A SYSTEMS APPROACH TO MODEL THE CONCEPTUAL DESIGN PROCESS OF VERTICAL TAKE OFF UNMANNED AIRCRAFT VEHICLE (VTUAV)

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ABSTRACT

UAVs are emerging as the next generation of airborne scouting assets due to their ability to penetrate deep into enemy airspace, plod on designated target areas, detecting mortal weapons and conducting damage appraisals. The major developments of UAVs thus far have been fixed-wing focussed. The missions envisaged for UAVs require a rotary-wing component for missions beyond the scope of fixed-wing UAVs. Rotary-wing UAVs also referred as “Vertical Takeoff UAVs” (VTUAVs) are presently in advanced research and development stages, to address the operational gaps of UAV deployment. To meet the mission requirements, state-of-the-art mission systems and autonomous systems, on-board fixed wing UAVs need to be investigated for application on VTUAVs.

In this paper, the life-cycle of rotary-wing development is investigated from an independent viewpoint for the development of a modified architecture for VTUAVs design. The resulting architecture provides avenues of automation in the design process of rotary wing. Later, an advanced design framework is proposed which comprises of ‘system-of-system’ methodologies to develop an automated VTUAV design methodology.

INTRODUCTION

As the world-over militaries continue to evolve their concept of operations, they are increasingly looking for ways to bypass traditional manned ports of debarkation for conflicts in and near unfriendly territories, and are attracted to the benefits of runway independence and ‘vertical envelopment’ tactics [1-9]. However, a critical key to a highly reliable and less maintainable aircraft is its comprehensive preliminary and detailed design [10, 11]. A preliminary design framework and its duly paradigm has been devised for VTUAVs that performs mission analysis and generates mission profile, develops UAV ground and airborne system, designs mission payload, estimates weight, power, & centre-of-gravity location required for the configuration, and layouts inboard and external profile of the aircraft.

AUTOMATED DESIGN ARCHITECTURE

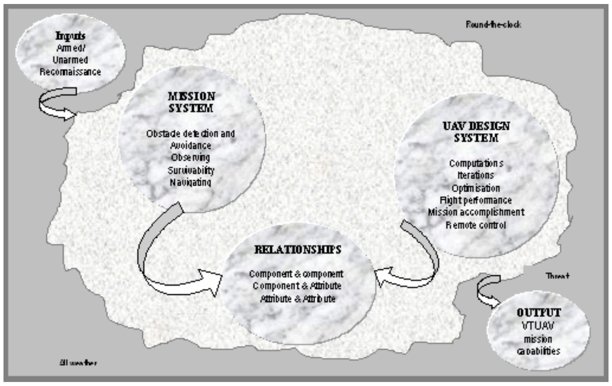

Fig. 1: UAV Design Architecture

The novel design architecture for UAV designs, afresh or an upgrade, to enhance aircraft performances in rapidly evolving mission requirements was developed by Rathore [12]. (Fig 1) It was contrived based on an input-process-output system configuration to identify the system components, their attributes and the operational environment. The two major identified components, with its attributes are as follows: (a) Design, and; (b) Mission. The architecture incorporated automation as an assimilated design component, thereby ensuring less number of intricate relationships (components & components, components & attributes, and attributes & attributes) feasibility. The inputs to the system remained operational needs; operational

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environment continued to be – threat infested, round-the-clock and all weather. The process output was a conceptual VTUAV design with primarily scheduled mission capabilities of reconnaissance and surveillance, high altitude scientific research and fire detection.

