EXPLORATORY DESIGN OF AN AIR LAUNCHED RECOVERABLE UAV FOR VERSATILE ROLES: A SYSTEMS PERSPECTIVE

BY

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July, 2021

Dedication

I dedicate this thesis to my Family for their support and RCMS Faculty for their guidance.

STATEMENT OF ORIGINALITY

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

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Declaration

I hereby declare that the work presented in the following thesis titled as *"Exploratory Design of An Air Launched Recoverable UAV for Versatile Roles: A Systems Perspective"* is my own effort, except where otherwise acknowledged and that the thesis is my own composition. All the secondary data has been cited properly in dissertation report and accordingly sources have been mentioned in references.

Fakhar Abbas

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List of Abbreviations

AEC	Aviation Engineering Complex
AHP	Analytical Hierarchy Process
ALFA-S	Air Launched Flexible Asset-Swarm
CAS	Close Air Support
CDR	Critical Design Review
CODE	Collaborative Operations in Denied Environment
COTS	Commercial-Off-The-Shelf
CM	Configuration Management
CS	Control Station
CY	Calendar Year
DARPA	Defense Advanced Research Projects Agency
ERP	Enterprise Resource Planning
EO	Electro Optical Systems
EW	Electronic Warfare
FY	Financial Year
GSE	Ground Support Equipment
HMI	Human Machine Interface
HOQ	House of Quality
HAL	Hindustan Aeronautics Ltd
IR	Infrared Systems
ISR	Intelligence, Surveillance & Reconnaissance
MBSE	Model Based System Engineering
MCDM	Multi Criteria Decision Making

OOSEM	Object Oriented Systems Engineering Model
PDR	Preliminary Design Review
PKR	Pakistan Rupee
PoC	Proof of Concept
QFD	Quality Function Deployment
RCS	Radar Cross Section of Aircraft
ROM	Rough Order of Magnitude Cost
SDLC	System Development Life Cycle
SEAD	Suppression of Enemy Air Defense
SEMP	System Engineering Management Plan
SoW	Standoff Weapon
SRD	system Requirement Document
SYSE	System Engineering
SYSML	System Modeling Language
TNT	Trinitrotoluene Explosive
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
UML	Unified Modeling Language
UR	User Requirement
URD	User Requirement Document
USD	United States Dollar

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Abstract

Autonomous / semi- autonomous Unmanned Aerial Vehicles (UAVs) have been in use for decades e.g., target drones, cruise missiles, Medium Altitude Long Endurance (MALE) UAVs etc. UAVs have demonstrated their role and importance in wide range of applications. Contemporary UAV employment concepts require multiple type of relatively inexpensive autonomous/semi-autonomous UAVs in volley quantities to undertake multiple tasks simultaneously. Air forces are increasingly counting on unmanned systems in contested environments to counter the risk of threatening technologies. In order to execute critical missions, forces require ability to send number of small UAV swarms with coordinated, distributed capabilities. This will provide them with improved operational flexibility at much lower cost as compared to expensive, manned platforms, particularly if they could be retrieved for reuse. Another desire is to have technical commonality and scalability of UAVs which will enable more efficient management of ground support equipment, training facilities etc. Scalability also allow the UAVs to be more efficient and facile enabling their features to be upgraded or down-sized as per mission requirements at much lower cost. It is inefficient to field and operate a multitude of unrelated vehicles with uncommon hardware, software, architecture. The thesis is the system level study of unmanned aerial vehicle that is air launched and is recoverable to address these futuristic employment concepts of airpower. The study has been conducted to explore desirable sub-systems and technological options that can be integrated to form envisioned air-launched UAV. Moreover, analysis of major requirements using Analytical Hierarchy Process (AHP) has also been carried out to weigh their relative importance and to find their priority eigen vector.

.

Keywords: Autonomous / Semi-Autonomous Vehicles, Low Cost, Recoverable, Swarms, Scalability, Technical Commonality, Analytical Hierarchy Process, Systems Engineering

Chapter 1

Introduction

1.1 Background

Unmanned Aerial Vehicles are being employed and deployed worldwide for multiple roles. The importance of UAS is increasing and evolving over the past two decades. It is expected that the air space would be cluttered with several types and variants of UAVs ranging from their use for military and other purposes in the future. Realizing the potential that UAVs and robotics are key technology areas that will enable any nation to counter the range of threats or potential threats posed to its interests, the topic has been chosen.

Traditional air operations involve using manned fighter aircraft equipped with mission-specific and desired delivery capabilities to provide required control of the air. The envisioned UAV will enhance the survivability of manned aircraft by allowing them to stay further away from enemy threats and closing the gap by launching an unmanned aircraft that can achieve the desired mission objectives.

Systems Engineering focuses on designing, integrating, and managing complex systems over their entire life cycles. Systems engineering ensures that all foreseeable aspects of a system are considered and integrated to achieve the objectives of the whole. The thesis is aimed to study operational utilization, system-level design challenges, and technological options to meet those objectives. Moreover, tradeoffs between operational requirements, engineering challenges, program cost, and project management framework have also been studied. Research has been conducted to explore desirable sub-systems that can be used for integration and present a Systems Engineering Plan for envisioned low-cost air-launched UAV.

1.2 Research Scope

This study explores the design of an air-launched UAV that is recoverable and can operate in tandem / network. The mission focus of the UAV would be to collect distributed intelligence, surveillance, and reconnaissance (ISR), close air support (CAS), patrol / interdiction, decoy, desired Electronic Warfare (EW) capabilities, and as a standoff weapon. The system-level study includes the following:

(a) Operational Need Assessment

(b) Concept of Operations (Conops)

(c) User Requirements

(d) Preliminary Design Specifications

(e) System Architecture

(f) Physical Architecture

(g) System Level Design including Subsystems

(i) Avionics Systems (Flight Controller, Guidance, Navigation, Mission Computer, Power Requirements)

(ii) Mechanical Systems (Air vehicle, Structure & Propulsion)

(iii) Payloads Options (ISR, EW, RCS, Warhead)

(h) Management & Optimization.

(i) Verification and Validation criteria

(j) Preliminary Design Review

(k) Launch and Recovery techniques

(l) System Integration

(m) Systems Engineering Management Plan (SEMP)

1.3 Motivation / Research Relevance

Air operations have heavily relied on increasingly capable multi-function manned aircraft to execute critical missions. Improved capabilities to detect and engage these manned aircraft from longer ranges have increased vehicle design, operation, and replacement costs. The capability to send large numbers of small unmanned aerial vehicles with coordinated, distributed capabilities can provide forces with improved operational flexibility at a much lower cost than with expensive, all-in-one manned platforms. If these unmanned systems could be retrieved for reuse, they can be instrumental in reducing the cost of the mission. So far, the technology to project volley quantity of low-cost, reusable UASs over great distances and to retrieve them is under study and is out of reach.

1.4 Research Objectives

The study's objective is to use systems engineering of air-launched recoverable UAVs for versatile roles to develop system-level understanding and challenges. Unmanned systems and robotics are key technology areas that will enable any nation to counter the range of threats or potential threats posed to its interests on the modern battlefield. The envisioned UAV will integrate with most existing fighter and cargo aircraft. Its capability will enable greater operational risk-taking across the spectrum of missions. These missions range from ISR, mobile target attack, Suppression of Enemy Air Defenses (SEAD), and Close Air Support (CAS) missions requiring volley quantities of air vehicles operating in a coordinated manner in access denied environments/ areas.

1.5 Organization of Thesis

The thesis is divided into six chapters. The first chapter covers the research background, scope, motivation/ relevance, objectives, and thesis organization.

In Chapter number two comprehensive literature review has been conducted covering System Engineering Approach, Model-Based System Engineering Analytical Hierarchy Process, its significance in System Engineering, Mathematical Modeling using AHP, Quality Function Deployment, ongoing work in the field of UAV swarms, Inspiration from ongoing work, missing links and voids in literature.

In chapter three, development methodology, development phases, verification and validation of requirements, project milestones, configuration management, and risk management have been covered.

Chapter number four entails the system-level design of UAVs. It covers the design process, including operational need assessment, CONOPS, preliminary design specifications, system architecture, physical architecture, UAV subsystems, swarm management, and optimization. Towards the end of the chapter significance of the preliminary design review has been covered.

Chapter number five covers the Analysis part of the thesis in which UAV criteria have been analyzed using AHP. Pareto analysis has been carried out to find out the most critical requirements. Moreover, house of quality has been used to translate user requirements into system requirements.

Chapter number six covers the conclusion, addition to the body of knowledge, limitations, and implications for future work.

Chapter 2

Literature Review

2.1 Brief History

Air operations are being undertaken through manned aircraft. However, improved capability to detect and neutralize manned aircraft from long ranges is driving up the cost of design, manufacturing of manned aircraft, and their projection to threat. Unmanned airborne operations are growing in scope and scale. Futuristic airpower employment concepts envision the use of UAVs in volley quantities in tandem with piloted vehicles to increase their efficacy and to reduce the risks imposed to manned aircraft in accomplishing critical missions.

2.2 System Engineering Approach

As per Jeff A Estefan, System Engineering Approach is document-centric that heavily relies on document-based artifacts to capture much of the system specifications, design information, requirements, interface control and system architecture design descriptions [1]. Thus, Systems Engineering Approach can be defined as "Collection of related processes, methods, tools, and environment used to support the discipline of System Engineering" [2].

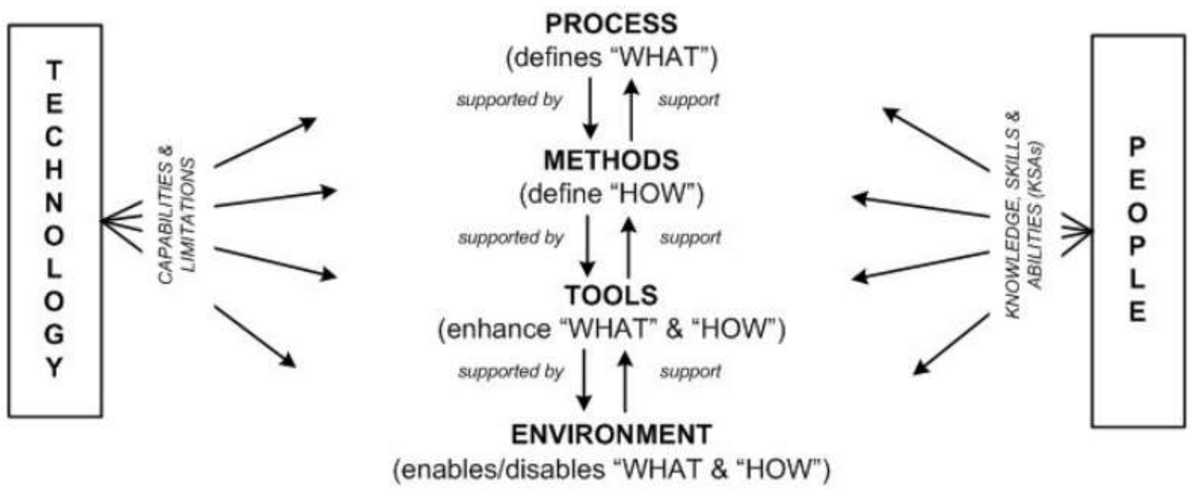


Figure 2.1: Systems Engineering Approach [1]

This document-based approach to systems engineering lacks precision, the correlation has inconsistencies while shifting from one artifact to another and poses difficulties in maintaining and reusing information. This information is often spread across documents utilizing text, formal/informal drawings and spreadsheets. However, the Systems Engineering approach provides the baseline for system design and development and is vital for any large-scale project. Although there are different tools available for modernizing system engineering, however; part of it still exists in the form of several documents for referring back to the processes and ensuring consistency in approach. The traditional Systems engineering approach also provides the baseline for the Model-Based Systems Engineering Approach.

2.3 Model Based Systems Engineering (MBSE)

According to INCOSE [3], Model-Based Systems Engineering is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. In MBSE, there is a paradigm shift from document centric approach to model centric approach. Digital Models have been standard in engineering since the late 1960s, but MBSE goes beyond digital models; it involves the development of operational models that lead to the development of system models that yield sub-system or component models. Various tools are available for MBSE, e.g., SysML, Capella, Arcadia, enabling engineers to more readily understand design and analyze a system design before it is built. Although MBSE has been able to get away with a document-centric approach to an extent, however; a significant part of systems engineering, including user requirement documents, requirement traceability, system requirement documents, still exists in the form of documents generated manually or through ERPs.

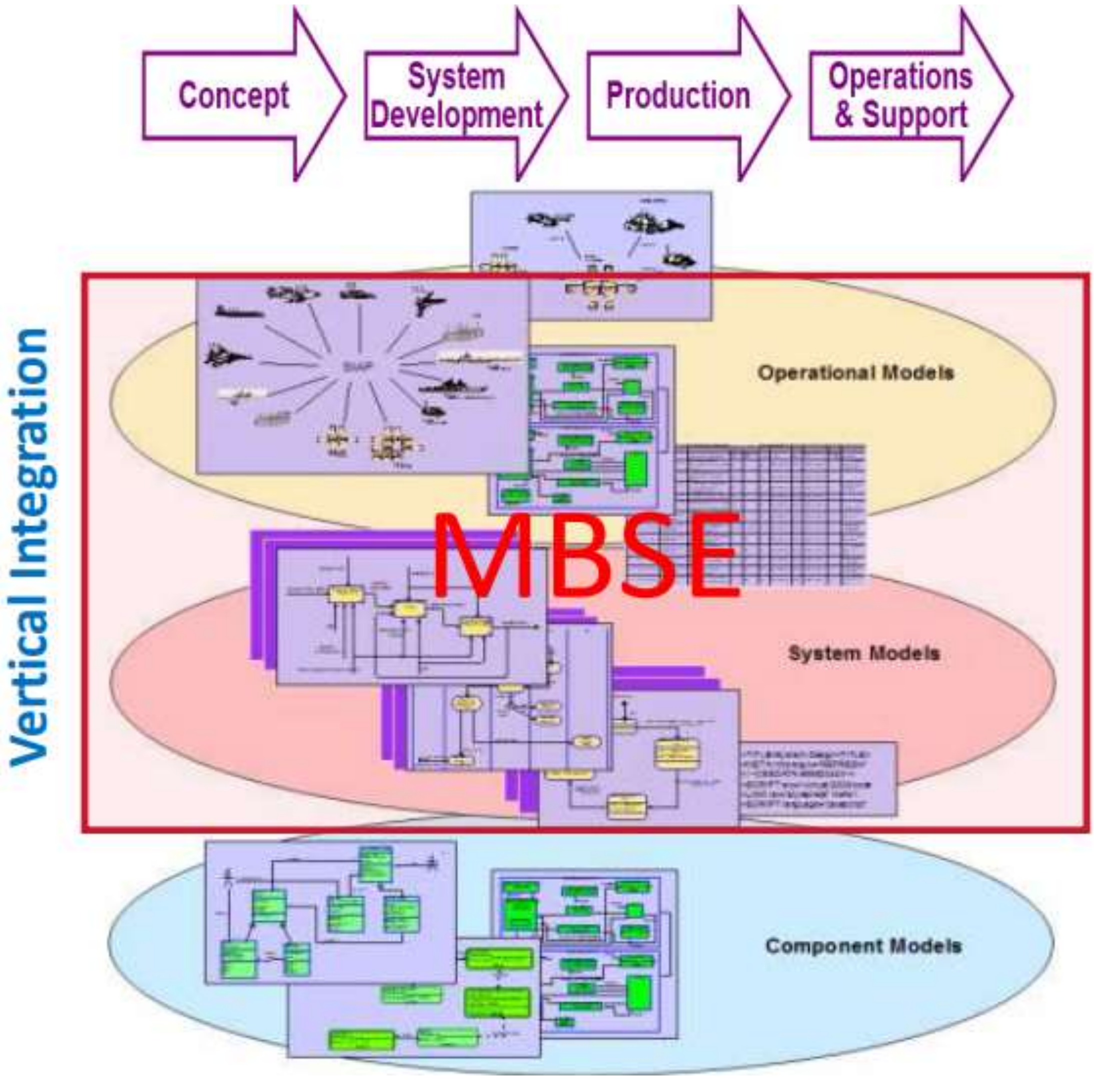


Fig 2.2: Conceptual Depiction of Model Based Systems Engineering [4]

2.4 Analytical Hierarchy Process (AHP)

Multi-Criteria Decision Making (MCDM) is a challenging problem in every field in recent times as some decisions cannot be backed by scientific reasoning and quantitative measures. MCDM requires a methodology to reach a logical conclusion. AHP is a decision-making methodology for organizing and analyzing complex decisions. Professor Thomas Saaty developed AHP in 1980 [5]. It allows structuring the decision hierarchically by reducing its complexity and showing relationships between requirements, objectives, or criteria and their possible alternatives [6]. Its most significant advantage is that it allows intangibles such as experience, preferences, and intuition in a logical and structured way. Thus, AHP methodology helps make rational decisions where quantitative measures are not available, especially in operations, product design, logistics, management, etc. [7].

AHP also aids in developing tiered selection criteria. The criteria are formed based on user requirements vis-à-vis available alternatives. Then laid down criteria are evaluated based on weighting factors [8]. AHP provides practical guidelines and techniques for problem structuring. It can be used to select between several options, prioritize the requirements and remove their mutual inconsistencies. As a result, it helps in assigning the numerical values to subjective judgments or a criterion and consequently combining the decisions for decision-making on a single scale. In the present thesis, AHP has been used in thesis to prioritize the user requirements and finally finding the priority eigenvector for criteria laid for envisaged Air-Launched Recoverable UAVs for versatile roles.

