Comparative Analysis of Fixed-Wing, Rotary-Wing and Hybrid Mini Unmanned Aircraft Systems (UAS) from the Applications Perspective

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Abstract: *Mini Unmanned Aircraft Systems (UAS) present distinct design challenges due to their man-portable, field-deployable profile. The implications of various unmanned aerial vehicle (UAV) design configurations for Mini UAS applications are discussed in this study. Fixed-wing, rotary-wing, and hybrid Mini UAS design configurations are analysed and compared based on performance parameters specified by various manufacturers to assess appropriateness for military and civil applications. Mini UAS designed for military applications can meet most requirements in the civil domain. However, the reverse is seldom feasible because of several restrictions imposed by combat conditions. Fixed-wing Mini UAS have significant limitations for military applications, primarily because of launch and recovery considerations. For civil applications, the fixed-wing configuration provides multiple advantages. The benefit of the rotary-wing configuration's compact size to overcome various battlespace restrictions for military applications does not translate to other performance parameters, and this is a serious limitation for its applications. The hybrid profile has significant design advantages that can be leveraged for both military and civil applications. The interrelation between design, end-use requirements and terrain restrictions presented in the paper provides an insight into the implications of the design configurations of Mini UAS for various applications.*

Key Words: *Mini UAV, UAS Design, UAV Applications, Classification UAV*

1. INTRODUCTION

The 2003 Operation Iraqi Freedom was the coming of age of the smaller UAS, wherein these systems established itself as a critical component of the US Military's newly introduced network-centric warfare concept and post-gulf war. Since then, the rise of the smaller UAS has been exponential [1]. For most modern militaries across the world, UAS has now become an inescapable requirement in the arsenal of military equipment systems. Based on the analysis of the works of various authors and manufacturers, Ramesh and Jeyan [2] quantified the parameters for Mini UAS as endurance of 3–4 hours, range of 30–40 kilometres, operating altitude in the region of 3500 m above mean sea level (AMSL), and maximum take-off weight (MTOW) of approximately 30 kg. Analysis by Kotsemir [3], shows a spike in unmanned systems research in recent years. A significant portion of the research is devoted to the smaller

UAS. Multiple market survey reports suggest growth in the UAS market with a compound annual growth rate (CAGR) higher than 14% during the period from 2020 to 2025. The growth is expected to be driven by the small UAS segment [4]–[6]. Considering the expected growth of the Mini UAS, it is important to have a clear understanding of the implications of the impact of various UAV configurations on the deployment and employment of the Mini UAS. Fixed-wing, rotary-wing and hybrid aircraft design configurations have implications not just for the rest of the subsystems, but also for the applications of the unmanned system. Numerous articles focusing on specific applications like the use of Mini UAS for agriculture, remote sensing, and similar topics are available. However, the implications of various Mini UAS design configurations have received limited attention. The purpose of this paper is to analyse the effect of different design configurations of UAVs for Mini UAS applications.

2. DESIGN CONSIDERATIONS FOR SUB-SYSTEMS OF MINI UAS

UAS comprises numerous sub-systems, as depicted in Fig 1. Readers can refer to books by Austin or Sadraey [7], [8] for a more detailed explanation of the sub-systems. The capabilities of each sub-system collectively impact the performance of the overall system. The correlation between the design aspects and sub-system performance that impact the deployment and employment of the Mini UAS are discussed in the succeeding paragraphs.

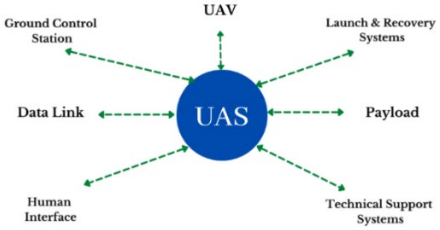

Fig. 1 UAS Sub-systems

2.1 UAV. The UAV is the airborne component of the UAS, which is also referred to as a drone or remotely piloted aircraft (RPA). Fixed-wing, rotary- wing, and hybrid are the three most popular types of Mini UAVs. Ramesh and Jeyan [9] bring out the significance of terrain in the employment and deployment of Mini UAS. In terrains that precludes vehicular mobility, the UAV must be man-portable, allowing the crew to physically carry the system to the launch site. Therefore size and weight does not become a major limiting factor.

2.2 Ground Control Station (GCS). The ground-based control station serves as the interface between the operators and the rest of the system. Typically, the GCS for Mini UAS is mobile. It can be a ruggedized laptop or can be housed within an 'all-terrain' vehicle. Interested readers can obtain further details from the references [7], [8], [10]. GCS based on all-terrain vehicles can effectively operate in desert, urban, and coastal environments. To a limited extent, vehicle-based GCS can also operate in jungle terrain. However, for mountain terrain, Mini UAS will have to be dependent on portable GCS.

