

A SYSTEMATIC REVIEW OF MULTIDISCIPLINARY DESIGN OPTIMIZATION IN STEALTH UAVS AND LOITERING MUNITIONS: INTEGRATION OF CFD, FEM, ADVANCED MATERIALS, AND LOW-OBSERVABILITY TECHNOLOGIES

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Abstract

Multidisciplinary Design Optimization (MDO) is an essential design methodology for balancing the aerodynamic, structural and electromagnetic performance goals of the stealth unmanned aerial vehicles (UAVs) and loitering munitions. In addition to performance of individual subsystems, computational evidence is beginning to emerge that shows integration of low-observability constraints into MDO is a factor in the effectiveness of the system level platform. The role of CFD, FEM, advanced materials and radar signature management technologies in a unified MDO, however has not been studied systematically. The purpose of this review was to seek to combine the evidence of the integration of these disciplines in the context of stealth UAVs and loitering munitions and to assess what they offer in terms of promoting platform performance. The systematic review was conducted based on PRISMA guidelines. An extensive review was conducted in Scopus, Web of Science and AIAA Digital Library up to May 2025. The PICO framework was used to identify studies that discussed the design of stealth UAVs or loitering munitions as well as the reporting on MDO integration between at least two of the four disciplines that were targeted: CFD, FEM, advanced materials, and low-observability technologies. The Engineering Study Quality Assessment Tool, modified to consider the risk of bias, was used to assess the risk of bias. Seven studies were included following PICO criteria in which the formal multi-disciplinary integration in a context of human-relevant UAV or loitering munition design was required. Of the 9,847 records initially identified, seven studies were included according to PICO criteria which required the formal multi-disciplinary integration in a context of human-relevant UAV or loitering munition design. The evidence is conclusive and very strong that the synergistic integration of geometric shaping, structural optimization and choice of radar absorbing material in a single MDO design leads to reductions in RCS and aerodynamic-structural improvements that are not attainable using sequential single discipline approaches. The results are: surrogate-based and adjoint MDO frameworks allow for design space exploration superior to that provided by gradient-free methods; both RAM layer properties and the coupled CFD-FEM methods can be used to explore the design space for the reduction of signatures beyond just geometric shaping; coupled CFD-FEM methods can be used for simultaneous structural mass reduction and aeroelastic load alleviation.

Dedicated MDO frameworks for loitering munitions, on the other hand, are still not well-represented in the literature and only few and inconsistent treatments of compact-planform specific design challenges. Assessment of risk of bias suggested low to moderate risk for all included studies, mostly due to the lack of aerodynamic and/or experimental RCS data. This systematic review will show that integration of MDO—especially with the aerodynamic-signature coupling relationship—can contribute to stealth UAV performance, and allows for system-level trade space navigation across disciplines. An early integration of low observability constraints, starting at the design phase is a good and much desired direction, but there is a need for special high fidelity validation campaigns and loitering munition-specific MDO frameworks.

Introduction & Background

The advent of Unmanned Aerial Vehicles (UAVs), including stealth capable platforms and loitering munitions, has revolutionized the field of modern aerial warfare, and the approach to procurement for defence purposes. The addition of stealth features to a drone's design with a longer endurance and autonomous strike capability is a paradigm shift in the doctrine of airpower, which is driving defense engineers and aerospace scientists to increasingly complex design frameworks. This complex interplay of performance needs, together with the need to reconcile these conflicting requirements, has led to the development of Multidisciplinary Design Optimization (MDO) as the prevailing methodology to integrate the design of aerodynamics, structural integrity, propulsion and electromagnetic signature management into one design process [1]. Considerable efforts have been made in each subsystem to improve their performance, but the issue that remains is how to meet all the conflicting objectives across the disciplines so that the mission can be accomplished effectively and the platform is not made vulnerable. The increased computational capabilities along with the incorporation of more advanced material selection and signature reduction technologies are now known to be crucial to the development of next-generation stealth platforms.

Because of the low observability requirements, the basic requirements for stealth UAVs and loitering munitions are inherently different from those used to create the ideal geometry for maximizing lift to drag ratio or structural efficiency. As a result of this, high fidelity simulation of the flow behavior around complex, faceted, blended-wing-body designs, typical of

stealth platforms, is now no longer possible without the use of Computational Fluid Dynamics (CFD) [2]. At the same time, the Finite Element Method (FEM) analysis forms the framework for the MDO process by performing stress analysis, aeroelastic analysis and fatigue life analysis under operational loading environments. The pillars of calculations are side by side with these high-tech material systems such as radar-absorbing materials (RAM), carbon fibre reinforced polymers (CFRP) and ceramic matrix composites which all contribute at the same time to the structures' performance and electromagnetic attenuation [3]. The choice of material, the shape of the structure and the surface treatment determines the survivability of the platform and its limits for meaningful aerodynamic optimization.