2.5 Use of AHP in Systems Engineering

Requirement Engineering is the process of defining, documenting, and maintaining the requirements. It is a process of gathering and explaining the features and services envisaged by the system. Requirement elicitation, specification, prioritization, and management is an essential part of Systems Engineering. Systems Engineering is nothing but an art and science of developing an operable system that meets user requirements within given constraints [9]. AHP in Systems Engineering can be used for requirements analysis and finding out their relative weightage to give them due to priority for translating them into sub-systems. A systems engineer is well acquainted with the requirements of a system and the available alternatives. AHP can help make tradeoffs based on customer requirements which is a critical part of the systems engineering process [10]. Using AHP methodology, a systems engineer can weigh different available options based on the stakeholders' requirements or priorities. System design level decisions often concern several criteria whose selection is at the bidding of the decision-makers [11]. In the absence of AHP, these various criteria are likely to be measured on different scales since they are intangible, leading to inconsistent system design. Thus, AHP provides system engineers a way of assessing criteria in a more meaningful and quantitative manner. Moreover, Analytic Hierarchy Process provides a structured and disciplined approach for deciding by considering multiple criteria on a single scale.

2.6 Mathematical Modeling of Problem Using AHP

AHP provides a mathematical model based on which the decision makers having a difficulty to make qualitative decisions can arrive at logical and mathematically backed decisions. AHP algorithm is based on two steps. **First step** is assigning relative weight to the decision criteria **Second step** involves the relative ranking of the alternatives. These alternatives are compared pairwise with each other and the final weightage of each option is found by multiplying weightage of each lower hierarchy i.e. weightage of C1 is C1*A1+ C1*A2 + C1*A1

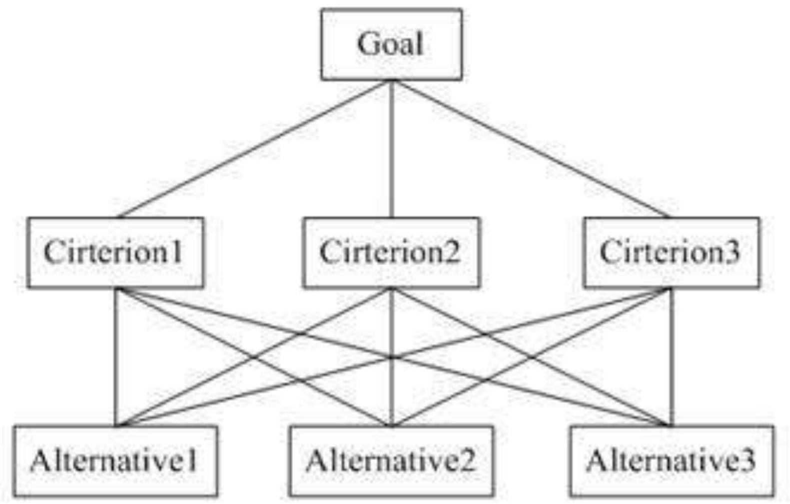


Figure 2.3: Analytical Hierarchy Process

After arranging the problem in hierarchy, pairwise comparison is drawn at each level and the degree of consistency is calculated. AHP is based on two axioms which are: -

(a) All alternatives are independent of each other

(b) Alternatives at a certain level of hierarchy are not dependent on lower or higher-level alternatives.

The best part of AHP decision making methodology is that, qualitative & quantitative information can be compared by using informed judgements to derive weights and priorities. Table 2.1 shows the relative ranking scale used for pairwise comparison in AHP. It ranges from 1 to 9 based on relative importance of the alternative. If an alternative is extremely important than other then it will be rated at 9. Essential or strong importance will be rated as 5. Normally the odd numbers are used. AHP checks the consistency of judgments using equation

$Ax=\lambda x$ where

A	=	Comparison Matrix of order n x n		
x	=	Eigen Vector of order n x 1		
λ_{max}	=	$\frac{1}{n}\sum_{i=1}^{n}(\lambda_i)$	=	Eigen Value

n	=	number of criteria
Consistency index (CI)	=	$(\lambda_{max} - n) / (n-1)$
Consistency Ratio (CR)	=	CI / RI

The value of CR for number of criteria is shown below

$CR \leq 0.05$	,	n	=	3
$CR \leq 0.08$	,	n	=	4
$CR \leq 0.1$	**,**	**n**	**$\geq$**	**5**

Where A is a pairwise comparison matrix of order n x n

x is the eigen vector or priority vector of order n x 1

λ_{max} is the eigen value

Saaty suggests that if that ratio exceeds 0.1 or 10% it means that the set of judgments are too inconsistent and require revision. AHP has certain inherent limitations which are as follows: -

(a) Any additional deletion of criteria requires complete re-evaluation

(b) It requires repeated evaluations until consistency ratio comes under 0.1

(c) AHP is very difficult to use for criteria more than seven. The axioms on which AHP is based are not true all the time

2.7 Quality Function Deployment

The quality function deployment method was initially developed in Japan in 1966 to help transform the voice of the customer into engineering characteristics for a product. Although different System Engineering tools are available that can be used for developing a system model, Quality Function Deployment is one such tool that does it directly and conveniently. QFD is a structured approach for converting the voice of the customer or requirements into product characteristics, i.e., a specific plan to produce a product to meet those needs. It is a powerful tool for converting vague customer requirements into consistent, unambiguous technical requirements, which can define the subsystems. QFD has been used in this thesis for translating the user whats into system hows. The generic template for HoQ used for QFD is shown in figure 2.3. QFD can also be used sequentially for converting customer requirements into design requirements, then design requirements into engineering design, engineering design into product characteristics, product characteristics into required processes and thus so on and so forth. Thus, QFD allows systems engineers to translate system requirements into a product with required traceability [13]. QFD has been used in thesis to convert the user requirements into system requirements.

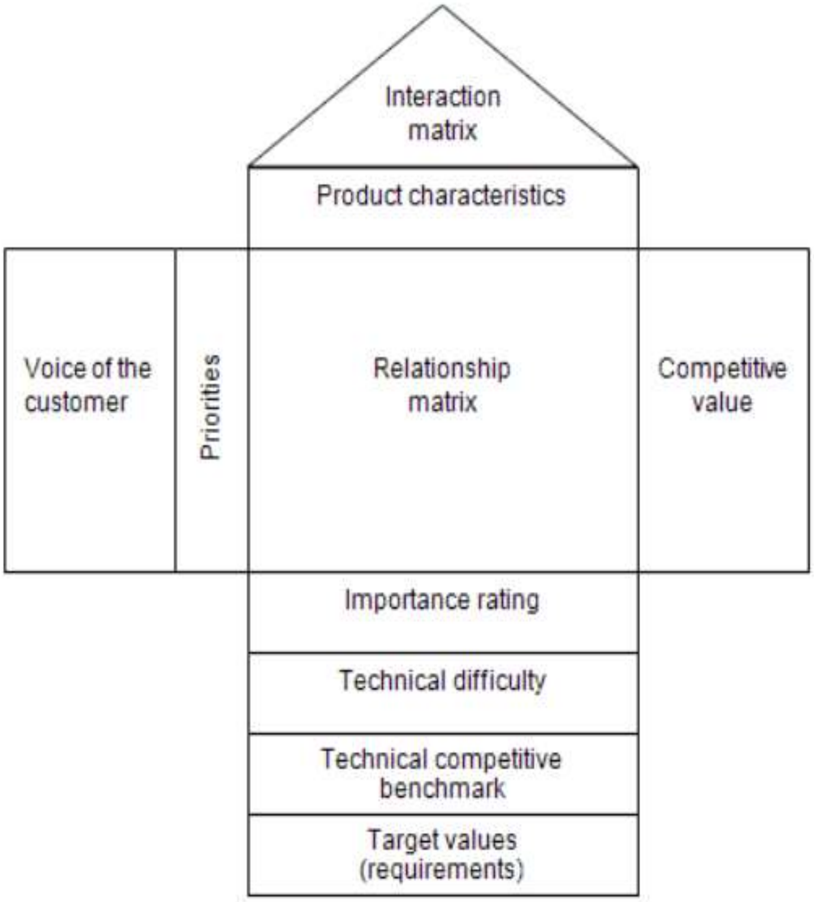


Figure 2.4: House of Quality Template [14]

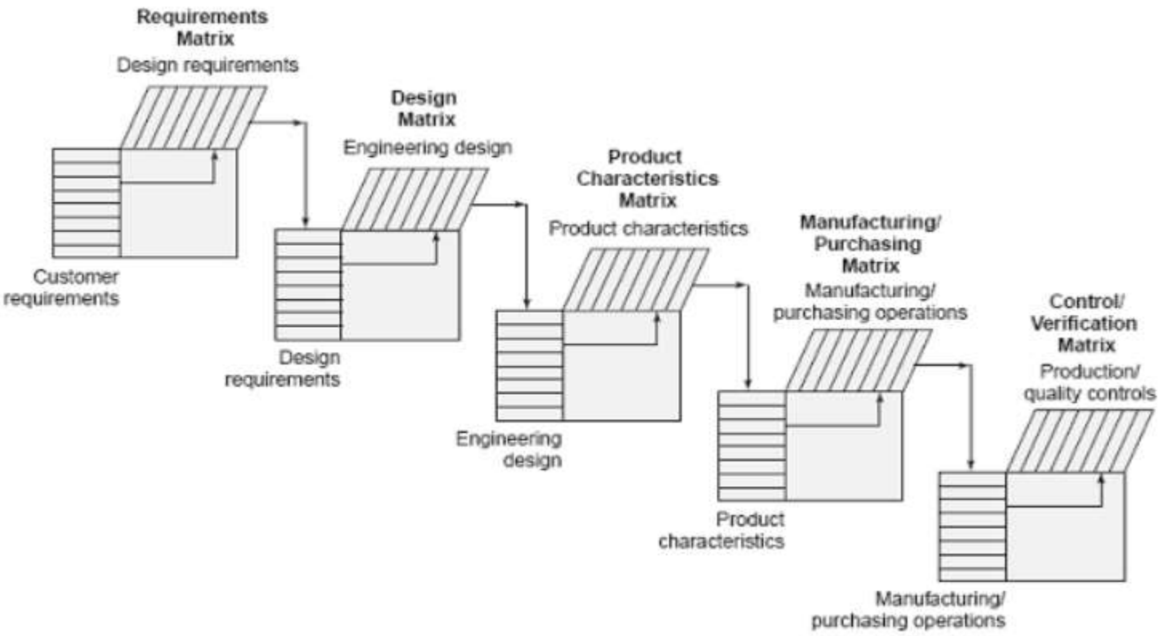


Figure 2.5: Waterfall Relationship of QFD Matrices [14]

2.8 Ongoing Research Work

Technologically advanced militaries worldwide have incorporated UAVs as a new critical and combat-enhancing component of their inventory. US is considered as the pioneer in UAV development and employment. Air forces worldwide are heavily investing in swarming drones. Presently at least 24 countries are developing unmanned military aircraft with swarming applications. A review of few such programs is presented below:

(a) DARPA Gremlin X-61A & LongShot Programs. These DARPA-sponsored programs [16,17] envision launching groups of UASs from existing large transport, bomber, or fighter aircraft while remaining out of range of adversary defenses. On completion of the mission, they can be retrieved mid-air through a cargo/transport aircraft like C-130, which will carry them back to prepare for their next mission. Their expected lifetime is about 20 uses and is likely to provide significant operational advantages over other expendable and conventional platforms with reduced mission and maintenance costs. DARPA started another program named LongShot in FY-20 with a startup investment of 22 Mil USD. Its objective is to disrupt the paradigm of air combat operations by demonstrating air-launched UAVs capable of employing current air-to-air weapons, significantly increasing engagement range and mission effectiveness. The program aims to design, fabricate, and flight tests a demonstration system to prove the concept's viability.

Figure 2.6 (L-R): DARPA Gremlins X-61A and LongShot Air Launched Drones

(b) DARPA Program CODE. CODE [18] stands for **C**ollaborative **O**perations in **D**enied **E**nvironment. This program aims to develop algorithms and software for unmanned aircraft that would extend mission capabilities and improve their ability to conduct autonomous / semi-autonomous operations in denied or contested airspace. The program aims to use AI in drones to overcome the limitation of continuous and dedicated control by the operator supported by numerous telemetry and data links.

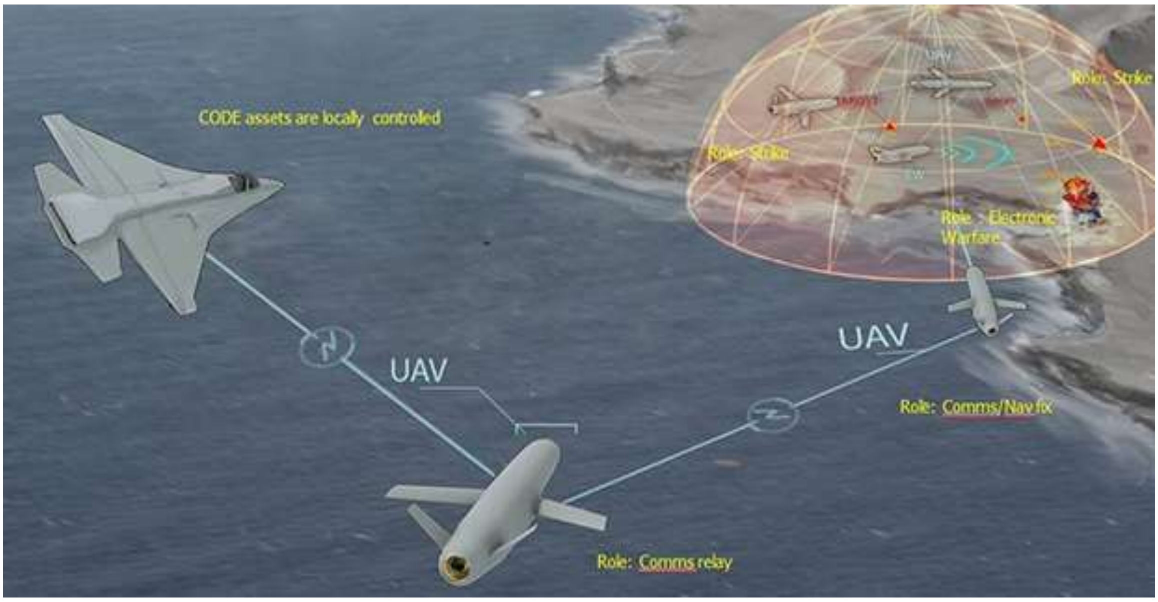


Figure 2.7: Collaborative Operation in Denied Environment

(c) Flock-93. Flock-93 [19,20] of Russia envisions multiple 100-drone swarms, each armed for engaging multiple targets. Zhukovsky Air Force Academy is developing the concept in collaboration with private industry. The concept was displayed first time at Moscow's Interpolitex-2019 security exhibition. It involves simultaneously launching of hundred autonomous/semi-autonomous drones, each armed with a 5.5-pound warhead. The drones will be flying wings capable of taking off and landing vertically. Although Russia carried out a small-scale proof of concept (POC) in Kavkaz-2020 exercises, Flock-93 is presently a concept requiring extensive work, deliberations, and evolution of enabling technologies.

(d) Chinese WZ-8/DR-8/GJ-11. WZ-8 [21,22] is also referred to as DR-8. It is an air-launched, high-speed, high-altitude reconnaissance UAV that is recoverable via runway. It has a rocket engine and was displayed on Chin's 70th anniversary parade in October 2019 for the first time. At the same time, GJ-11 is a UCAV with stealthier exhaust and radar-evading capabilities. These versions are designed to be launched from the H-6 bomber. Their primary objective is to conduct deep strikes and surveillance of critical targets.

Figure 2.8 (L-R): Chinese WZ-8/ and GJ-11

(e) Indian Program ALFA-S. ALFA [23] stands for Air Launched Flexible Asset-Swarm. It is being developed by a team of engineers and software experts at state-run Hindustan Aeronautics Ltd (HAL) and New Space Research and Technologies, a Bengaluru-based startup. Together they are working to develop and fly the first Indian swarm drone prototypes. These UAVs can be packed in containers and launched from aircraft. Each swarm could have dozens of individual drones. If detected, some of the drones may get shot down, but their large number is likely to overwhelm enemy air defenses, ensuring a high probability of mission success. They call it as future of aerial warfare capability. They intend to transform them into smart drones with increased maturity in artificial intelligence algorithms. India has over 30 startups in the design and development of drones.

Figure 2.9: Indian ALFA-S (Concept Diagram)

2.9 Inspiration from Ongoing Work

This study explores the system-level design of an air-launched UAV that is recoverable and can operate in tandem / network. It may undertake versatile roles that vary from collecting distributed intelligence, surveillance, and reconnaissance (ISR), close air support (CAS), patrol / interdiction, air-launched decoy, Electronic Warfare (EW), and as a standoff weapon.

2.10 Missing Links / Voids

Although the literature discusses the design and development of UAVs however it does not use systems engineering concept on air-launched part UAV and use of open system architecture to enable COTS based development, this void has been fulfilled through this study. Since technology has come a long way. Computational powerhouses are available at a fraction of the cost of their predecessors. If open system architecture based on industrial standards is adopted, the development will be easier and faster. Moreover, in the second part of the study, the Analytical Hierarchy Process has been used to evaluate UAV laid down criteria based on user requirements. This helped in prioritizing the subsystems to reach an optimum system design. Thesis may be utilized in the subsequent development of UAV.