2.3 Launch and Recovery Station (LRS). Launch and recovery is a critical design consideration for the Mini UAV, more so in mountain and jungle terrain. For fixed-wing Mini UAS, the launch and recovery systems can range from hand launched to catapult launch and the recovery can be through parachute, net, arresting cable or simple glide. On the other hand, vertical take-off and landing (VTOL) configurations have simpler launch and recovery. Hand launched fixed-wing UAVs, because of their small size, will have limited range and endurance.

Therefore, fixed-wing Mini UAVs will have to rely on a launch mechanism. The heavier the UAV, the bulkier will be the launch mechanism. The operational implications, advantages and disadvantages brought out in Dossier [11], continue to be relevant. Sadraey [8], provides a detailed account of the complexities involved with the launch mechanism associated with fixed-wing UAVs. Recovery is the process of returning an aircraft to a controlled landing. Sadraey [8] outlines numerous recovery techniques in great depth. A VTOL UAV's recovery is simple, especially now that navigation and control technology has progressed. In the absence of a runway, landing procedures for fixed-wing Mini UAS are far more complicated [12]. Techniques used for recovery of Mini UAS include skid or belly landing, a guided flight into a catchment net, skyhook recovery, guided flight onto an arresting pole and parachute deployed landing. Belly landing is the simplest of the lot, wherein the UAV can be landed in a small area. However, this technique is more suited for smaller UAVs. For a guided flight into a catchment net, the net is suspended between two poles with the net extremities attached to purchase lines, which are attached in turn to energy absorbers. Skyhook recovery, used by the Scan Eagle UAS, has a similar mechanism. Both these techniques facilitate zero-length recovery, but the added equipment adds to the overall weight of the UAS. Setting up these recovery systems is time consuming, and they have a significant logistic footprint. For fixed-wing UAVs, parachute based recovery is the most popular, primarily because the possibility of damage to the UAV is the least, and this technique requires minimal logistics. Details of parachute recovery systems have been extensively covered by various authors [13], [14]. Automation of the parachute recovery adds to the accuracy of landing. But accurate point landing can be challenging because wind speed impacts the directional control during the descent of the UAV after parachute deployment. Hard landings and the UAV being dragged along the ground are other major concerns. Descent of these systems can be automated using evolutionary algorithms, and parachute deployment at very low altitudes is frequently programmed to reduce drift distance. A large volume is needed to place the parachute inside the UAV, and the parachute adds to the weight of the flying machine. Hence, despite being the most popular amongst all the recovery techniques for fixed-wing UAVs, parachute landing has numerous criticalities.

2.4 Datalink. Mini UAS is expected to operate beyond line of sight (LoS), and the communication between the UAV and the control station is established through a radio frequency (RF) based datalink. The datalink interface is shown in Fig 2.

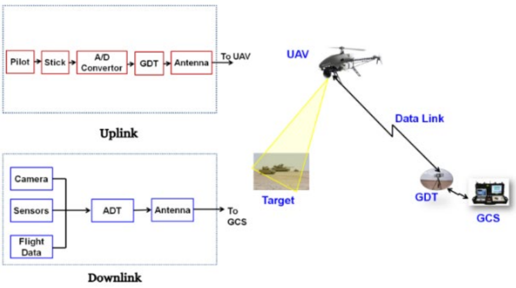

Fig. 2 Datalink for Mini UAS

The ground data terminal GDT is physically connected to the GCS through a cable or can be integrated into the GCS [8], [15]–[17]. GDT must be located at a vantage point to obtain the maximum possible LoS range for the datalink is a critical factor, because the range of the datalink is the range of the UAS. In rugged terrain, the carriage of GDT along with the GCS can pose problems.

2.5 Payload. Payload provides the output from the system, and the type of payload to be used depends on the intended applications. Elaborate details of payloads are available in the references [8], [18].The type of payload to be employed is determined by the mission. The three most common payload types are (a) daytime EO cameras, (b) infrared cameras for night vision, and (c) synthetic aperture radar (SAR) [19], [20]. Payload design has to factor in the mass, volume and power requirements. Other considerations include image integration, onboard or ground processing for image presentation, video interface, downlink bandwidth and effective range in dynamic applications. Lightweight and compact payloads are essential requirements for rugged terrain.

2.6 Technical Support Systems. Maintenance equipment, power supply equipment, transport items and such support items form part of the technical support systems [7], [8]. Since most subsystems of Mini UAS are dismantled for transportation, ease of assembly under field conditions is an important criterion. The weight and volume of carrying containers and other technical support systems cannot be overlooked when Mini UAS are expected to operate in rough terrain with limited vehicular movement.

2.7 Human Interface. Typically, the Mini UAS crew comprises two to three individuals [7], [16], [21].When the system is to be transported on a vehicle, the weight and volume are not of much consequence. However, when the same is to be carried by the crew, then weight and volume become a critical design factor. The weight and volume of the other components of the system like ruggedized laptop-based GCS, GDT and technical support systems have to be factored in while considering the ease of transportation. These additional items can weigh anything between 5 and 10 kg or more. Hence, it is important to limit the weight of the systems.

