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«Παραμετρική σχεδίαση ενός πολύ χαμηλού κόστους περιπλανώμενου πυρομαχικού»

Διατριβή που υπεβλήθη για τη μερική ικανοποίηση των απαιτήσεων για την απόκτηση Μεταπτυχιακού Διπλώματος Ειδίκευσης

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Abstract

Ever since the first manned flight that took place at Kitty Hawk, North Carolina on December 17, 1903, engineers and aviators were dreaming of remotely piloting airplanes. The idea of developing flying vehicles that could be controlled from the ground, was so fascinating, that many experiments and tests were made during the 1st World War from Britain and the USA. Their capabilities in the battlefield were limitless and no one could ever imagine the extent of their use by the end of that century. Nevertheless, those vehicles, also known as UAVs (Unmanned Aerial Vehicles) did not serve for military purpose only. They are broadly used by individuals for taking pictures, by private companies for broadcasting live events, by health centers for carrying medicines or supplies to areas that other means or humans could not approach due to high risk, such as search and rescue or reconnaissance missions and even by farmers in agriculture for planting. This thesis aims to analyze the importance of a specific category of military UAVs, known as loitering munitions and to describe briefly the steps that are followed by aeronautical engineers, in order to design a certain type of a loitering munition, step by step and of course from scratch. It focuses on the field of Defense, in particular the Greek Armed Forces, and the main purpose is to present a way to develop a light and low-cost loitering munition with specific dimensions. It will be portable, so the soldier can carry it in his vest or his backpack and its activation and launch will be very quick, so the response in case of a hostile threat will be immediate. This small fixed-wing drone will be equipped with a propeller at its back end and will dispose foldable wings, so as to fit in an EU's specific dimensions tube. It will also have sensors and a high-resolution camera, in order to able to participate in many types of missions, from a simple reconnaissance to a detailed strike against any target, moving or hidden. The soldier will bring with him a small tablet that will provide all the necessary data and telemetry of flight. Through this screen, he will be able to fly the drone to the target area and back if needed. As technology advances, Armed Forces around the world have to keep up with it and evaluate continuously their weapon systems, in order to be combat ready. UAVs provide one of the best solutions for upgrading an army and enhancing its lethality, because one of its numerous benefits, is their low cost. This gives the opportunity to any country, rich or poor, developed or not, to buy or manufacture such types of aerial vehicles and protect its territory against any kind of threat. Greece has ceased the opportunity and has entered dynamically into the field, by joining and applying the strategic concept of other NATO armies all across the alliance. Key factors are the funding and the investment on military research programs under the auspices of the Hellenic Ministry of Defense and also

with the help from the EDF (European Defense Fund), the Commission's instrument that supports Research and Development in defense.

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Abbreviations

UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
RPA	Remotely-piloted Aircraft
RPAS	Remotely-piloted Aircraft System
GLUAS	Grenade-Launched Unmanned Aerial System
GCS	Ground Control Station
NATO	North Atlantic Treaty Organization
EDA	European Defense Agency
EU	European Union
EDF	European Defense Fund
EASA	European Union Aviation Safety Agency
ICAO	International Civil Aviation Organization
CSIS	Center for Strategic and International Studies
EEA	European Economic Area
FPV	First Person View
AA	Air to Air
AI	Artificial Intelligence
SEAD	Suppression of Enemy Air Defense
EO/IR	Electro-Optical/Infra-Red
STANAG	Standardization Agreement
HALE	High Altitude Long Endurance
MALE	Medium Altitude Long Endurance
LOS	Line of Sight
BLOS	Beyond Line of Sight
MSL	Mean Sea Level
AGL	Above Ground Level
JTF	Joint Task Force
MTOM	Maximum Take Off Mass
AoA	Angle of Attack
AWACS	Airborne Warning and Control System
SATCOMS	Satellite Communications
LEO	Low Earth Orbit
GPS	Ground Positioning System
FPV	First Person View
RCS	Radar Cross Section
ISR	Intelligence, Surveillance and Reconnaissance
ISTAR	Intelligence, Surveillance, Target Acquisition, Reconnaissance
IDF	Israeli Defense Forces
ELINT	Electronic Intelligence
SIGINT	Signal Intelligence
FLR	Front wing Lower than the Rear
FUR	Front wing Upper than the Rear
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
CAI	Composite Affordability Initiative

AoA	Angle of Attack
b	Wingspan
A	Aspect ratio
L	Lift force
D	Drag force
L/D	Lift to Drag ratio
E	Endurance
R	Range
V	Velocity
S	Surface
ϱ	Air density
σ	Relative air density at specific flight altitude
W_o	Takeoff gross weight
W_p	Payload weight
W_b	Battery weight
BMF	Battery Mass Fraction
S_{ref}	Wing reference area
S_{wet}	Wetted area
P	Engine power
K	Induced drag factor
E_{sb}	Battery specific energy
n_{b2s}	Total system efficiency from battery to motor output shaft
n_p	Propeller efficiency
g	Acceleration of gravity
C_{Lmax}	Maximum lift coefficient
C_{Lc}	Ideal cruise lift coefficient
C_{Li}	Wing ideal lift coefficient
Re	Reynolds number
MAC	Mean aerodynamic chord
C_{Do}	Zero-lift drag coefficient
e	Oswald span efficiency factor
Γ	Dihedral angle
Λ	Sweep angle
λ	Taper ratio
C	Chord
α_t	Twist angle
i_w	Incidence angle
$(t/c)_{max}$	Maximum thickness-to-chord ratio
ac	Aerodynamic center
cg	Center of gravity
D_f	Maximum fuselage diameter
L	Length of fuselage
l_{opt}	Optimum tail arm
ε	Downwash angle
C_m	Pitching moment coefficient

Introduction

UAVs offer a more efficient and less risky way of carrying military operations when compared to the typical manned aircraft. The interest in the development of Unmanned Aerial Vehicles, or better known as drones, has increased in the defense industry, particularly in the Army, where they are primarily designed for carrying out various military operations. The Global Traffic Management Operational Concept states: "An Unmanned Aerial Vehicle is a pilotless aircraft in the sense of Article 8 of the Convention on International Civil Aviation, which is flown without a pilot-in-command on-board and is either remotely and fully controlled from another place (ground, another aircraft, space) or programmed and fully autonomous" (ICAO, 2011). This understanding of UAVs was endorsed by the 35th Session of the ICAO Assembly. In fact, UAVs are part of Unmanned Aerial Systems (UAS), a more general term that is used to describe the whole system of the UAV, which is in fact an "ecosystem" that includes the UAV as a structure, the autonomous or human-operated control system, usually on the ground, ship or another airborne platform and finally, the communication/command/control (C3) system. According to Systems Theory (Von Bertalanffy, 1968), a UAV can become fully operational, only if all of its subsystems cooperate appropriately and adequately. In addition, UAVs are part of dual-use items, which, along with related regulations, are defined in EU law (Annex I of Regulation (EU) No. 2021/821) as products, including software and technology, that are commonly used for non-military purpose but may also have military application (European Parliament, 2021).

This thesis contains 6 chapters that are organized in a way that enables the reader to understand the basic structure of a UAV and how it works. Through the structural design and the basic principles of flight, we will eventually end up in the selection of the most suitable type of loitering munition for the Greek Armed Forces, with all the initial desires fulfilled, such as the low-cost, the effectiveness, the suitable launch method and the easy guidance. In other words, it has to be "user friendly". First of all, let's have a quick look in the history of UAVs and familiarize with the basic terminology, necessary to understand important components and procedures.

Chapter 1

§1.0 Basic terminology

§1.1 Electronic warfare (EW)

Electronic Warfare is defined as "Any military action involving the use of electromagnetic and directed energy to control the electromagnetic spectrum or to attack the enemy" (Department of Defense, 2020).

§1.2 System

A System is the combination of elements that function together to produce the capability required to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes and procedures needed for this purpose; that is, all things required to produce system-level results (National Aeronautics and Space Administration, 2007).

§1.3 Unmanned Aerial Systems (UAS)

Sometimes also called Unmanned Aircraft Systems, are sets of configurable electronic and electromechanical components consisting of an Unmanned Aerial Vehicle, a remote electronic controller and a command-and-control data system/link connecting the two so that they can communicate (BAE Systems, 2024).

§1.4 Unmanned Aerial Vehicle (UAV)

An aircraft which is intended to operate with no pilot on board.

§1.5 Remotely Piloted Aircraft (RPA)

An aircraft where the flying pilot is not on board the aircraft. This is a subcategory of unmanned aircraft.

§1.6 Remotely Piloted Aircraft System (RPAS)

A set of configurable elements consisting of a remotely-piloted aircraft, its associated remote pilot station(s), the required command and control links and any other system elements as may be required, at any point during flight operation (ICAO, 2017).

§1.7 Loitering munitions

Loitering munitions, often dubbed “kamikaze” or “suicide drones,” are a disruptive innovation in contemporary warfare, combining the precision of missiles with the versatility of drones. These missile-drone hybrids are characterized by their ability to “loiter” or hover over targets, waiting for the optimal time to strike (Defense and Security Monitor, 2024). According to Paul Scharre, an American author and former Ranger of the U.S. Army, who had been deployed in Afghanistan and Iraq, loitering munitions are much more like smart missiles, rather than aircraft, because they can decide whether to engage their target or not (Scharre, 2018).

Figure 1: Loitering munition’s canister launch (SmartEncyclopedia, 2022)

Chapter 2

§2.0 Historical review

§2.1 History of UAVs

The concept of UAVs dates back to 428 – 347 B.C., with the so called "Flying Pigeon" designed by the Greek mathematician and philosopher Archytas, father of Mathematical Engineering. This flying structure was made of wood, used steam to move through space and was considered as the first study of how birds fly. Its furthest flight distance was 200 m. Many experiments were made after this, and in 1483, Leonardo Da Vinci invented the "Flight Machine", also a wooden structure, ancestor of today's helicopters, since if took off and lanced vertically, with the use of rotors. Almost four and a half centuries later, the USA entered the 1st World War and they developed the first unmanned aerial vehicle in 1918, named "The Kettering Bug" that was actually a flying torpedo with a length of 12 ft and a wingspan of 15 ft, weighting almost 530 lbs. Technology kept evolving through the years and after the 2nd World War, new types of UAVs appeared, with the development of the "Firebee", in 1959. As a part of the "Red Wagon" program, its mission was to collect data through images in distant areas and to avoid detection from enemy radars. A few years later, during the Vietnam War, UAVs were extremely necessary for reconnaissance missions and the collection of data, through imaging. American F-4 Phantoms II (manned aircraft) were usually shot down after intense dogfights with enemy's MIG-21s, which had the advantage of being faster and more maneuverable. The idea was to send UAVs in risky areas and protect the pilots from being killed, spending at the same time less money for fuel. After the end of the Cold War (1991) and the collapse of the USSR, a new era of UAVs began. The USA proved once again their cutting-edge technology, with the development of the ancestor of one of the most successful UCAVs ever built. The MQ-1 Predator. This product of the USAF served as a key factor for the NATO forces during the war in Bosnia in 1995. This was the first time that a UAV could take part in a joint operation and cooperate with armed forces in air and land. From reconnaissance and surveillance missions to close air support for the allied manned aircraft, the Predator proved the significant advantage of the use of UAVs in military operations. Today, newest versions are being widely used, such as the MQ-9 Reaper and the RQ-4 Global Hawk, America's masterpieces in UAV technology and take part in every kind of mission, anywhere and anytime.

Figure 2: General Atomics MQ-9 Reaper (Military.com, n.d.)

§2.2 Case study: Nagorno – Karabakh

The last 2 decades paved the way for the next generation of drones and the enhancement of their capabilities in the battlefield. One of the conflicts that played a key role and pointed clearly the advantages of the UAVs and more specifically the loitering munitions, was the Nagorno - Karabakh war, between Armenia and Azerbaijan, in 2020. For 6 weeks, Armenian forces suffered severe damage from Azerbaijan's UAVs (mainly Bayraktars TB-2 that were remotely piloted from Turkish pilots) and loitering munitions (mainly KARGU). After the collapse of the USSR in 1991, those two nations craved for their independence. The region of Nagorno – Karabakh belonged to Armenia. However, Azerbaijan's increase in defense budget and strategic alliance with Turkey and Israel, provided it with many types of UAVs and loitering munitions (Stijn Mitzer and Joost Oliemans, 2021). Its drone arsenal, outperformed by far Armenia's arsenal, which was actually consisted of conventional weapons. In the following Figure that presents a research from 2007 to 2023, the difference of those two countries before the start of the war, in terms of military budget and investments is obvious.

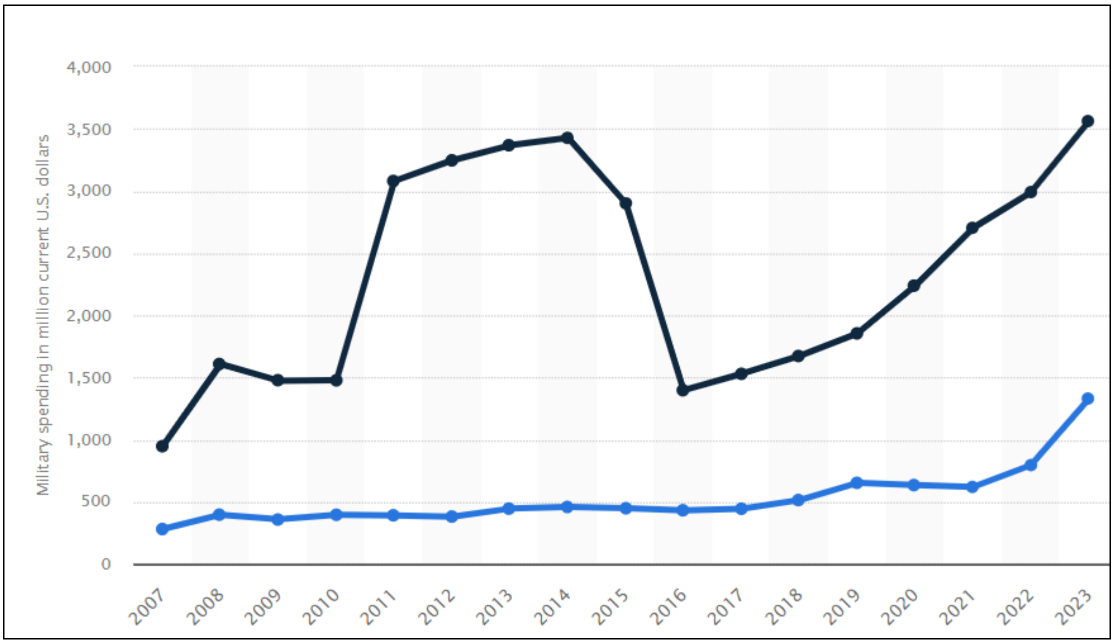


Figure 3: Military spending in million U.S. dollars of the two countries (Statista Research Department, 2024)

Azerbaijan's investment in UAVs provided it with a great advantage against Armenia's armed forces that were fighting in the trenches and in the mountains, while their enemy flew their drones from their own territory, inside protected Ground Control Stations. The battle conditions and the psychology of the fighters, obviously were not the same, so apart from the precisions strikes and the thermal imaging from the EO/IR sensors, drones had a negative effect and a psychological impact on the mentality of the enemy. UAVs and loitering munitions can also cooperate with the artillery and serve as a great tool for the infantry that is advancing and is close to enemy lines. In other words, they increase survivability and collect vital enemy data, by enhancing surprise attacks and increasing the ambushes, since they can loiter above the enemy for several minutes and keep an eye on hostile movement (U.S. Army, 2019). Smaller drones and loitering munitions are used mainly by platoons and companies, while larger reconnaissance UAVs are used by regiments and battalions. The following Figure presents a comparison between the armed forces of Azerbaijan and Armenia.