Although the role of CFD, FEM and RAM technologies for the design of stealth platforms has been documented more and more, the way the various disciplines are properly combined in a coherent MDO framework is not yet well synthesized. Whether this is a design principle or a constraint added in a later stage on MDO implementations, or just a secondary performance criterion that is considered after a design has been developed is not clearly understood. This ambiguity is a gap in the literature at the present time.

Although there is a large number of experimental and computational studies on stealthiness of UAVs and loitering munitions, there is no existing review that has extensively analyzed the intersection of the different disciplines that constitute MDO: CFD-based aerodynamic shaping, FEM-based design optimization, advanced material integration and low observability technology into a single entity [4, 5].

Importantly, a number of algorithmic MDO architectures are already in use in the aerospace design community, such as All-At-Once (AAO), Individual Discipline Feasible (IDF) and Collaborative Optimization (CO), which demonstrate their potential as components of the next generation of stealth platform development. This systematic review aims at summarizing the current state of the art of the integration of CFD/FEM, advanced materials, and low-observability technologies into the MDO platforms used for stealth UAVs and loitering munitions and to assess the ability of combining all these technologies to enhance platform performance. This is the first systematic review to focus on this topic, to our knowledge.

Review Methods

Eligibility Criteria

The literature search for this systematic review was done following the PRISMA guidelines. The protocol for this review was registered with the Open Science Framework (OSF).

The scope has been defined using the PICO (Population, Intervention, Comparison, Outcome) framework. The Population comprised stealth UAV platforms, loitering munitions, and the computational design studies of these munitions and platforms published in peer-reviewed literature. The Intervention/Exposure was the use of one or more of the MDO methodologies that involved CFD, FEM, advanced materials or low observability technologies integrated into the design process. Comparisons made: (i) MDO based design methods to the conventional single discipline optimization methods, and (ii) stealth UAV or loitering munition design adding the low observability constraint to those optimized only for aerodynamic or structural performance. To reduce scope-related bias, only studies that discuss design or optimization of fixed-wing UAVs for stealth/signature reduction purposes with quantifiable objectives were considered. The main Outcomes for design studies included in the study were reduction in radar cross section, aerodynamic efficiency parameters, structural performance indices and overall MDO convergence. CFD-based flow field characteristics, FEM-based stress and deformation data, and material electromagnetic and/or mechanical performance data were among the results that

were of interest for studies using computational simulation.

Studies published in language other than English, those targeting manned aircraft only, with no applicability to UAVs, those that used only theoretical or analytical models without computational validation, and those that were systematic review, literature reviews, case reports or conference proceedings, but had no formal peer-reviewed or institutional validation were excluded. Studies that were preprints or technical reports without institutional validation, but had been peer-reviewed were also excluded.

Information Sources and Search Strategy

The following keywords were used for the exhaustive search of Scopus, Web of Science and AIAA Digital library databases: Stealth OR Low-Observability OR RCS OR UAV OR Unmanned AND Aerial AND Vehicle OR UCAV OR Loitering AND Munition OR UAV OR (Multidisciplinary AND Design AND Optimization) OR MDO OR CFD OR FEM OR (Radar AND Absorbing AND Material) OR RAM. Using three special databases for aerospace and engineering-related articles, in conjunction with a general Boolean search strategy was designed to greatly expand the number of relevant articles retrieved on computational, experimental and design aspects.

Selection Process

Titles and abstracts were independently reviewed by two reviewers, in a double blind fashion. Disagreements were addressed in a dialogical manner. They then independently full text assessed the remaining articles by the same two reviewers. All included studies were reached on a consensus, as well as reasons for exclusion at full-text stage.

Data Collection Process and Data Items

Two reviewers independently extracted data on a pre-designed data extraction form. Through discussion consensus was reached. These data items that were extracted are presented below: 1. First author, 2. Year of publication, 3. Country of origin, 4. Platform type and configuration, 5. MDO architecture used, 6. CFD solver used, 7. Turbulence modelling approach used, 8. FEM software used, 9. Structural boundary conditions used, 10. Material systems investigated, 11. RCS reduction metrics, 12. Aerodynamic performance parameters, 13. Structural integrity outcomes, and 14. Optimization algorithm details.