3. APPLICATIONS OF MINI UAS

3.1 Civil Applications of Mini UAS. The low cost of production and operation made the Mini UAS an attractive proposition for applications in the civil domain [8], [16], [23], [24]. As per Blyenburgh [25], UAS for civilian applications can be categorised into three user groups: commercial, non-commercial and government non-military. Commercial applications include aerial photography, aerial spraying & dispensing, and similar low scale activities involving low requirements of range and endurance. For most commercial applications, MAVs are the preferred option because of their low cost. Energy and electrical facility monitoring, pipeline inspection, survey & mapping, infrastructure support, agriculture, and similar activities are part of non-commercial activities. Mini UAS can meet the range and endurance requirements for non-commercial applications. Government non-military organisations like police, customs, border guard, coast guard, and various other departments are increasingly using UAS for various applications. Forest protection and wildfire monitoring, remote sensing, search and rescue, emergency response, traffic control tasks, maritime patrol, and many more similar roles are assigned to the Mini UAS. Most of these tasks involve range and endurance, beyond the capability of MAVs. Therefore, for most operations by government non-military organisations, Mini UAS are the preferred option. Some tasks, like maritime patrolling involving long range and endurance, may even require a higher class of UAS. Battlespace and operating terrain conditions impose several restrictions on the employment and deployment of the UAS, more of which will be discussed later in this paper. On the other hand, UAS for civil applications are predominantly limited by regulatory restrictions, as brought out by Elias [26]. UAS like Tekever AR3, Skeldar V-200, Copter 4, and many other Mini UAS, designed for military use are also used for civil applications. Most manufacturers design the system primarily for a military role with the ability to undertake various civil applications.

3.2 Military Applications of Mini UAS. Austin [7], elaborates on the utility of Mini UAVs for mobile battle groups for tactical level operations. Mini UAS are commonly employed for ISTAR (intelligence, surveillance, target acquisition, and reconnaissance), BDA (battle damage assessment), and other tactical missions [16], [27], [28]. Most militaries around the world address warfare at three levels: strategic, operational, and tactical [29]–[31]. Mini UAS is expected to operate at the tactical level. At the tactical level, potential combat power is translated to achieve goals set at the operational level. The tactical level essentially deals with individual battles and engagements [29], [30], [32]. Based on the levels of warfare, command groupings called echelons are formed. Echelons are combat force structures corresponding to a set of standard sizes into which units can be grouped. Divisions and subordinate forces form the tactical echelons of the combat force structures. The division assigns the mission and the specific area of operations to the subordinate echelons in the tactical battlespace (TBS). These subordinate echelons may be brigade combat teams, multifunctional brigades or functional brigades [29], [33], [34]. Key factors that define the tactical battlespace are areas of influence, interest, operations, and the forward line of own troops (FLOT) [35]. A representative image of the areas, shaped by ground terrain profiles, is depicted in Fig. 3.

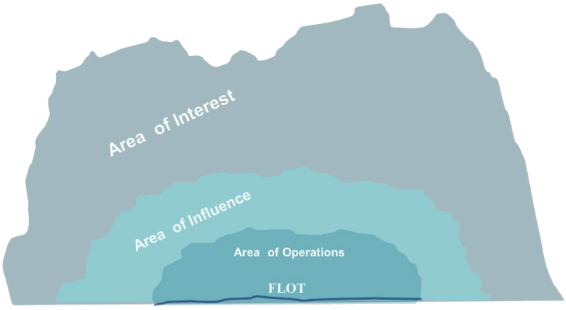

Fig. 3 Depiction of TBS

4. DESIGN CONFIGURATIONS OF MINI UAS

The design and performance requirements of various sub-systems of the UAS are influenced by the design of the UAV for all classes of UAS. Most Mini UAVs fall into three categories: (a) fixed-wing, (b) rotary-wing, and (c) hybrid. Each of these has relative merits and demerits from applications perspective. The required specifications for endurance, operational ceiling altitude, and MTOW will depend on the terrain in the TBS and the type of task for the Mini UAS. Due to the distance between FLOT and the forward edge of the brigade area of interest, the datalink range requirement of at least 30 km is non-negotiable among the Mini UAS operating parameters. Based on the data from various manufacturers, the current analysis of various types of Mini UAS is based on two specific parameters: datalink range of at least 30 km and wingspan/rotor diameter not exceeding 5 m. It is pertinent to note that the data from the manufacturers may not be entirely accurate. Accordingly, the present study is based on a best-case scenario for various parameters. For example, trade-offs in endurance, based on payload weight, has not been considered. Instead, for the purpose of analysis, maximum endurance has been taken into account. In few cases, where the data is not available on the company website, the same has been obtained through correspondence. “Not available (NA)” has been mentioned wherever the data could not be obtained.