Chapter 3

Development Methodology

3.1 Reference Design

The development methodology of UAVs revolves around reference design. The reference design is chosen, and the required design is formulated based on user requirements by improving/ tweaking the reference design. The new design is checked aerodynamically and structurally analyzed for inconsistencies. In envisioned UAV, most of the subsystems, including mission computer, electronics system, telemetry, datalink, are foreseen as commercial of the shelf (COTS) equipment and would be integrated with UAV airframe/air vehicle. In contrast, airframe, Control Station (CS), and Support Equipment (SE) can be developed with the help of an industrial partner.

3.2 Development Phases

As envisioned, the development can be divided into undermentioned four phases. The details of each phase are elaborated in subsequent paragraphs.

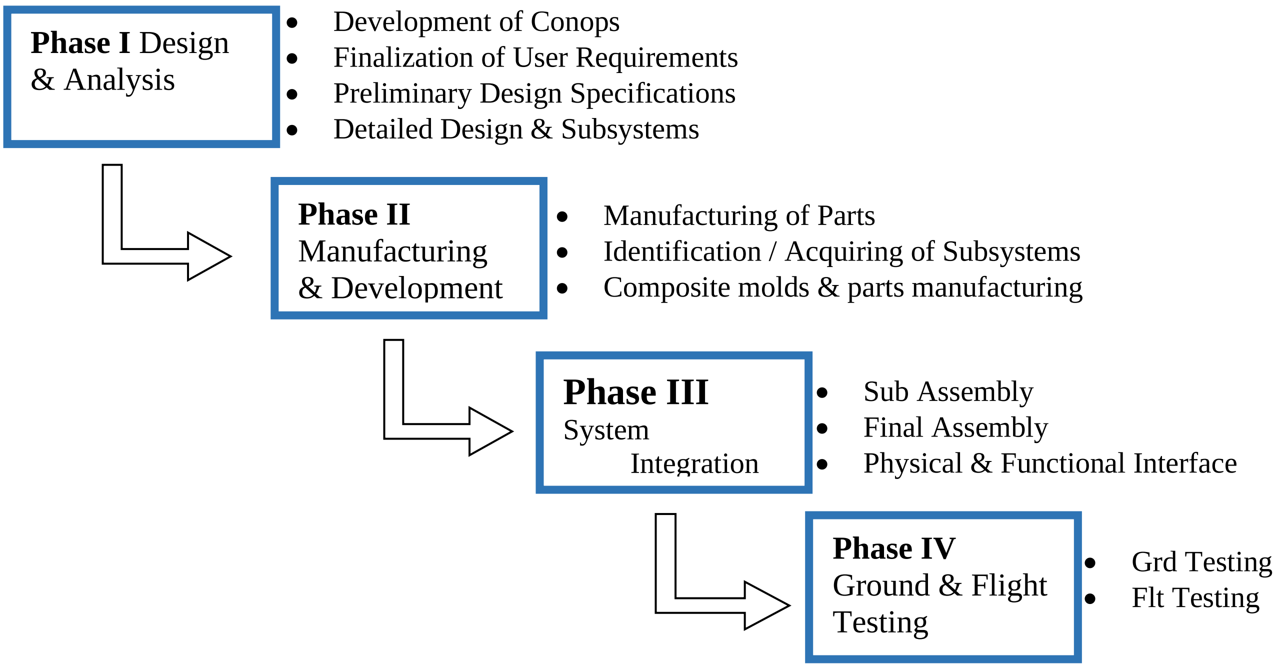


Figure 3.1: Development Strategy of UAV

3.3 Phase I – Design & Analysis

3.3.1 Concept of Operations (ConOps)

Conops is a user-oriented document that describes the characteristics of envisioned system from the user's perspective. It describes the user organization, mission, and objectives from an integrated systems point of view and communicates overall qualitative system characteristics to all stakeholders. It also explains the user needs it will fulfill and its relationship to existing systems. Conops obtains the consensus among the customer and developer on the operational concept of a proposed system. Conops can be updated throughout the study cycle and becomes part of the Operations and Support document towards the end.

3.3.2 User Requirement Document

Initially, the User Requirements Document (URD) document must be developed, which subsequently leads to the development of a System Requirements Document (SRD) that would cover all the technical and system-level details. System requirements are classified as follows:

(a) Functional Requirements

(b) Non-Functional Requirements

3.3.3 Requirement Traceability and Verification

Requirement traceability is the process of linking the requirement throughout the verification and validation process. Requirement ID has information about the type of requirement and its relevant sub-system. As the needs and test procedures are developed, the requirements IDs are assigned and included in the updated documents. Ideally, conditions should be traced to the specific test step in the testing protocol in which they are tested. IDs are assigned to the formulated requirements of the envisioned system and are attached as **Appendix "A".**

3.3.4 Preliminary Design Specifications

The preliminary design phase begins with selecting reference design, i.e., its weight, dimensions, and geometry. Here the aerodynamic analysis is carried out, stability and control derivatives are estimated after numerous iterations and trade-offs between various system performance requirements. Computational Fluid Dynamic analysis is carried out at different flight conditions, angles of attacks, and their combination. This helps in the authentication of design.

3.3.5 Detailed Design & Subsystems

The preliminary design of the UAV would be carried out based on conceptual design. The detailed internal structure of each part, like the wing, fuselage, including ribs, spars, longerons, stringers, bulkheads, are designed in CAD software. The structure is then analyzed through the FEM technique. This leads to the development of detailed engineering drawings of each part and subsystems.

3.4 Phase II – Manufacturing & Development

3.4.1 Prototyping

The prototype manufacturing phase requires CNC machinery, composite material / metal, assembly, jigs, and fixtures. Moreover, before prototyping, a technical data pack must be prepared as per the guidelines of **MIL-STD-31000B**. It requires name, numbering, classification, and elaborate CAD drawing of all parts. Subsequently, after completion of the technical data pack, manufacturing of UAV can commence. As envisaged, the UAV skeleton would be made of metal, and the skin would be made of composite material. As worked out, UAV comprises over 800 parts, including metal and composite parts. Efficient inventory management and quality control mechanism is also required to be in place during prototyping. The UAV would be assembled with the help of assembling jigs and fixtures. As envisaged, at least 03 prototypes would be required for ground test, flight-test and testing of swarming algorithms.

3.4.2 Control Station (CS)

Control Station comprising of consoles and data terminals will be designed and can be manufactured in collaboration with local industrial partners as per **NATO Standard 6518**.

3.5 Phase III – System Integration

3.5.1 Sub-Assembly

After manufacturing of metal and composite parts and sub-system development, sub-assembly of air vehicle would be initiated.

3.5.2 System Integration & Final Assembly

COTS items like datalink, payload, and avionics suite would be finalized, procured, and integrated as per requirements. An industrial collaborator may be involved in the system integration phase for swift completion of the task. Subsequently, the local teams can be formulated to accomplish future upgrades, changes, or the deletion program to replace COTS items with indigenous systems. A complete UAV would assemble after system integration.

3.6 Phase IV – Testing

After the assembly and system integration, ground testing of the UAV and its subsystems would be conducted. If deemed feasible and cost-effective, a ground-launched version may be developed for initial testing before taking it to the aircraft for air launching. Later, the aerial trials would be conducted at various flight conditions, heights. However, the verification of the system would be accomplished by fulfilling the requirements of the system engineering process and recommended aviation standards. After the qualification of the system, the prototype would be offered to the user for ops testing. Subsequently, the production of UAV may be carried out.

3.7 Verification & Validation

This activity is intended to verify that the system design satisfies user/stakeholder requirements and validate that it conforms to the required standards. It includes developing verification plans, procedures, and methods (e.g., inspection, demonstration, flight test). System-level use cases, scenarios, and associated requirements serve as primary inputs to the development of the test cases along with the associated verification procedures. The verification procedure can be modeled using the same activities and artifacts described for modeling the operational system. The requirements management database is updated during SDLC to trace the system requirements and design information for corresponding system verification methods, test cases, and results. The full description of each object-oriented Systems Engineering activity and process flows are provided in the cited book by Friedenthal, Moore, and Steiner [36]. Different types of applicable standards are attached as **Appendix 'B'**. Moreover, system reports and documents which can serve as a reference for verification and validation are mentioned below:

(a) System Requirement Documents

(b) Aerodynamics Reports including CFD Analysis, Performance Analysis, Static & Dynamic Stability derivatives

(c) Structural Design & Analysis Reports

(d) Avionics Systems Diagram and Reports

(e) Flight Controls System Reports

(f) Propulsion System Reports

(g) Electrical System Diagrams Reports

(h) Flight Test Plan Reports (generated using Control Station)

3.8 Milestones and Expected Deliverables

In order to review the development process and to avoid its time or cost overrun, it is divided into milestones. The development process of envisioned UAV has also been divided into 10 millstones which are as follows:

(a) Milestone No 1: Development and finalization of Detailed Design Report (DDR). The anticipated timeline for the same is T_o + 03 months where T_o is the project kickoff date

(b) Milestone No 2: Detailed Design of sub-systems. The subsystems should be able to meet preliminary design specifications, otherwise PDR & DDR review will be conducted. The anticipated timeline for the same is T_o + 06 months

(c) Milestone No 3: Development of CAD Models of all mechanical parts of UAV. Moreover, development of swarming algorithms and their demonstration via simulation software. The anticipated timeline for the same is T_o + 09 months

(d) Milestone No 4: Development of Mission planner, HMI of control station. Flying a simulated mission using control station without payloads. Development of launch and recovery mechanism for cargo and fighter aircraft. The anticipated timeline for the same is T_o + 12 months

(e) **Milestone No 5:** Development of at least half parts of UAV, the models of which were presented in Milestone No 3. Test report of development and integration of UAV avionics suite. The stipulated timeline for the same is T_o + 15 months

(f) **Milestone No 6:** Initial demonstration of developed swarming algorithm using simulators. The timeline for the same is T_o + 18 months

(g) **Milestone No 7:** Demonstration of developed Human Swan Interaction interface. Moreover fabrication / development of complete mechanical parts of UAV. Furthermore, procurement of all COTS items also to be completed. The anticipated timeline for the same is T_o + 21 months

(h) **Milestone No 8:** Ground Test of developed UAV with integrated control station. The anticipated timeline for the same is T_o + 21 months

(i) **Milestone No 9:** Flight Test of developed UAV with its control station (with ground launch mechanism, if considered feasible). The anticipated timeline for the same is T_o + 24 months

(j) **Milestone No 10:** Flight Test of developed UAV with its control station onboard cargo aircraft. The anticipated timeline for the same is T_o + 30 months

3.9 Configuration Management

According to **MIL-HBDK-516C**, Configuration Management (CM) falls under the umbrella of Systems Engineering. CM encompasses the system management activities concerned with the formation, maintenance, change control, and quality control of the scope of the work. A configuration is the set of functional and physical characteristics of a final deliverable defined in the specification of a project. CM can be regarded as asset control, and it is essential even if multiple or future versions of a deliverable are not planned. CM is a valuable tool for providing control of the deliverables and avoiding mistakes and misunderstandings.

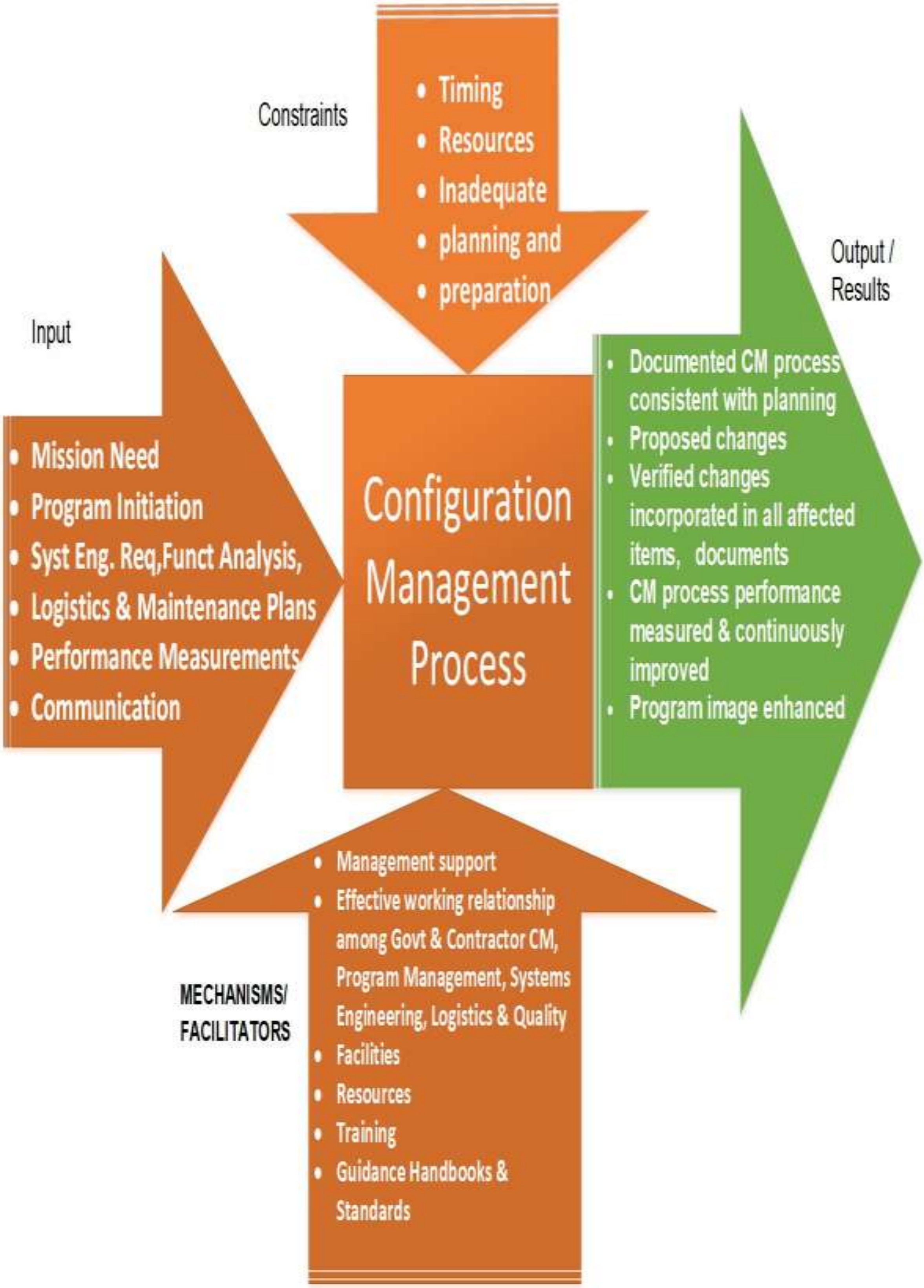


Figure 3.2: Configuration Management Process

3.10 Risk Management

Risk Management is also one of the critical areas to be focused on during any system development life cycle. The risk management process covers identifying risk areas, assessing their impact on the success of SDLC, and developing a risk response strategy to mitigate or avoid these risks to keep SDLC on track. Risk factors mainly affect the program from schedule, performance, functionality, and cost perspectives. Thus, a proactive approach to managing risks earlier and developing a contingency plan instead of reacting to the crisis can be useful.

3.10.1 Risk Identification

Although it is not possible to identify all risk factors that may arise in SDLC at a planning stage. It requires extensive brainstorming and brain writing. Potential risk areas for UAV development are as follows:

(a) Cost Overrun
(b) Schedule Overrun
(c) Human Resource related Risks
(d) Inaccessibility / delay / denial of selected hardware
(f) Delay in Funds Availability
(g) Extensive change in user requirements
(h) Delay due to Regulatory Bodies
(j) Implementation Failure
(k) Force Majeure

3.10.2 Risk Assessment & Response

Risk assessment is vital to find out the likelihood / main causes of risk occurrence during SDLC. Risk areas identified are assessed based on their causes of occurrence, their risk level is determined, and appropriate risk response to mitigate or abate the risk is devised. Risk areas are mainly categorized into three levels, i.e., high, medium, and low. Risk levels classified as high can severely impact SDLC execution. Medium-level risks can hamper project efficiency and disturb timelines, whereas lower-level risks will have minimal effect on the program. A risk chart depicting these risk factors along with their potential impact and probability of occurrence with regard to development of UAV is shown in Figure 3.3 below:

Probability ↓ / Impact →	Low	Medium	High
Low	--	Delay due to Regulatory Body	Cost Overrun
Medium	Schedule Overrun	HR Related Risks	Implementation Failure
High	Inaccessibility / Delay / Deny of Selected H/W	Funding Delays	Extensive Change in User Requirements

Figure 3.3: Risk Chart

Chapter 4

System Level Design

4.1 The Design Process

As per Fleeman, [24] UAV design is an iterative process where operational need analysis is carried out based on the mission requirements defined by the user; operational concepts are derived, the design analysis generates new concepts, and the cycle repeats. Raymer [25] mentions that those involved in the design process can never agree on where the process begins. However, most aircraft designs generally have a starting point anchored to a reference design or a previous design for similar purposes. In UAVs, the absence of human opens the design space, enabling designs to be more mission-driven than in the design of conventional manned systems. As a result, current UAV designs range from those for which the airframe might appear comparable to the size of manned aircraft to as small as the size of a paper plane. However, the design process remains the same, which is illustrated in the following figure [24].

