5-10% of the Low-Order method results.

Convergence of the mass, momentum and energy equations typically occured within 1000-1500 iterations, with all residuals flat-linning at or below 1E-5. Further refinement of the model will be performed in a follow-on study, applying mesh restrictions and refinements in the airplane wake in order to better asses the vehicle drag.

2. Physics

Based on previous experience in aircraft studies using STAR-CCM+, the physics were modeled using a Reynolds Averaged Navier Stokes (RANS) solver, with a 2^{nd} order segregated flow model (convection/ diffusion). One of the many driving factors in laminar to turbulent flow transition are 3D effects, where higher pressure gradients in one direction, over another direction (see figure 4), induce instabilities in the boundary layer, thus creating transition. A two-equation turbulence model was applied with the assumption that the flow characteristics to be modeled were of similar Mach Number, Altitude and surface roughness (thereby imposing a critical Reynolds Number) for the operating conditions of the vehicle. Additionally, based on equation 11, the wing may be assumed to be completely turbulent due to wing sweep alone.

$$Re_{trans} = -6.0559E^{+5} * \Lambda_{LE} + 2.6799E^{+7} \quad (11)$$

where Re_{trans} is the Reynolds number above which transition occurs due to leading edge (LE) wing sweep, Λ_{LE}.

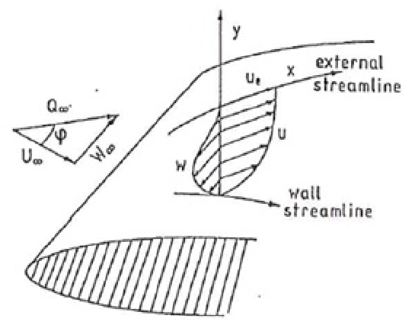


Figure 4. The 3-Dimensional Boundary Layer.

An SST (Menter) $k-\omega$ model was applied, with compressibility correction and all y+ wall treatment. Both, previous studies, and available literature, reveal that the SST model was more appropriate for this aerospace application as it blends the near-wall turbulence $k-\omega$ model with the transition region captured by the $k-\epsilon$ model. Based on standard day atmospheric conditions, the model was run at: Mach 0.55 at 30k, 15k, and 5k ft, respectively, for α and β combinations of [0, 4, 8, 12] and [0, 3, 6] degrees, respectively.

III. Initial Results

The Mach 0.55 test cases were important to this study because the lower-order results were obtained using an in incompressible solver. Once a good correlation was obtained between the lower-order method and the CFD, a full test matrix was examined [a]. Examining first the higher Mach numbers, at the optimized cruise condition, Mach 0.60, followed by more computationally expensive low Mach numbers, Mach 0.20 (canister deployment), where a low-Reynolds number correction model was applied. In this flight regime, the CRaM is prone to lateral-instabilities due to high angles-of-attack combined with asymmetric gust loads or crosswind. Cases will be investigated in the $\alpha = 10^o - 16^o$ range, to observe stability characteristics. Initial results are presented in figures 6 & 7. These figures reveal good correlation of the VLM results (color map) compared to the CFD results (mesh). The linearity of the VLM results is attributed to the inability of the vortex lattice model to predict and solve for flow separation and flow asymmetry. In contrast, the CFD results display non-linear trends as expected, demonstrating the effects of flow separation and angularity

[a]At the time of the writing of this report, these tasks are still being carried out

as the angle-of-attack and angle-of-side-slip are increased, see figure 5. Both, the longitudinal and lateral-directional results are stable and compare well with similar size aircraft coefficients available in literature.[8,13]

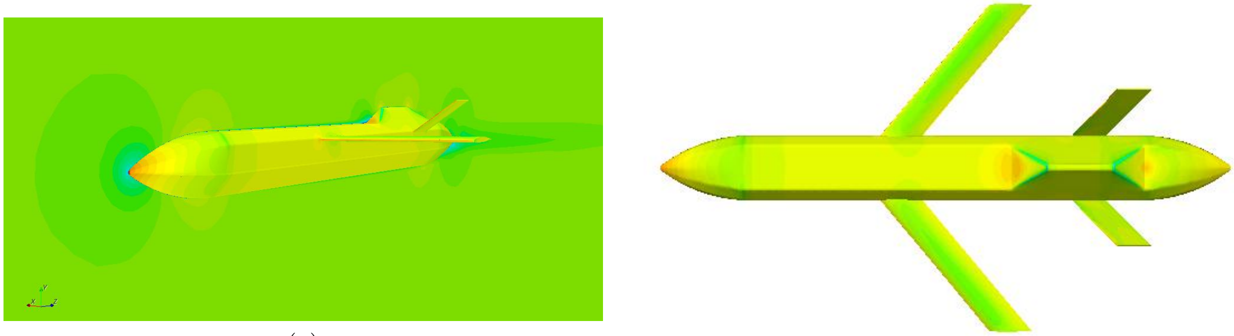
The following quantities are a result of the initial CRaM vehicle investigation (further refinement will enhanse the validity of these results):