4.1 Fixed-Wing Mini UAS. Fixed-wing UAVs have very good flight endurance and can therefore cover large areas in one sortie. Simple design, heavier payload carrying capability, and minimal maintenance requirements are the other advantages offered by fixed-wing aircraft [36]. Fixed-wing Mini UAVs require a runway or a launch and recovery mechanism for operations. Take-off and landing for fixed-wing Mini UAVs are major considerations for employment, particularly in the TBS. Table 1 lists the characteristics of various fixed-wing UAS with a minimum data link range of 30 km and a wingspan of less than 5 m.

Table 1 – Fixed-Wing Mini UAS parameters

UAS	Manufacturer	Wingspan (m)	Maximum Datalink Range (km)	Ceiling Altitude (m) AMSL	Maximum Endurance	MTOW (Kg)	Launch	Recovery
Spy'Ranger 330	Thales Group	3.9	30	*NA*	2 hours	14	Catapult	Belly
PD-1	Ukrspec Systems	4	100	3000	10 hours	40	Runway	Runway
PD-2	Ukrspec Systems	5	200	4700	10 hours	55	Runway	Runway
Leleka-100	Ukrspec Systems	1.9	45	1500	2 hours 30 minutes	5.5	Catapult	Belly
Tekever AR3	Tekever Autonomous Systems	3.5	100	*NA*	16 hours	23	Catapult	Parachute/ Net
Orbiter II	Aeronautics Defense Systems	3	100	*NA*	4 hours	10.3	Catapult	Parachute/ Net
Scan Eagle	Insitu Boeing	3.1	100	5950	18 hours	26.5	Catapult	Skyhook
Scan Eagle 3	Insitu Boeing	4	100	6096	18 hours	36.3	Catapult	Skyhook
RQ-15 Neptune	DRS Technologies	2.1	75	2440	4 hours	36	Catapult	Parachute
Borey 20	UAVOS	4.3	120	3500	5 hours	26	Catapult	Parachute
Sitaria E	UAVOS	5	60	6000	12 hours	39	Runway	Runway
Albatross	Applied Aeronautics	3	50	*NA*	4 hours	10	Runway	Runway
Penguin C MIL UAS	UAV Factory	3.3	100	5000	20 hours	23	Catapult	Parachute
Strix-DF	Alpi Aviation	3	50	4480	4 hours	10	Catapult	Parachute
Rolta Mini UAV	Rolta India Limited	2.8	20	3500	4 hours	10	Catapult	Parachute
Fulmar	Thales Group	3	90	4000	12 hours	20	Catapult	Parachute
UAV Raybird-3	Skyeton	2.9	120	3500	28 hours	23	Catapult	Parachute
BirdEye 650D	Israel Aerospace Industries	4	150	4572	15 hours	30	Catapult	Parachute
Aerosonde	Textron Systems	3.7	140	4572	14 hours	36.4	Catapult	Net
DVF 2000 ER	Survey Copter	3.3	50	3000	7 hours	22.5	Catapult	Parachute

NA – Not Available

4.2 Rotary-wing Mini UAS. The primary advantage of rotary-wing UAVs is their vertical take-off and landing (VTOL) capability. This feature permits operation within a smaller vicinity without the requirement of a landing/take-off area. Rotary UAVs can hover and conduct agile manoeuvring, allowing them to fly missions in confined spaces [36]. As a result, rotary-wing UAVs are best suited for ISTAR missions that demand precise manoeuvring and the ability to keep visual on a single target for a longer period of time. The slow speed and hover capability of the rotary-wing UAV enables capturing data more accurately and in more detail. Another advantage of rotary-wing UAVs is that they can be folded up into a much more compact configuration for ease of carriage. While there are numerous advantages, rotary-wing UAVs are not without disadvantages. Rotary-wing UAVs consume much more energy as compared to fixed-wing UAVs just to stay in the air. Therefore, it takes more power to sustain flight for a rotary-wing compared to a fixed-wing UAV. Hence, rotary-wing UAVs tend to have much shorter endurance. Lower speed also implies that the aircraft will take a longer time to reach the target area, resulting in additional dead mileage. Rotary-wing Mini UAS involve greater mechanical and electronic complexity, which has been offset to a large extent by the advancement in technology [8], [16]. Details of various rotary-wing UAS with a minimum data link range of 30 km and a rotor diameter of less than 5 m are as per Table 2.