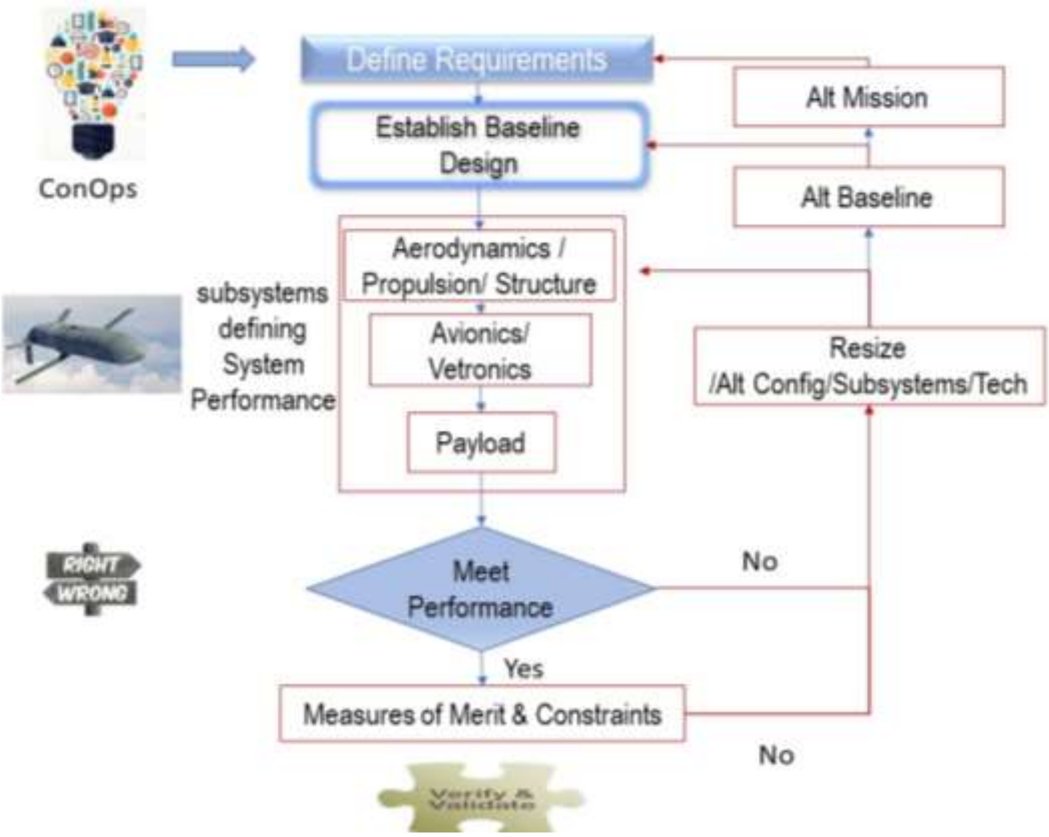


Figure 4.1: The Design Process of Air Launched Recoverable UAV

4.2 Operational Need Assessment

Operational needs assessment defines the business and mission need for providing systems, services, capabilities, or platforms to end-users and other stakeholders. It develops a business case that justifies the return on investment to obtain funding for a system or system of systems [26]. Thus, operational need assessment leads to the development of the concept of operations. To check the operational viability of envisioned UAV, data on the most important user requirements were mapped to evaluate existing operational systems vis-à-vis envisioned system. The details are attached as **Appendix 'C'**. The results show that envisioned system is better capable of meeting the operational requirements than the existing system.

4.3 Concept of Operations (Conops)

The envisioned UAV is required to meet the following needs

(a) Air launch from mobile base (cargo / fighter aircraft) to do away with the requirement of traceable runway or ground launchers

(b) Wider area of influence as compared to a ground based / immobile platform

(c) The element of surprise and psychological impact of a power projection that has no geographical limits

(d) Reusable UAV with on ground recovery allowing rapid force projection and greater risk taking at lower life-cycle cost for operations in denied environments

(e) Rapid and safe multi-UAV launch and recovery. Inbuilt systems to allow safety and reduced time spent on relaunching of UAVs

(f) Integration of existing payloads, communication subsystems, data links and other available hardware

(g) Scalability to support the independent launch or group employment i.e., single to volley quantities of UAVs from one or more aircraft and their recovery

(h) Supports autonomous capabilities that let swarms to operate together with minimal supervision

(i) Robust Intra-swarm communications

(j) Adaptive, anti-jam network for distributed sensing, decision making, information sharing and coordination

(k) Minimal requirement of ground / air support equipment

(l) Modular design and minimal maintenance yielding a small logistics footprint and two-level support (operations level and factory level)

(m) Low-cost, limited-life airframe designed for reuse along with low-cost supporting systems

4.4 User Requirements

User requirements are the user needs that are required to be fulfilled by the system. They are also termed as Stakeholder needs. These are the system level requirements that describe the functions which the system as a whole should fulfill to satisfy the needs of user or stakeholders [27]. These requirements are the initial criteria for design consideration. As per **MIL-HDBK-516C (Section 4.1)** [28] these high-level requirements are allocated down through design hierarchy as the system requirements evolve with system design. User requirements are then elicited to the respective design teams to be met by the respective sub-system and area experts. Thus, these requirements dictate the individual subsystem requirements, characteristics, and features that they **"Must Have"**. User requirements are often classified as functional and non-functional requirements. The detailed user requirements of envisioned UAV are placed as **Appendix 'A'.**

4.5 Preliminary Design Specifications

The purpose of defining preliminary design specifications (performance parameters) is to develop quantitative framework. This not only helps in meeting the user requirements but will also help in selection of cost-effective solution in meeting those requirements. Major performance requirements are mentioned below whereas the details are attached as **Appendix 'D'**.

(a) Mission Radius / Loiter Time 100 nm / 1.0 hr

(b)	Maximum Payload	55 lbs
(c)	Maximum Cruise	0.2-0.6 Mach
(d)	Maximum Launch Altitude	30 kft
(e)	Launch Quantity	1 to 4 air vehicles
(f)	Turnaround Time	< 24 hrs
(g)	Payload Power Requirement	500 W

(h) Flexible Payloads Imaging electro-optical/infrared systems, synthetic aperture radar, laser designator, electronic warfare suite, electronic attack package and kinetic kill etc.

4.6 System Architecture

The system architecture is the conceptual model that defines the structure of the system. It is the formal description and representation of a system organized to support reasoning about the structure and behavior of system components. The system architecture is normally depicted using a system architecture diagram. UAV System architecture diagram outlines system components and their subsystems to be developed that will work together to implement the overall system. The system architecture is described in Fig 4.2

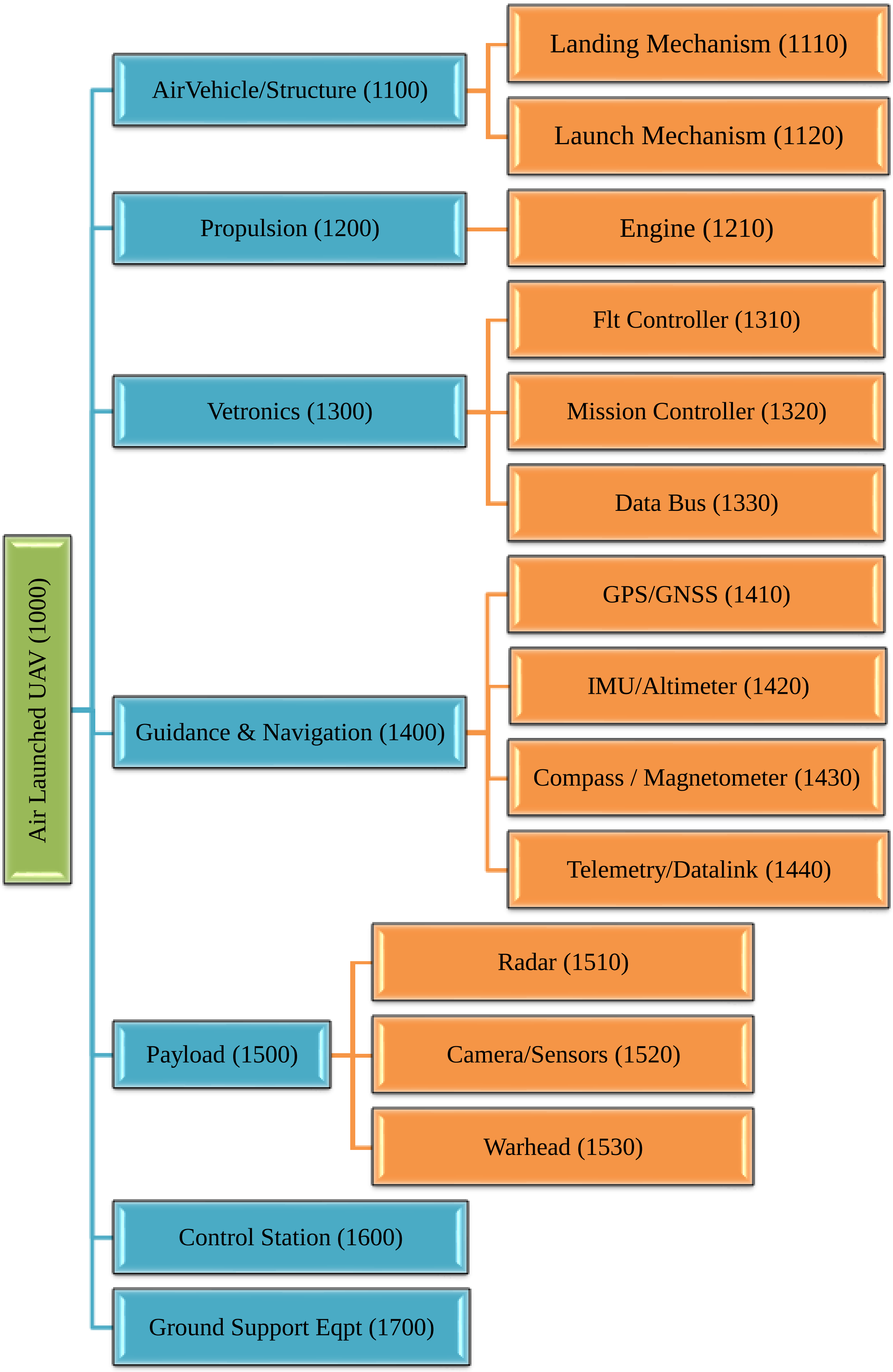


Figure 4.2: Air Launched UAV System Architecture

4.7 Physical Architecture

Physical architecture describes the physical layout of a system and its components. It refers to the physical representation of the structure or organization of the physical elements of the system. The physical architecture should conform to the user requirements and preliminary design specifications [29].

Figure 4.3: Air Launched UAV Physical Architecture

4.8 UAV Subsystems

4.8.1 Air Vehicle

Air Vehicle is the airborne part of the UAV that mainly includes its airframe and structure. To make the UAV cost-effective and expendable (about 20 missions), composite material is planned to be used. The manufacturing techniques range from molding, weaving, or 3D printing. The structure has been designed to provide maximum strength and stiffness with minimum weight. The shape has been designed to optimize the design for maximum efficiency to choose reliable control laws for aircraft stability. Significant dimensions of envisioned UAV are mentioned below, whereas the design details are attached as **Appendix 'E'**.

(a) Vehicle Dimensions 4.26 L x 0.58 W x 0.53 H (in meters)

(b) Wingspan 3.48 meters (supercritical airfoil)

(c) Gross Vehicle Weight 1320 lbs (600 Kg)

The weighing capability of large-to-small UAVs was studied and compared to the overall airframe cost for U.S. military systems (including the communication and control systems). The trend-line shows that the airframe cost is a bit over the U.S.$1M per hundred pounds of payload. This implies that larger payloads require larger, more expensive airframes. Moreover, this also shows that the airframe is needed to be sized according to the payload.

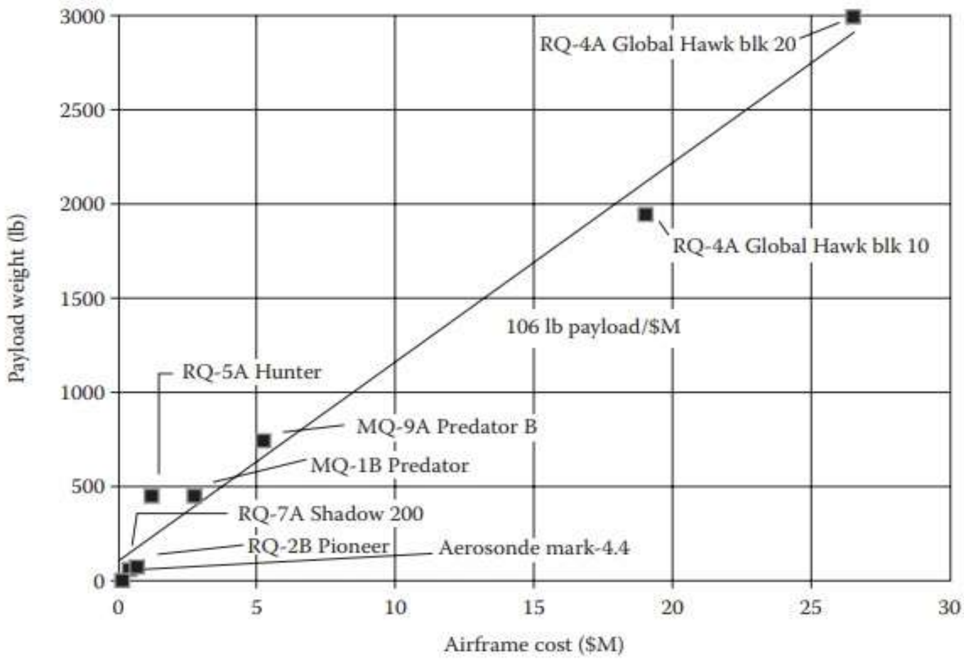


Figure 4.4: Payload Weight Capability of US UAVs [30]

4.8.2 Propulsion

The performance of a UAV mostly depends upon its propulsion system, with the greatest performance provided by turbine engines, followed by internal combustion engines followed by electric motors. Figure 4.5 illustrates the performance of several contemporary UAVs with a different type of engines. These are primarily military systems with data supplemented by the 2009 UVS Yearbook and product brochures [31]. The UAV propulsion system is chosen based on the mission requirements, where excess power required for subsystems and payloads is an essential driver for the selection. CFD Analysis of reference design was carried out at different Angle of Attacks to find out the C_L/C_d ratio. It was found that this comes out to be between 10-12. Data attached as **Appendix 'F'**. The required thrust for the engine comes out to be between 600 N to 800 N. Based on the required thrust; a turbojet engine was selected to meet the performance requirements of envisioned UAV. Engine model and details are attached as **Appendix 'G'**.

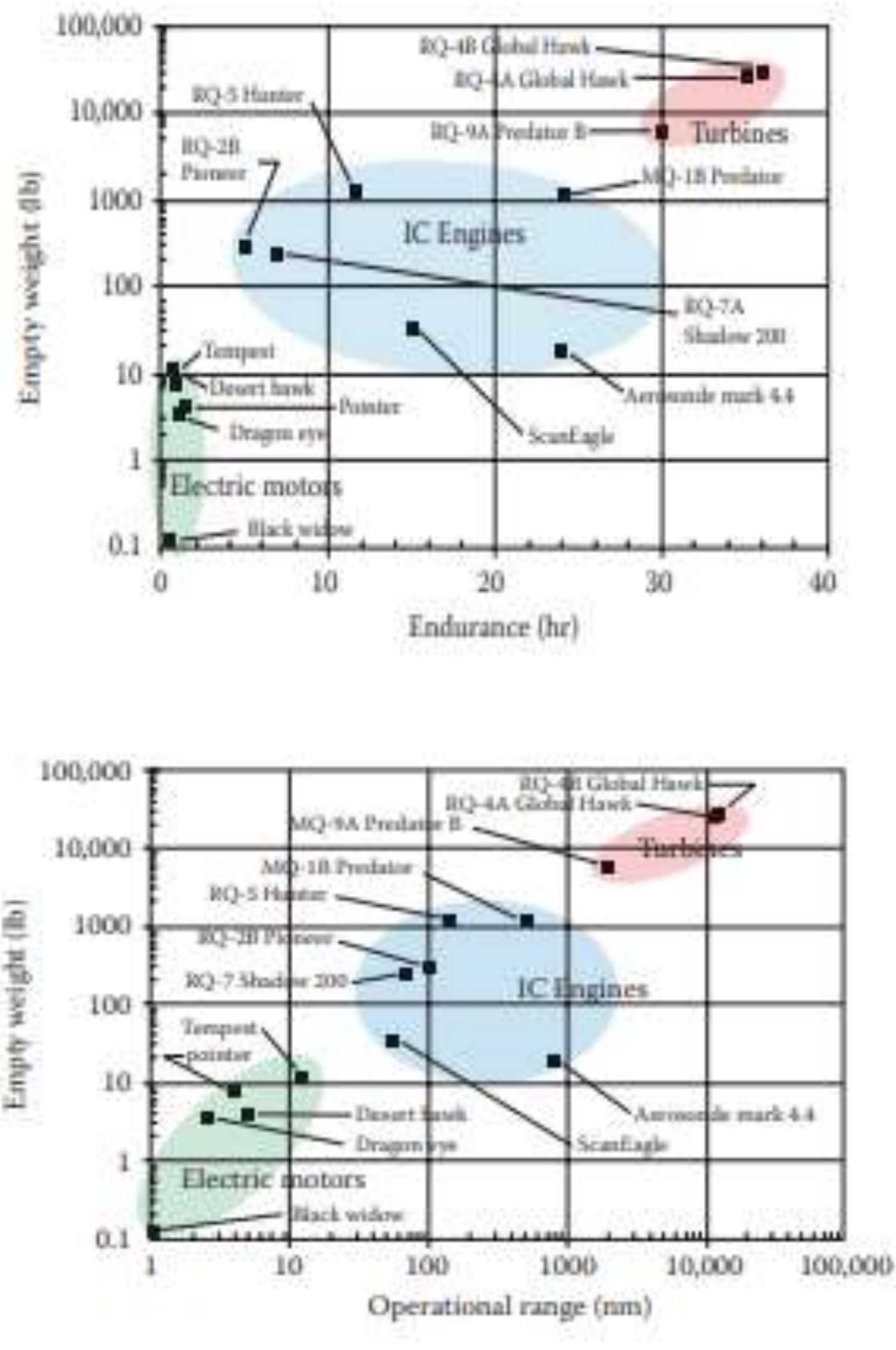


Figure 4.5: Performance of Contemporary UAVs with Different Type of Engines

4.8.3 Vetronics

(a) Flight Controller. The flight controller performs essential flight control functions such as navigation, stabilization, and autopilot. Autopilot is a key to enabling aircraft to be reliably controlled without a human pilot on board. **Elmer Sperry** is generally credited with the development of the first true autopilot used in a UAS. Flight Control System is critical for UAV in terms of reliability, fault tolerance, safety, and endurance of the air vehicle. There are mainly three types of Flight controllers, i.e., Closed Source Flight Controllers, Open-Source Flight Controllers, and Customized Flight Controller.