- Descent Range $_{engine\ out}$ = 60 nm
- Descent Range $_{engine\ lit}$ = 570 nm
- Total Mission Range $_{engine\ lit}$ = 850 nm
- Fuel Fraction: $W_f/W_o = 0.15$
- Payload Fraction: $W_p/W_o = 0.72$
- Launch Weight: $W_o = 380$ lbs
- Overall Dimensions = 9.5 x 1 x 1 (l, w, h) [ft.]
- Propulsion System = JetCat P-200 (single engine)

IV. Concluding Remarks

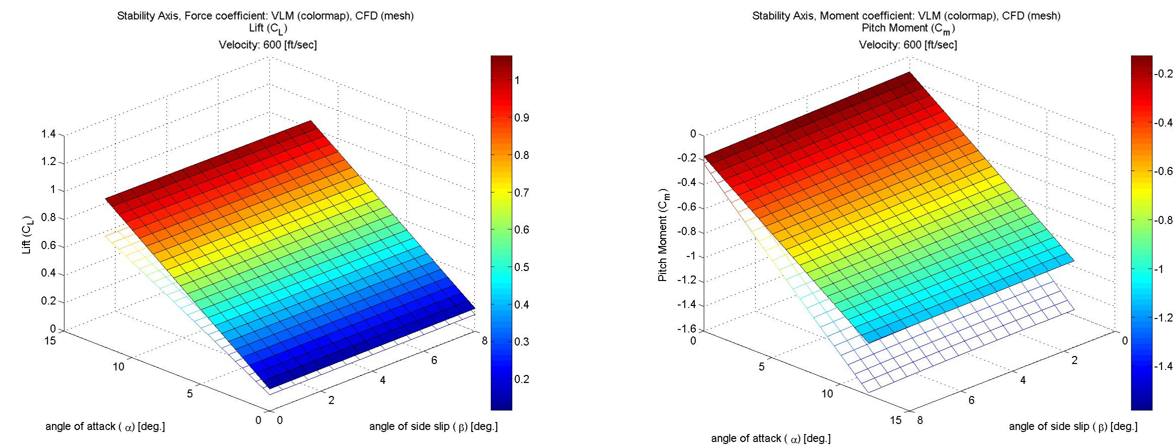
The present investigation into the CRaM UAV configuration, reveals that MDO methods provide a fast, accurate and cost-effective return on the time invested into the trade study. It was also found that the higher-order methods confirm the findings, with increased accuracy, compared with the lower-order methods. Initial results reveal that the present configuration is sufficiently stable, when compared with the literature.[8,13] The CRaM configuration appears to be robust and capable of performing missions of re-supply, reconnaissance, or aerial RF relay. CFD analysis is continuing to validate the design through the coupling of an MDO routine to a parametric CAD model, and the results will be presented in a future report. Additionally the MDO routine is currently being revised to handle larger scale problems and larger design spaces with the implementation of *evolutionary algorithms* like the genetic algorithms available in MatLab. This will enable the MDO routine to truly *evolve* and synthesize an optimal airplane design from arbitrary starting points, with a more global search algorythm.

This is a first-level attempt to prove the results of the lower order method using more accurate CFD based results. Further confidence in the design will be achieved when the computed results in-hand are validated through additional CFD analysis and modeling studies, with the intent to later perform wind tunnel testing.