Table 2 – Rotary-wing Mini UAS parameters

UAS	Manufacturer	Rotor Diameter (m)	Datalink Range (Km)	Maximum Celling Altitude (m) AMSL	Maximum Endurance	MTOW (kg)
Copter 4	Survey Copter	2.2	40	2500	2 hours 30 minutes	30
HEF 32 Airboxer	High Eye.	1.6	35	3048	4 hours	30
Skeldar V-200	UMS Aero Group	4.6	200	3000	5 hours	235
Skeldar V-150	UMS Aero Group	3.5	100	3048	4 hours	150
SDO 50V2	Swiss Drones	2.8	40	3000	2 hours 30 minutes	87
HoverEye	Bertin Technologies’	2.1	35	3000	60 minutes	25
Vapor 55	AeroVironment	2.56	56	3657	60 minutes	24.9
Vapor 35	AeroVironment	1.95	56	3657	60 minutes	14.5
UVH 25EL	UAVOS	2.6	67	3500	90 minutes	25
UVH 170	UAVOS	2.6	350	5000	5 hours	45
Camcopter S-100	Schiebel	3.4	200	5486	10 hours	200
Alpha 800	Alpha Unmanned Systems	1.8	30	3000	2 hours 30 minutes	14
Alpha 900	Alpha Unmanned Systems	2.07	50	*NA*	4 hours 30 minutes	25
Black Eagle 50	Stedicopter	2.2	150	3048	4 hours	35
SR200	Rotomotion	3	30	2500	4 hours	50
Anavia HT-100	ANAVIA	3.7	200	3000	4 hours30 minutes	120
R-350	UMS Aero Group	3.5	80	2500	2 hours	150

4.3 Hybrid (Fixed-Wing VTOL) Mini UAS. A hybrid or fixed-wing VTOL UAV combines the VTOL capability of a rotary-wing with the standard forward propulsion of a fixed-wing UAV [16], [37]–[41]. Tilt rotors, tail sitters, and quadplanes are the most common designs for hybrid Mini UAVs. It has three distinct flight modes, fixed-wing mode, transition mode, and helicopter mode. It vertically takes off and lands, and once airborne, it flies like a fixed-wing aircraft. Furthermore, it doesn't require a runway and has the capability to land like a helicopter. In many hybrid VTOL UAVs, rotary lift propellers are typically incorporated into the aircraft's wings, which then transition for forward flight. Due to their VTOL capability, high flight speed, and long endurance, fixed-wing VTOL UAVs are being extensively used both for military and civil applications. Since there is no requirement of a complex launch and recovery mechanism, the VTOL platform requires less ground based support infrastructure and physical space. The slower ascent and descent of VTOL aircraft improves safety during landing and take-off phases. As compared to fixed-wing UAS, the slight sacrifice in flight performance (endurance and range) is well made up with the increase in terrestrial mobility, since the aircraft can be moved much closer to target areas and attain hover mode in a shorter space of time. While VTOL provides a little less in terms of aerodynamic performance compared to fixed-wing, it is significantly superior to rotary-wing aircraft. A stable and smooth transition is one of the most important requirements for hybrid UAVs. Avoiding or minimising operational losses that might be encountered in the transition phase is a critical design challenge. Loss of altitude during transition can lead to instability, which in turn can lead to a rough transition. Controlling the loss has serious implications for flight safety. In the case of tilt rotors, the downstream hitting the wing during hover produces a large downward load on the wing. The airflow rebounding from the wing affects hover performance, the rotor's efficiency stability and flight safety of the aircraft. Another notable disadvantage for hybrid Mini UAS is their low endurance. Table 3 shows the details of hybrid UAS with a minimum data link range of 30 km and a wingspan of less than 5m.

Table 3 – Hybrid Mini UAS parameters

UAS	Manufacturer	Wingspan (m)	Maximum Datalink Range (Km)	Ceiling Altitude (m) AMSL	Maximum Endurance	MTOW (Kg)
PD-1 FW VTOL	Ukrspec Systems	4	100	3000	7 hours	40
PD-2 FW VTOL	Ukrspec Systems	5	200	4500	8 hours	55
EOS C UAS (VTOL)	Threod Sys	5	50	4500	2 hours	14.2
WanderB VTOL	Blue Bird Aero System	3.1	50	*NA*	2 hours 30 minutes	14
ThunderB VTOL	Blue Bird Aero System	4	150	*NA*	12 hours	35
Zala 421-16EV. (VTOL)	ZALA Aero	2.8	50	2000	4 hours	10.5
Yangda FW-320 VTOL	Yangda	3.2	50	3500	2 hours 30 minutes	20.3
V-Bat118	Martin UAV	2.7	150	*NA*	8 hours	39.9
V Bat128	Martin UAV	2.95	150	NA	11 hours	56.9
Penguin B VTOL UAV	UAV Factory	3.9	100	4000	8 hours	30
DeltaQuad Pro VTOL UAV	Vertical Technologies	2.4	150	4000	2 hours	6.2
Bayraktar VTOL UAV	Baykar	5	150	4572	12 hours	30
V500P Hybrid	Yanmu	3.8	30	4500	4 hours	50
SV1 Vanguard	Sunbirds SAS	4	50	3600	5 hours	15
CGT50 VTOL	A-techSYN	4.7	80	5486	6 hours	55

Fixed-Wing VTOL Rotator — FVR–90	L3Harris Technologies	4.7	100	5486	16 hours	54
Aerosonde HQ	Textron Systems	3.7	140	3048	8 hours	48
NA – Not Available						