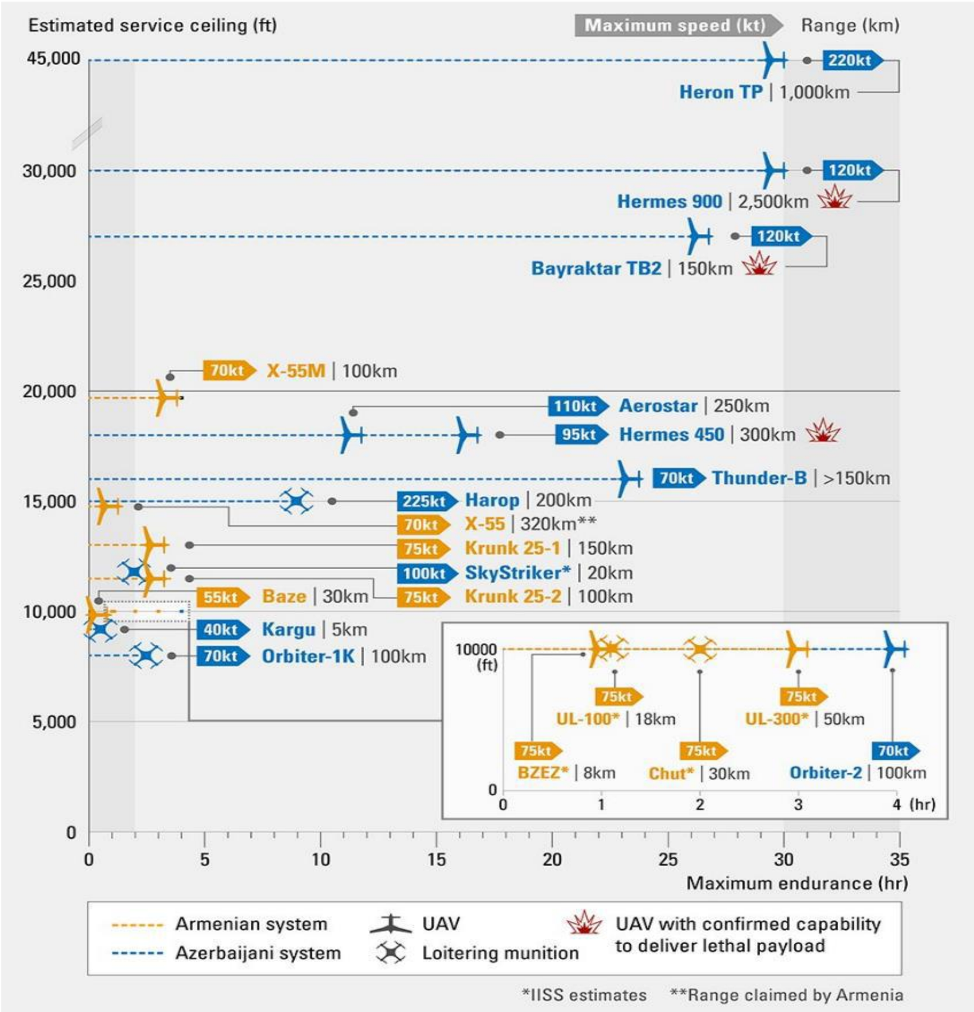


Figure 4: Armenian and Azerbaijani military weapons capabilities (The International Institute for Strategic Studies, 2021, p. 5)

Azerbaijan had invested in buying larger drones for various types of missions and combined perfectly surveillance missions with detailed strikes, while Armenia not only lacked missiles (CSIS, 2020) and drones, but also, the very few it possessed, were mainly quadcopters and generally small drones that could not be used properly. A key domain that was developed at the time, was the Command and Control, also known as C2. This refers to the credibility and the assurance of communications on the one hand and on the other hand, the application and the exploitation of the information from the sensors. Because modern battlefield is a dynamic environment and the situation changes rapidly. Winner is the one who has the largest amount of correct data at the right time, before it's too late. Azerbaijan proved that a less powerful country in terms of means and weapons, compared to more developed countries like the USA or Russia, could win in a conflict and destroy its opponent. Furthermore, these new combat tactics affected the opponent's psychology, so fear and insecurity took the place of braveness and willing to fight. Armenian fighters were also disappointed because their progress was too slow and they could not reverse the facts. Without moral, they were just waiting for the enemy drones to hit. On top of that, the use of UAVs for the increase of propaganda, another element of the psychological war, should also be mentioned. The spread of false news and falsified information from the media, deeply affects the mentality and the upcoming decisions from the enemy and that threatens the ability for decision-making, putting into danger the lives of soldiers. In this war, the first organized propaganda through the use of UAVs was achieved and that created a false reality for the Armenians, causing military, political and internal disturbances. On the other hand, Azerbaijan was completely satisfied by its strategy and policy, since it had developed diplomatic relations with Turkey and they all knew the result of that conflict from the very first day. A UAV's cost was estimated around 2000 – 5000 euros, while a guided missile costed ten times more. So, with the TB-2 Bayraktar from Turkey and many loitering munitions (kamikaze drones) from Israel[1], Azerbaijan's arsenal was by far superior to Armenia's. The investment in UAVs had paid off well.

§2.3 UAVs in modern warfare

The war in Nagorno – Karabakh was a milestone in the use of UAVs in the battlefield and taught us many more things than those just mentioned above. Another great thing we learnt from this conflict, was the development of new types of missions and the fact that UAVs had numerous capabilities and could achieve practically anything a manned aircraft could do, but with a significantly less amount of money spent by a government. An example of a new type of mission was the SEAD (Suppression of Enemy Air Defense). These missions use a cheap decoy that flies ahead in a certain distance from the manned or unmanned aerial vehicle and penetrates the enemy territory. In that way, enemy's radars activate the air defense systems, in order to shoot it down. The decoy gets destroyed, but the position of the AA guns in now known to the following aircraft, so guided bombs are used against enemy's air defense. The following Figure depicts a SEAD mission during the Nagorno – Karabakh war, where pilotless Antonov An-2's were used as decoys, after they had been converted to autonomous systems. Nowadays, loitering munitions are used in such types of missions to a great extent, mainly for their low cost and precision strikes.

[1] Harop, Orbiter and SkyStriker are some examples of Israeli loitering munitions and UAVs

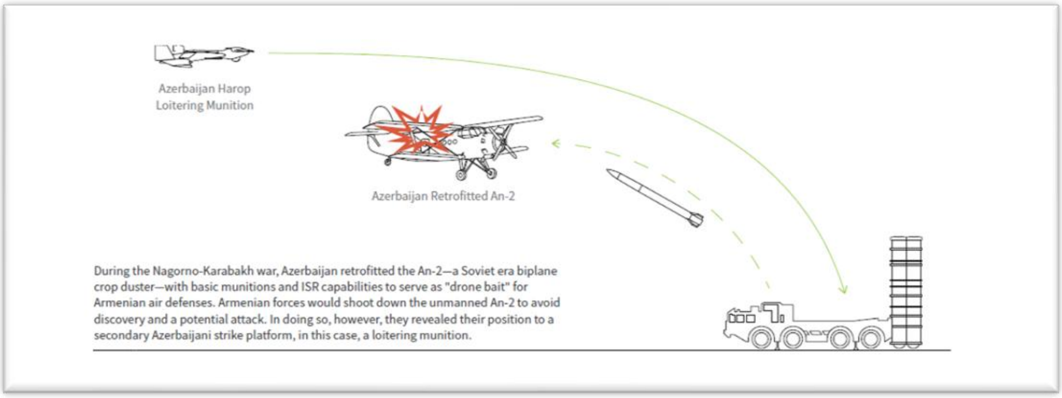


Figure 5: SEAD mission (CSIS, 2022, p. 15)

Many military analysts around the globe studied carefully this war, because the tactics that were used there, are also used in all the other conflicts that followed, for example the war between Russia and Ukraine (24th of February 2022) and the recent war in the Middle-East between Iran and Israel (1st of April 2024). Today, the foundations have already been laid, both for offensive and defensive fight and the modern era conflicts are based primarily on the use of long-range missiles, UAVs and loitering munitions.

Figure 6: Battlefield of the 21st century (skynews, 2023)

§2.4 War between Russia and Ukraine

On February 24th, 2022, Russia began a “special military operation”, according to military officials and the Russian government. Many months later, this so-called operation turned into an invasion against Ukraine and day by day, it keeps getting worse. It’s the largest scale invasion of a country against another, after World War II. It's also a modern type of war and the main weapons used are missiles and UAVs. Two years after, new capabilities of UAS are being discovered, while scientists and military personnel search new ways of countering these threats.

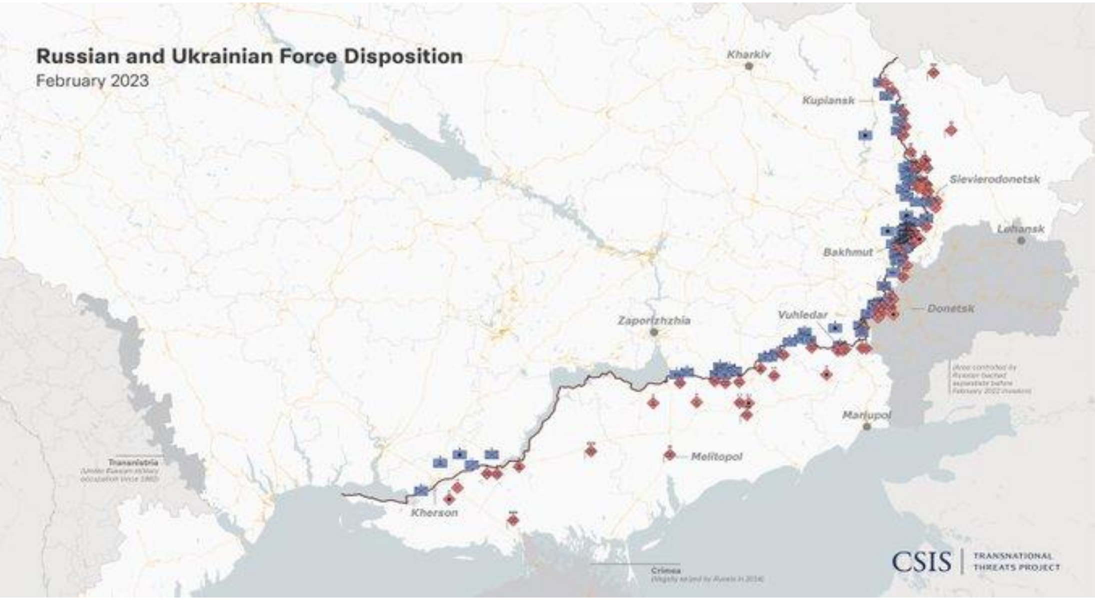


Figure 7: Russian and Ukrainian Force Disposition (CSIS, 2023)

After the lessons learned from Nagorno-Karabakh, Russia studied carefully Azerbaijan's tactics and used them to fight Ukraine, while possessing a larger number of UAS and of course long-range missiles, its advantage over other countries. The following Figure presents some of the UAVs that Russia has in its arsenal.

Company	Location	Type of UAVs	Other Products	Number of Employees	UAV annual production rate (2023)
STC	St. Petersburg	Orlan-10 (-20, -30)	No	2200	200-300
Kronshtadt UAV factory	Dubna	Orion	No	1500	<10
Luch Design Bureau (Vega Holding)	Rybinsk	Tipchak, Lastochka-M	Avionics	800	<20 of each type
ZALA Aero Group (Kalashinkov)	Izhevsk	ZALA drones, KUB-BLA, Lancet	Counter-UAV EW systems	100	200-300
Izhevsk Unmanned Systems (Kalashnikov)	Izhevsk	Granat-1 (-2,-3,-4), Takhion	No	180	<100
Supercam Unmanned Systems	Izhevsk	Supercam	No	250	150
Eniks	Kazan	Eleron	Flying Targets	300	<50
UZGA	Yekaterinburg	Forpost, Zastava, Altius	Light commerial aircrafts, repair of engines	4300-4500	<10 Forpost, <10 Zastava, single UAVs Altiius (protoypes)
Novosibirsk aircraft plant	Novosibirsk	S-70 Okhotnik	Su-34, parts for combat and commercial aircrafts	6800-7000	Single UAVs for trials (prototypes)

Figure 8: UAVs in Russia's arsenal (Foreign Policy Research Institute, 2023)

The most common missions for Russian UAVs, were Reconnaissance and gathering of intelligence, in order to locate and destroy strategic targets, like industries for electric power production, factories that produce ammunition and roads that Ukrainians used for supplies transportation. To achieve that, Russia disposed a great variety of UAVs and loitering munitions that came from Iran, like the Shahed-131 and Shahed-136. For reconnaissance missions, target location and electronic warfare, other types of UAVs were used, like Orlan-10. Israel Aerospace Industries had also provided Russia with the Searcher Mk II, a UAS comprised of a long-endurance UAV with sensors, special software to provide security from jamming and a GCS with antennas, to achieve the best possible control in long distances. The following Figure shows the complete set of the system.