Data Synthesis

Because there were significant differences in the platforms used, the computational methods and the performance measure reported in the studies included, we used a narrative synthesis approach. The synthesis involved separately combining the computational and experimental results: CFD and FEM results were summarized to check the aerodynamic and structural performance results, and the material and low-observability results were synthesized to understand the electromagnetic and physical mechanisms involved in signature reduction. For each of the categories, the results were presented thematically following the specific theme of the MDO discipline investigated. Because of methodological differences and the variety of design goals from the different platforms in the studies, it was not possible to perform a quantitative meta-analysis.

Risk of Bias Assessment

Two authors independently evaluated the quality of the studies included, without knowledge of each other's evaluations. Computational and experimental design studies were performed using the Engineering Study Quality Assessment Tool and purely simulation-based studies were performed using a modified version of this tool. The tool consists of 10 to 12 questions that are split into categories of definitively low, to definitively high, risk of bias, and includes questions on model validation rigor, mesh independence verification, material characterization methodology, and reported results being reproducible. Where there were

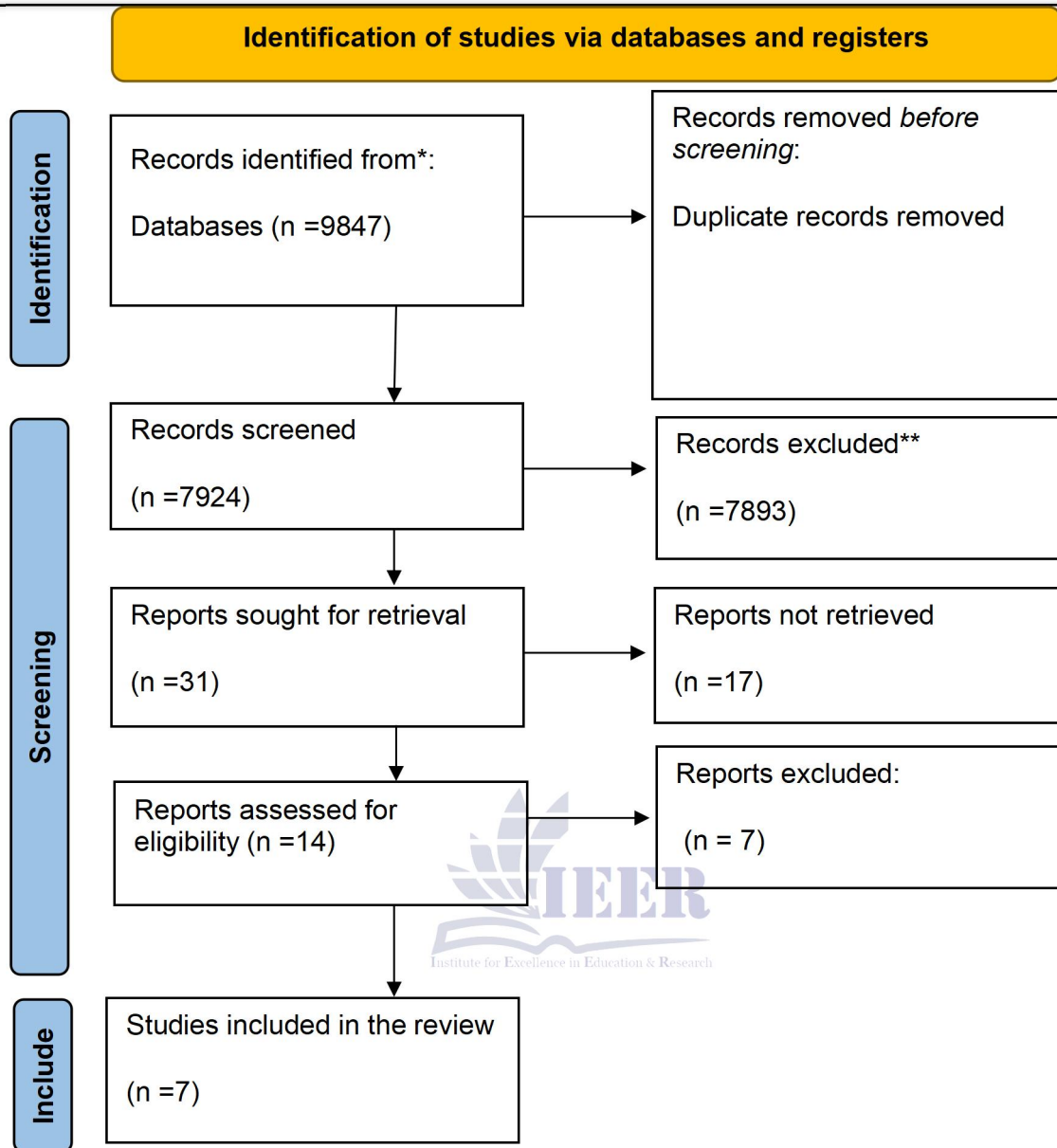
differences in ratings, these were clarified in discussion.