5. ANALYSIS AND IMPLICATIONS OF PERFORMANCE PARAMETERS OF FIXED-WING, ROTARY-WING AND HYBRID MINI UAS

Since the larger UAS were based on fixed-wing platforms, the smaller UAS that came into existence much later possibly followed the same design configuration. Therefore, in the current analysis, fixed-wing systems are more prevalent than the other two variants. However, of late, many manufacturers are upgrading the fixed-wing platform to a hybrid version. Penguin and PD UAS are examples of upgradation. Rotary-wing UAS made their entry much later, and manufacturers opting for hybrid systems are relatively new. Performance metrics vary considerably between fixed-wing, rotary-wing, and hybrid Mini UAS designs, both within and between design configurations. This is primarily because there is no universal definition of Mini UAS and different manufacturers adopt different benchmarks. Although categorised as "Mini UAS" by the manufacturers, most UAS under consideration are not necessarily man-portable field deployable systems. The succeeding paragraphs present a comparative analysis of the three design configurations.

5.1 Size. As seen from Fig 4, hybrid Mini UAS are larger than the other two variants. The average wing span of hybrid Mini UAVs is approximately 10% higher than its fixed-wing counterpart. Although UAVs are usually dismantled before transport and reassembled before deployment at TBS, the larger size of the hybrid UAV can prove to be a criticality in rugged terrain. As brought out earlier, the absence of complex launch and recovery systems tilts the balance in favour of hybrid UAVs. Rotary-wing Mini UAVs are relatively more compact, with an average rotor diameter of 2.7 m. On an average, rotary-wing aircraft are smaller in size by 21% and 29% than their fixed-wing and hybrid counterparts, respectively. The compact size has two major advantages, particularly for military applications. First, the aircraft presents itself as a smaller target against enemy fire. Second, the small size provides the ability to manoeuvre in restricted spaces, a critical factor in combat conditions.

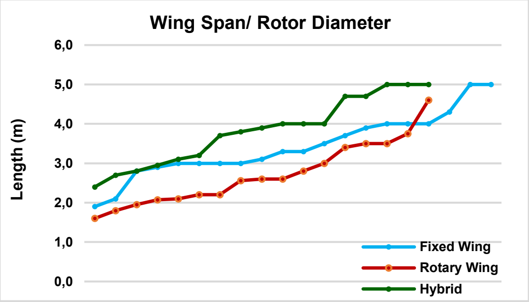

Fig. 4 Wingspan/rotor diameter of Mini UAV

5.2 Datalink Range. Longer datalink ranges, as evident from Fig 5, provide adequate flexibility in the deployment of the UAS, and the advantage can be exploited by all three design configurations of Mini UAS. Fixed-wing Mini UAS were the first off the blocks, and therefore they operated with datalink systems that had older communication technology. On the other hand, rotary-wing and hybrid systems, being relatively new, had the advantage of more matured technology. Hence, the average datalink range of rotary-wing and hybrid systems is higher than the fixed-wing Mini UAS. Most of the fixed systems, currently in use, have upgraded the datalink and operate at longer ranges, at par with the other two systems. Vapor 35, Vapor 55 and UVH 170 have satellite-linked communications systems. For these UAS, the maximum endurance range has been considered as the maximum datalink range and that explains the range spike for rotary systems. Due to the advancements in communication technology, the 30 km range requirement for Mini UAS is not a criticality. Incorporation of satellite communication will further make the datalink range restrictions irrelevant.

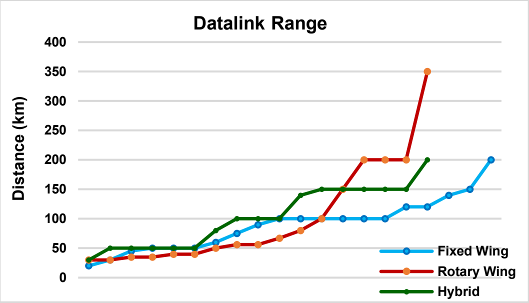

Fig. 5 Datalink ranges of Mini UAS

5.3 Ceiling Altitude. As seen from Fig 6, rotary-wing Mini UAS operate at a lower ceiling altitude than the other two variants. The average ceiling altitude of rotary-wing systems is around 3000 m AMSL, which is around 20% lower than the average altitude of fixed-wing systems, which is around 4100 m AMSL. More than half of rotary-wing Mini UAS have a ceiling altitude below 3100 m AMSL, making them unsuitable for mountain operations. The bulk of fixed-wing and hybrid systems fly at altitudes above 3500 m AMSL, with some exceeding 6000 m. However, the complexity of the launch and recovery mechanisms associated with fixed-wing systems restricts their employment in rugged mountain terrain with higher altitudes. Hybrid systems with an average ceiling altitude of more than 4000 m have no such restrictions and are suited for all terrain conditions. However, relative to fixed-wing systems, hybrid systems fly at a lower altitude for the same wingspan and MTOW. Fixed-wing UAS like PD 1 and PD 2, as well as their VTOL equivalents, are examples of the same.