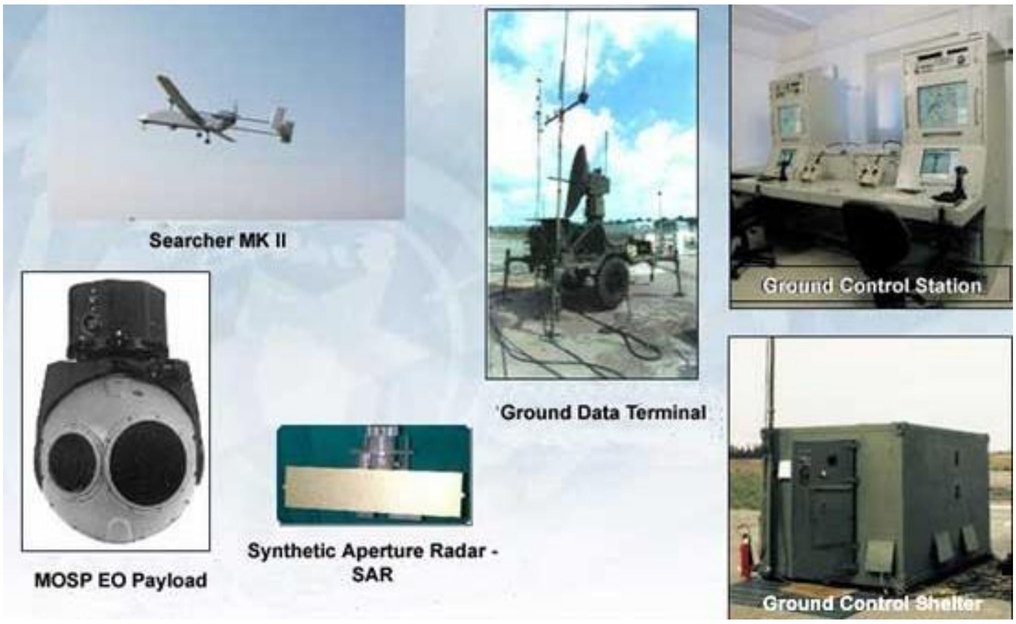


Figure 9: Searcher Mk II of IAS (Defense Studies, 2011)

UAVs are also very important in telecommunications, as they can transmit data to manned aircraft, such as AWACS, or directly to a fighter or a bomber, in order to destroy specific targets. Those systems are directly connected to satellites and they use datalinks to communicate (SATCOMS). In that way, data can be processed immediately, without any kind of delay. In the following Figure, we can see the connection between satellites, UAVs and GCS. A UAV can also be connected to one or more other UAVs and exchange data.

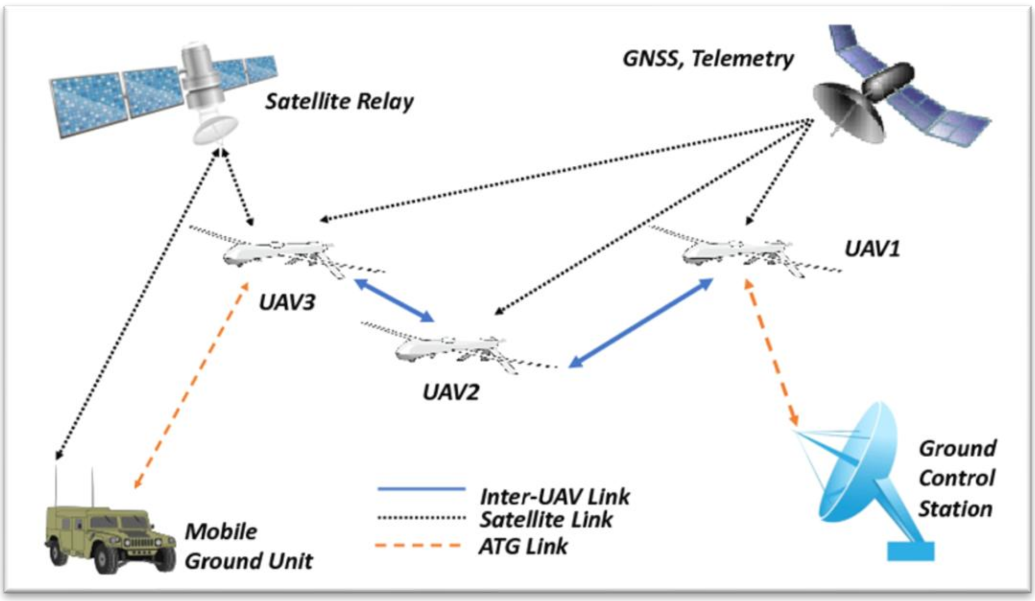


Figure 10: Data transmission through UAVs (militarydrones, n.d.)

Ukraine on the other side, is not as powerful country as Russia and does not dispose such a large arsenal with so many different types of UAVs. So, the only solution to fight back, was to join NATO. After that big step, allied countries such as France, Germany and primarily the USA provided Ukraine with a great number of defensive and attack systems, from UAVs and loitering munitions, to long range missiles that could harm Russia deep in its own territory. Financial aid is also provided from the U.S. government quite often. One of the main problems that Russia encountered in this war, was the American low-orbit constellation Starlink of SpaceX, which was impossible to be overridden, due to the large number of LEO satellites. This enabled the secured communication between military and political leadership of Ukraine and the troops in the front line of the battlefield, despite the jamming efforts of Russia. From its side, Ukraine managed to create small labs of loitering munitions production, mainly in shelters, below the ground. Ukrainian soldiers used commercial and cheap FPV drones and attached bombs and different kinds of warheads to them with tape or tire-ups. These are the cheapest solutions that they could come up with, but they were so effective, that many more countries started applying this principle and develop their own cheap loitering munitions. Those new battle tactics are like guerilla-war, where hidden soldiers use FPV drones to hit and destroy enemy vehicles, tanks, helicopters or even soldiers. These commercial modified drones can be used day and night and provide precision strikes with the lowest possible cost. They can be transferred in backpacks and do not need runways or canisters to takeoff. In the following Figure, we can see a kamikaze drone used by the Ukrainians.

Figure 11: Ukraine's kamikaze drone (The Economist, 2024)

While Ukraine uses small FPV kamikaze drones for precision strikes, Russia uses bigger UAVs for Surveillance and Reconnaissance. The data collected from these UAVs are directly transmitted to the artillery and their long-range missiles hit the targets. Without an artillery, Ukrainian soldiers can't use their drones in the same way. Their advantage, is that they know their territory better than anyone else and they use it to their profit. That's also why they are not attacked with small FPV drones so often. The Figure below, shows the use of Russian UAVs and the transmission of data to their artillery.

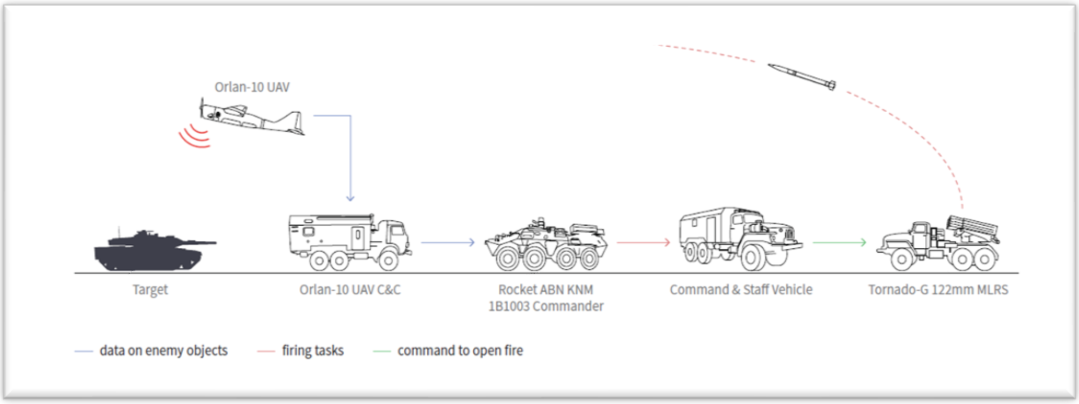


Figure 12: Russian artillery (CSIS, 2022, p. 21)

In this war, in contrast to the war in Nagorno-Karabakh, many applications of EW were more visible, one of which the so called "jamming". It's probably the most common way of destroying an enemy drone, especially nowadays where drones have a very small RCS and is extremely difficult to shoot them down with missiles. Through jamming, someone can interfere in the frequency that the drone receives from its transmitter and literally take control of it. He can either destroy it by crashing it down, or even locate where it was launched from. There is also a common technique called GPS "spoofing", where a drone loses its orientation and cannot locate anymore its exact position through space and this results in falsified navigation. One of the reasons that loitering munitions are so popular, is the fact that they are made for impact, so they will be destroyed eventually, comparing to other strategic and largest drones. In the following Figure, we can see the GPS spoofing and how it works.

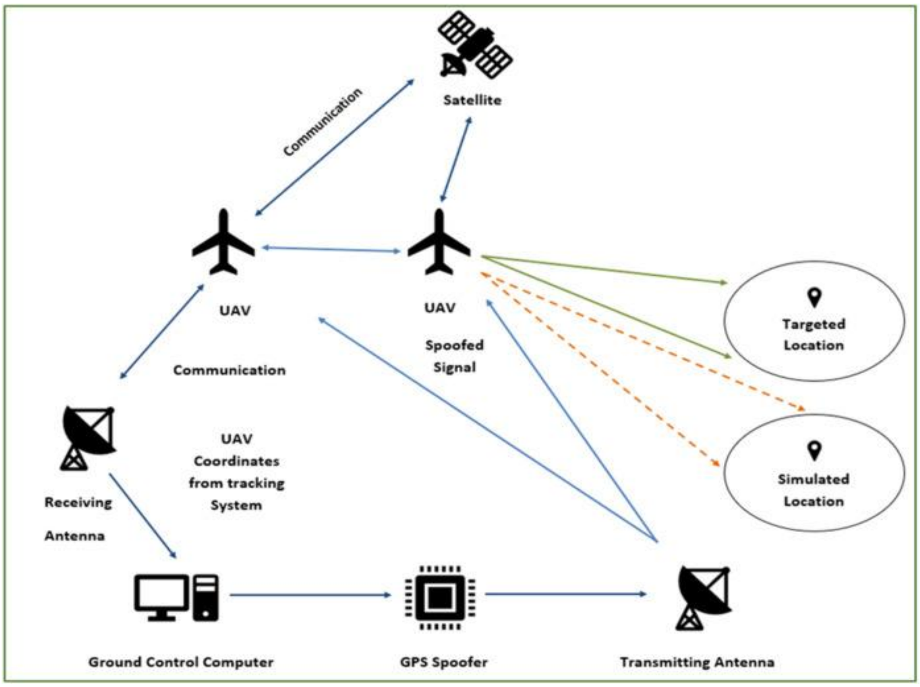


Figure 13: Architecture of GPS spoofing (Energy Reports, 2021)

As a countermeasure, in some of the most modern loitering munitions, wires are used in order to navigate them instead of GPS, because the GPS's signal can be detected and jammed, whereas long cables allow the full control of the kamikaze drone until the moment of impact. These drones act like wire – guided missiles. Russians applied first this technique in August 2024, because Ukraine advanced in the Kursk region. In the Figure below, the Russian fiber-optic drone is presented.

Figure 14: Russia's fiber-optic drone (Interesting Engineering, 2024)

It is true that at first, only the most economically and technologically advanced countries of the world could have UAVs and use them for civil and military purpose. After those two wars who stood as milestones in military history, the use of UAVs for ISR/ISTAR missions is no more a privilege of the most powerful nations. Everyone has now access in this cheap and effective solution and this is why loitering munitions tend to become more and more popular in modern-era battlefields around the globe.

§2.5 Middle East

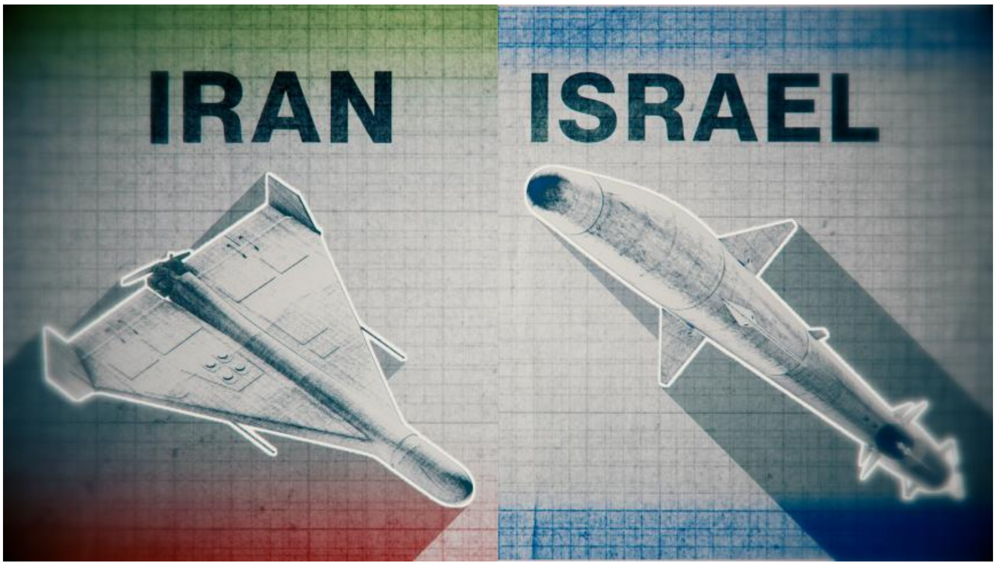


Figure 15: Iran vs Israel (Bloomberg News, 2024)

On April 1st, 2024, Israel conducted an airstrike in the embassy of Iran in Damascus, Syria. The building was destroyed and among the sixteen dead people, they found seven military advisers from the Islamic Revolutionary Guard Corps (IRGC) and a senior commander in Quds Force, Mohammad Reza Zahedi (REUTERS, 2024). From that day, there was an escalating tension in Israel's relations with the neighbor nations, especially with Iran. Since then, things are getting worse every day and as we speak, Israel, Iran, Liban, Yemen and the paramilitary groups of Hezbollah and Houthis are preparing for a full-scale invasion. Their key weapons? Loitering munitions (E. Karatzas, 2024). They manufacture them locally, they buy parts from the Internet and they try to produce as many as possible. Quantity over quality. On April 13th, the whole world witnessed the capabilities of Iran's loitering munitions, as they launched in the middle of the night, more than 160 drones, around 120 ballistic missiles and about 20 cruise missiles against Israel that were destroyed by the famous Iron Dome of Israel (IDF, 2024) and the precious help from the U.S. forces in the region. Among the loitering munitions, the Shahed-131, Shahed-136, Shahed-238 (which is three times faster) and Karar were used, as well as the

Arash-2 UAV. Those systems were launched all at once and they could fly together at formation, through satellite guidance, specific algorithms and the ability to track and analyze through sensors their environment and the position of the others. This is one of the newest capabilities of UAS and is called swarming (Paul Scharre, 2014). In the Figure below, a swarm of Shaheds-136 is presented.

Figure 16: A swarm of Shahed-136 (SWARAJYA, 2024)

The immediate exchange of information through Israel and the USA, led to the destruction of enemy's drones and missiles, but at what cost? Iran's ballistic missiles cost around 100.000 dollars each, while a single loitering munition such as the Shahed-136 does not exceed 50.000 dollars (The Guardian, 2024). In total, this attack costed Iran around 100-200 million dollars. In an interview in Ynet News, Brigadier General Reem Aminoach, who served as a former financial advisor to the IDF chief of staff, noted that Israeli Arrow missiles cost 3.5 million dollars each, Sling missiles 1 million dollars and on top of that, we have to consider also the cost of the jet fighters that took off to destroy enemy's drones and missiles. The total cost was more than 1.2 billion dollars (The Guardian, 2024). This is why loitering munitions are the most popular choice of every country for its arsenal.

They have also become a key feature of the conflict in Yemen, where various factions, including the Saudi – led coalition, the Houthi rebels and other non – state actors, have increasingly used these weapons. The following Figure's graph presents the number of events of Houthi drone attacks in Saudi Arabia, United Arab Emirates, Yemen and International waters, from 2016 to June 2024. In Yemen, this number keeps rising.