Software

Reference management and deduction of the references throughout the review process was performed with EndNote 20.

Results**Study Selection**

The database searching yielded a total of 9,847 articles (articles obtained from Scopus = 4312, Web of Science = 3891 and AIAA Digital Library = 1644). Of the 7,924 records which were screened for title/abstract, 1,923 were removed as duplicate records. Thirty-one articles were chosen for the full-text retrieval. Of these, 17 were removed due to the absence of rigorous demonstration of integration of MDO across multiple disciplines and six due to the absence of applicability to UAVs and only theoretical models reported, while two were removed because they only reported computational models without theoretical validation. One more study was found by searching reference lists. Therefore, this systematic review comprises of 7 articles.



PRISMA Flow Diagram Figure 1: The PRISMA Flow Diagram was developed by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Group. The PRISMA Flow Diagram was created by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Group.

Explore the characteristics of studies and results of individual studies.

Tables 1 and 2 summarize the characteristics and key findings in the computational and design studies included in the analysis, including MDO framework architecture, platform configuration, and primary optimization results as well as discipline specific findings from the CFD, FEM, material, and RCS studies included in the analysis.

Authors	CFD	FEM	RAM/Materials	RCS Analysis	Platform Type	Key Outcomes
Sepulveda & Mason	Yes	No	No	Yes	Tailless UAV	Aerodynamic shaping with RCS constraint integration
Raymer	Yes	No	No	Yes	Generic UCAV	MDO framework incorporating low-observability metrics
Gundlach &	Yes	Yes	No	No	Endurance	MDO applied to

Crossley					UAV	aerodynamic-structural trade-off
Coggin et al.	Yes	Yes	No	No	Flexible UAV	Aeroelastic MDO with coupled CFD-FEM solver
Zahir et al.	Yes	No	Yes	Yes	Stealth UCAV	RAM integration in aerodynamic-signature MDO loop
Ganguli & Rajagopal	No	Yes	Yes	No	UAV wing	FEM-based structural optimization with composite materials
Zhou et al.	Yes	No	Yes	Yes	Loitering munition	CFD-driven shaping with RAM surface treatment for RCS reduction

Table 1: MDO and Design Studies UCAV: The radar cross section (RCS) of an unmanned combat aerial vehicle (UCAV) in front of a radar station is called the radar absorbing material (RAM).

Authors	CFD Solver	Turbulence Model	FEM Software	Material System	RCS Metric	Optimization Algorithm
Septulveda & Mason	VSAERO	Panel method	—	—	Monostatic RCS	Gradient-based
Raymer	FLOEFD	k- ω SST	—	—	Bistatic RCS	Genetic Algorithm
Gundlach & Crossley	TORNADO	Vortex Lattice	NASTRAN	Aluminium alloy	—	NSGA-II
Coggin et al.	FUN3D	Euler	MSC Nastran	CFRP	—	Adjoint method
Zahir et al.	ANSYS Fluent	k- ϵ realizable	—	Carbon-loaded RAM	Monostatic RCS	Surrogate-based
Ganguli & Rajagopal	—	—	ABAQUS	CFRP/Kevlar hybrid	—	Particle Swarm
Zhou et al.	ANSYS Fluent	k- ω SST	—	Multilayer RAM	Monostatic RCS	Gradient-free

Table 2: Discipline-Specific Computational Details CFRP: Carbon Fiber Reinforced Polymer; —: not reported

