Aircraft Design Applied to Unmanned Aerial Vehicle (UAV) Development: First Weight Estimation Improved Through Benchmarking for Small UAVs

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Abstract: The surveillance of the "Blue Amazon" is essential to strengthening national sovereignty, protecting strategic natural resources, and monitoring maritime activities of interest. Unmanned Aerial Vehicles (UAVs) are a viable solution to support such monitoring. Within this context, the Drone Competence Center (DCC), an initiative by SENAI CIMATEC under the framework of the Bahia Aerospace Technology Industrial Park (PITA-BA), employs UAV development as a Project-Based Learning tool to train a new generation of engineers. Given that this team is undertaking its first project of this nature, the initial challenge was to identify realistically achievable objectives. The second challenge was to select an aircraft design methodology appropriate for the project. When applying Raymer's aircraft design methodology, it was observed during the preliminary weight estimation phase that adopting the obtained results conservatively would render the project unfeasible. This paper presents the adopted solution, combining the statistical methods described by Raymer (2018), which rely on historically consolidated data to estimate weight fractions for different aircraft classes, with a comparative analysis (benchmarking) involving small commercial UAVs currently available in the market. Three weight fractions were analyzed relative to the maximum takeoff weight (W_0): empty weight fraction (W_e/W_0), fuel weight fraction (W_f/W_0), and payload weight fraction (W_p/W_0). Results indicate that the empty weight fraction tends to decrease as W_0 increases, the fuel weight fraction shows moderate growth with aircraft size, and the payload weight fraction exhibits no strong correlation with W_0, being more dependent on the mission profile. The study found that We values ranging from 40% to 60% are feasible for conservative design approaches. While methodologies for designing manned aircraft can be applied to UAVs, critical analysis is essential to evaluate results and propose solutions that ensure these projects stand out in different design stages.

Keywords: aircraft design, unmanned air vehicles (UAV), weight estimation.

1. Introduction

The "Blue Amazon" represents an area of extreme strategic importance for Brazil, covering approximately 4,450,000 km² [1]. Effective monitoring of this region demands the implementation of various technological solutions, with Unmanned Aerial Vehicles (UAVs) being a particularly notable option.

The Drone Competence Center (DCC) is an initiative of SENAI CIMATEC aimed at developing skills in Aeronautics and Unmanned Aerial Systems. Conceived alongside the establishment of the Bahia Aerospace Technology Industrial Park (PITA-BA), this initiative develops such competencies through Project-Based Learning (PBL), with a primary mission of monitoring vessels and swimmers along the coast of Salvador and in the Bay of All Saints.

As Barros [2] notes, performance targets are a fundamental aspect of aircraft design. These targets typically include maximum level-flight speed, takeoff and landing distance, and maximum range. For surveillance missions that aim to maximize flight duration, the primary performance target becomes maximum endurance. Consequently, for operations prioritizing endurance, the adoption of a fixed-wing UAV is the most appropriate choice.

In aircraft design, one of the initial steps is the first weight estimation. When applying the method described by Barros [2], the empty weight fraction (We/W_0) was found to range between 60% and 80%. For the DCC, which must adopt a conservative design approach, such results were incompatible with project feasibility. Furthermore, a literature review revealed a complete absence of studies specifically addressing this stage of weight estimation in the context of UAVs.

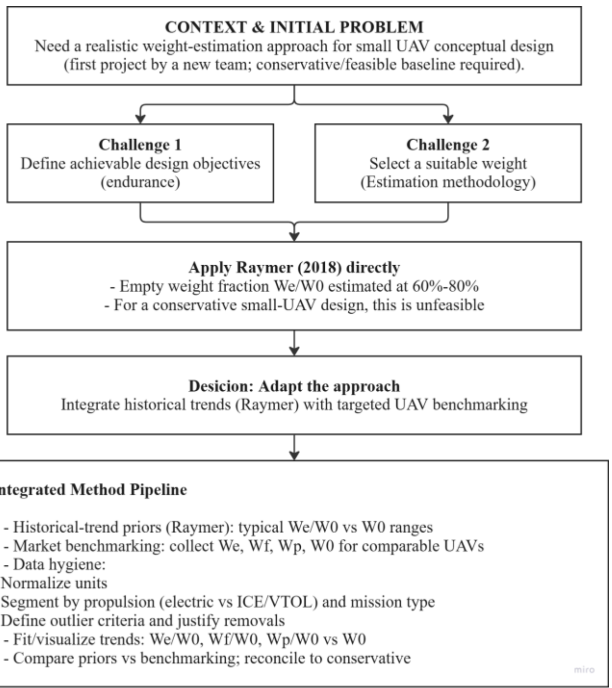
To address this gap, a methodology was developed that combines historical trend analysis with a dedicated benchmarking framework focused on surveillance UAVs. This integrated approach aimed to produce more realistic and applicable results for small UAV conceptual design.