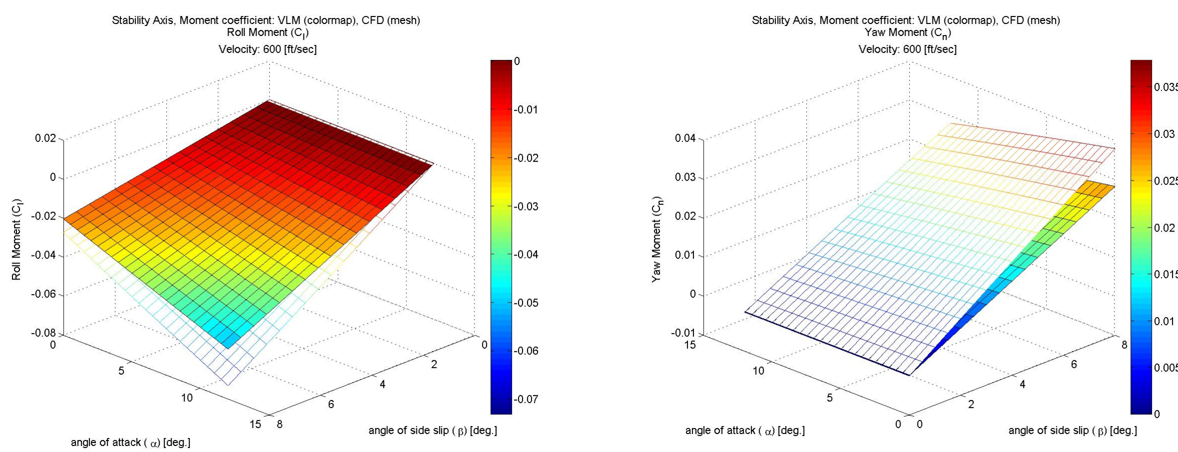
(a) (b)

Figure 5. CRaM flow visualization: Velocity Magnitude (a), Wing Pressure (b).



(a) (b)

Figure 6. CRaM Lift Coeff. (C_L) (a), CRaM Pitch Moment Coeff. (C_m) (b).



(a) (b)

Figure 7. CRaM Yaw Moment Coeff. (C_n) (a), CRaM Yaw Moment Coeff. (C_n) (b).

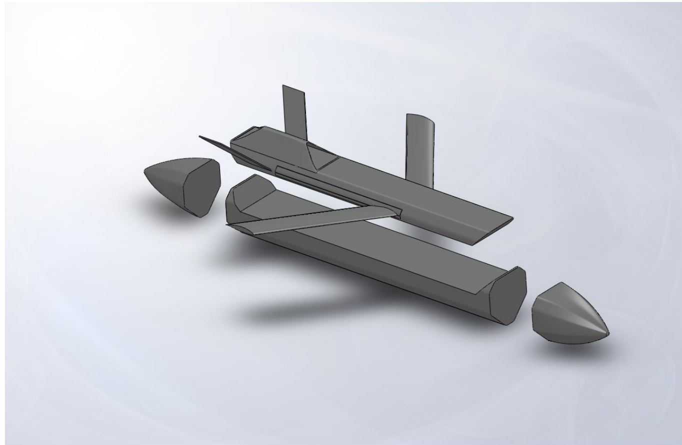
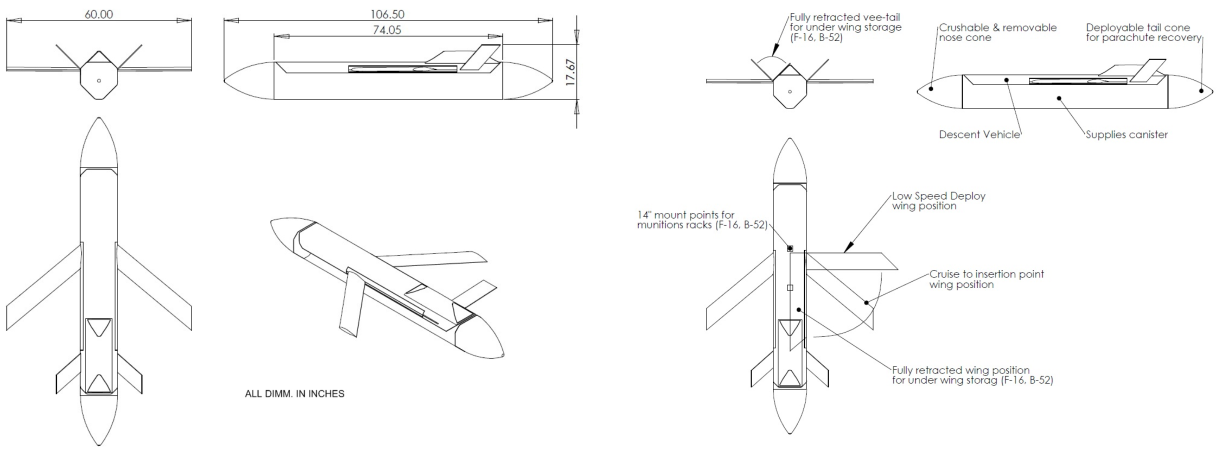


Figure 8. CRaM Exploded View.



(a) (b)

Figure 9. CRaM preliminary geometry (a), CRaM design description (b).

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