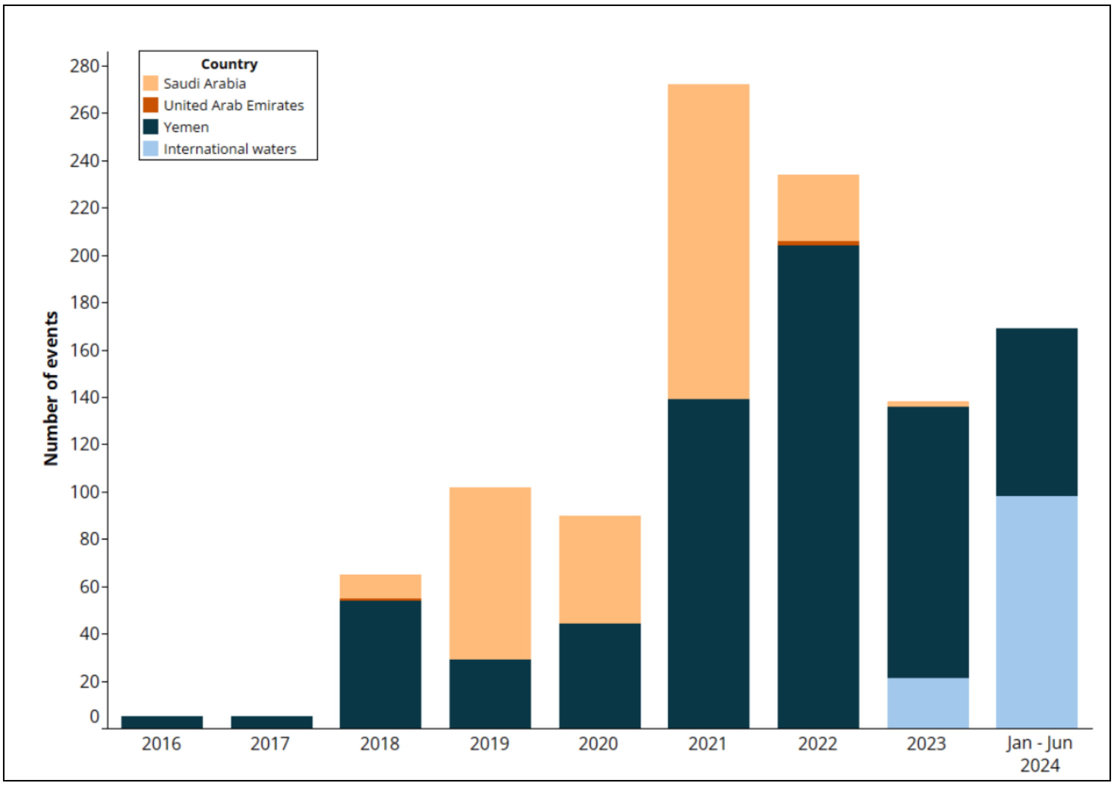


Figure 17: Houthi drone attacks (ACLED, 2024)

Their deployment in Yemen has heightened the lethality and complexity of the conflict. For instance, the Houthis have reportedly used Iranian – supplied loitering munitions, such as the Qasef – 2K, to target Saudi military assets and infrastructure. These weapons are effective in both urban and rural settings, complicating air defense efforts and leading to significant civilian casualties due to the challenge of distinguishing military targets from civilian ones. The Institute for the Study of War, published an article that refers to the events of September 13, 2024 in the West Bank, in Gaza strip, in Lebanon and in Yemen, where loitering munitions were used.

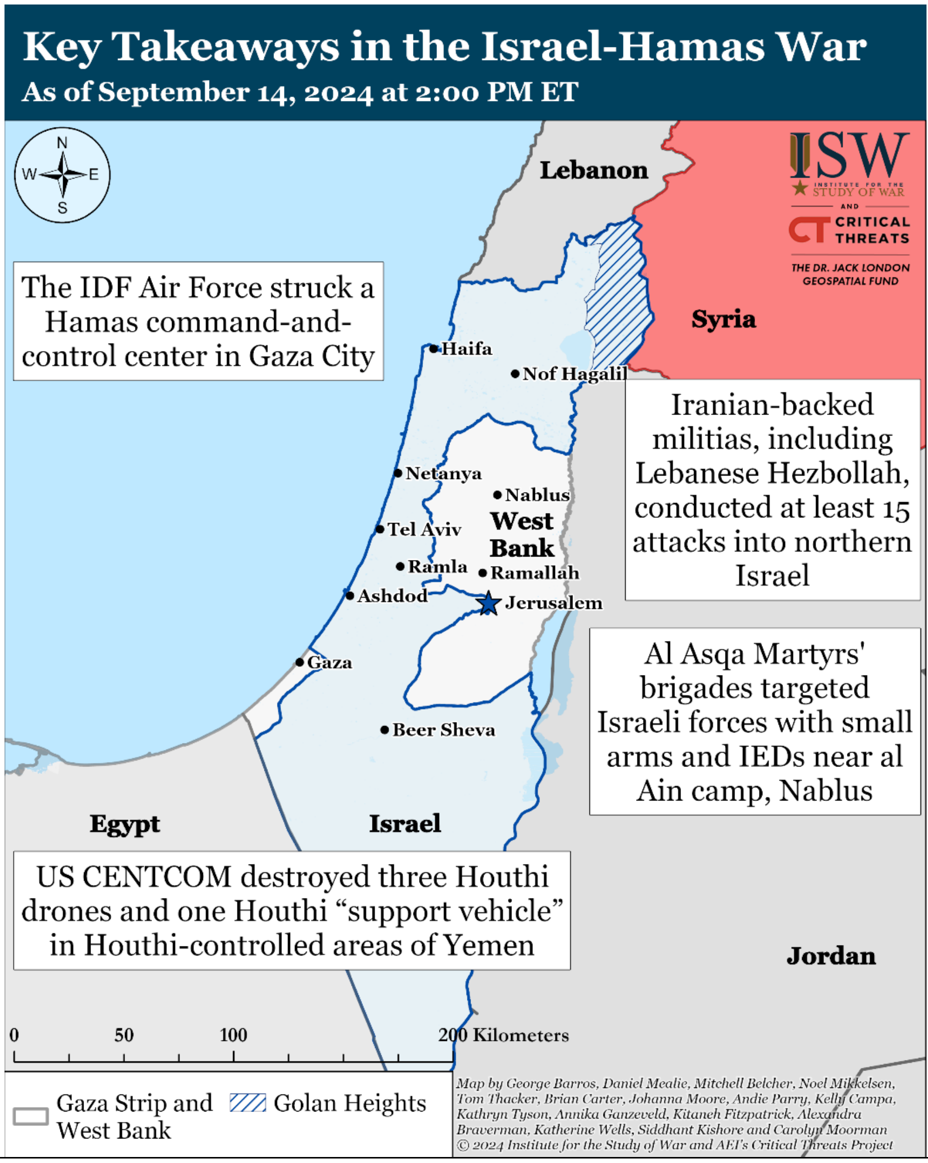


Figure 18: Aftermath of the attacks of September 13, 2024 (ISW, 2024)

The growing use of loitering munitions in Yemen, illustrates the increasing reliance on drone warfare in modern conflicts, where asymmetric actors can level the battlefield against technologically superior adversaries, further escalating the humanitarian crisis in the region.

Chapter 3

§3.0 UAVs classification

§3.1 Military UAVs Classification – NATO standards

The term "UAV" is practically used for bigger vehicles (NATO Class II and III), while the term "drone" refers to smaller vehicles (NATO Class I). This classification according to NATO standards is based on their weight. In fact, in the context of interoperability and effective cooperation across the Alliance, NATO members have come up with a common set of standards and have developed rules that describe specific procedures. In that way, the allies can communicate faster and more accurately, without being obliged to translate from one language to another. These standardization techniques are known as STANAGs and each STANAG is given a unique number. In our case, the classification of UAS corresponds to NATO STANAG 4670, as shown on the following Figure.

Class	Category	Normal Employment	Normal Operating Altitude	Normal Mission Radius	Primary Supported Commander	Example Platform
Class III (>600 kg)	Strike/Combat	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre	Reaper
	HALE	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre	Global Hawk
	MALE	Operational/Theatre	Up to 45,000 ft MSL	Unlimited (BLOS)	JTF	Heron
Class II (150 kg – 600 kg)	Tactical	Tactical Formation	Up to 18,000 ft AGL	200 km (LOS)	Brigade	Hermes 450
Class I (<150 kg)	Small (>15 kg)	Tactical Unit	Up to 5,000 ft AGL	50 km (LOS)	Battalion, Regiment	Scan Eagle
	Mini (<15 kg)	Tactical Subunit (manual or hand launch)	Up to 3,000 ft AGL	Up to 25 km (LOS)	Company, Platoon, Squad	Skylark
	Micro (<66 J*)	Tactical Subunit (manual or hand launch)	Up to 200 ft AGL	Up to 5 km (LOS)	Platoon, Squad	Black Widow

Table 1: NATO STANAG 4670

*Maximum kinetic energy attained

§3.2 Military mission examples of UAVs

Some of the most common military mission types a UAV can take part in, are the following (Congressional Research Service, 2021):

- Intelligence, Surveillance and Reconnaissance/ Intelligence, Surveillance, Target Acquisition, Reconnaissance (ISR/ISTAR):
    - Intelligence (I): The collection and analysis of information to understand enemy capabilities, intentions and locations.
    - Surveillance (S): The continuous monitoring of an area or target over time to gather real-time data (e.g. border patrolling and maritime surveillance).
    - Target Acquisition (TA): The identification and precise location of targets for potential engagement.
    - Reconnaissance (R): The collection of data on enemy forces, terrain and other factors in a specific area to inform military decisions.
- Communications Relay (Congressional Research Service, 2021):
    - UAVs can transmit data in real-time to ground stations or command centers, allowing for rapid analysis and decision-making. The USAF has modified the RQ-4 Global Hawk, by adding the Battlefield Airborne Communications Node (BACN) and a variety of ELINT, SIGINT sensors, to provide both voice communications and tactical datalinks (Congressional Research Service, 2021).

Figure 19: USAF EQ-4 Global Hawk (Breaking Defense, 2021)

- Search and Rescue/ Casualty Evacuation (SAR/CasEvac) (Paul Scharre, 2014):
  - UAVs can assist in locating survivors in high-risk areas and also collecting them (AirMed and Rescue, 2015).
- Air-to-Air missions and bombing raids:
  - Many UAVs are equipped with advanced targeting systems and weaponry, allowing them to engage and destroy enemy targets with high precision. The USAF is planning to convert strategic bombers, such as the B-21 to uncrewed aircraft (Congressional Research Service, 2021, pp. 1-3). In that way, the pilot can remotely fly it and complete the mission without any risk.
  - UAVs can even be equipped with algorithms and AI that allow them to dogfight against manned aircraft. Recently, DARPA used human pilots to train a model of AI and modified F-16's, by converting them to unmanned aircraft. When the pilot tried to dogfight them, he would always lose. This is also known as the Ace Program (DARPA, 2024). Boeing also demonstrated a program called Loyal Wingman, where a UAV is used to team up with crewed aircraft and provide support (BOEING, 2021).

Figure 20: The Loyal Wingman project (BOEING, 2019)

Figure 21: DARPA's ACE program (DARPA, 2024)

- Electronic Warfare (Congressional Research Service, 2022):
  - ➢ Certain UAVs also serve as EW platforms (Congressional Research Service, 2019) and carry specific equipment, suitable for frequency jamming. For example, the USAF has developed a decoy, called MALD (Miniature Air Launched Decoy) and MALD-J, which is a jammer, in order to protect their aircraft from enemy's jamming. Those decoys emit frequences and are similar to manned aircraft in enemy's radars.

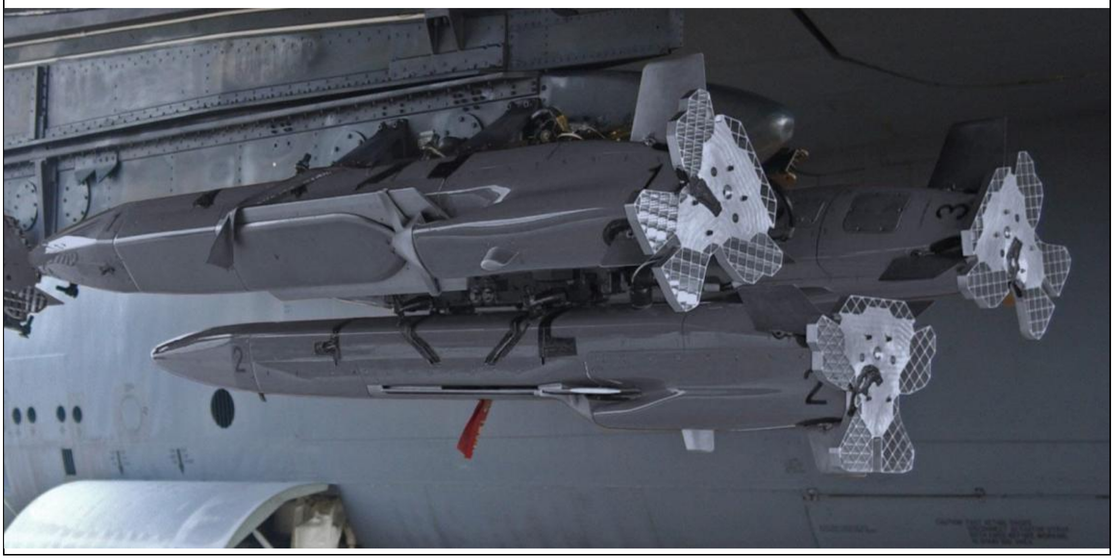


Figure 22: Miniature Air Launched Decoy (Congressional Research Service, 2022, p. 11)

- Suppression of Enemy Air Defense (SEAD):

- These are critical military operations that destroy enemy air defense systems, to ensure the safety of friendly aircraft. Their extremely high risk, led to the development and use of UAVs that can fly over enemy territory and perform the tasks that a manned aircraft would perform. The result though will be even better, because air defense systems use data of manned aircraft, so they cannot recognize easily the different flight mode of the UAVs, since they can perform extremely high maneuvers and rapid changes in their course (Congressional Research Service, 2022, p. 13).

- Air-to-Air Refuel:
  - US Navy uses the carrier-based MQ-25 Stingray, a UAS suitable for carrier landings that serves as a tanker for Aerial Refueling (Congressional Research Service, 2022, pp. 5-6).

Figure 23: F-18 Hornet aerial refueling from MQ-15 Stingray (Mentour Pilot, 2021)

- Anti-Submarine Warfare (ASW):
  - Certain UAVs equipped with dipping sonars, are used to track enemy submarines, but they are not ready yet to replace ASW helicopters or maritime patrol aircraft.