2. Methodology

The methodological approach adopted in this study was based on Raymer's (2018) aircraft design methodology, which relies on statistical estimations derived from historical weight trends of a wide range of aircraft types. To adapt this process for small UAVs, the method was complemented with a structured benchmarking analysis of UAVs currently available on the market.

A schematic flowchart of this process (Figure 1) summarizes the reasoning adopted in this work, from the identification of the main challenges to the implementation of the proposed solution. The diagram shows how the initial application of Raymer's methodology yielded empty weight fraction values (We/W_0) between 60% and 80%, which were incompatible with the conservative design requirements of the project. It also illustrates how combining historical trend analysis with targeted UAV benchmarking allowed the team to obtain more realistic values (40%–60%), enabling the project to proceed successfully. By visually mapping the problem-solving process, the flowchart clarifies the rationale behind each step and provides a replicable framework for similar UAV conceptual design efforts.

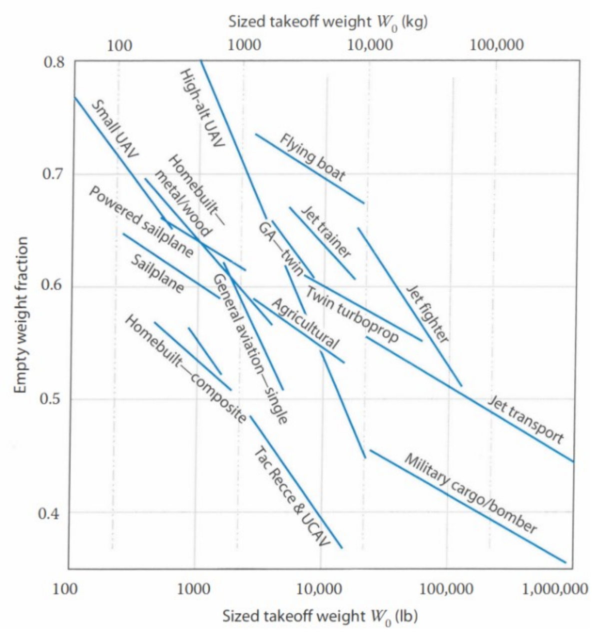
Figure 1. Flowchart of Problem Identification and Solution Approach



2.1 Raymer's Methodology (2018)

Raymer's methodology for estimating the empty weight fraction (We/W_0) uses historically consolidated data from the technical literature covering various aircraft categories. Figure 2 illustrates the typical ranges of empty weight fraction as a function of maximum takeoff weight (W_0) for these categories.

Figure 2. Empty weight range based on historical trends method [2].



Here, empty weight (We) refers to the structural mass of the aircraft, excluding fuel and payload, whereas maximum takeoff weight (W_0) includes all components: structure, fuel, payload, and onboard systems. This graph serves as a key reference during the conceptual design stage, particularly when specific weight data is unavailable.

For example, a comparison between Military Cargo Bombers and Flying Boats shows notable differences: cargo bombers present a considerably lower We/W_0 ratio, reflecting the need to maximize structural efficiency for heavy payloads, while flying boats require reinforced structures for water operations, resulting in higher We/W_0 values. These variations highlight that empty weight fraction depends not only on aircraft size, but also strongly on operational mission requirements.