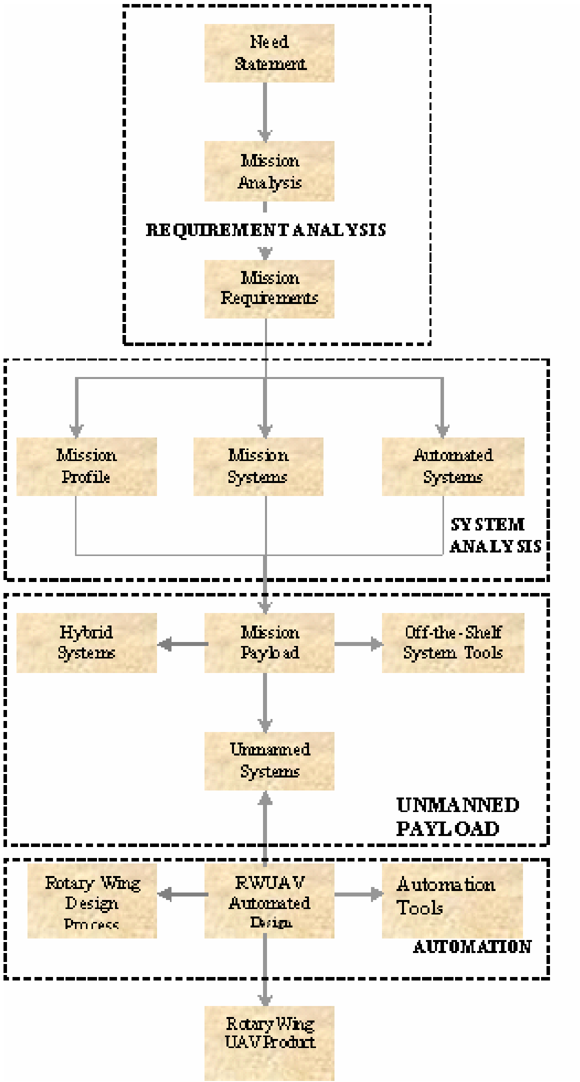

Fig 2 Automated design architecture for RW Aircraft

Decisively the architecture results in chronological identification of procedural breakdown phases, inturn ensuring superior mission specific design. These phases (Fig. 2), in succession, include:

- **REQUIREMENT ANALYSIS**
  It comprises of a needs statement on VTUAVs for detailed analysis to stipulate the mission requirements. Mission feasibility should be primarily determined before tabularising afresh mission requirements;

- **SYSTEM ANALYSIS**
  It results in establishment of VTUAVs mission profile that identifies requirements of mission systems and automated systems. The phase progressively constricts mission's ubiquitous scope and ensures its unambiguity;

- **UNMANNED PAYLOAD ANALYSIS**
  It comprises of mission payload investigation to identify the payload suitable for manned, unmanned and hybrid systems. Cohesive 'UAV fixed and payload compatible ground system design', 'UAV airborne fixed component design' and 'UAV airborne variable mission specific payload design' [13] activities are carried out; and

- **AUTOMATION**
  Programmed rotary wing design process is consequently applied to generate mission specific VTUAV design.

FORMULATION OF DESIGN FRAMEWORK EXEMPLAR

The developed automated architecture provided the framework for automation of VTUAV preliminary design methodology. The chronological stages to achieve these are the following:

- **RPD (REQUIREMENT PROPOSAL DOCUMENT) SPECIFICATIONS**
  The preliminary design process commences with a set of design requirements tabulated in RPD and obtained from the operational needs and environment established by the potential customer. Critical design requirements that govern the preliminary design are**:** payload, speed, range, power and rate-of-climb. [14] Operational design constraints include physical dimensions (aircraft length, wing span, and rotor diameter), disc loading, noise level, tip speed and rotor-coefficient. Australian civil aviation safety authority (CASA) standards that govern the design and safety of the aircraft are presented in "*CASR Part 101*" [15] and includes rules based on weight category, registration and certification, altitude of operation and usage of communication network. Constraints are also governed by state-of-the-art technology (engine-type) and support infrastructure (mechanical, electrical, electronics, avionics, optronics, mission system etc.).