(i) Closed Source Flight Controllers. They are designed for specific platforms and applications and are not adaptable to customization. Furthermore, the lack of standardization of flight controller architecture and the use of proprietary closed-source software also prevents its porting from one platform to another.

(ii) Open-Source Flight Controllers. There are good number of open-source flight controllers available off the shelf. The protocols and functionality of these controllers is available and is documented. Moreover, their source code can also be modified as per requirements or application. Due to this dual advantage, open-source flight controller with programmable autopilot was selected. Pix Hawk 4 shown in Fig 4.6 is considered as one of the suitable open-source flight controllers for UAV.

(iii) Customized Flight Controller. A customized controller can also be designed in MATLAB™ for use in the longer run.

Figure 4.6: Pix Hawk 4 Flight Controller with Programmable Autopilot

(b) Mission Computer. Apart from the Flight controller computations, the mission computer is vital to perform two other calculations necessary for swarming. Firstly, are the computing requirements for swarming algorithms, and secondly, the application or payload-specific computing requirements. Both computations can be performed on a single companion computer onboard UAV, which was earlier implemented on separate computers. This is possible because of the low cost, low weight, and high-performance computers available off-the-shelf. Some candidate computing platforms are Raspberry Pi, ODROID, PC-104, NVIDIA Tegra® K1, NVIDIA Jetson TX2, and NI Crio. Out of which NI Crio shown in fig 4.7 is considered as the suitable option due to its computability with military and industrial grade hardware.

(c) Data Buses. Since the envisioned UAV is based on commercial off-the-shelf items, thus 1553 bus alone cannot be used. Its use will limit the peripherals to military-grade only. Therefore, real-time data automation buses used in industry like EtherCat TSN (Time-Sensitive Networking) are shortlisted. Ethercat as a protocol will bring the power and flexibility of ethernet for automation, motion control, real-time control systems. Ethercat as standardized in IEC 61158 along with Rs-485 will be used for real-time computing requirements.

Figure 4.7: UAV Mission Computer (NI Crio)

4.8.4 Guidance and Navigation

Guidance and Navigation form a vital part of envisioned UAV. The involved sub-systems usually come as a package and are covered in following paragraphs: -

(a) **GPS/GNSS.** Global positioning system and Global navigation system provide accurate global location information. GPS is subject to jamming and denial and its accuracy also varies on various factors. Moreover, it has update rate of 1-10Hz per second.

(b) **IMU.** Inertial Measurement Unit on UAV is used to measure relative position changes of the vehicle. The IMU are prone to accumulative drift errors. Therefore, the GPS-IMU combination can be used to get the accurate location from the GPS and to maintain the changes to the location during GPS updates by using the IMU. The IMU is usually integrated within the flight controller hardware but it can also be added externally. There are numerous commercially available 6 DOF MEMS based IMU sensors e.g., MPU 6040

(c) **Altimeters.** It is used to measure the height of the UAV in either AGL or ASL depending on the technology used. There are three major types of altimeters i.e., Laser, Radio, Barometric and Radio altimeters. In good coverage areas GNSS can also be used to get the height of the vehicle.

(d) Compasses/Magnetometers. Onboard compasses / magnetometers can point to the direction of magnetic north and this information can be used to augmenting guidance and navigation

(e) Telemetry / Datalink. Normally datalinks used for communication in military drones are proprietary. This is because, if acquired off the shelf, without proper contract, they can be banned under pressure. Datalink transmits location, remaining flight time, distance, location to target, distance from control station, payload information, airspeed, altitude and many other required parameters to control station. The most popular frequencies used in drones are 400M Hz, 900 MHz alongside Satcom systems. There are numerous short, medium and long-range telemetry systems available off the shelf. The data link shortlisted for UAV is DLS-100™. This datalink is optimized for UAVs.

4.8.5 Payloads

The UAV will be able to carry under mentioned payloads: -

(a) Imaging (Thermal / Electro-optical /Infrared)

(b) Meteorological Sensors

(c) Luneburg Lens

(d) LIDAR

(e) Synthetic Aperture Radar (SAR)

(f) Jammer

(g) TNT

(h) Kinetic

4.9 Control Station

The control station (CS), is the part of the UAS that provides the control interface to the operator. It provides the interface to the operator for managing, supervising, and initiating high-level mission commands to the UAV. The main sub-system of the control station is the Human

Machine Interface (HMI). HMI is the software interface to the operator to plan the mission, and then it converts the high-level commands into mission objectives. These commands are then transmitted to the UAV. Commands issued through the Control Station range from a pilot sending real-time joystick altitude-control command to manually flying the UAV. Normally, the operator plans, upload the mission, and then monitors it through Control Station. HMI provides a supervision interface to the operator for monitoring the mission progress. It also provides the operator with an interface to cancel the mission or its objectives during the mission. In the case of manual mode, the pilot/operator steers the UAV through a control station or, in other words, in manual mode, CS acts as the cockpit of the UAV.

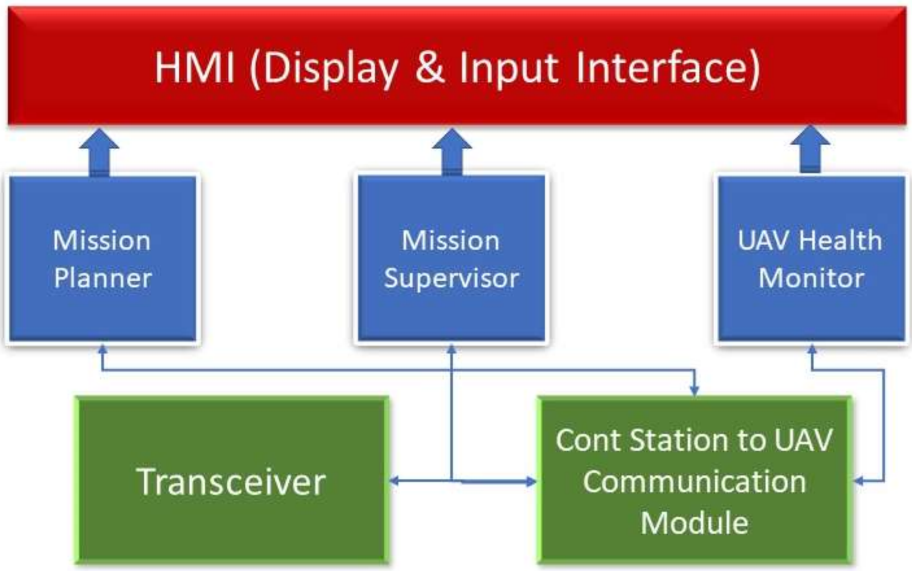
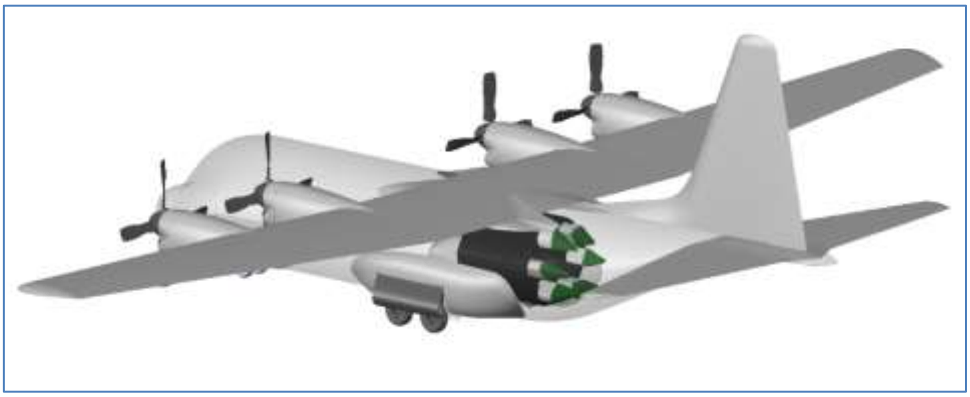


Figure 4.8: Control Station High Level Architecture

Figure 4.9: Envisioned UAV Control Station

4.10 Launch Mechanism

A safe, repeatable approach is envisaged that can be adapted to launch multiple air vehicles (max 04) from existing cargo / fighter aircraft in the fleet. The launch system should have an open-architecture design that fits the existing cargo and fighter aircraft infrastructure with no permanent modifications to existing aircraft or equipment. In case of launch from cargo aircraft, a removable rotary launcher has been envisioned. It can launch 6-8 UAVs. Moreover, a control station can also be located in the plane to control the launched UAVs. However, in this case, the telemetry, datalink antennae are required to be mounted on aircraft. In the case of fighter aircraft, the UAV can be installed on the pylon.



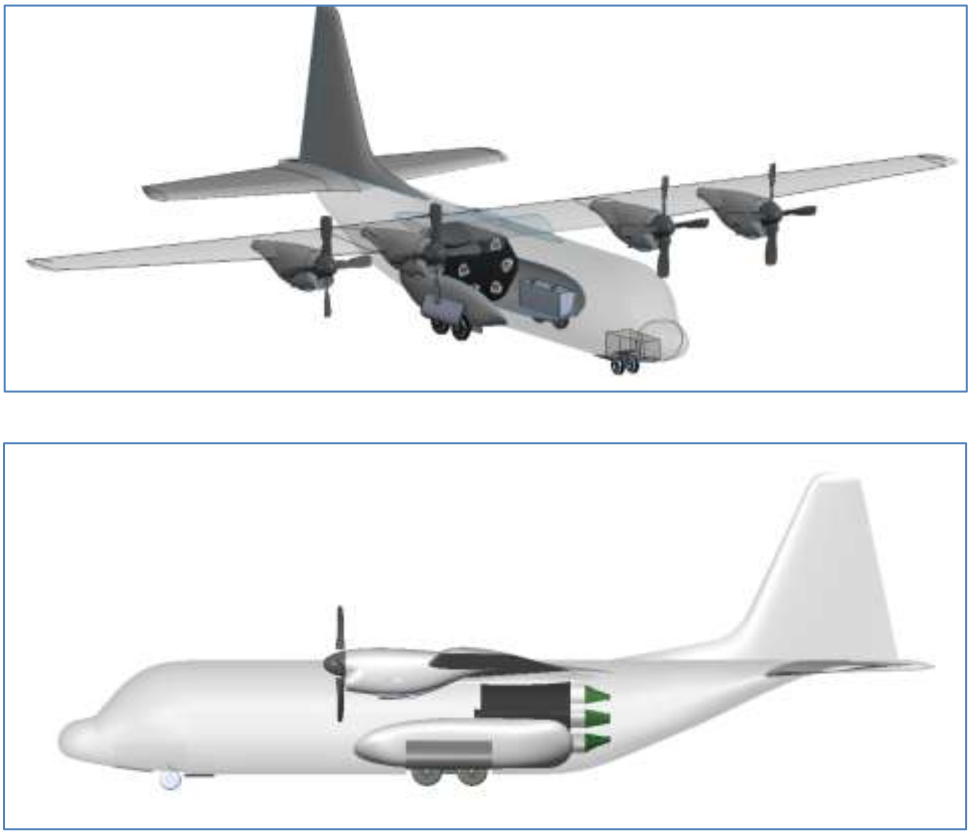


Figure 4.10: Launch Mechanism of UAV from Cargo Aircraft

4.11 Recovery Mechanism

Initially, parachute recovery is considered suitable for envisioned fixed-wing UAV system requiring a high degree of mobility. This allows air vehicle recovery onto unprepared terrain. However, while recovery, the descent environment and the impact of wind are considered. The cruciform canopy is selected after considering the relative merits of cruciform, round, and parafoil canopies [35]. The safe rate of descent is between 3.5 to 5.5 m/s which led to the diameter of the parachute as around 15 meters. The equation used for calculating the diameter of the round parachute is

$$D = \sqrt{(8mg)/\pi\rho C d v^2}$$

where D = Parachute diameter in meters

m = mass of falling aircraft/rocket (measured in kgs)

g = acceleration due to gravity

ρ = density of air = 1 .22 kg/m^3

π = 3.14159

C_d = Drag coefficient of parachute = 0.75 - 1.5 for round canopy

V = Impact velocity (4.0 m/s)

4.12 Ground Support Equipment

Following ground support equipment is envisaged for supporting transportability of UAV on ground:

S No	Ground Support Equipment	Qty/UAV
1	Wing Support	02
2	Fuselage Support	04
3	Hydraulic Jacks	02
4	Jig for transporting UAV after recovery	01
5	Tool Kit	01
6	Transportation Trolley	01

Table 4.1: List of UAV Ground Support Equipment

Figure 4.11: UAV Transportation Trolley

4.13 Modular Open Architecture

Modular open architecture has long been recognized as potentially beneficial as it increases the potential pool of performers that can be acquired off the shelf and integrated. This takes the design away from any proprietary restrictions on interfaces and modules. Modular open architecture is one of the foremost requirements mentioned in the DARPA program CODE.

4.14 Swarm Management and Collision Avoidance

Swarm Management and collision avoidance require self-optimization of individual drones, optimization of joint efforts between drones, and efficient swarm control by the human user, at multiple levels of abstraction. A distributed relative localization framework is required allowing each drone to autonomously localize itself with respect to the other drones in the swarm and enabling fast propagation or dissemination of this localization information everywhere in the swarm and to the control station. The framework can be implemented using each drone's Internet of Things (IoT) enabled hardware platform. This hardware will support 3D swarming applications and will eventually facilitate the efficient interaction between the drones, intra-swarm, inter-swarm along with human operator at the control station.

The selected hardware allows a single user to control the movement and formation of the swam concerning the leader drone, using an intuitive remote-control interface. This swarm is a self-organizing structure having the behavior of a multi-agent control system. Its formation flying principle is associated with a remote user/operator through a wireless communication system between the operator and the swarm. In a swarm, there is a single leader drone leading other. The hierarchy can be made complex with multiple clusters or superclusters, each having its leader. Leader drones communicate with the control server, sharing the collected data.

To have a UAV capable of operating in tight/dense formations, a collision avoidance algorithm is required to be implemented. These algorithms are based on reliable trajectory prediction for autonomous control along with emergency evasive maneuvering. Ultrasonic sensors for collision avoidance are also available for integration with existing platforms.

4.15 Flight Termination

This feature includes contingency actions that result in termination of flight, i.e., its immediate landing. Once activated, this feature will caution the UAV to check whether it is in a hostile or friendly environment. In case of a friendly atmosphere, it will activate its landing procedure. However, in the case of hostile territory/environment it may start its self-destruction mechanism depending upon the range or vicinity of the friendly area.

4.16 Preliminary Design Review

A Preliminary Design Review (PDR) is undertaken during the concept development phase of the System Development Life Cycle (SDLC). The purpose of PDR is to review system architecture by explaining the concepts and driving parameters. It elucidates the reason behind choosing the particular architecture and approves it as the design baseline. Subsequently, its purpose is to compare the chosen architecture with the excluded architecture. It provides a quantitative analysis that gives confidence that the requirements are driving the architecture and prototype. During concept design, alternatives are generated using Pugh Matrix or Morphological box or similar alternative generation techniques. This is the stage when detailed mathematical models are not available, but a vague qualitative understanding exists. During the PDR, utility analysis is undertaken to find the alternatives which the stakeholder prefers. Subsequently, multiple design options are generated, and the most viable amongst them are selected. The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with the detailed design. It shows that the correct options have been selected, interfaces have been identified, and verification methods described.

In PDR, concept generation and selection are flexible. If the wrong concept is selected or some important detail has been overlooked, the decision can be reverted without weighty consequences. It must be kept in mind that an optimal system cannot be designed by combining a set of optimal system elements. As System Engineer, we are interested in the best combination of components rather than a combination of best components to present the most desirable end product to the stakeholder.

Chapter 5

Analysis, Results & Discussion

5.1 Analytical Hierarchy Process

The analytic hierarchy process (AHP) approach has been widely used in multicriteria decision-making (MCDM). AHP has the advantage that the whole number of comparisons can be reduced via a hierarchy structure, and the consistency of responses can be verified via a consistency ratio. AHP helps in decision-making by quantifying the qualitative attributes. It is widely applied as a comprehensive and systematic method to choose the best alternative under the limitations of time and resources. In this chapter, the priority requirements mentioned in Appendix A have been analyzed.

5.2 Analysis

The problem is stated, and the goal is derived from developing an Optimal Air-Launched recoverable UAV as per the requirements. The criteria / attributes required to achieve the plan have been identified. The hierarchy structure is composed by mentioning the factors from high to low levels based on importance as considered for the system.