Figure 24: Schiebel S-100 drone (Navy Lookout, 2023)

- Logistics and Supply Delivery:
    - ➢ UAVs can take part in cargo and supplies delivery missions. The U.S. Department of Defense, used for example K-MAX, a UAS helicopter that would carry many pounds of cargo and deliver it to U.S. troops in Afghanistan (Military.com, 2019). Apart from ammunition, humanitarian aid can also be supported with the use of these platforms, during peace-keeping missions, in collaboration with organizations such as the U.N.


Figure 25: U.S.M.C. K-MAX Helicopter (Seapower, 2016)

- Mine Detection and Clearence:

- Minefields pose a significant threat to soldiers and are present in almost every battlefield around the world. Mines are very difficult to be tracked, because they cannot be easily seen without some sort of sensor, but scientists search new ways of detecting them. A promising solution is the use of drones with appropriate sensors, because they are expendable and can replace humans in risky operations. Such types of drones are used for example in Ukraine (SciAm, 2023).

Figure 26: Explosive Ordnance Disposal (EOD) team (Sensors, 2021)

Figure 27: Modern era battlefield (overtdefense, 2020)

§3.3 Civil UAVs classification – EASA

Civil UAVs are organized in a similar way by EASA. There are three main categories:

1. **Open:** The "Open Category" for drones refers to the regulatory framework established by aviation authorities, such as EASA and other international bodies, to simplify the use of drones for a variety of non-commercial and commercial purposes. Here are the key aspects of this category:
   - Risk-based classification
     - Low risk: The operations are considered low risk to people, property and other airspace users.
     - No prior authorization: Generally, no prior authorization or operational approval is required if the operator adheres to the rules.
   - Subcategories: The Open Category is divided into three subcategories based on the risk level and operational limitations:
     - A1 (Fly over people)
       - Drones weighing less than 250 g.
       - Fly over people but not over large gatherings.
       - Maintain a safe distance from uninvolved people.
     - A2 (Fly close to people)
       - Drones weighing less than 2 kg.
       - Keep a safe horizontal distance of at least 30 meters from uninvolved people.
       - Additional requirements might apply, such as competency tests.
     - A3 (Fly far from people)
       - Drones weighing less than 25 kg.
       - Operate in areas where there are no uninvolved people within a 150-meter horizontal distance.
   - Operational conditions:
     - Visual line of sight (VLOS): The drone must be operated within the visual line of sight of the pilot.
     - Maximum altitude: Typically limited to 120 meters (400 ft) AGL.
     - Geographical zones: Compliance with geographical zones and restrictions established by the relevant aviation authority.
   - Drone classification and CE marking:
     - Drones must meet specific technical requirements and be classified (e.g. C0, C1, C2, C3, C4) based on their weight and capabilities.

    - The CE marking indicates conformity with safety, health and environmental protection standards for products sold within the European Economic Area (EEA).
- Competency and Training:
    - Basic competency requirements for drone operators.
    - Online training and testing for certain subcategories (e.g. A1 and A3).
    - More detailed theoretical knowledge examination for higher risk operations (e.g. A2).
- Insurance and Privacy:
    - Operators are encouraged to have liability insurance.
    - Respect for privacy laws and regulations when capturing images or video.

Examples of Open Category operations:

- Recreational flying in parks or open fields.
- Aerial photography.
- Surveying land without entering restricted areas.
- Educational or research activities.

2. **Specific:** In the context of drone regulations, specific categories of drones are defined to ensure appropriate safety measures based on their operational risk and capabilities. These categories are outlined to address both recreational and professional drone use, adhering to national and international aviation standards.

Examples of Specific Category operations:

- Beyond Visual Line of Sight (BVLOS).
- Flying in populated areas or near sensitive infrastructure.
- Transporting goods, including dangerous goods.

3. **Certified:** The "Certified Category" for drones is designed for high-risk operations that demand a level of safety. It includes drones and operations that pose significant risks to people, property, or other aircraft and therefore require rigorous certification processes for both the drones and their operators. Some of the key features of this category are the following:

- High-risk operations:
    - Operations that cannot be conducted safely under the Open or Specific categories.

- Includes activities such as transporting people, carrying dangerous goods or operating in highly populated areas.

- Certification requirements:
  - Drone certification: Drones must be certified for airworthiness by the relevant aviation authority, similar to manned aircraft.
  - Operator certification: Operators must obtain specific certifications demonstrating their ability to conduct high-risk operations safely.
  - Operational approval: Each mission requires approval from aviation authorities, ensuring that safety measures are tailored to the unique aspects of the operation.

Examples of Certified category operations:

- Passenger transport.
- Large cargo delivery.
- Critical infrastructure inspection.
- Emergency response and medical deliveries.

The classification of civil drones can be organized in the following Table:

<table>
<tr><th>CLASS</th><th>MTOM</th><th>Subcategory</th><th>Operational restrictions</th><th>Drone operator registration?</th><th>Remote pilot qualifications</th><th>Remote pilot minimum age</th></tr>
<tr><td>C0</td><td><250 g</td><td rowspan="2">A1/A3 (Not over assemblies of people)</td><td rowspan="5">Operational restrictions on the drone’s use apply</td><td>Yes (Not if toy or fitted with camera/sensor)</td><td>Read user’s manual</td><td>No minimum age (certain conditions apply)</td></tr>
<tr><td>C1</td><td><900 g</td><td rowspan="4">Yes</td><td rowspan="4">Check out the QR code in EASA’s website for the necessary qualifications to fly these drones[2]</td><td rowspan="4">16</td></tr>
<tr><td>C2</td><td><4 kg</td><td>A2/A3 (Fly close to people)</td></tr>
<tr><td>C3</td><td rowspan="2"><25 kg</td><td rowspan="2">A3 (Fly far from people)</td></tr>
<tr><td>C4</td></tr>
</table>

Table 2: Classification of civil drones (EASA, 2024)

[2]https://www.easa.europa.eu/en/domains/drones-air-mobility/operating-drone

§3.4 Levels of autonomy

Concerning the UAV's autonomy, there are five levels, starting from zero autonomy and reaching up to full automation. Level zero requires the presence of a human pilot from drone's takeoff to its landing. In this case, the drone flies manually. As we reach the final level, the drone is capable of performing all the necessary maneuvers by itself and becomes fully operational without human intervention. To achieve that, special algorithms that control its flight plan and flight controls are necessary and are combined with AI, that replaces the pilot. The following Figure shows all the levels of autonomy. We can notice that as we reach the final level, AI takes more and more control of the drone.

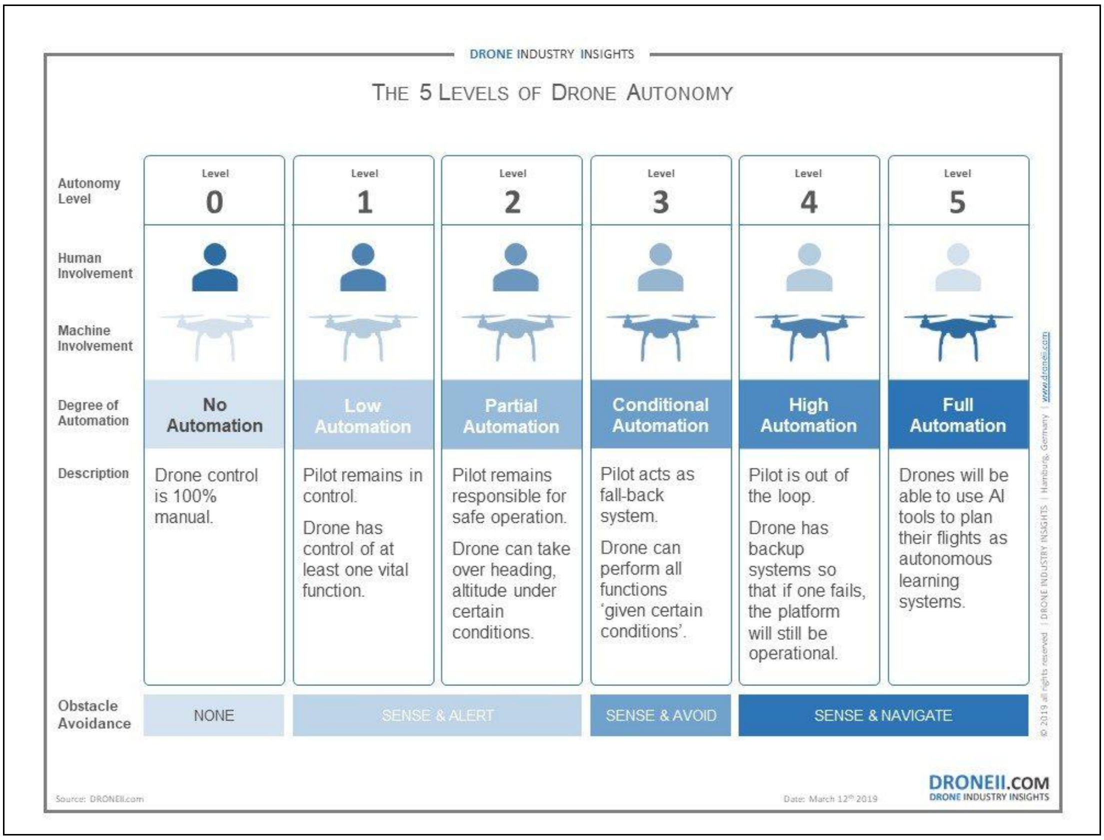


Figure 28: The five levels of drone autonomy (Jeffrey L. Harrigian, 2021, p. 15)

§3.5 Systems Engineering

Systems Engineering is defined as a methodical, multi-disciplinary approach for the design, realization, technical management, operations and retirement of a system. A System, is the combination of elements that function together to produce the capability required to meet a need (NASA, 2019). Some of the key concepts in Systems Engineering are the following:

Systems thinking: This is the core of systems engineering. It involves understanding the system as a whole, how its parts interact and how it fits within a larger context. It also helps engineers address complexities and interdependencies.

Lifecycle approach: Systems engineering considers the entire lifecycle of a system, from conceptual design through development, production, operation, maintenance and disposal. This approach helps to identify issues early and plan for the future, including upgrades. The following Figure, shows the lifecycle of the system, along with the three phases of design, the Conceptual design, the Preliminary and the Detail design. More analysis on these phases will be conducted later in this chapter.

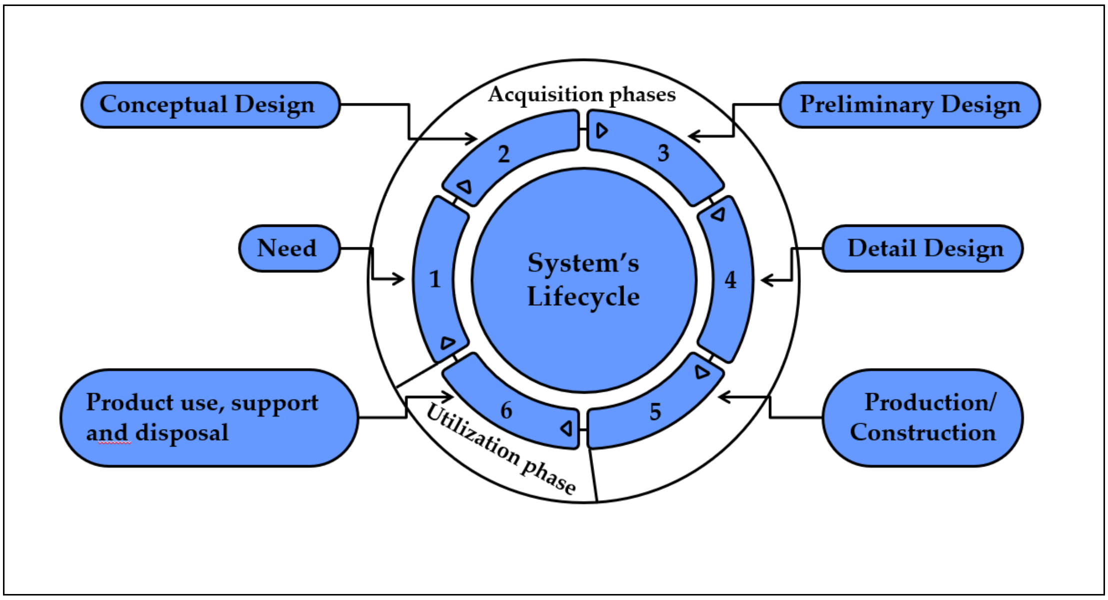


Figure 29: System's lifecycle (Mohammad H. Sandraey, 2013, p. 22)

System architecture and design: Architecture defines the structure and behavior of the system, while design specifies the components and how they interact. This stage involves creating models, simulations and prototypes. The Figure below, shows a model that presents the relationship between the activities of the design phases.

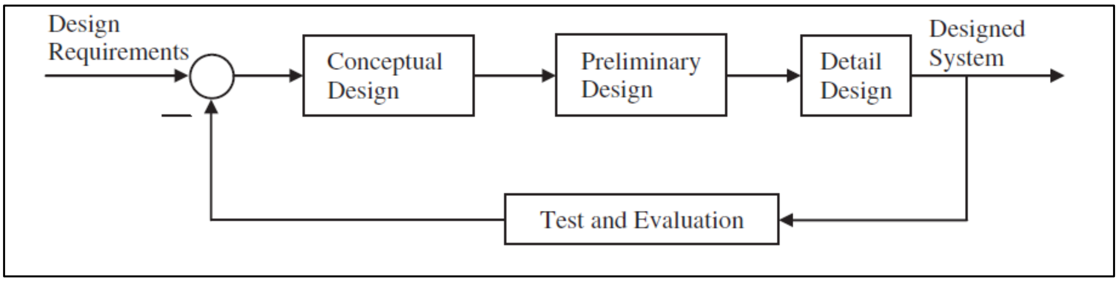


Figure 30: Relationship among the design activities (Mohammad H. Sandraey, 2013, p. 22)

Interdisciplinary collaboration: Systems engineers work across various domains, integrating knowledge from different fields such as mechanical, electrical, software and human factors engineer. This collaboration ensures that the system functions as intended in all environments.

Risk management: Systems engineering involves identifying, analyzing and mitigating risks throughout the project lifecycle. Risks could be technical, financial or schedule-related and addressing them early can prevent project failures.

Configuration management: This involves managing changes to the system throughout its life. It ensures that changes are controlled, maintaining the integrity of the system over time. There are numerous applications of Systems Engineering in different domains, including:

Aerospace and Defense: Designing complex systems like aircraft, spacecraft, UAVs and defense systems.

Automotive: Developing integrated vehicle systems, including autonomous driving technologies and autopilot.

Information Technology: Managing large – scale IT infrastructure, software development and cybersecurity.

By integrating various disciplines and focusing on the entire lifecycle, systems engineering ensures that complex systems operate efficiently and effectively. A loitering munition, is indeed a system, composed by its elements and the proper function and combination of these smaller parts is vital for the normal function of the UAV.

§3.6 What is design?