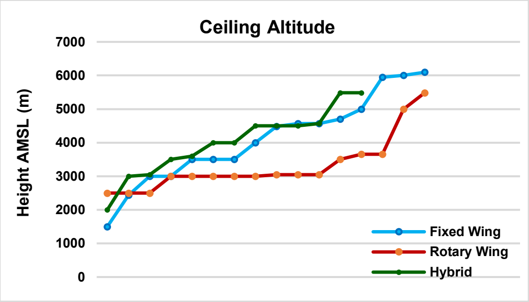

Fig. 6 Ceiling altitude of Mini UAS

5.4 Endurance. Endurance comparison between the three configurations is depicted in Fig. 7. With an average flight time of nearly 11 hours, fixed-wing Mini UAS have a significant advantage in terms of endurance. Fixed-wing planes have a 40% greater average endurance than rotary planes. Fixed-wing aircraft have a 40% longer average endurance than rotary aircraft. In the rotary-wing category, Camcopter S-100 has 10 hours, but the MTOW is 220 kg. On the other hand, PD-1 fixed-wing aircraft, with a 40 kg MTOW, has the same endurance.

Skeldar V-200 has an endurance of only 5 hours, despite having a 235 MTOW. The MTOW of Camcopter S-100 and Skeldar V-200 are considerably higher than the 30 kg MTOW parameter for Mini UAS. The average endurance of rotary-wing UAS falls below 3 hours if these UAS are not taken into account. Lower endurance becomes a critical factor when the launch point is far from the objective. Persistent surveillance missions also necessitate longer endurance. As a result, the majority of these Rotary UAS are unsuitable for combat operations Hybrid systems have less endurance than fixed-wing systems, as seen with the VTOL variant of the PD-1 and PD-2 UAS dropping endurance. The average endurance of hybrid aircraft under consideration is 34% lower than that of fixed-wing aircraft.

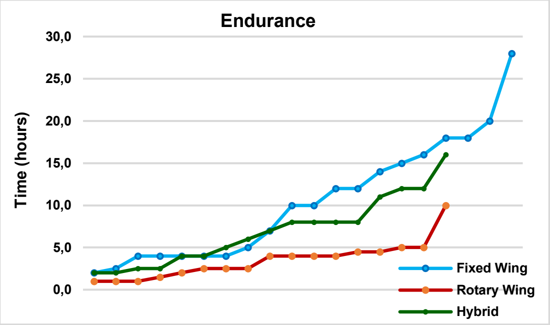

Fig. 7 Endurance of Mini UAV

5.5 MTOW. High MTOW is the biggest disadvantage of rotary Mini UAVs. As seen from Fig 8, rotary-wing Mini UAVs have significantly higher MTOW as compared to the other two configurations. The average MTOW of rotary-wing Mini UAVs under consideration is 75 kg, which is considerably higher than the 30 kg limit.

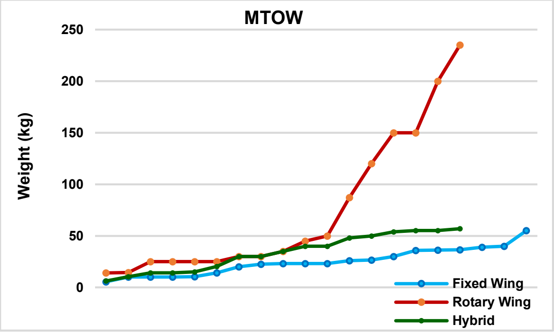

Fig. 8 MTOW of Mini UAV

Heavier UAVs will have to be transported on a vehicle, and this becomes a critical limiting factor for employment in mountain and jungle terrain where vehicular movement is restricted. On the other hand, approximately a quarter of the fixed-wing aircraft under consideration have MTOW more than 30 kg. However, as brought out earlier, the most critical consideration for the employment of fixed-wing Mini UAS is the launch and recovery mechanism. UAVs like the runway launched Sitaria E with 39 kg MTOW, despite satisfying most tactical requirements, cannot be employed in the TBS if there is no runway in proximity to the TBS. Hence, higher MTOW is a liability. More than half of the hybrid aircraft under consideration have MTOW greater than 30 kg. In order to exploit the VTOL capability of hybrid systems, it is essential that the hybrid Mini UAVs weigh less to facilitate employment in all terrains without restrictions.

6. FINDINGS AND IMPLICATIONS

Due to the dearth of relevant data in the open domain related to these systems, few Mini UAS could have been missed out in the study. However, the analysis with the available data does provide insight into design implications for these systems. Based on the analysis, the following are the specific findings and implications from the present study.

6.1 Applications. Combat conditions and operating terrain impose numerous restrictions on the employment and deployment of UAS in military applications. The employment of UAS for civil applications, on the other hand, is predominantly restricted by regulatory standards. Mini UAS, developed primarily for military applications, can also be used in a civil role with suitable payloads. Consequently, most manufacturers design the systems primarily for military roles, with the ability to undertake various civil applications. Due to regulatory restrictions, most UAS used for commercial applications operate within a short range, usually within visual line of sight. The flexibility to launch close to the target implies that range is not a major criticality for civil applications. Types of civil applications also influence the required range. An aircraft used for pesticide spraying can operate within line of sight. But government non-military applications like coastal patrolling will require longer ranges. Considering various parameters of a Mini UAS and TBS, the highest tactical echelon at which a Mini UAS can be employed is the brigade.