Raymer's approach also includes an empirical equation for calculating We/W_0 as a function of W_0, the coefficients A and C (derived from previous designs), and the wing sweep factor constant Kvs (used to distinguish conventional wings from variable sweep wings):

$$\frac{We}{W0} = A \cdot W0^{c} \cdot Kvs \tag{1}$$

Table 1 shows typical values of coefficients A and C for different aircraft classes, as reported by Raymer (2018). This table, while useful, is primarily based on manned aircraft data and is therefore less reliable when directly applied to small UAVs.

Table 1. Empty weight fraction coefficients based on Raymer's historical trends method (2018).

Aircraft Category	A	A [Metric]	C
Sailplane unpowered	0.86	0.83	–0.05
Sailplane powered	0.91	0.88	–0.05
Homebuilt metal/wood	1.19	1.11	–0.09
Homebuilt composite	1.15	1.07	–0.09
General aviation single engine	2.36	2.05	–0.18
General aviation twin engine	1.51	1.40	–0.10
Agricultural aircraft	0.74	0.72	–0.03
Twin turboprop	0.96	0.92	–0.05
Flying boat	1.09	1.05	–0.05
Jet trainer	1.59	1.47	–0.10
Jet fighter	2.34	2.11	–0.13
Military cargo/bombe	0.93	0.88	–0.07
Jet transport	1.02	0.97	–0.06
UAV Tac Recce & UCAV	1.67	1.47	–0.16
UAV high altitude	2.75	2.39	–0.18
UAV small	0.97	0.93	–0.06

2.2 Benchmarking

Benchmarking is a strategic analysis tool that integrates qualitative and quantitative information to enable structured comparisons between systems, products, or processes, using established standards or best practices as references [4, 5]. In this study, benchmarking was applied through market research and comparative analysis of technical parameters documented for small UAVs.

Given the observations from Figure 1, along with the data in Table 1 and Equation (1), it became evident that Raymer's empty weight fraction estimates (W_e/W_0) were not compatible with the conservative design approach of this project — particularly since it was being carried out by a newly formed engineering team developing its first aircraft.

Directly adopting Raymer's coefficients for small UAVs could lead to structural oversizing, increasing complexity and costs unnecessarily. Therefore, it was essential to develop a benchmarking methodology specifically oriented toward small UAVs, aiming for more realistic estimates that align with their operational and structural characteristics.

Table 2. Benchmarking data for selected UAVs (weights in kg).

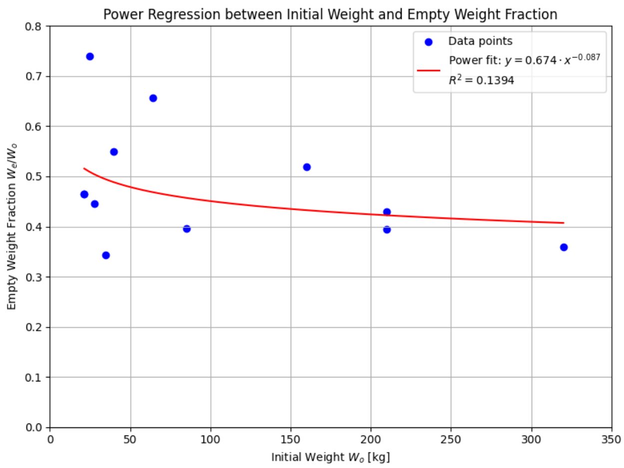
Aircraft	W0	We	Wf	We/W0	Wf/W0	Wp/W0
PD-1	40.00	22.00	8.00	0.55	0.20	0.25
Penguin B - 12h	21.50	10.00	5.78	0.47	0.27	0.27
Penguin B - 15h	21.50	10.00	5.78	0.47	0.27	0.27
Nauru 500	25.00	18.50	4.50	0.74	0.18	0.08
Star-X VTOL-6500HP	160.0	83.00	37.00	0.52	0.23	0.25
Star-X VTOL-4910HP	64.00	42.06	16.94	0.66	0.26	0.08

Star-x GP-6000	210.0	90.00	70.00	0.43	0.33	0.24
NAJA F10-200W	35.00	12.00	15.00	0.34	0.43	0.23
Star-x GP-8000	210.0	83.00	77.00	0.40	0.37	0.24
NAJA SUPER E-EYE-5000	85.00	33.64	31.36	0.40	0.37	0.24
NAJA E-EYE 3220	28.00	12.50	7.50	0.45	0.27	0.29
APOLLO -5 UAV	320.0	115.0	155.0	0.36	0.48	0.16

3. Results and discussion

From the benchmarking conducted, sufficient data was gathered to estimate the empty weight of the aircraft using the historical trends method. This approach allowed for direct correlation between the collected parameters and the predictive models established in [2], thereby improving the robustness of the weight estimation. Based on this analysis, a series of graphs was generated specifically for small UAV applications.