  A key list of design requirements and constraints has been compiled based on the parameters discussed above. The requirements selection-window consists of: MTOW *weight*, cruise *speed*, mission *range*, *endurance* at mission range, and operating *ceiling.* Constraints imposition-window includes p*hysical dimensions,* choice of *engine-type*, and *safety regulations.*

- **MISSION ANALYSIS**
  Based on the desired aircraft mission, an exhaustive analysis is carried out. It involves two activities:

  a) Scrutinising mission viability
  Foremost task for a practical aircraft design configuration is a feasible mission. Usually this activity is 'no-issue' as RPD discusses pros and cons of the desired mission comprehensively, but it is highly recommended for the design agency to ensure that their resources are stockpiled to match the requisites. A collection of present and possible future missions is tabulated in Table 1 and 2.

  b) Developing profile layout
  The mission profile is an essential conglomeration of sequential steps that are to be chronologically pursued to ensure a successful completion of mission. During the making of the mission profile, estimated time usage for each profile activity will be marked and notified [16, 17]. Eventually, all time notification will be added and the total mission time will be computed. This value is critically essential as it will determine the aircraft's fuel consumption [16]. The procurement of mission time value concludes mission analysis activity

Table 1: Mission Classification-I

Common Civilian Missions	**Other Civilian Missions**
• Reconnaissance & Surveillance Mission System	• Forestry Vigilance
• High Altitude Scientific Research Mission System	• Forestry Assistance
• Fire Detection Monitoring Mission System	• Agricultural Monitorship
	• Agricultural Aide
	• Power Monitorship
	• Disaster and Relief Assistance
	• Weather and Environmental Monitorship
	• Scientific and Geological Research Aide

Table 2: Mission Classification-I1

Generalised Defence Missions	**Tactical Defence Missions**
• Provide Imagery (video/still) and Geo-locate (EO/IR/SAR)	• Deploy Forces / Conduct Manoeuvres - dominate the combat area
• Provide Target Return (multi-spectral/radar/lidar) Data (MTI/surface-search/ (AEW))	• Develop Intelligence - collect intelligence
• Illuminate, Range, and/or Designate	• Develop Intelligence - produce intelligence
• Relay (from/to airborne / ground platforms / sensors / communications networks)	• Deploy Forces / Conduct Manoeuvre - navigate and close forces
• Detect, Identify, and Geo-locate Communications / Non-Communication Electronic Emissions	• Exercise Command and Control - assess situation
• Electronic Attack	• Employ Firepower - process targets
• Electronic Protect (self/other platforms)	• Employ Firepower - attack targets
• Detect Nuclear, Biological, and Chemical (NBC) Emissions	• Exercise Command and Control - acquire, analyse, communicate information and status
• Dispense (chaff, ground sensors, incapacitating agents, logistical supplies, meteorological sensors, NBC sensors, pamphlets, sonobuoys)	• Protect The Force - rescue and recover
• Weapon Delivery Assignments (Docile Territory / Enemy Territory)	• Deploy Forces / Conduct Manoeuvre - maintain mobility
• Provide Imagery (video/still) and Geo-locate (EO/IR/SAR)	• Protect The Force - enhance survivability

- **MISSION SYSTEM ANALYSIS**
  The primary objective of this activity is "Study of the mission systems on-board rotary wing aircraft and autonomous systems to formulate a mission payload that meets the mission requirements." Payload selection should ensure zero-level redundancy, optimal compactness, and apt weighage. Table 3 and Table 4 represent comprehensive UAV payload classification [*14*]

Table 3: Payload Classification-I

Payload I

Acoustic Sensors
- Acoustic Sensor
- Target Locators
- Speed Measurers
- Imaging Sonar

Communications
- Transmitters
- Transponders
- Emitters
- Amplifiers
- Voice Relays
- Telemetry Equipment

Electro-optical Systems
- EO/IR
- Line Scanners
- Integral Optical Systems

Table 4: Payload Classification-II

Payload II

EW Systems
- ELS
- RWR
- Dispensers
- ELINT
- Passive Systems

FLIR/Thermal Imaging Systems
- Infra-red Surveillance Systems
- Infra-red Reconnaissance Systems