According to Daniel P. Raymer, whose methodology is going to be used at this thesis, "Aircraft Design is a separate discipline of aeronautical engineering – different from the analytical disciplines such as aerodynamics, structures, controls and propulsion (D. P. Raymer, 2018, p. 1). Design is the creation of a geometric description of a thing to be built." Many will think that aircraft design is just a simple drawing, but it's not that simple. It's a very demanding task and requires deep knowledge of plenty of fields of science, such as aerodynamics, structures and materials, physics, mathematics and many more. Design begins with an idea, a concept and step by step, it evolves in a detailed draft, ready to be manufactured. Throughout this process, the initial concept is reconsidered again and again and keeps improving. The procedure of this constant evaluation is presented in the Figure below.

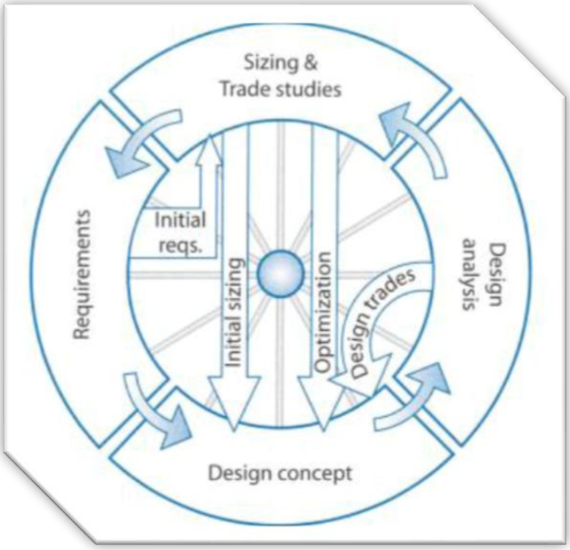


Figure 31: The Design Wheel (D. P. Raymer, 2018, p. 3)

The Design Wheel is an illustration of how initial requirements and design concept keep constantly changing through the design process. After the initial concept, sizing takes place, where numerous calculations define the next step. This step can either be a step forward, or a step back, because new adjustments may be required. As the process keeps going, the wheel turns and new calculations are made, that may lead to further examination of the initial concept. The fact that the set of requirements constantly changes as the aircraft or in our case the loitering munition is designed, makes the whole design process, an iterative process. The wheel won't stop spinning, until the most suitable set of requirements for our mission is found.

§3.7 Phases of Aircraft Design

As mentioned earlier, there are three major phases of Aircraft Design. Each phase, comes with its own level of detail and they are all equally important, if the designer wants a smooth transition from the customer's requirements to the fabrication of the UAV. Figure 32, shows these three phases.

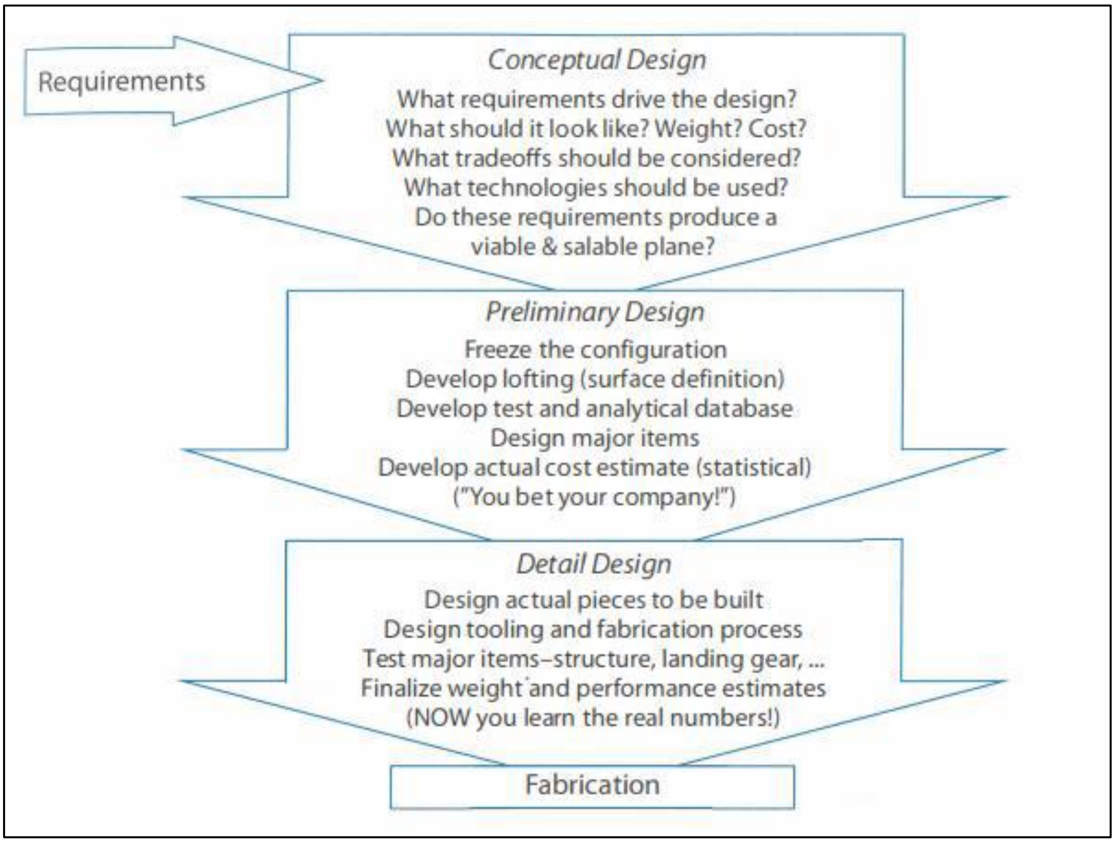


Figure 32: Phases of Aircraft Design (D. P. Raymer, 2018, p. 13)

1. **Conceptual Design**

The first phase of Aircraft Design, is relevant to the categorization of the initial set of requirements. During this phase, which contains plenty of tradeoffs and optimizations, through system planning (e.g. Gantt chart), feasibility analysis, sizing and performance analysis, a result is generated. This result serves as the beginning of the second phase of Aircraft Design, the Preliminary Design. The process of the Conceptual Design is presented in the following Figure.

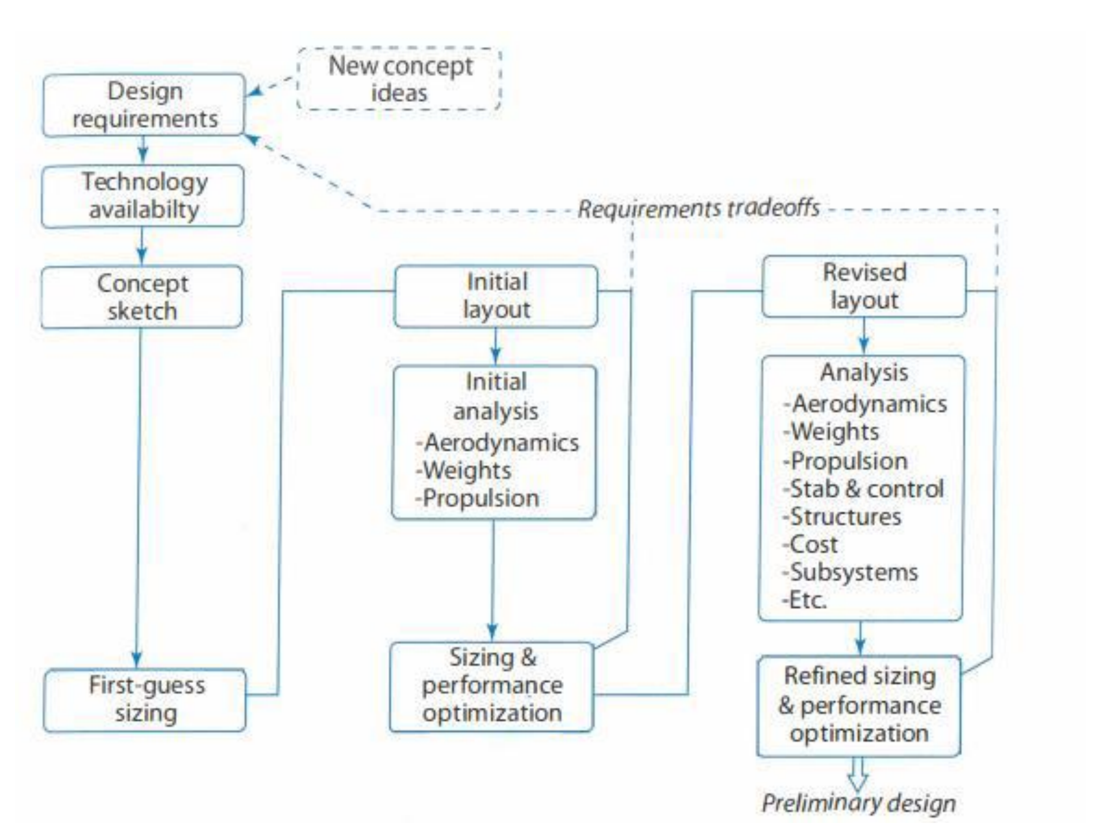


Figure 33: Conceptual design process (D. P. Raymer, 2018, p. 19)

2. **Preliminary Design**

Once the major changes are over, the second phase of Aircraft Design takes place. The Preliminary design phase is an early stage of Aircraft Design, where the basic configuration and characteristics of the aircraft are defined. It involves translating mission requirements, such as payload, range and speed, into a feasible design concept that balances performance, cost, safety and regulatory compliance. This phase includes initial sizing of major components, aerodynamic and structural analysis, propulsion selection, weight estimation, stability and control analysis and performance evaluation. The goal is to develop a comprehensive design concept that meets all requirements and serves as the foundation for the detailed design phase, ensuring the project is technically viable, cost – effective and safe. It is in this phase that numerous calculations are made, in order to determine the three following fundamental parameters:

- Aircraft maximum take-off weight (MTOW or W_{TO})
- Wing reference area (S_{ref})
- Engine thrust (T) for jet-engined aircraft or Engine power (P) for propeller aircraft

The procedure that is followed, is presented in Figure 34.

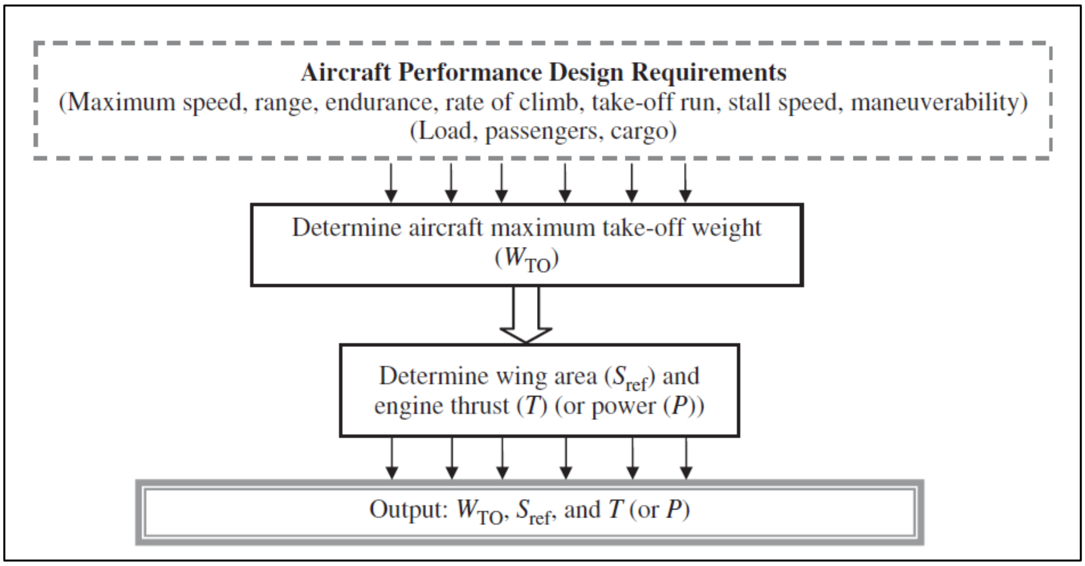


Figure 34: Preliminary design phase (Mohammad H. Sandraey, 2013, p. 94)

3. **Detail Design**

The Detail Design phase is the last phase of Aircraft Design, where the Preliminary Design is transformed into a complete, manufacturable product. This phase involves refining every aspect of the aircraft's design, including the precise dimensions, structural details, materials and integration of all systems. Detailed engineering drawings, CAD models and specifications are created for components like the wings, fuselage, landing gear and control surfaces. Extensive structural, aerodynamic and system analyses are conducted using advanced computational methods like FEA and CFD to validate the design against safety, performance and regulatory requirements. Critical systems, such as propulsion, avionics, electrical and hydraulic systems, are integrated and thoroughly tested virtually and physically to ensure seamless operation. Designs are optimized for weight, strength, manufacturability and cost – efficiency, with an emphasis on meeting stringent certification standards. The Detail Design phase also involves developing manufacturing plans, tooling designs and assembly processes to ensure the aircraft can be produced efficiently. The phase culminates in a Critical Design Review (CDR), where the design is assessed for readiness for production, confirming that it meets all technical safety and performance objectives.

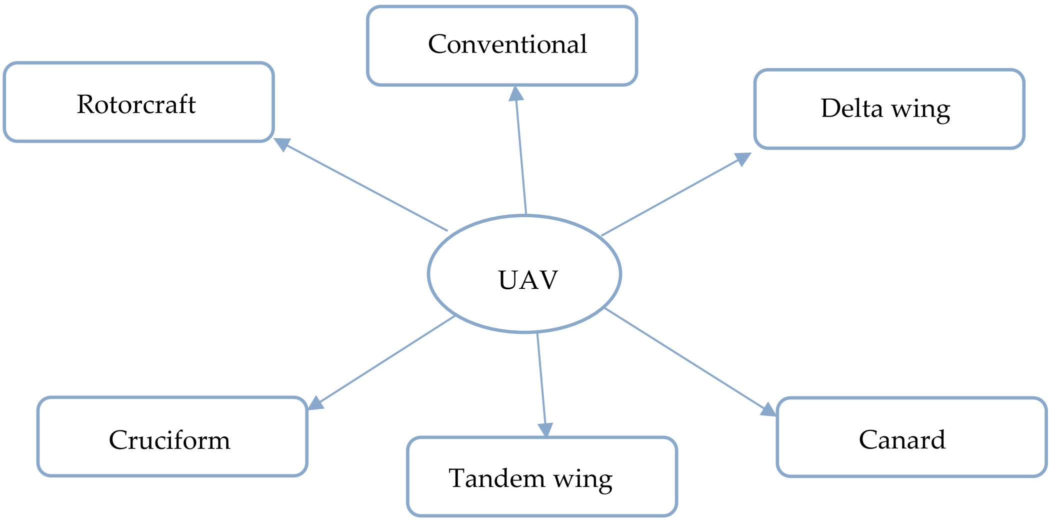
This thesis focuses on the Conceptual Design of a lightweight loitering munition. Preliminary and Detail Design are out of the scope of this paper.