Figure 3. Empty weight percentage based on historical trends and benchmarking method. We: empty weight; W_0: take-off weight; y: power-type trend line; R^2: coefficient of determination.



As shown in Figure 3, there is a clear relationship between the empty weight fraction (We/W_0) and the maximum takeoff weight (W_0) for the UAVs analyzed. A decline in the empty weight fraction is observed as the total weight increases, suggesting improved structural efficiency in larger UAVs. While the adjusted trend equation captures this tendency, the coefficient of determination (R^2) indicates a relatively high dispersion of data.

When excluding outliers, it becomes evident that for UAVs with maximum takeoff weights between 0 and 50 kg, the empty weight fraction generally falls between 40% and 60%. This range is particularly relevant for supporting the preliminary stages of conceptual design, as it provides a more realistic conservative estimate for small UAVs.

Figure 4. Fuel weight percentage based on historical trends and benchmarking. Wf: fuel weight; W_0: take-off weight; y: power-type trend line; R^2: coefficient of determination.

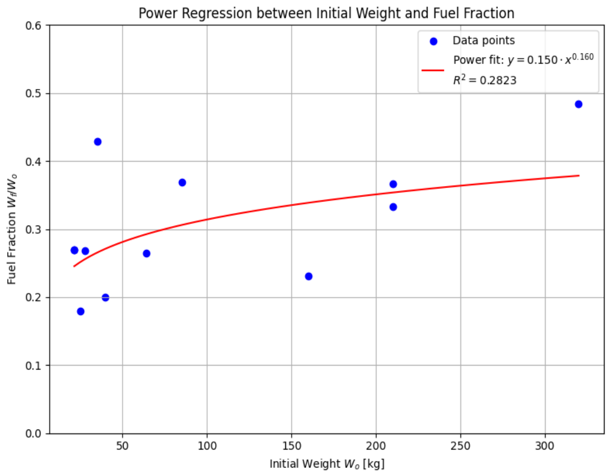


Figure 5. Payload weight percentage based on historical trends and benchmarking. Wp: payload weight; W_0: take-off weight; y: power-type trend line; R^2: coefficient of determination.

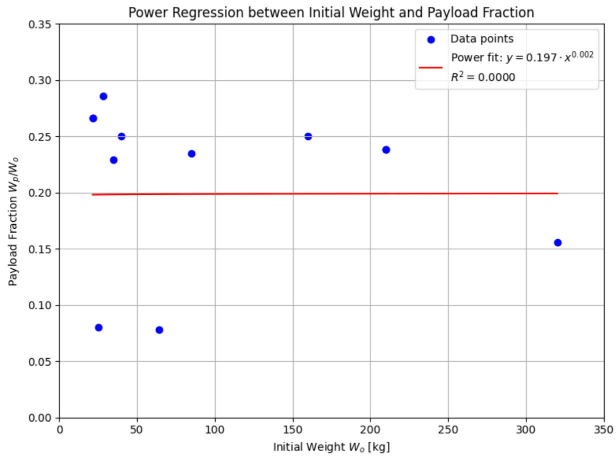


Figure 4 illustrates the relationship between the fuel weight fraction (W_f/W_0) and W_0. The analysis reveals a positive trend: the fuel weight fraction tends to increase with total aircraft weight. The adjusted trend curve reflects this tendency, and although the coefficient of determination indicates a moderate correlation, the observed dispersion reflects the diversity of operational profiles and propulsion systems among the UAVs analyzed.