6.2 Sub-systems. Mini UAS comprises a number of subsystems, and the capabilities of each of these subsystems collectively determine the deployment and employment of the Mini UAS in the TBS. Compact, lightweight, and portable GCS are essential requirements for Mini UAS, more so in terrain where vehicular movement is restricted. Apart from terrain, combat conditions also necessitate lightweight and portable GCS for military applications. Soldiers in combat are expected to wear heavy protective gear and carry weapons and ammunition. In rugged terrain where the UAS must be physically transported, the human interface subsystem in any configuration can become the weakest link in the overall system. Military missions such as intelligence gathering, reconnaissance, and surveillance must be carried out with stealth. This implies that UAS for military applications must operate at longer ranges. Tactical considerations will govern the location of the GDT to obtain the longest datalink range, and for that, the GDT will have to be deployed at a vantage point. In rugged terrain, heavy and bulky GDT is not desirable because of mobility restrictions. Payload weight affects MTOW and endurance, while the volume impacts the size of the UAV. Weight and volume become critical factors when the payload has to be physically carried in the TBS. The capability of the payload should be such that the Mini UAS should be able to fly at AGL altitudes beyond the range of the small arms to avoid being targeted by hostile forces. For tactical applications, Mini UAS is primarily used for ISTAR missions, and the payload should cater for the same. Mini UAS are used for diverse civil applications, and the payload selected should correspond to the mission requirement.

6.3 Comparison between Fixed-wing, Rotary-wing and Hybrid configurations.

The relative performances of fixed-wing, rotary-wing and hybrid configurations are summarised in Table 4. Simple design, long endurance, and low MTOW are the advantages offered by the fixed-wing Mini UAV. Almost two-thirds of the fixed-wing systems under consideration satisfy all the parameters quantified for Mini UAS. However, fixed-wing aircraft's bulky and complex launch and recovery mechanisms make them unattractive for military applications, particularly in terrains with limited mobility. Such complex systems for small aircraft are not desirable, even for civil applications. Hand launched fixed-wing UAVs might meet the requirements for civil applications and battalion level military requirements, but their capabilities will fall short of the requirements for brigade level operations. The availability of a runway enables the launch of larger UAVs for civilian applications. Hence, fixed-wing configuration is suitable for most civil applications. Since the impact of terrain is also less for most civil usage, fixed-wing aircraft are a viable option because of the numerous advantages they offer.

Amongst the three design configurations, the rotary-wing configuration is best suited for TBS applications. However, the advantages of the compact size of the rotary-wing for military applications do not translate to other parameters. None of the rotary-wing systems under consideration fulfils all the criteria quantified for Mini UAS. With the exception of a few, the vast majority of rotary-wing UAVs fail to reach the 3500 AMSL altitude ceiling. As seen from the analysis, the advantages of rotary-wing UAVs are negated by their significantly higher MTOW. Although most manufacturers claim to have designed these systems primarily for military usage, the combined effect of terrain and combat conditions is not taken into account in the design. It is critical for designers and manufacturers of rotary-wing UAVs to boost the endurance while decreasing MTOW to exploit the compact frame and launch and recovery advantage.

Although a late entrant to the Mini UAS arena, with its demonstrated capability, the hybrid systems have a promising future. Consequently, fixed-wing Mini UAV manufacturers are revamping their platforms to include VTOL capability. Shorter wing spans, lower MTOWs, and higher endurance are aspects that designers and manufacturers must consider to maximise the VTOL potential of hybrid Mini UAVs.

Table 4 – Comparison of Mini UAS configurations

UAV Configuration	Size	Datalink Range	Ceiling Altitude	Endurance	MTOW	Launch and Recovery
Fixed-wing	Moderate	Good	Good	Good	Good	Poor
Rotary-wing	Good	Moderate	Moderate	Poor	Poor	Good
Hybrid	Poor	Good	Good	Moderate	Moderate	Moderate

7. CONCLUSIONS

The interrelations between design, application related requirements, and terrain restrictions have been analysed and presented in this paper. Mini UAS design should meet diverse requirements: long range, high endurance light weight, small size and good ergonomics. Balancing the contradictory requirements will determine the efficacy of Mini UAS for its applications. Enhancing the performance parameters of the current rotary-wing design is essential to exploit the compactness and agility advantages of rotary-wing configurations, and the same is recommended for future work. Overcoming the limitations of present-day hybrid UAS in terms of size, MTOW, and endurance to leverage the design advantages of the hybrid profile for various applications is another aspect that requires further investigation.

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The whole responsibility for the accuracy of calculations, experimental data and scientific interpretation belongs entirely to the authors.

The author declares on his own responsibility that the paper has not been previously published elsewhere.