Integrated Systems
- ESM
- ECM
- Jammers
- Decoy

Radar
- Multimode
- Inverted
- Synthetic Aperture
- Ground Penetrating
- Millimetre Wave

- **DESIGN PARAMETRIC ANALYSIS**
  The primary aim of the activity is to validate the inputted design specifications and identify additional design parameters to be addressed for the design of VTUAVs. Foremost, validation is done for payload weight practicability. A set of equation in Table 5 are being presented in public domain for first time that determines maximum payload limit for a given take off weight. A regression plot of the MTOW weight and payload weight is shown in Charts 1, 2 and 3. Coefficient of regression is also notified in charts.

Table 5: Payload Vs MTOW Equations

Rwp - Micro UAV	Payload max=1.064 (0.0177(MTOW)^2 +0.1132(MTOW) + 0.0854)
Rwp - Small UAV	Payload max= 1.235(0.0025(MTOW)^2 + 0.0184(MTOW) + 3.6847)
Rwp - Large UAV	Payload max= 1.393(1E-05(MTOW)^2 + 0.1264(MTOW) + 22.25)

Next, power, endurance, speed and range substantiation has to be performed. A set of estimated equation have been developed and are tabulated in Table 6

Table 6: Other Critical equations

Minimum RSER (Speed*Endurance/Range) = 1
Maximum RSER (Speed*Endurance/Range) = 4
Minimum RWP (MTOW/POWER)= 6
Maximum RWP (MTOW/POWER)= 17