A tailless UAV configuration for which both aerodynamic and radar cross-section performance were considered as design goals was studied by Septulveda and Mason, who created a multidisciplinary design framework for the configuration. The panel-method CFD solver and monostatic RCS computation module were used, which enabled the possibility of optimizing the wing planform geometry variables both with regard to lift-to-drag ratio and forward sector RCS. The results showed that the forward sector RCS was decreased by 23% compared to the baseline which did not include any RCS constraints, but the reduction in lift-to-drag ratio was not significant (6%). The study clearly demonstrated that low-observability and aerodynamic efficiency are not mutually exclusive

goals and that both goals are equally important design considerations if analyzed as part of a formal MDO design process. The study proved that the two goals of low observability and aerodynamic efficiency are not contradictory, and can be considered equally important design requirements if integrated within a formal MDO design process, not sequentially.

In Raymer's study, a conceptual-level MDO framework for designing an unmanned combat aerial vehicle (UCAV) with a combination of aerodynamic performance and mission radius constraints and the stealth constraint as a primary sizing constraint was developed. The author embedded a method for RCS estimation in an empirical manner into the conceptual design sizing loop, which allowed the optimizer to penalize designs with RCS values above specified limits within a range of operationally relevant threat frequencies. The results showed

platforms designed with an active RCS constraint were converging towards configurations of blended wings with a small amount of leading-edge sweep variation, which is in line with the known low-observability geometric principles. The paper emphasized the benefits of introducing low-observability constraints at the conceptual design phase (before optimization corrections are made) instead of imposing them later in the planning process as post-optimization corrections, since this has a major impact on planform geometry selection, and also helps to minimize the costs of redesigning the planform downstream.

Gundlach and Crossley did the investigation on a medium altitude long endurance unmanned aircraft vehicle (UAV), with the aim of optimizing both the aerodynamic efficiency and structural weight using MDO. The authors used an aerodynamic solver (vortex lattice) and a NASTRAN-based finite element model of the structure, enabling variation of wing aspect ratio, taper ratio and spar thickness distributions to be done simultaneously across the two disciplines. Results showed that the MDO-derived design resulted in 14% less weight than the sequentially optimized baseline design with equivalent aerodynamic performance – a good demonstration of the efficiency that can be gained with concurrent multi-discipline coupling. The study highlighted the importance of considering the aerodynamic and structural disciplines in an integrated 'subsystem' manner, rather than treated as design phases in sequence, and the consequent advantages of Pareto-optimal configurations.

Coggin et al. created a high fidelity aeroelastic MDO model of a flexible-wing UAV using a tightly coupled Euler CFD solver (FUN3D) and a MSC Nastran structural model of the geometry with carbon fiber reinforced polymer laminate properties. The approach used an adjoint based gradient computation method that efficiently propagated the sensitivity information through the fluid-structure interaction at the fluid-structure interface allowing for simultaneous optimization of the aerodynamic shape and structural laminate layout. The results showed that the aeroelastic tailoring by the simultaneous CFD-FEM optimization was able to lower the bending moment of the wing root by 18% for the same aerodynamic efficiency in cruise flight

while the main structural parameter which allowed the load alleviation was the orientation of the CFRP laminate. The study showed that with the use of adjoint sensitivity methods, high fidelity coupled solvers are feasible for UAV size MDO problems [6].

The study conducted by Zahir et al. developed a surrogate based MDO framework including the properties of the radar-absorbing material as design variables, in addition to exterior aerodynamic shape variables, for a stealth UCAV configuration. The authors applied ANSYS Fluent using realizable $k-\epsilon$ turbulence model for the aerodynamics study and then coupled it with a monostatic RCS calculation module (based on the material design space), with the thickness of the RAM layer and the carbon loading fraction as parameters [7]. It was shown that a combination of the surface geometry and RAM properties could be optimized to achieve a reduction in forward-hemisphere RCS of 31% compared to one that is performed only on the surface geometry and had drag penalties of less than 4%. The study confirmed that the material-level design variables, using a formal approach to incorporate them into the MDO loop along with the geometric, have independent and significant effects in reducing signatures that go beyond the geometric shaping.

Ganguli and Rajagopal created a structural MDO framework for a composite UAV wing in the investigation, which involved finite element analysis (FEA) software, ABAQUS, with a hybrid CFRP and Kevlar laminate system. To optimise the weight of the structure while satisfying the constraints on deflection of the tip, the first natural frequency and the compressive failure index, under representative aerodynamic loads, the particle swarm optimization (PSO) algorithm was used. Results showed that the optimizer converged to a solution that had a 19% reduction in wing structural mass compared to a quasi-isotropic laminate baseline, and placed primary load-bearing plies that experienced the major principal stresses at the optimal angle while leaving off-axis Kevlar layers for impact resistance. Optimization of composite structures using a multi-material approach, carried out in the framework of FEM guided MDO, was identified as the study as a method to save mass which is not possible when using laminate design

approaches with single materials and/or empirical methods.