S No	Goal	Factors to be Considered
(a)	To develop Optimal Air Launched UAV	Ops in Contested Environment
(b)		Low Cost
(c)		Swarming / Scalability
(d)		Recoverable / Reusable
(e)		Air Launched (Multiple)
(f)		Multiple Payload Types
(g)		Autonomous / Semi-Auto Ops

Table 5.1: Priority Factors Considered for UAV

A priority matrix for mutual comparison of these seven factors was developed. For the priority matrix of order 7x7, the number of areas to be filled for the priority matrix is calculated using the following formula:

$$No\ of\ Areas\ to\ be\ filled = n\,(n-1)/2 \qquad (1)$$

where n = number of factors considered during UAV development. For seven factors, n=7

$$No\ of\ Areas\ to\ be\ filled = 7\,(7-1)/2 = 21 \qquad (2)$$

The standard for relative importance of criteria as told by Saaty [33] is mentioned in Table 5.2

Relative Importance	Definition	Remarks /Explanation
1	Equally Important	Two activities contribute equally to the objective
3	Moderate Importance of one over other	Experience and judgement moderately favoring one option over other
5	Essential or Strong Importance	Experience and judgement strongly favoring one option over other
7	Very Strong Importance	An activity is strongly favored over other
9	Extremely Importance	An activity favored over other over with highest possible order of affirmation
2,4,6,8	Intermediate Values between the two	Requiring in between grading of importance between the two states

Table 5.2: The Fundamental Relative Importance Scale used in AHP

Since these factors are independent thus, a comparison of these factors will also be performed independently. The relative importance of each factor on a scale of 1 to 9 based on subjective judgments as told by Saaty [34] was used for this pairwise comparison. The priority matrix deduced using the above comparison scale is as follows:

Criteria	Ops in Contested Environment C1	Cost C2	Open Sys Arch C3	Recoverable / Reusable C4	Multiple Launch/ Swarming C5	Multiple Payloads C6	Autonomous / Semi-Auto Ops C7	(C1*C2*C3*C4 *C5*C6*C7)
Ops in Contested Environment	1	3	3	3	5	5	7	**4725**
Cost	1/3	1	3	3	3	5	5	**225**
Open Sys Architecture	1/3	1/3	1	3	3	5	5	**25**
Recoverable / Reusable	1/3	1/3	1/3	1	3	3	5	**5/3=1.67**
Multiple Launch/ Swarming	1/5	1/3	1/3	1/3	1	3	3	1/15=**0.067**
Multiple Payloads	1/5	1/5	1/5	1/3	1/3	1	5	1/225= 0.004
Autonomous / Semi-Auto Ops	1/7	1/5	1/5	1/5	1/3	1/5	1	1/13125

Table 5.3: Pair-wise Comparison Matrix of Requirements for UAV using AHP

The **A1 matrix (pairwise comparison) of our requirements comes out to be**

$$A1 = \begin{bmatrix} 1 & 3 & 3 & 3 & 5 & 5 & 7 \\ 1/3 & 1 & 3 & 3 & 3 & 5 & 5 \\ 1/3 & 1/3 & 1 & 3 & 3 & 5 & 5 \\ 1/3 & 1/3 & 1/3 & 1 & 3 & 3 & 5 \\ 1/5 & 1/3 & 1/3 & 1/3 & 1 & 3 & 3 \\ 1/5 & 1/5 & 1/5 & 1/3 & 1/3 & 1 & 5 \\ 1/7 & 1/5 & 1/5 & 1/5 & 1/3 & 1/5 & 1 \end{bmatrix} \quad \text{--- (1)}$$

Now for computing **A2 matrix** we proceed as

Multiplying the entities in each row and taking the n^{th} root of the result. In our case n=7

Ops in Contested Environment = $(4725)^{1/7}$ = 3.3490

Cost = $(225)^{1/7}$ = 2.1678

Open Sys Architecture = $(25)^{1/7}$ = 1.5838

Recoverable/Reusable = $(5/3)^{1/7}$ = 1.0757

Multiple Launch/Swarming = $(1/15)^{1/7}$ = 0.6792

Multiple Payloads = $(1/225)^{1/7}$ = 0.4613

Autonomous / Semi-Auto Ops = $(1/13125)^{1/7}$ = 0.2580

The Matrix from Requirements comes out to be

$$= \begin{bmatrix} 3.3490 \\ 2.1678 \\ 1.5838 \\ 1.0757 \\ 0.6792 \\ 0.4613 \\ 0.2580 \end{bmatrix}$$

Now for normalizing each entry of this matrix we proceed as

The Sum of entities = 3.3490 + 2.1678 + 1.5838 + 1.0757 + 0.6792 + 0.4613 + 0.2580

= 9.5748

Diving each entity of matrix by this sum we get the matrix

$$A2 = \begin{bmatrix} 0.3498 \\ 0.2264 \\ 0.1654 \\ 0.1123 \\ 0.0709 \\ 0.0482 \\ 0.0269 \end{bmatrix} \quad \text{-----} \quad (2)$$

It is worth mentioning here that the sum of all entities of A2=1

A2 matrix gives us the relative importance of our requirements.

This is also called as **priority Vector** or the **Eigen Vector.**

Now to check the consistency criteria we proceed as follows

By multiplying A1 & A2 we get

$$A3 = A1 \times A2$$

$$A3 = \begin{bmatrix} 1 & 3 & 3 & 3 & 5 & 5 & 7 \\ 1/3 & 1 & 3 & 3 & 3 & 5 & 5 \\ 1/3 & 1/3 & 1 & 3 & 3 & 5 & 5 \\ 1/3 & 1/3 & 1/3 & 1 & 3 & 3 & 5 \\ 1/5 & 1/3 & 1/3 & 1/3 & 1 & 3 & 3 \\ 1/5 & 1/5 & 1/5 & 1/3 & 1/3 & 1 & 5 \\ 1/7 & 1/5 & 1/5 & 1/5 & 1/3 & 1/5 & 1 \end{bmatrix} \times \begin{bmatrix} 0.3498 \\ 0.2264 \\ 0.1654 \\ 0.1123 \\ 0.0709 \\ 0.0482 \\ 0.0270 \end{bmatrix}$$

Thus, the resultant matrix comes out to be

$$A3 = \begin{bmatrix} 2.6459 \\ 1.7643 \\ 1.2826 \\ 0.8513 \\ 0.5342 \\ 0.3921 \\ 0.2110 \end{bmatrix} \qquad \text{-----} \qquad (3)$$

Now we calculate λ as

$$A4 = A3 / A2$$

$$A4 = \begin{bmatrix} 7.5645 \\ 7.7925 \\ 7.7538 \\ 7.5774 \\ 7.5306 \\ 7.1384 \\ 7.1305 \end{bmatrix} \qquad \text{-----} \qquad (4)$$

Now for calculating λ_{max} we take the average of all 07 entities of A4 matrix which comes out to be

$$\lambda_{max} = (52.4877/7) = 7.4982$$

The consistency can be validated by determining consistency index (CI) and consistency ratio (CR). If the values of CI and CR are less than 0.1 (10%), judgments are considered reliable and trustworthy. Thus, CI was calculated from the formula:

$$CI = \frac{\lambda max - n}{n-1} \qquad \text{-----} \qquad (5)$$

$$CI = \frac{7.4982-7}{7-1} = 0.08 \qquad \text{-----} \qquad (6)$$

Next step is to verify consistency ratio. It is computed using formula given below:

$$CR = {}^{CI}/_{RI} \qquad \text{-----} \quad (7)$$

Random Consistency Index (RI) followed is:

N	1	2	3	4	5	6	**7**	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	**1.32**	1.41	1.45	1.49

Thus, in this case, CR will be

$$CR = {}^{0.08}/_{1.32} = 0.06 \qquad \text{-----} \quad (8)$$

As we can see that, CI & CR < 0.1 that corresponds to best case scenario for laid down criteria to be consistent. Thus, criteria to be followed while developing UAV should be based on weighting factors is given below:

S No	Critical Features	Weightage
(a)	Ops in Contested Environment	**35%**
(b)	Cost	**23%**
(c)	Open System Architecture	**17%**
(d)	Recoverable / Reusable	**11%**
(e)	Multiple Simultaneous Launch / Swarming	**7%**
(f)	Multiple Payloads	**5%**
(g)	Autonomous / Semi-Auto Ops	**2%**
	Total	**100%**

Table 5.4: Weightage of UAV Critical Features

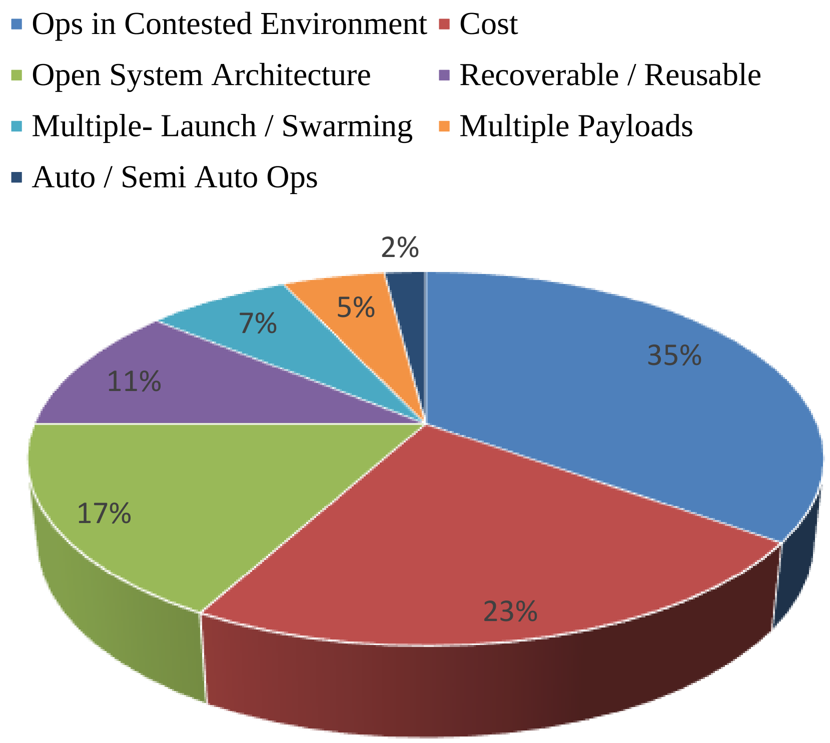


Figure 5.1: Pie Chart of Weightage of UAV Critical Features

5.3 Pareto Analysis

Pareto Analysis is a decision-making technique for assessing competing features and measuring their overall impact on achieving the goal. This allows the decision-maker to identify the prioritized features that will provide the most benefit. It is also called as 80/20 rule. After seeing the Pareto chart of critical features plotted in Fig 5.2, it becomes evident that the first four features, i.e., ops in a contested environment, cost, open system architecture, and recoverability, meets **86%** of the requirements; thus, these are the most critical features that are to be focused and implemented very diligently. The remaining three requirements make up only **16%** of the required features; thus, if at some time we have to tradeoff these features for cost or any of the first four features that can be considered.

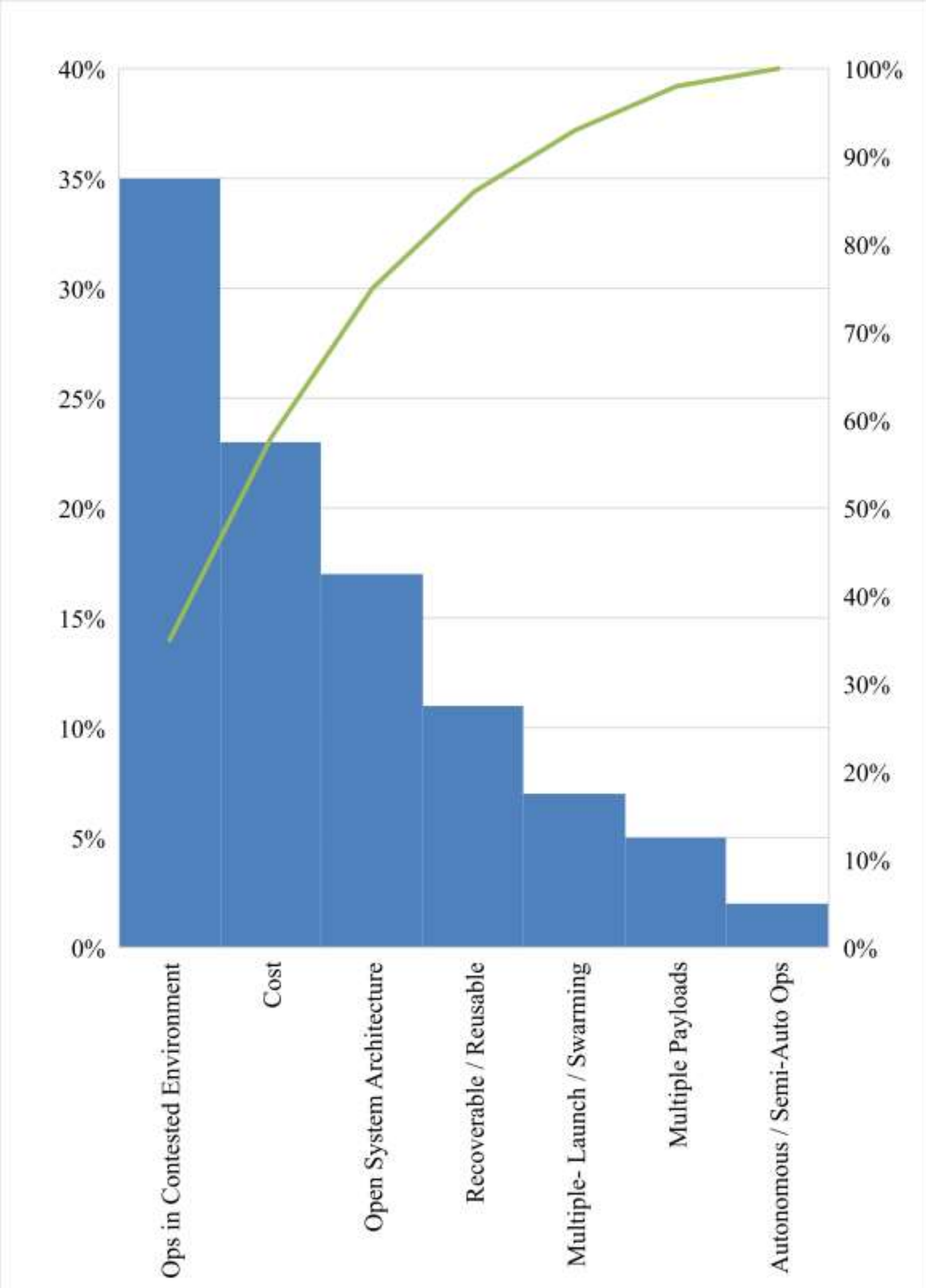


Figure 5.2: Pareto Chart of Critical Features

5.4 Quality Function Deployment

QFD is a systematic method for designing a product in way that it satisfies customers' needs. QFD is carried out in the planning phase. Its uses House of Quality as tool for translating user requirements into system requirements. HoQ for translating user requirements into system requirements is shown in Figure 5.3 below. Structured approach has been adopted for translating "Customer Requirements" mentioned in horizontal rows from S No 1 to 7 to "System (Functional) Requirements" mentioned in columns from S No 1 to 7.

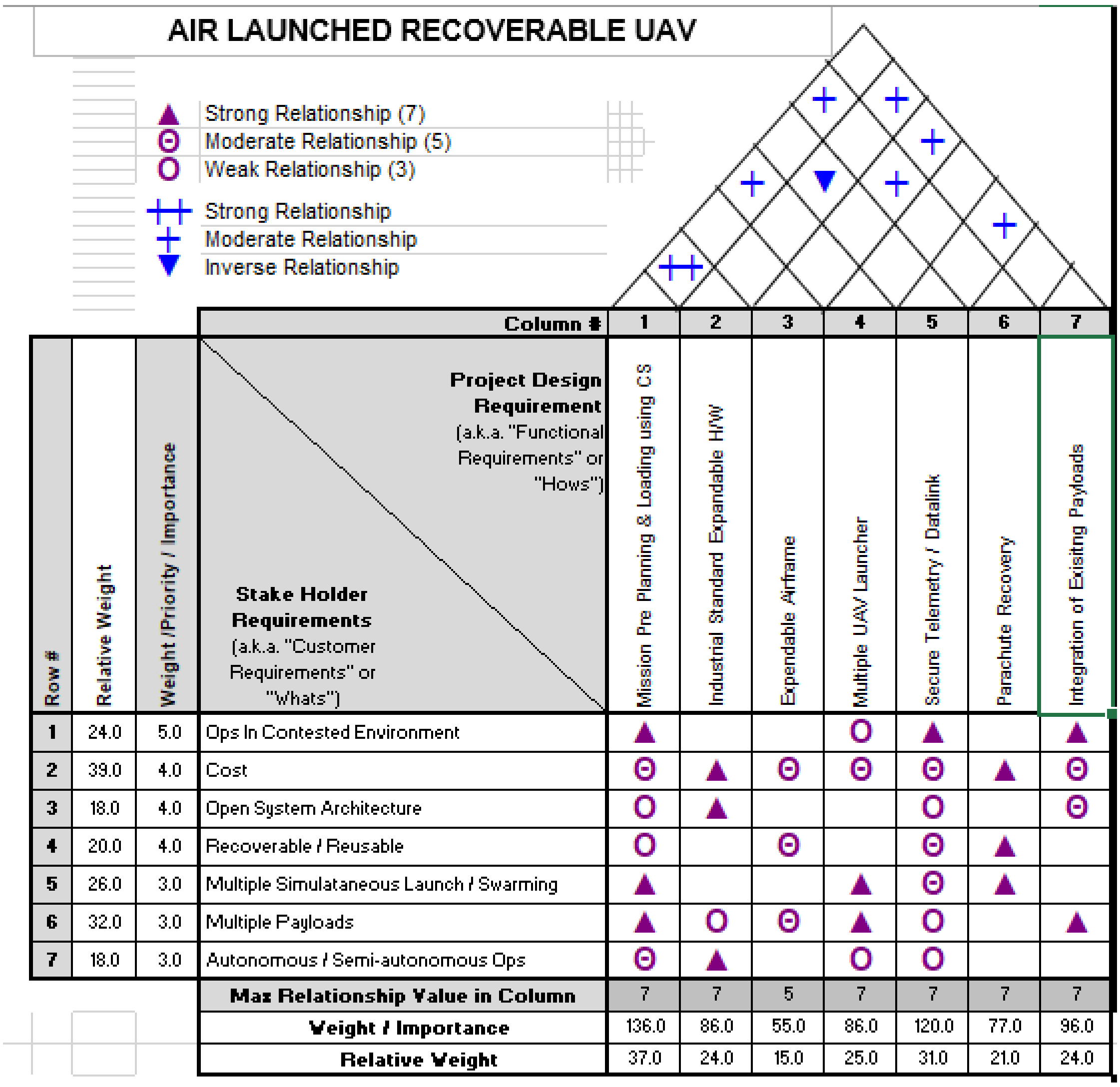


Figure 5.3: HoQ for Translating User Requirements into System Requirements

Chapter 6

Conclusion & Recommendations

6.1 Conclusion

Technology is driving the military application of UAVs into remarkable areas, with seemingly endless possibilities. UAVs are no doubt the future warhorse, and the country with the best drone technology would undoubtedly have an advantage in any future conflict. Pakistan, unfortunately, has lagged and has a lot of catching up to do in this crucial domain. Current technologies make UAVs more sophisticated than ever, with 'Drone Swarms' emerging as a real game-changer in future conflicts. In half a decade from now, swarms of unmanned drones would enter enemy airspace, fly autonomously to their target, use their advanced artificial intelligence algorithms to seek out and launch coordinated attacks on pre-designated targets, thus reducing the requirement for high-end, high cost, manned platforms. Future UAVs will also perform various tasks like supply, combat search and rescue, aerial refueling, and air to air combat.