Chapter 4

§4.0 Configuration of UAVs

Different types of UAVs are used for different missions and each has its own shape, its proper form that enables it to achieve its goal. For example, there are those that need to carry more weight (payload) and those that need to be faster and more maneuverable. So, the choice of UAV configuration depends on the particular requirements of the mission and the environment in which it will operate. In total, there are six configurations and each has its advantages and disadvantages. The main categories are the following:

- Conventional
- Delta wing
- Canard
- Tandem wing
- Cruciform
- Rotorcraft



§4.1 Conventional

Figure 35: Conventional configuration (CadNav, n.d.)

The conventional configuration resembles to a typical manned aircraft, with two types of fixed-wings, a bigger in the front and a smaller in the back, that stabilizes the course of the UAV. It also bears a vertical wing in the tail, whose configuration can also be varied. Some typical examples of tails are the following:

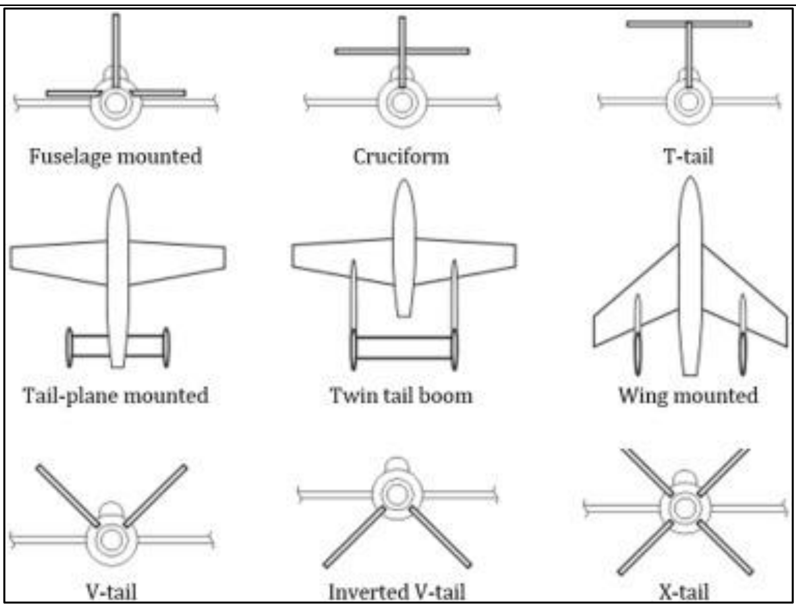


Figure 36: Tail configurations of UAVs (M. Hassanalian, 2020)

However, its drawback relates to the takeoff and landing requirements, as it requires a runway or a catapult system for launch and recovery, unless it has specific dimensions that permit its launch from a canister, or even from a grenade launcher. In that case though, the UAV must be foldable, so it's a more complex design. It is also less maneuverable at lower speeds, compared to a rotary-wing drone.

Advantages:

1. Loitering endurance:
   - This configuration comes with a large wingspan and a high aspect ratio wing. It offers longer flight time and stability, due to its efficient aerodynamics and it can operate in higher speed and longer range.
2. Great aerodynamic efficiency and maneuverability:
   - It is the most tested configuration, since it is based on conventional manned aircraft, that are used for many decades. It can also carry larger warhead.
3. Folding capability:
   - It can be stored and launched from a canister, or even a grenade launcher, if it is designed to meet the specific dimensions for each tube.

Disadvantages:

1. Low wing loading (W/S):
   - Wing loading is referred to as the ratio between the weight and the reference wing area. Since this configuration has a high aspect ratio, therefore a larger wing surface area, the wing loading will be lower, compared for example to a tandem wing.
2. Prone to gust:
   - In the case of a wind gust, the angle of attack changes suddenly as well as the speed and causes unstable flight for as long as the gust effect lasts.
3. Complex folding mechanism:
   - Although this configuration provides one of the best solutions for tube launch, the necessary folding mechanisms are slightly more complex to manufacture, since the UAV is not symmetrical.
4. Susceptible to wind gusts:
   - Conventional configuration fixed – wing drones are susceptible to wind gusts and behave differently compared to the delta – wing design, which is more stable. Wind gusts and turbulence can pose challenges during certain flight phases, like takeoff, landing or slow – speed maneuvers.

The following Table presents its advantages and disadvantages:

Pros	Cons
Loitering endurance	Low wing loading (W/S)
Aerodynamic efficiency	Prone to gust
Folding capability	Complex folding mechanism
High maneuverability	Wind gusts vulnerability

Table 3: Pros and Cons of Conventional Configuration

§4.2 Delta wing

Figure 37: Delta wing configuration (Renderhub, n.d.)

Delta wing UAVs feature a triangular wing design, which is characterized by a wide root and a narrow tip. This design is known for its aerodynamic efficiency and stability at high speeds, although, it generates less lift comparing to conventional configuration UAV, so it is not that suitable for endurance missions. Figure 38 presents the different versions of a delta-wing design.

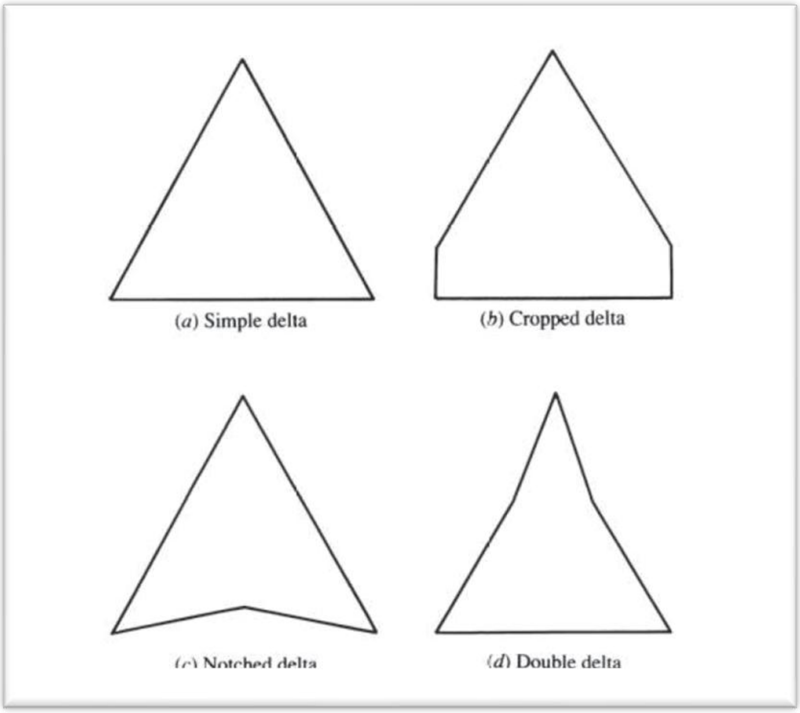


Figure 38: Different types of delta wings (Laurence K. Loftin, Jr., 1985, p. 254)

Advantages:

1. High structural efficiency:
    - The delta-wing is a more compact structure than the conventional or the canard configuration, since it has larger wing surface area.
2. Good aerodynamic efficiency:
    - Its shape enhances the maneuverability of the UAV and can perform better at higher speeds (the large surface area enhances lift).
    - The vortex separation of the leading-edge of the wing, is the reason for the enhanced lift generation (NASA, 1966, pp. 3-4). The following Figure shows the vortex flow of a sharp-leading-edge delta wing.

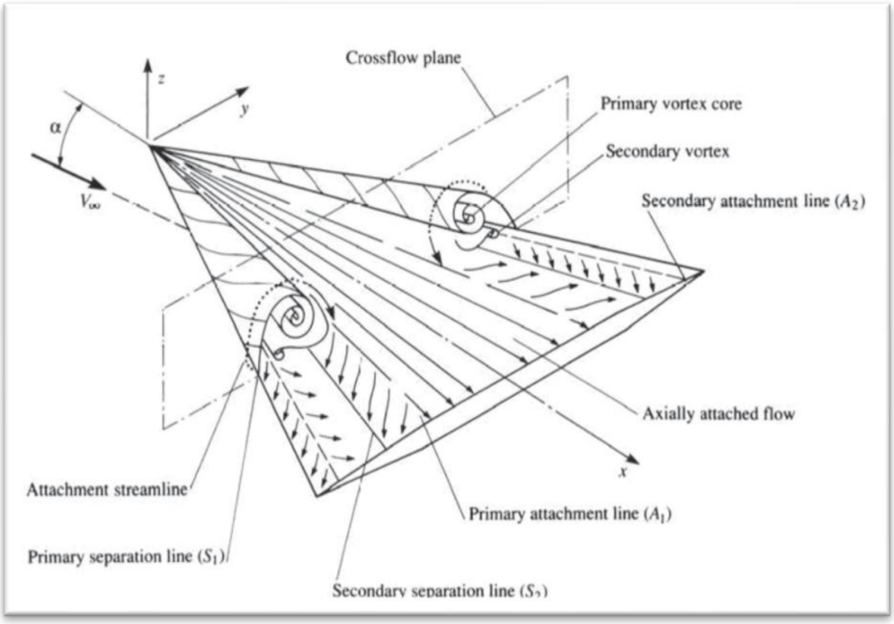


Figure 39: Vortex flow (John Stollery, n.d.)

- It is more efficient at high angles of attack and also gives the pilot more time to react in case of stall. The pressure distribution throughout the platform is depicted in Figure 40. Due to the high energy vortices, the pressure, hence the lift at the tip of the wings is higher, while in the middle surface, the pressure is smaller.

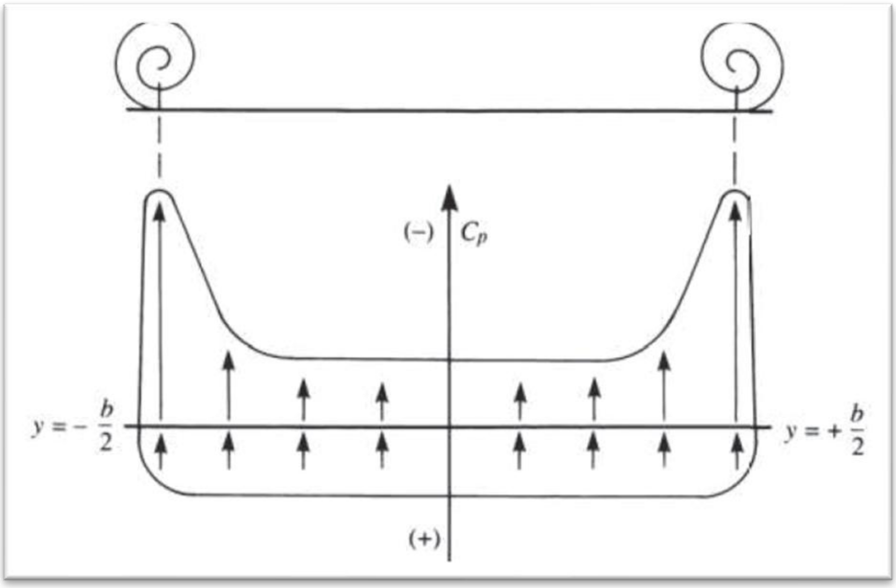


Figure 40: Pressure distribution on a delta-wing design (John Stollery, n.d.)

3. Simple construction:

- Delta wings are easier to be constructed and, in some cases, there is no vertical tail, like in the Shahed-136 for example, or the flying wing, so more UAVs of this type can be produced much quicker.

Disadvantages:

1. Poor low-speed performance:
   - This can affect the takeoff and landing procedures (loitering munitions are not affected, since they are designed to takeoff and strike a target).
2. Lack of vertical tail:
   - If the UAV is designed without a vertical tail, then its maneuverability is reduced and many stability and control problems are generated.

The following Table presents the pros and cons of this type of configuration:

Pros	Cons
High structural efficiency	Poor low-speed performance
Good aerodynamic efficiency	Lack of vertical tail
Stability at high angles of attack	Complex control systems
Simple construction	Higher drag at low speeds

Table 4: Pros and Cons of Delta configuration

§4.3 Canard

Figure 41: Canard configuration (Wikipedia, 2020)

The canard configuration is similar to the Delta wing, but features a small forward wing, the so called "canard", placed ahead the main wing. Some of the advantages and disadvantages of the canard configuration are the following:

Advantages:

1. Enhanced lift and control:
    - The canard surface provides additional lift, contributing to overall aircraft lift and reducing the load on the main wing. This enhances overall aerodynamic efficiency, but yet, it remains inferior to the conventional design.
2. Improved maneuverability:
    - The forward placement of the canard can improve pitch control and maneuverability, allowing for more agile movements and better performance in tight turns.
3. Natural stall resistance:
    - Canard configurations often result in the canard surface stalling before the main wing. Which naturally pitches the nose down and prevents a full stall of the aircraft. This can improve safety and stability, especially during low-speed flight.
4. Balanced lift distribution:
    - The lift produced by both the canard and the main wing can be more evenly distributed, potentially leading to better weight distribution and center of gravity management.
5. Efficient aerodynamic design:
    - Canard configurations can lead to reduced drag and improved fuel efficiency.

Disadvantages:

1. Complex aerodynamics:
    - Designing and optimizing the aerodynamics of a canard configuration can be a more complex task than this of a conventional configuration UAV, as it requires careful tuning of the interaction between the canard and the main wing.
2. Structural considerations:
    - The additional forward surface can add weight and structural complexity, potentially leading to increased manufacturing and maintenance costs.
3. Trim and stability issues:
    - Maintaining proper trim and stability can be challenging, especially under varying load conditions. The aircraft may require sophisticated control systems to manage pitch and stability effectively.

4. Higher drag at certain conditions:
   - While canard configurations can reduce drag in some regimes, they may also increase drag under certain conditions, particularly at high AoA or during maneuvers.
   - The downwash effect that is generated from the canard to the main wing, increases the induced drag.
5. Folding difficulty:
   - This design layout makes it difficult to use a folding mechanism, in order to launch the UAV from a canister, so a rail is usually needed.

Pros	Cons
Enhanced lift and control	Complex aerodynamics
Improved maneuverability	Structural considerations
Natural stall resistance	Trim and stability issues
Balanced lift distribution	Higher drag at certain conditions
Efficient aerodynamic design	Folding difficulty

Table 5: Pros and Cons of Canard configuration

§4.4 Tandem wing

Figure 42: Tandem wing configuration (A News ECONOMY, 2023)

Tandem wing configuration combines two or more sets of main wings arranged one behind another and can offer unique benefits when it comes to loitering munitions. Some of its pros and cons are the following:

Advantages:

1. Increased lift:

- The tandem design can generate more lift than a conventional configuration, as both wings contribute significantly to the overall lift. In case of using a runway for takeoff, it requires less space.

2. Improved stability:
   - Having two wings can enhance the longitudinal stability of the UAV, making it less prone to pitch instability. This can simplify control systems requirements.
3. Enhanced folding capabilities:
   - This configuration enables the UAV to be folded through a proper folding mechanism and be fitted into a tube of specific dimensions, ready for launch.
4. High aspect ratio:
   - The wingspan can be twice the length of the fuselage, since a tandem wing has two main wings that generate lift and in terms of loitering munitions and canister launch, this provides a relatively high aspect ratio.