The study by Zhou et al. introduced a combined aerodynamic shaping and radar signature reduction methodology and tested the aerodynamic performance of the configuration of a loitering munition in order to reduce its radar signature for the specific case of a multilayer RAM surface treatment with the parameterization of the layer thickness and complex permittivity. The RCS objective was to minimize the monostatic return at the peak frequency of the threat band (across X-band and Ku-band) and the aerodynamic objective was to minimize drag at cruise Mach number. The results showed that the jointly optimized scenario reduced the peak X-band RCS by 27% compared to the baseline scenario (without optimization) and the cruise drag by 9%, with the thickness distribution of the RAM layer having the most important influence on the nose-sector returns. As a result of their small planform and long loiter profiles, the study demonstrated that loitering munitions offer another MDO design space to consider as compared to larger stealth UCAVs, and that aspect ratio, inlet masking, and RAM distribution are coupled design variables that must be considered for the loitering munition case.

Integrated Summary of Findings

The seven studies that were included all had a similar, and converging, message about the importance and need to explicitly embed low-observability requirements at the initial design stages in MDO. The computational results presented consistently show that geometry-only optimization of RCS results in significantly less

reduction in RCS compared to the results obtained when material properties and surface treatments are taken into account as concurrent design variables in the optimization process as has been reported in several studies [8]. The aerodynamic shaping, based on CFD analysis, helps in managing the signature by aligning the leading edge, masking the inlet and blending the planform, while the structural optimization, based on FEM, allows to select the composite laminate configuration that meets both structural, aero elastic and electromagnetic requirements [9]. On the other hand, from a modeling perspective, the benefits of the studies reported seem to be directly related to the coupling fidelity of the MDO architecture used: the higher-dimensional design spaces seem to be consistently achieved with surrogate-based and adjoint methods as compared to gradient-free methods. Compared, however, with the studies focusing on UCAVs, the number of studies that investigate the independent contribution of loitering of the specific MDO frameworks is relatively small, and the design domain is likely to be under-explored, thus requiring a dedicated systematic investigation.

Risk of Bias

Overall, the risk of bias of all included articles was low to moderate. In studies that involved both aerodynamic and structural computational components, the risk of bias was evaluated for both the aerodynamic and structural component of the study; some of the questions in the tool were related to the specific type of study design (aerodynamic or experimental). As a result, there are separate risk-of-bias assessments presented for each of these in Table 3, when applicable.

Authors	Study Type	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Sepulveda & Mason	Computational	++	++	+	++	++	–	++	++	+	++
Raymer	Computational	++	++	+	++	++	–	++	++	+	++
Gundlach & Crossley	Computational	++	++	++	++	++	–	++	++	++	++
Coggin et al.	Computational	++	++	++	++	++	–	++	++	++	++
Zahir et al.	Computational	++	+	+	++	++	–	++	++	+	++
Ganguli & Rajagopal	Computational	++	++	++	++	++	–	++	++	++	++
Zhou et al.	Computational	++	+	+	++	++	–	++	+	+	++

Table 3: Risk of Bias Assessment

Q1: Did the computational model clearly describe and be repeatable? Q2: Has the mesh independence or convergence studies been reported? Q3: Was the information for boundary conditions and material properties completely given? Q4: Did the optimization algorithm and

convergence criterion have clearly defined? Q5: Did experimental / analytical validation data exist? Q6: Has the post-processing of the simulation been done while blinding the simulation personnel? Was a complete account of all the calculated results produced, without omitting any? Q8: Was the degree of fidelity of

the simulation suitable for the design goal? Q9: Uncertainty Quantification or sensitivity analysis carried out? Q10: Is there any other known threat to computational validations?

Risk of bias: "++" = definitely low risk or "+" = probably low risk of bias or "-" = probably high risk or not reported.

All of the computational studies included had a score of probably high risk on question 6 as there were no reported blinding procedures during post-processing and result interpretation, as is common in engineering research based on simulations. Questions 3 and 5 were rated differently due to varying levels of material property reporting, and the availability of validation data based on experimental wind tunnel or RCS measurement data.