In recent years, the use of Unmanned Aerial Vehicles has moved beyond the realm of military operations and has made its way into the hands of consumers and commercial industries. The applications of UAVs in commercial sectors are also endless. Many issues regarding their operations need to be considered before their widespread civil use is allowed. The challenges about large-scale operations of UAVs have ethical, legal, and societal implications that have to be addressed [15].

6.2 Limitations

A team of experts usually does system Engineering and the development of SEMP. However, in this case, the same has been done by a single researcher. Research in systems engineering may be encouraged amongst the students so that a group or team can conduct research; thus, more in-depth study of complex systems can be carried out.

6.3 Addition to the Body of Knowledge

It is a pioneering research study based on a system engineering approach for developing an Air-Launched Recoverable UAV for versatile roles. The author also determined the seven features' criteria and analyzed their importance using AHP, which was not done earlier. This study covered preliminary system design at the subsystem level. Due to the limitation of a single researcher, component level study could not be done.

6.4 Recommendation for Future Work

The future combat arena will see both the manned aircraft and the UAVs/UCAVs in complementary roles enhancing the overall combat potential of the force. Air force along with the industry needs to work on these technologies as public - private partners. The study on UAV has the potential to grow by incorporating the following capabilities which can be taken up for future work:

(a) Use of Improved AHP for criteria analysis.

(b) In-depth study of each sub-system. However, this would require more number of researchers.

(c) Development and Implementation of Artificial Intelligence Algorithms for autonomous / semi-autonomous systems.

(d) Development and Implementation of intra-swarm communication algorithms and their implementation using IoT hardware.

(e) Development and Implementation of Threat Evaluation and Weapon Assignment Algorithms (TEWA).

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Appendix 'A'

USER REQUIREMENTS OF AIR LAUNCHED RECOVERABLE UAV AND THEIR TRACEABILITY

S No	Requirement ID	Requirement
1	UR-01	A low-cost UAV shall be developed for Intelligence Surveillance & Reconnaissance (ISR), EO/IR, SAR, LD, EA, COMMINT, ELINT EW, Decoy etc.
2	UR-02	The UAV shall be able to carry standard air to ground and air-to-air payloads for UAVs.
3	UR-03	UAV shall be capable of launching from C-130, fighter (JF-17) aircraft
4	UR-04	UAV shall be capable of being launched from 30,000 ft
5	UR-05	UAV launcher shall have capability of simultaneous launch of 04 UAVs
6	UR-06	UAV shall be able to provide minimum 500 Watt of power to its payload
7	UR-07	UAV shall have scalable, open system architecture based on industrial standards for integration of available off-the-shelf items.
8	UR-08	UAV shall have rapid and safe multi-UAV air launch mechanism/ recovery (parachute).
9	UR-09	UAV should have limited-life reusable airframe.
10	UR-10	UAV shall be able to perform day and night missions, with laser finder/tracker, moving target indicator and Geo tagging.
11	UR-11	UAV shall be flyable without loss of reliability with 15 knot crosswinds; 30 knot headwinds; in rain, sleet, hail, and snow and in icy conditions.
12	UR-12	UAV shall be equipped with data or Satellite link capabilities for controlling and electrooptical data transmission.
13	UR-13	UAV shall be able to operate in hostile EW environment.
14	UR-14	Single Control Station shall be able to handle at least 04 UAVs with ability to operate at least 02 in autonomous and 02 in manual modes simultaneously
15	UR-15	Control Station shall be combination of "control terminal" and "data terminal".
16	UR-16	Control Station shall have side-by-side seating configuration for pilot/controller and payload operator.
17	UR-17	System ergonomics and displayed data shall follow standard aviation conventions and terminologies.
18	UR-18	Control Station display and GUI shall have inter-changeable displays.
19	UR-19	Mission commander should have separate display to monitor autonomous mode UAVs.
20	UR-20	Control Station software / Human Machine Interface shall be able to plan and validate mission plan before its loading.

21	UR-21	Control Station shall be housed in NATO standard 20 feet container (20 x 8 x 8) capable of being lifted by fork lifter and portable and transportable in C-130.
22	UR-22	UAV should be able to perform pre-flight tasks / checks in minimum time. (< 1 min)
23	UR-23	UAV shall spend minimum time on main runway and operating surface for its pre task checks and procedures.
24	UR-24	All payloads shall be controllable through data link by and operator on ground or in another aircraft (C-130, JF-17, AEW etc).
25	UR-25	UAV shall have rocket motor as engine, supporting throttling and safety during all phases of flight.
26	UR-26	UAV shall be equipped with Automatic Flight Control System (AFCS) capable of taking up autonomous / semi-autonomous operations with safety.
27	UR-27	System shall have on board UHF/VHF radios of Rohde & Schwarz with secure communication feature.
28	UR-28	The navigation systems shall be equipped with integrated BAIDU, GPS, GLONASS and FOG based INS system.
29	UR-29	UAV shall be equipped with auto recovery system along with corresponding software logic.
30	UR-30	UAV shall be equipped with self-protection suite against radar guided and IR Missile threats.
31	UR-31	UAV shall have satellite connectivity for extended range operations.
32	UR-32	UAV shall have Radius of Action (ROA) of 100 NMs with, loiter time of 01 hr.
33	UR-33	The UAV shall be equipped with handshake feature for handing over subsequent GCS for enhancement of it ROA.
34	UR-34	The UAV shall be low RCS (0.1 m^2) with stealthy design features (futuristic).
35	UR-35	The UAV shall have on board IFF System.
36	UR-36	The UAV should be able to equip with ACMI LRUs.
37	UR-37	For maximum safety and reliability, the platform shall have redundancy in critical systems i.e., flight controls, hydraulics, and electrical etc.
38	UR-38	UAV shall have covert anti Collison beacon and position lights along with standard taxi and landing lights.
39	UR-39	The gadgetry and flight control operation of UAS shall be operator friendly and must support initial training on the system.
40	UR-40	An advanced procedural trainer and flight simulator trainer for enhancing training module of aircrew and practice all critical in air and on ground emergencies shall also support UAS.
41	UR-41	Airframe shall have minimum 3 hard points to carry payload of total 110 lbs. (01 each under wings and 01 under belly)
42	UR-42	The UAV must be able to do gimbaled optical sensor will be able to adjust in 0.1-degree increments with an accuracy of 0.01degrees in azimuth and 01 degree in elevation.
43	UR-43	UAV shall be parachute recoverable
44	UR-44	Control station shall be able to display the strength of received control and EO/IR signal.

45	UR-45	Command / Telemetry link shall have at least 10 selectable/ programmable channels.
46	UR-46	Telemetry link shall be operatable on existing frequency band of user.
47	UR-47	Telemetry shall be able to play back with the time expansion off 100th of a second.
48	UR-48	Control station antennas should have an option to select sector by user-defined parameters.
49	UR-49	UAV shall be able to return to base of origin or as programmed in mission with requisite ground support
50	UR-50	UAV shall have Automatic self-destruction capability.
51	UR-51	UAV and its control station should be compatible for integration with existing SAR/ECM/ESM equipment of user
52	UR-52	UAV onboard system shall have capability to record any payload data with encryption.
53	UR-53	Control station shall be modular architecture.
54	UR-54	Control Station shall be protected against environmental hazards along with EMP protection.
55	UR-55	Post mission analysis tools shall be part of the control station
56	UR-56	Subsystems to be selected for providing life cycle supportability and availability for at least 30 years.
57	UR-57	UAV shall have built in test system (BIT)
58	UR-58	UAV shall have onboard Link-17 (futuristic)

Appendix 'B'

APPLICABLE DOCUMENTS AND STANDARDS

S No	Standard	Title
01	STANAG 4671	UAV System Airworthiness Requirements (USAR)
02	MIL-HDBK-516C	Department of Defense Handbook Airworthiness Certification Criteria
03	MIL-STD-810F	Environmental Engineering Considerations and Laboratory Tests
04	MIL-STD-704F	Interface Standard: Aircraft Electric Power Characteristics
05	MIL-STD464C	Interface Standard: Electromagnetic Environmental Effects, Requirements for Systems
06	MIL-HDBK-454	General Guidelines for Electronic Equipment
07	MIL-HDBK-863	Wiring Data and System Schematic Diagrams
09	MIL-DTL-38999M	Detail Specification: Connectors, Electrical, Circular, Miniature, High Density, Quick Disconnect, Environment Resistant, Removable Crimp and Hermetic Solder Contacts
10	MIL-STD-F-5572	Design Assurance Guidance for Airborne Electronic Hardware
11	MIL-A-8870	Military Specification: Airplane Strength and Rigidity Vibration, Flutter, And Divergence
12	MIL-S-8812D	Steering System, Aircraft General Requirements
13	SAE-ARP4754	Guidelines For Development of Civil Aircraft and Systems
14	SAE-ARP4761	Guidelines And Methods for Conducting the Safety Assessment Process On Civil Airborne Systems and Equipment
15	ASTM E8	Standard Test Methods for Tension Testing of Metallic Materials
16	ASTM D3039	Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
17	ASTM D790	Standard Test Methods for Flexural Properties of Unreinforced And Reinforced Plastics And Electrical Insulating Materials
18	DO-178C	Software Considerations in Airborne Systems and Equipment Certification
19	DO-254	Design Assurance Guidance for Airborne Electronic Hardware

Appendix 'C'

OPERATIONAL NEED ASSESSMENT OF AIR LAUNCHED RECOVERABLE UAV

S No	Priority Requirements	Cruise Missile	MALE UAV	Loitering Munition	Standoff Weapon	Envisioned System
1	Ops in Contested Environment	7	3	7	7	5
2	Low Cost	5	3	5	7	5
3	Swarming / Scalable	1	3	1	1	7
4	Recoverable / Reusable	1	7	1	1	5
5	Air Launched (Multiple)	5	3	7	7	5
6	Multiple Payload Types	1	7	1	1	5
7	Autonomous / Semi-Auto Ops	7	5	7	7	7
	Total Score (Present)	27	31	29	33	39
8	AI Collaborative Ops (futuristic)	1	5	1	1	7
9	Manned Unmanned Tandem Ops (futuristic)	1	5	1	1	7
10	Loyal Wingman (futuristic)	1	3	5	1	5
	Total Score (Incl Futuristic Growth)	30	44	36	34	58

Legends: Not Capable = 1 Less Capable = 3 Medium Capability = 5 Highly Capable = 7

Appendix 'D'

UAV PERFORMANCE REQUIREMENTS

S No	Parameter	Specifications	Remarks
Main Design Parameters			
(a)	Speed	0.3 – 0.8 Mach	
(b)	Max Range	180 Kms	Depends on Launch Altitude
(c)	Loitering Time	01 hr	Depends on Launch Altitude
(d)	Maneuvering Capability	Upto 03 Gs	
(e)	Max Payload Weight	25 Kg	
(f)	Dimensions	4.2 x 0.57 x 0.52 meter	
(g)	Fuselage Shape	Lifting body Airframe	
(h)	T/W Ratio	>10	
(j)	Flight Control Surface	Tail Based (X-Type)	
(k)	Aero foil	Super Critical	for enhanced L/D
(l)	Wings	Foldable for easy Platform Integration	similar to REK & other SOWs
(m)	Material	Composite	Carbon-Fiber, Kevlar, PEEK, Fiberglass
(n)	Manufacturing Techniques	• Weaving • Casting • 3D Printing	
(o)	Lifespan	Limited (20 Missions)	Only Airframe will be replaced when expended
(p)	Structure Optimization Objective	Low Cost and limited life	
Payload			
S No	**Payload Type**	**Specs**	**Remarks**
(a)	Payload Type	• Electro-Optical • EW	

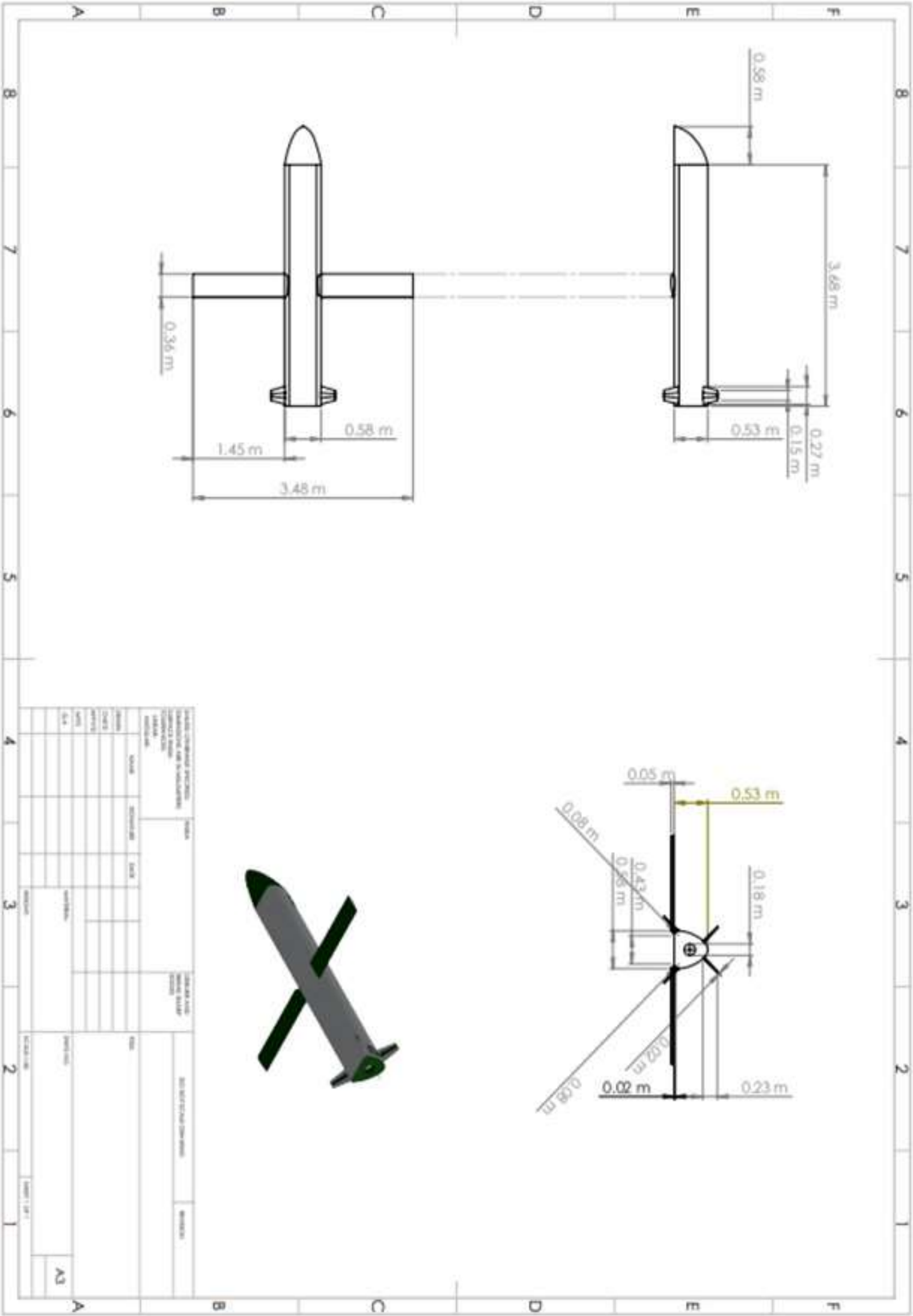
		• Anti-Radiation • Warhead • Decoy	
(b)	Launch	• Ground • C-130 • Fighters	If deemed feasible
(c)	Recovery	Parachute	
(d)	Mission Planning & Control	Pre-Planned as Semi-Autonomous Swarm Operation using software	
(e)	Payload Bay	Nose Cone	
(f)	Payload Bay Dimension	0.5 x 0.4 x 0.4 m (Approx)	
(g)	Payload Power	500 watts for 01 hr	
(h)	Max Payload Weight	25 Kg	
(j)	Payload Bus	• EtherCat TSN • RS-485 • 1553	
(k)	Integration Architecture	Focus on easy Hardware software Integration architecture so that multiple types of payloads from different OEMs can be integrated.	
(l)	Payload OEM	Existing / 3rd Party Payload Integration done by collaborative efforts	
(m)	Electro-Optical	Thermal Imager with Automated Target Recognition & Tracking	
(n)	Electronic Warfare	• ELIENT Jammer	
(o)	Anti-Radiation Seeker	• Direction Finder Receiver Kinetic Kill Payload	
(p)	Air Launched Decoy	Luneburg Lens for RCS Enhancement	
(q)	War Head	• Kinetic TNT	
Engine			
(a)	Engine Thrust	Upto 900N / 92 Kgf	
(b)	Engine Type	Turbojet Engine	TEI-TJ300
(c)	Throttling Capability	Yes	