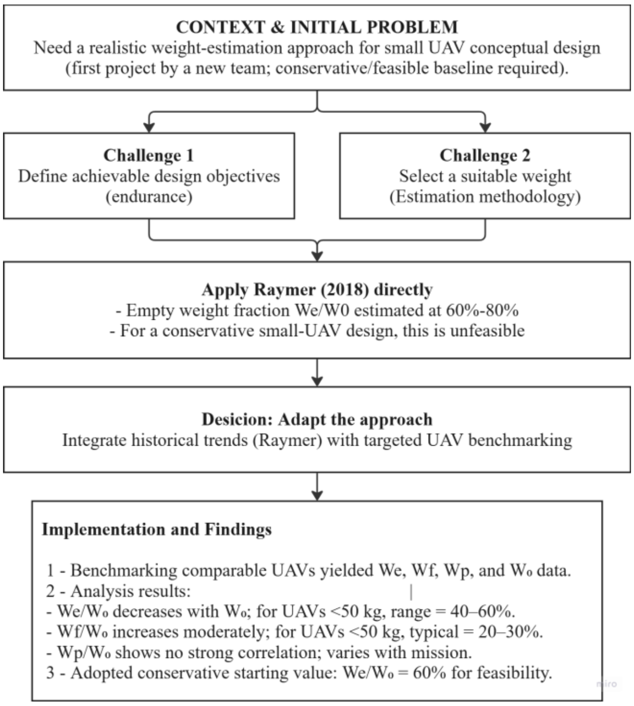
For UAVs weighing less than 50 kg, the fuel weight fraction is predominantly concentrated between 20% and 30%, which serves as a practical reference range for early-stage design considerations.

Finally, Figure 5 presents the relationship between the payload weight fraction (W_p/W_0) and the maximum takeoff weight (W_0). The data shows no significant correlation between payload fraction and total aircraft weight, as confirmed by the low R^2 value from the regression analysis. This suggests that payload sizing is determined primarily by mission requirements and operational needs rather than by the aircraft's total size.

This finding reinforces the importance of defining payload specifications through detailed mission analysis, rather than adopting proportional scaling with W_0. Benchmarking specific mission types thus becomes a key step in establishing accurate payload requirements for UAV projects.

To consolidate the findings and provide a clear overview of the analytical process, Figure 6 presents a synthesis flowchart summarizing the key steps from the initial problem identification to the final weight estimation adopted in this study. The diagram outlines the sequence from the early application of Raymer's method—whose results were incompatible with a conservative small-UAV design—through the integration of historical trend data and targeted UAV benchmarking, to the observed trends in empty weight, fuel weight, and payload fractions. This visual representation serves as a concise reference, highlighting the rationale behind the adopted conservative baseline (We/W_0 = 60%) and providing a replicable framework for similar UAV conceptual design efforts.

Figure 6. Design Summary Flowchart



3. Conclusion

The results of this study demonstrate that combining internally developed benchmarking with historical trend analysis can serve as a reliable method for the initial estimation of aircraft weight in small UAV projects. The findings showed that the empty weight fraction (We/W_0) initially predicted by Raymer's methodology (60%–80%) was not feasible for the project's conservative design approach. However, by integrating benchmarking data from comparable UAVs, a more realistic range of 40%–60% was established, which supports the feasibility of the conceptual design phase.

Based on these conservative estimates, it was possible to define an initial empty weight fraction of 60% for project development, even for a novice engineering team. The design process is expected to continue prioritizing optimization strategies aimed at increasing endurance and reducing empty weight — for instance, through topological optimization.

The analysis of payload weight fraction (Wp/W_0) highlighted the importance of a deep understanding of the mission profile. Payload definition should be informed by comprehensive data collection and discussions with stakeholders to ensure that operational requirements are precisely met. This step is critical in UAV design and differs from conventional aircraft design, making payload benchmarking an indispensable part of the process.

Future developments could explore:

(a) expanding the benchmarking database with UAVs performing analogous missions to establish a reference framework for other projects;

(b) deepening the comparative analysis between airplane and UAV design requirements — for example, examining communication range versus endurance trade-offs; and
(c) reducing empty weight through structural optimization methods such as topology optimization.

The study confirms that while traditional aircraft design methodologies can be applied to UAV design, they must be critically adapted to the UAV's unique operational profile. Critical thinking and methodological adjustments are essential to obtain results that enhance project feasibility and performance across different design stages.

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