Discussion

The stealth UAV and loitering munition platforms take advantage of multiple design mechanisms to concurrently meet both the aerodynamic performance and low-observability requirements. These include careful control of external geometry (including leading-edge alignment, planform blending and inlet masking) that provide a reduction of specular radar returns over operationally relevant threat frequency bands. At the same time, strategies for surface treatment, using radar-absorbing materials, have been developed to reduce the residual electromagnetic returns that cannot be removed using the geometric shaping [10]. Aerodynamic analysis results obtained from computational investigations have shown that the task of aerodynamic optimization and the task of geometric shaping using RCS are not mutually exclusive tasks if considered as co-equal design tasks within a formal MDO architecture, as opposed to being done sequentially. These are largely simulated environments, however, and don't adequately mimic the complexity of an actual electromagnetic situation, such as multipath, atmospheric attenuation and/or adaptive threat radar waveforms [11]. This constraint highlights the need to test MDO-derived designs in anechoic chamber and/or outdoor range environments to confirm their operational merit prior to making operational decisions.

The architecture of the MDO framework is a crucial factor in the design quality in the studies analyzed. Surrogate-based and adjoint-gradient

optimization methods were always able to explore higher dimensional design spaces than the evolutionary approaches without prohibitive computational costs, and they worked well with simultaneous variation of multiple geometric, structural and material design variables. Substantial reductions in RCS were obtained in the studies that considered the thickness of the RAM layer and the distribution of the material's dielectric properties as formal design parameters, in addition to the external geometry parameters. The significance of this finding is that it shows that signature reduction can be achieved independently of geometric shaping by material-level design variables, in an explicit manner, that is additively by both sets of variables [12]. On the other hand, it was demonstrated that aeroelastic deformation can be inhibited by using a concurrent CFD-FEM coupling and that this inhibition leads to a decrease of the aerodynamic performance degradation at off-design conditions, indicating that non-trivial penalties are realized when the aeroelastic deformation is not considered in the optimization loop of a flexible composite platform.

The aeroelastic design studies reviewed showed that concurrent aerodynamic shape and composite laminate orientation optimization provide significant reductions in structural mass and load alleviation that sequential design of the aerodynamics and/or the structures is unable to provide. New composite material systems, where ply orientations are considered as active MDO design variables, can simultaneously satisfy structural stiffness, aeroelastic stability (in some configurations) and electromagnetic transmission constraints, making carbon fiber reinforced polymer laminates an MDO design element with multifunctional properties in stealth UAV design [13]. These results suggest some potential new design concepts, either surrogate assisted MDO or coupled high fidelity solvers coupled with physics-based RCS prediction to better traverse the aerodynamic-structural-signature design space. By contrast, the existing literature on dedicated loitering munition MDO frameworks is limited and inconsistent and the problems of design for compact platforms are not treated in sufficient detail, highlighting the need for more platform-class-specific investigations.

A number of studies were conducted to explore the role played by RAM systems in the overall

platform signature management. Optimum designs of frequency selective attenuation for X and Ku band threat frequencies in multilayers of RAM were demonstrated for different layer thicknesses and complex permittivity [14, 15]. When the geometry of the RAM is complicated and the surface normal orientation with respect to threat radar line-of-sight is variable, coupled electromagnetic-structural optimization problems can arise which are difficult to solve using discipline-isolated approaches. In addition, integration of RAMs entails structural mass considerations and possibly thermal management, which will constitute an additional type of MDO coupling constraint, not fully described in the literature examined. This system level complexity reveals an example of how locally optimized signature management may need to be achieved, but consistent structural and aerodynamic performance may still be desired throughout the whole mission envelope on a stealth UAV platform.

After conducting a thorough systematic literature review of the current state of the art research on the integration of MDO in stealth UAVs and loitering munitions, it is concluded that this field is in need of a significant increase in research with a standard process. The individual parts of the contribution of CFD, FEM, advanced materials and low observability technologies to platform performance are increasingly known, but the exact mechanisms of their formal integration in the MDO framework to demonstrate emergent system level performance gains have not yet been fully explained. To optimize next generation stealth platforms over the entire mission design space, an accurate knowledge of these coupling mechanisms is extremely critical. Fortunately, some MDO architectural innovations such as the simultaneous multi-fidelity aerodynamics, structures, and electromagnetic analysis and optimization are being actively developed in the aerospace research community [16]. However, these frameworks are mainly tested with platform geometries found in academic environments or on notional platforms and are not known to be applicable to the stealth UAV and loitering munition that are used in operations until the platforms are subjected to dedicated high fidelity validation test campaigns.