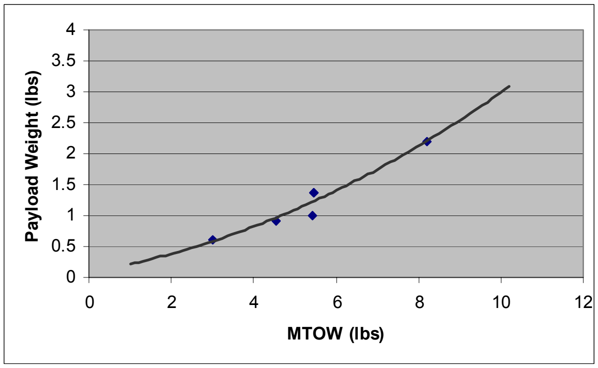

Chart 1: Payload Vs MTOW regression plot – Micro UAVs

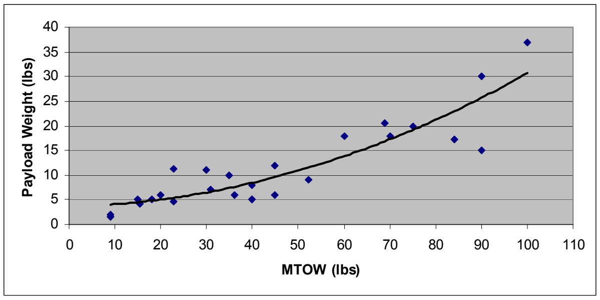

Chart 2: Payload Vs MTOW regression plot - Small UAVs

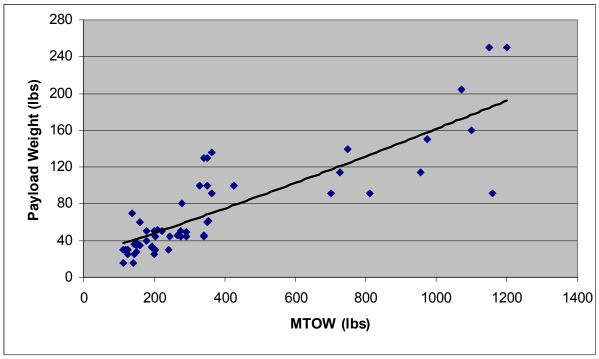

Chart 3: Payload Vs MTOW regression plot – Large UAVs

The second phase of the activity is to identify additional parameters and make necessary initial assumptions on the pretext that they are substituted by true values later on. An initial power estimate is an essential requisite for proceeding with design activity. To obtain it, inputted parametric values are compared with the similar values of existing UAV from the database. The UAV database will consists of records of UAVs (Electric engine/Non-electric engines/Gliders), drones and skeeter's. The database fields will include: *Name, Mission, Length, Wing span, Rotor span, Body diameter, Launch weight, Engine* (number, make and model)*, Power, Manufacturer, Mission type, Speed, Endurance, Range, Altitude and Other-Information* (comments). A close in-range comparison results in appropriate matches and the best engine match is an automatic choice.

- **APPLICATION OF AUTOMATED DESIGN METHODOLOGY PARADIGM**

The first step is to compute the fuel weight. Depending on the selected engine type, the specific fuel consumption is estimated and then, together with gross aircraft weight, net fuel weight is calculated. This fuel weight is in succession added to the gross weight of aircraft. If the calculated output is inline (10% sway-margin) with the database weight output, then no iteration is carried out.

Assuming disc loading at the max allowable level, the net projected area of the aircraft is calculated. The projected area of the VTUAV is calculated based on the initial drawing developed from comparative analysis of VTUAVs of same class and the inboard profile developed from the mission payload. This will eventually result in vertical drag calculation as it is dependent on the coefficient of drag, disk loading and the projected area of the aircraft in remote wake [11].

Next, the main rotor system is designed. Out of main/tail, coaxial and tandem rotors; coaxial rotors are very popular with VTUAVs as they result in smaller fuselage by reducing the aircraft silhouette. Also, the two coaxial counter rotating rotors of similar shape and size, rotating with same speed and in opposite direction, allow for a greater lifting capability. This is due to complete power usage by the main rotor system. Henceforth, rotor diameter is evaluated from disk loading, tip speed comes from maximum speed and number of blades is obtained from solidity [10-11].

In forward flights, the drag experienced by the VTUAV is parasite and profile drag. Parasite drag is due to non-lifting surfaces and the rotor profiles contribute to the profile drag. Parasite drag coefficient is evaluated from gross weight, form factor and coefficient of factor. The profile drag coefficient is calculated from average angle of attack and Mach number [10].

The power required for forward flight will be evaluated from profile and parasite drag, gross weight, disc area, and tip speed. This value should be less than the initially estimated power.

Eventually, refinement of weight and balancing of the aircraft need to be carried out. Weight refinement is iterative and will result in alteration of previously determined values. The ideal position for the CG in the x-axis is slightly ahead of the main rotor shaft. The CG balancing of the aircraft is done with and without the onboard payload. Payload positioning should ensure distribution of load symmetrical around center-of-gravity of the aircraft, & mounting of payload such that no large moment arms are generated and produced vibrations are minimised.

- **OUTPUT VERIFICATION**
  The VTUAV stability concludes the process and results in a better designed and a centrally stabilised UAV. The inboard profile and the external profile of the aircraft are generated in the process. The chosen coaxial counter rotating rotor system led to the design of a VTUAV that is optimised for size and weight. Further investigation is required into the use of advanced materials and technology to further reduce the aircraft weight [18-19].

  To verify the output, a test program with generated values is run against current UAVs on similar close parametric performances. Proximity in ranges justifies a good preliminary design, else wise the whole process needs to be iterated.

CONCLUSION

The conceptual design methodology is a principled approach to obtain better UAV designs. It will serve as a critical tool to filter out various improbable and impractical mission specific designs. It is more adaptive and open to improvisations. The design of the VTUAV can be used as a platform for follow-on research. The architecture and formulated methodology are generic and hence can be successfully applied to other VTUAV on different missions. Likewise, both methodology and architecture are robust and capture all the components needed to conceptually design the aircraft.

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