(d)	Launch Altitude	Ground till 30,000 feet	
(e)	Engine Reusability	Yes	Turn-Around Time < 24 hours
(f)	Cruise Fuel Consumption	19 Kg / Min (Approx)	0.75 KN Thrust, 0.6 Mach
(g)	Engine Turn-Around Time	< 12 hours	
Vetronics			
(a)	Flight Controller	Tail Based Flight Control Auto Engine Throttling	
(b)	Mission Computer	SOC Based with Realtime-OS	NI Crio
(c)	Guidance & Navigation	• MEMS INS / GPS • Kalman Filters Path Planning Algos	
(d)	Data link	• Control-Station Comm • Inter-Vehicle Comm • Telemetry & Remote-Control • COTS Datalink Radios	
(e)	IFF Transponder	Optional (future addon)	
(f)	Avionics Bus Architecture	• EtherCat TSN (Time Sensitive Networking) • RS-485	1553 for integration of existing payloads and Ethercat for Industrial Bus
(g)	Artificial Intelligence Hardware	• Embedded GPU • CUDA Software Framework	AI Hardware for semi-autonomous swarm operation
(h)	Avionics Software Architecture	• Realtime Linux OS • Latest APIs & Libraries (2020) Custom software for Mission computer and sensors, actuators, radios and payload integration	
(j)	Power	• Battery • Vehicle Power Distribution Payload Power Distribution	
(k)	Mission Planning & Control	Pre-Planned with Semi-Autonomous Swarm Operation	
Launch Mechanism			
(a)	Ground	• Rail-Launched • Truck Mountable Launcher with Control-Station • Upto 06 Vehicles on a single truck	If deemed feasible

(b)	C-130	• Launch from C-130 belly • Removable Rotary Launcher mounted in belly with no permanent Mod to C-130 Aircraft • Upto 06-08 Vehicles can be launched	Datalink Antenna needs to be mounted if Control-Station placed on C-130
(c)	Fighter	• Aircraft Integration Ground Based/ C-130 Control (if swarming required)	
Recovery & Storage			
(a)	Recovery Scheme	• Parachute Based (Drogue and Main chute) • Parachute Dia 15 meters • Servo Actuated and Side Release	Dia calculated using MATLAB
(b)	Ground Recovery & Transportation Equipment	• Truck/ Flatbed • A recovery trolley	
(c)	Storage	No special storage requirement	
(d)	Handling Safety	Non-Explosive components thus no special safety requirement	
System Integration			
(a)	Launch Platform Integration	• Ground Launcher & Control-Station • C-130 Belly Launcher & Control-Station Fighter Rail Launcher & WMMC/ Mission-Computer (store integration challenges)	
(b)	Payload Integration	• 3rd Party Payloads (developed by various agencies/ OEMs) Open Architecture for Payload Hardware/ Software Integration	
(c)	Datalink Integration	Control-Station/ Vehicle Datalink Integration using COTS Radios	Phase-2: Custom Datalink Radios Interfacing with C-130 and Fighters
(d)	AI Server Integration	Vehicle Mission computer interfacing with Artificial Intelligence Server running on Control-Station (via Datalink)	
Mission Planning & Controlling			
(a)	Mission Planning	Pre-Planned Mission	

(b)	Mission Control	Control-Station on Ground or in C-130	
(c)	In-Flight Coordination	Semi-Autonomous with Centralized Artificial Intelligence	AI Server in Control-Station which communicates via Datalink
(d)	Swarm Operation	Yes	
(e)	Future Addons	Fully Autonomous Mission with Distributed Artificial Intelligence	Vehicles communicates among themselves via datalink and take decisions (without involving AI server on control station)

Appendix 'E'



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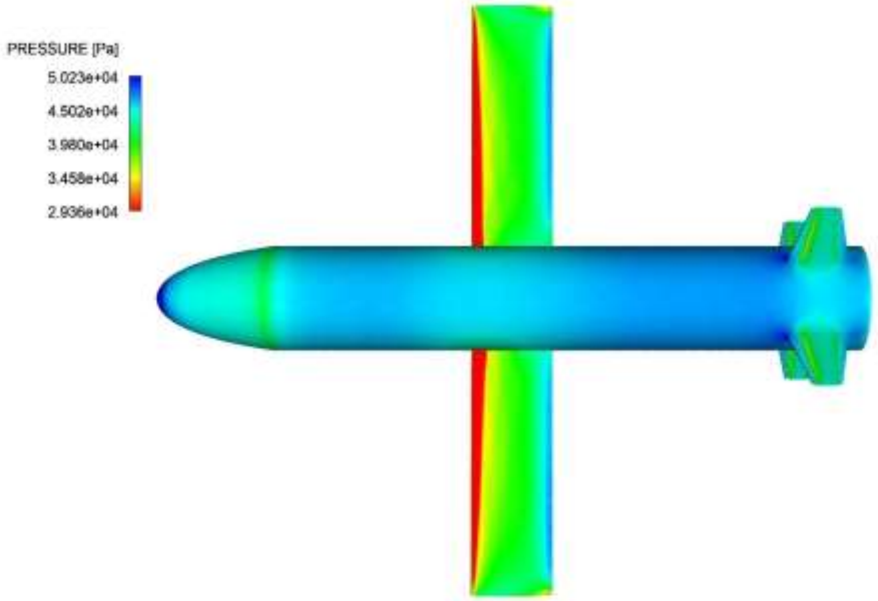
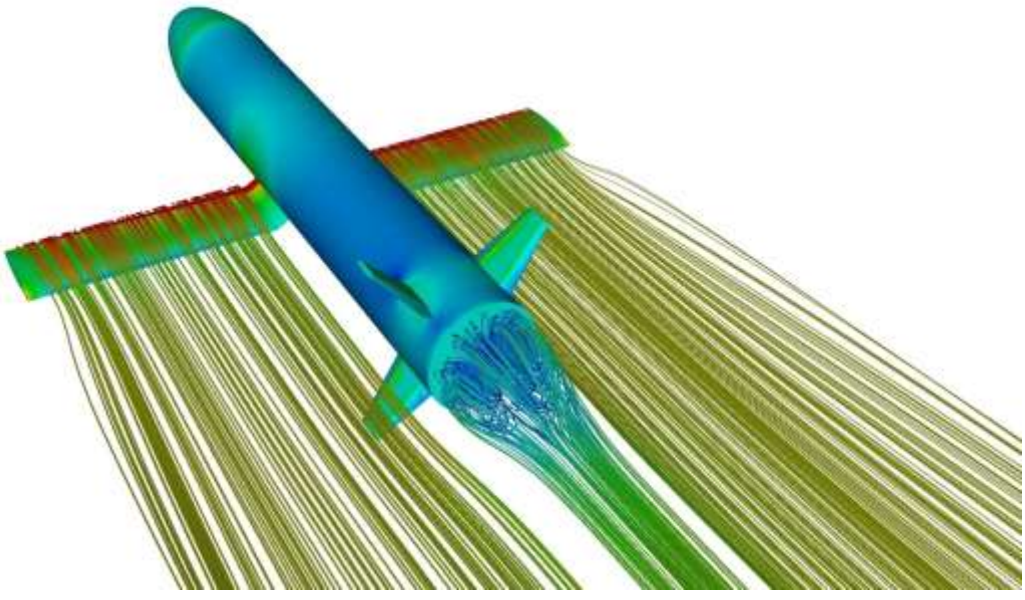
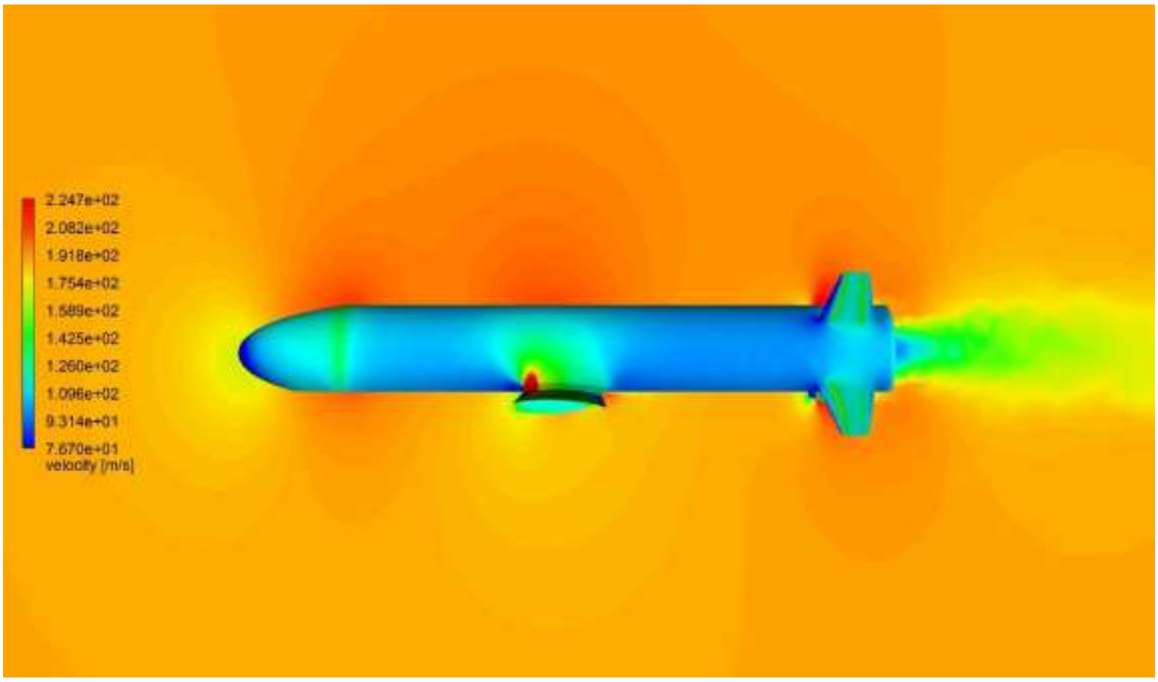
0.36 m
0.58 m
1.45 m
3.48 m
0.53 m
0.15 m
0.27 m
0.05 m
0.53 m
0.08 m
0.43 m
0.18 m
0.02 m
0.23 m
A3

Appendix 'F'

CFD ANALYSIS OF UAV



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1.589e+02
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1.260e+02
1.096e+02
9.314e+01
7.670e+01
velocity [m/s]

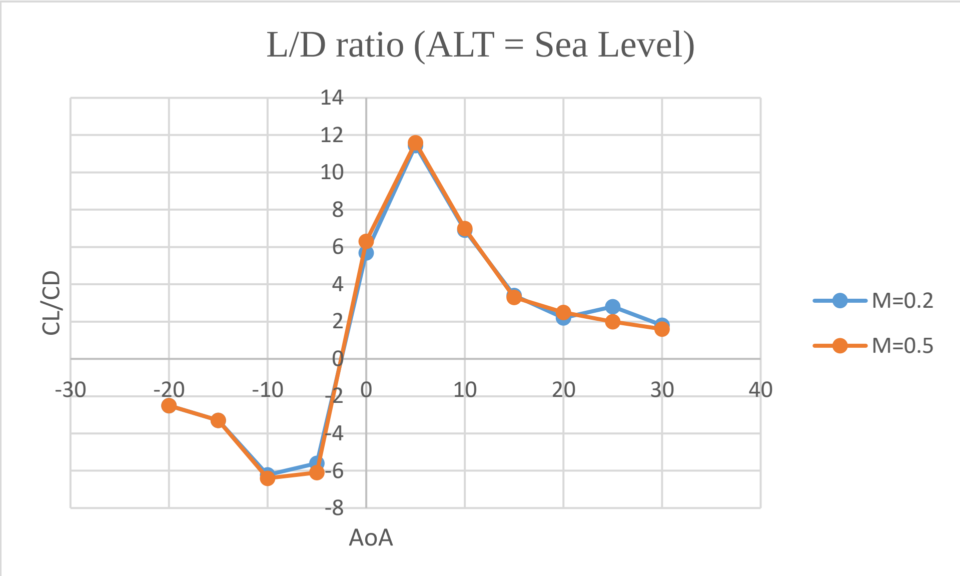
LIFT TO DRAG RATIO AT DIFFERENT ANGLE OF ATTACKS

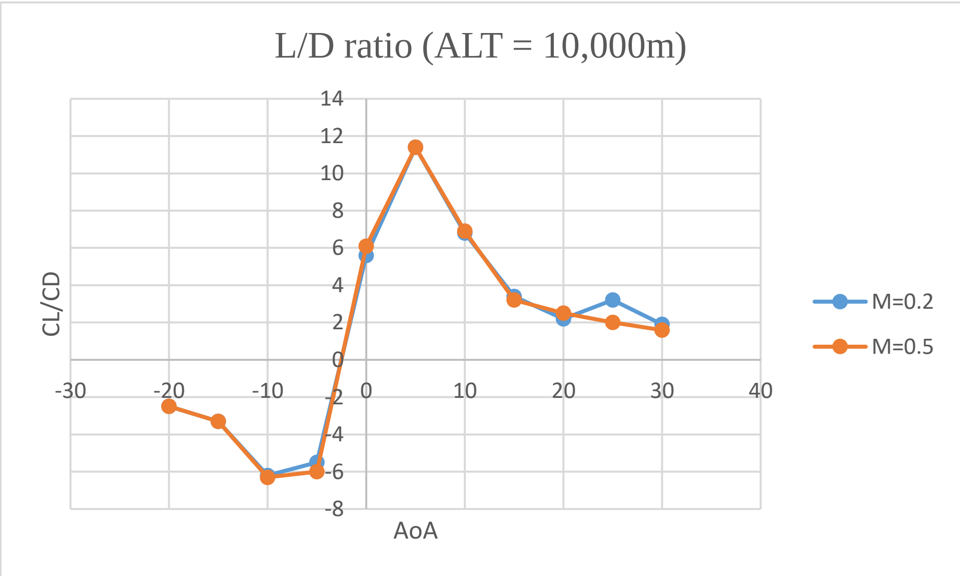
S No	AoA	C_L	C_d	C_L/C_d
Altitude =Sea Level			Mach No 0.2	
1	-20	-2.5	3.3	-0.76
2	-15	-10.72	3.6	-2.9
3	-10	-9.31	1.8	-5.1
4	-5	-5.68	1.5	-3.5
5	0	0	0.7	0
6	5	5.33	0.4	11.2
7	10	8.62	1.2	6.88
8	15	9.99	2.9	3.4
9	20	3.22	1.4	2.2
10	25	-1.9	-0.6	2.8
11	30	-4.6	-2.4	1.9
Altitude =Sea Level			Mach No 0.6	
1	-20	-8.8	5.5	-1.6
2	-15	-8.3	2.9	-2.8
3	-10	-8	1.5	-5.1
4	-5	-5	1.4	-3.9
5	0	0	0.6	0
6	5	5.4	1.4	11.4
7	10	7	1	7
8	15	7.8	2.3	3.3
9	20	9.2	3.5	2.5
10	25	10.5	5.095	2
11	30	11.5	6.864	1.6

LIFT TO DRAG RATIO AT DIFFERENT ANGLE OF ATTACKS

S No	AoA	C_L	C_d	C_L/C_d
Altitude =10,000 m			Mach No 0.2	
1	-20	-2.9	3.5	-0.8
2	-15	-10.7	3.6	-2.9
3	-10	-9.2	1.8	-5.1
4	-5	-5.6	1.5	-3.6
5	0	0	0.6	0
6	5	5.2	0.4	11.2
7	10	8.5	1.2	6.8
8	15	10	2.9	3.4
9	20	3.5	1.5	2.2
10	25	-1.4	-0.4	3.2
11	30	-4	-2	1.9
Altitude =10,000 m			Mach No 0.6	
1	-20	-7.9	5.2	-1.5
2	-15	-7.6	2.7	-2.7
3	-10	-7.8	1.5	-5
4	-5	-5.6	1.4	-3.9
5	0	0	0.6	0
6	5	5.2	0.4	11.17
7	10	7.29	1.05	6.9
8	15	7.2	2.2	3.2
9	20	8.1	3.2	2.5
10	25	9.2	4.5	2
11	30	10	6.072	1.6

LIFT TO DRAG RATIO AT DIFFERENT ANGLE OF ATTACKS





Appendix 'G'

UAV TURBO JET ENGINE