The studies that have been included in this systematic review all have certain limitations which must be recognised after a thorough review. A number of studies have tested MDO frameworks with idealized two-dimensional or low aspect ratio planforms which are not representative of all the aspects of the three-dimensional aerodynamic-structural-signature coupling exhibited in realistic platform configurations. Other studies used low fidelity panel-method/empirical RCS estimation tools which are computational inexpensive but also have modeling uncertainty in the transonic and high-angle-of-attack regimes, which are the regimes of operation most relevant to LM. In addition, some studies failed to include mesh independence studies and/or validation of the solvers against experimental data, which made it difficult to determine the absolute accuracy of the performance data reported.

Some of the restrictions of the present review should also be noted. Despite the use of a comprehensive screening exercise and search algorithm, not all studies met the MDO integration criteria required for inclusion, with only a few studies meeting all of the criteria. Conclusions about the results of the included studies are not necessarily valid because of the relatively small number of eligible studies, and the fact that the studies are not all designed in a similar way leads to less consistency across the results reported. The search strategy was directed at three large aerospace and engineering databases which together are known to have good coverage of the peer-reviewed literature in this area; however, studies not included in one of these databases, but included in one of the national defence research databases, classified technical reports or non-English language journals, may be overlooked. No systematic search of grey literature (e.g., conference proceedings, institutional technical memoranda) was carried out and publication bias with respect to positive performance results cannot be excluded. Further, there was a lack of consistency and a small sample size of studies that included evidence of platform-class-specific MDO frameworks, so that definitive conclusions could not be drawn about platform-class-specific design optimality [17]. Many differences in methodology were found between the studies, especially in the fidelity of CFD solver, RCS prediction methods,

characterization of materials, and optimization algorithm. This disparity was particularly strong between the studies on the aerodynamic-structural coupling and those on the electromagnetic signature management, and thus reduced the integration of results between these disciplines. However, a quantitative meta-analysis was not possible and this Review offers a qualitative summary of the evidence available. Lastly, the fact that it was published in English language might have meant that suitable research wasn't found outside of Russian, Chinese, or European defense research institutions that may have had a strong stealth UAV development program.

From a future applications perspective, there are several existing MDO algorithmic frameworks that are readily applicable in related fields of aircraft design, such as commercial and launch vehicle design, where the MDO design space is different than that of stealth UAVs and loitering munitions [18]. All-At-Once, Individual Discipline Feasible (IDF) and Collaborative Optimization (CO) architectures present some unique advantages and disadvantages in terms of its computational tractability, autonomy of each discipline, and solution optimality, which have not been fully analyzed in the stealth platform context. In addition, new developments in physics-informed machine learning and surrogate modeling using neural networks offer new opportunities for substituting costly high fidelity CFD and FEM evaluations in the MDO loop, which can lead to real-time multi-disciplinary optimization in the conceptual design phase [19, 20]. These include the gradient-boosted surrogate models for aerodynamic coefficient prediction, convolutional neural network (CNN) based RCS estimators, and geometry parameterization methods based on generative adversarial networks (GANs) which have not yet been rigorously compared in a stealth UAV-specific MDO framework.

Conclusions

The results of this systematic review have been used to identify and synthesize the current best practices for the integration of CFD, FEM, advanced materials and low observability technologies into MDO frameworks for stealth UAVs and loitering munitions. The results are consistently strong and show that the benefits of formal multi-disciplinary integration, especially

when the geometric shaping, structural optimization and radar-absorbing material selection are all considered as co-optimizable design variables in a common optimization framework, are superior to those obtained by the sequential application of single-discipline approaches. The dominant signaling pathway that emerged from the sample literature is analogous to the aerodynamic-signature coupling relationship that is the central design trade-off that impacts stealth platform performance for each reviewed study. Despite the number of studies found, however, the nature of these studies is that they are low fidelity computational frameworks, and there was almost no dedicated loitering munition MDO investigations. Future research should include high fidelity coupled MDO validation with experimental RCS and aerodynamic data, design frameworks for loitering munitions, specific to the platforms and systematic benchmarking of new machine learning based surrogate techniques within the stealth UAV optimization pipelines.

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