Disadvantages:

1. Complex aerodynamics:
   - It might be harder to control, because the front wings can generate more drag and this will affect the rear wings, hence, the stability of the UAV. However, with proper sizing, if the front wings are placed higher comparing to the rear, then this disadvantage can turn into an advantage. There are two basic configurations for tandem wings, the FLR (front wings lower than the rear) and the FUR (front wings upper than the rear). In the FLR configuration, which is the most beneficial, the downwash of the front wing affects the rear, by decreasing the angle of attack, delaying at the same time the flow separation on the leading edge of the front wing. In the FUR configuration, the lift force of the rear wing and its angle of attack are increased due to the wake flow of the front wing, so the stability of flight gets slightly affected (Energies, 2022). Those configurations refer to manned and unmanned aircraft with relatively larger gaps between the front and rear wings.As we see in the following two Figures, the smaller the gap between the two sets of wings (front and rear), the more intense the slotted wing effect (NASA, 2020). In this phenomenon, the air that comes from the front wing is already energized and can contribute to a better lift distribution in the rear wings. There is also a significant delay in the flow separation of the front wings, since the air current that goes beneath the front wing, to rear wing, can deteriorate the turbulence

of the trailing edge. This can be beneficial in terms of stalling, during high angles of attack, if the front wings can no longer generate lift.

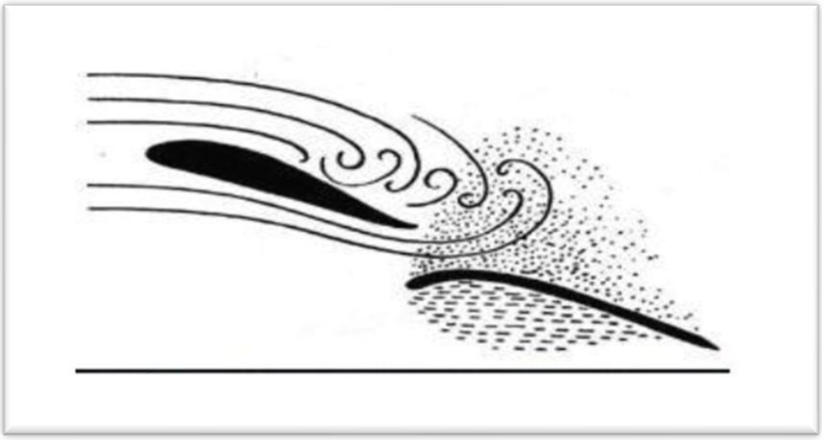


Figure 43: Stalling moment in a tandem wing configuration (MIGNET Henri, 1934)

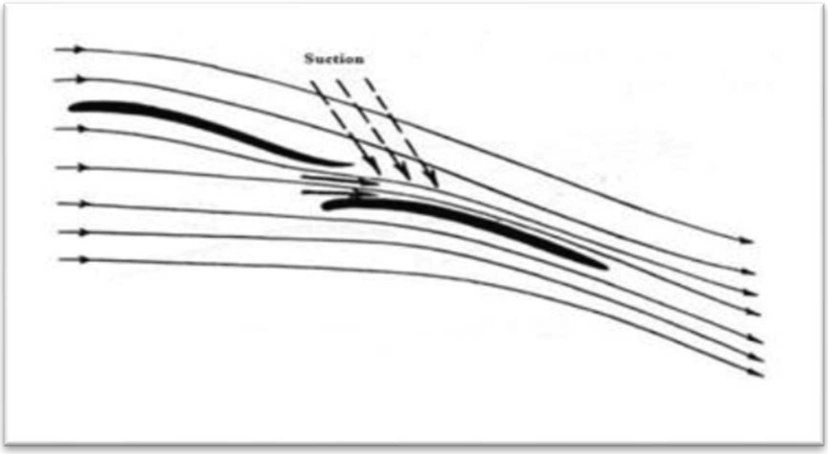


Figure 44: Slotted wing effect (Energies, 2022)

2. Flight envelope limitations:
   - Tandem wing UAVs may have a narrower flight envelope, meaning they might not perform as well across a wide range of speeds, altitudes or other environmental conditions, compared to other designs (Transport and Aerospace Engineering, 2017). This is because they combine many features such as speed, stability, foldability or canister launch, of numerous configurations of UAVs.

Pros	Cons
Increased lift and stability	Complex aerodynamics
Enhanced folding capabilities	Downwash effect
Relatively high aspect ratio	Flight envelope limitations

Table 6: Pros and Cons of Tandem configuration

§4.5 Cruciform

Figure 45: Cruciform configuration (The droning company, 2024)

In this configuration, the airframe resembles to a cross or "cruciform" shape when viewed from above. There are four distinct wings, extending from a central fuselage, typically in a symmetrical pattern. In general, this configuration is mostly used on missiles and some of the main reasons, are the following:

Advantages:

1. Advanced maneuverability:
   - "Maneuverability can be defined as the space required to alter the flight trajectory, while flying at a fixed speed and can be estimated as the minimum angle of turn (RAYNER, J.M.V., 1988)". This configuration is suitable for combining high speed with sharp maneuvers. The reason for that, is the ability of the UAV to act as a missile and change immediately its angle of attack. In fact, according to Dagan Lev Ari, the Sales and Marketing Director of the UVision company, a company that manufactures cruciform wing Loitering Munitions, "three buttons appear on the Operator Control Unit, for steep, medium and shallow angles, with the choice of selecting point detonation, fragmentation or delayed action" (EDR ON-LINE, 2021). Hence, flexibility is greatly enhanced.

Disadvantages:

1. Limited wingspan:

- It is difficult to store and launch from small tubes, so bigger launchers are used, to provide enough space for the wings to fit in. Nevertheless, the wingspan is limited, even in these smaller tubes. For example, in the case of HERO 30, the wingspan is almost equal to the length of the fuselage, as we can see in the Figure 46.

2. Non – optimal airflow:
   - Unlike streamlined or swept – back designs that minimize drag by cutting through the air, the cruciform configuration structure can cause turbulence and increased resistance, especially at high speeds. This can decrease flight time or performance in windy conditions.

Figure 46: Cruciform UAV launch (ARES Osservatorio Difesa, 2021)

Pros	Cons
Advanced maneuverability	Length less or equal to the wingspan
Higher wing loadings	Limited wingspan
Increased airspeed	Non-optimal airflow

Table 7: Pros and Cons of Cruciform configuration

§4.6 Rotorcraft

Figure 47: Quadcopter configuration (Armadni Noviny, 2020)

A rotorcraft, is a UAV whose flight principles are based on the principles of helicopters. It uses rotors that provide the necessary power in order to fly and there are various configurations, depending on the number of rotors and their place. For example, there is the conventional helicopter configuration, the tandem rotor, with two lifting rotors, the coaxial rotor, where the two rotors are placed one above the other and spin around the same vertical axis and the meshing rotor, where the two rotors are placed side by side and tilted by an angle (Jay Gundlach, 2012, p. 148). These are all helicopter configurations, but there are also UAVs that are equipped with more rotors, like the quadcopter for example. These are called multi-copters. The number of rotors, determines the name of the multi-copter.

Advantages:

1 Vertical Takeoff and Landing (VTOL):

- Helicopters and multi-copters are capable of VTOL, so there is no need for a runway or an open space for takeoff and landing. No initial speed is required.
- This type of landing is extremely useful, especially in demanding areas, where the terrain does not allow conventional procedures.

2. Hover capability:

- Helicopters and multi-copters, have the ability to maintain their altitude and literally stay still in the air. This is called hovering.

3. Easy to fold:

- These types of UAVs have revolutionized the takeoff procedure, because they can be designed to fit in any type of tube. They are small, cheap and very effective.

- New methods of takeoff are being examined lately, like the promising use of Grenade Launchers, like the U.S. M203. Smaller drones line the Ninox 40 or the Drone 40 can be launched from these tubes, just like normal grenades, since they have these specific dimensions. Each soldier can carry a number of these drones and use them for surveillance and precision strikes, because they can loiter and also serve as kamikaze drones.

4. Increased control and stability:
   - They are lightweight, so their response to maneuvers is immediate.

Disadvantages:

1. Low endurance:
   - Their small size leaves no room for a large power source, so generally, smaller batteries are used. The average flight time for these types of UAVs, does not exceed 45 minutes.
2. Low speed:
   - Unlike fixed-wing UAVs, helicopter or multi-rotor UAVs cannot fly as fast, because their rotors are placed vertically, so they lack in aerodynamic efficiency.
3. Small warhead:
   - Smaller warheads are used, due to limited space. In the case of larger warheads, like the ones seen in Figure 11 the flight time decreases, because more power is used to carry the extra weight.
4. Limited field of view:
   - Restricted camera angle: Given the compact size and payload restrictions, grenade – launched drones typically have limited camera angles.
5. Blind spots: They may not have full 360 – degree vision, leaving blind spots that could make it hard for operators to get a comprehensive understanding of the environment.

Figure 48: Grenade-launched drone (Indomiliter, 2022)

Pros	Cons
Vertical Takeoff and Landing	Low endurance
Hover capability	Low speed
Easy to fold	Small warhead
Increased control and stability	Limited field of view

Table 8: Pros and Cons of rotorcraft configuration

The following Tables, provide an overall summary of the advantages and disadvantages of all the different configurations mentioned above. Different types of criteria are used that indicate the strong and weak points for the six configurations:

Configuration	Pros	Cons
Conventional	Loitering endurance Aerodynamic efficiency Folding capability High maneuverability	Low wing loading (W/S) Prone to gust Complex folding mechanism Wind gusts vulnerability
Delta wing	High structural efficiency Good aerodynamic efficiency High maneuverability Stability at high angles of attack Simple construction	Poor low-speed performance Higher drag at low speeds Complex control systems Visibility issues
Canard	Enhanced lift and control Improved maneuverability Natural stall resistance Balanced lift distribution	Complex aerodynamics Structural considerations Trim and stability issues

	Efficient aerodynamic design	Higher drag at certain conditions Folding difficulty
Tandem	Increased lift Improved stability High wing loading Enhanced folding capabilities Relatively high aspect ratio	Complex aerodynamics Downwash effect Flight envelope limitations
Cruciform	Higher wing loadings Advanced maneuverability Increased airspeed	Length less or equal to the wingspan Limited wingspan Non – optimal airflow
Rotorcraft	Vertical Takeoff and Landing Hover capability Easy to fold Increased control and stability	Low endurance Low speed Small warhead

Table 9: Pros and Cons of each configuration

Table 10 contains the criteria that were used by the author of this thesis, in order to come up with an overall efficiency result for every type of configuration. This result points out the most effective configuration for the development of a loitering munition that meets the client's demands. In this case, it should be a small, low – cost and fixed – wing kamikaze drone that can be folded and launched by a small tube. This method of prioritizing and evaluating design criteria based on the author's requirements is usually met in plenty of aeronautical engineering books, like the Aircraft Design: A Conceptual Approach, by Daniel P. Raymer, in the last chapter, or the Unmanned Aircraft Design: A review of fundamentals, by Mohammad Sandraey.

Criteria / Config.	Endurance	Maneuverability	Speed	Payload	Foldability	Overall efficiency
Conventional	10	7	7	7	7	7,6
Delta	7	7	10	10	1	7
Canard	7	10	7	10	1	7
Tandem	10	7	3	7	10	7,4
Cruciform	7	10	5	5	3	6
Rotorcraft	1	10	1	5	10	5,4

Table 10: Configurations comparison

Criteria importance	Level
Very Low	1
Low	3
Medium	5
High	7
Very High	10

Table 11: Levels of importance

Table 11, presents the overall importance or priority of the Figures of merit above. Level "1" stands for very low importance and level "10" shows high priority. As we can see from Tables 10 and 11, the most efficient configuration is the conventional. Its speed and payload capacity might not be the highest and its folding mechanism might be challenging to develop, but in order to combine most of the necessary criteria for accomplishing the mission, a configuration of this type would be the most suitable option.

In the following Table, the «✓» symbol, indicates the superiority of one category over the other.

Comparison	Rotary-wing	Fixed-wing
Flight stability	✓	x
Endurance	x	✓
Range	x	✓
Emergency landing	x	✓
Engine loss – mission efficiency*	✓	x
Flight control	x	✓
L/D ratio	x	✓

Table 12: Rotary-wing vs fixed-wing

*In case of engine loss, a fixed-wing drone can glide through the air and perform an emergency landing, but no one can guarantee that the mission will be accomplished. On the contrary, a rotary-wing drone, if it is equipped with specific algorithms that control stability, it will be able to remain in the air and carry on its mission, for as long as battery can provide power.

§4.7 Aerodynamics and Flight Dynamics

While Aerodynamics is the study of how air interacts with solid objects in motion, like airplanes, drones or missiles, Flight Dynamics deals with the motion of the object itself. Hence, how it moves and changes orientation in three – dimensional space under the influence of aerodynamic forces, weight and propulsion. Aerodynamics plays a crucial role in the design and performance of drones, influencing their stability, efficiency and maneuverability. Fixed –

wing drones, just like manned aircraft, rely on the same aerodynamic principles to generate lift, control thrust, reduce drag and optimize flight in various environments. At its core, as mentioned above, aerodynamics deals with the behavior of the air as it interacts with solid objects. The interaction between the air mass and the flying object, is generated through Shear – Layer friction and pressure (D.P. Raymer, 2018, p. 390). Drones typically use either multirotor design or fixed – wing design. Sometimes they also use both. The basic flight principles are not the same, since multirotors remain airborne with the use of their propellers that generate lift, while fixed – wing drones use their wings.

In terms of fixed – wing drones, they behave similarly to traditional airplanes. Their wings generate lift as they move forward through the air and smaller surfaces control their horizontal and vertical direction. The basic forces of flight are the following:

- **Lift (L):** This is the upward force that opposes gravity and allows the drone to fly. It is generated by the wings, because of the pressure difference between the upper and lower area of each wing.
- **Weight (W):** This is the gravitational force that pulls the drone down to the earth and equals to m*g, where m is the mass of the flying object and g is the acceleration due to gravity (≈ 10 m/s^2 for the earth's gravitational field).
- **Thrust (T):** This is the forward force generated by the drone's propulsion system.
- **Drag (D):** This is the resistance the drone experiences as it moves through the air, due to friction of the air molecules and the surface of the airframe.

According to Bernoulli's Principle and his study in fluid dynamics, we are now able to explain how lift is generated (NASA, n.d.). Figure 49 presents the anatomy of an airfoil, along with the airflow above and beneath its surface. The air in the upper surface, moves faster than the air beneath the airfoil, because the shape of the airfoil is curved at the top and that forces the air to speed up. This results in pressure drop, so a difference between the upper and lower surface of the wing is generated. This is how lift is generated, because the low – pressured air tends to move to a higher-pressure level and that pushes the wing upwards. However, if the flying object moves horizontally through the air, without any Angle of Attack (angle that is formed between the direction of the airflow and the wing's chord line), according to Newton's 1st Law, the object will keep moving in a straight line (Britannica, T. Editors of Encyclopedia, 2024). In other words:

$$\Sigma F_y = 0 \Rightarrow L - W = 0 \Rightarrow L = W \qquad \text{(eq. 4.7.1)}$$

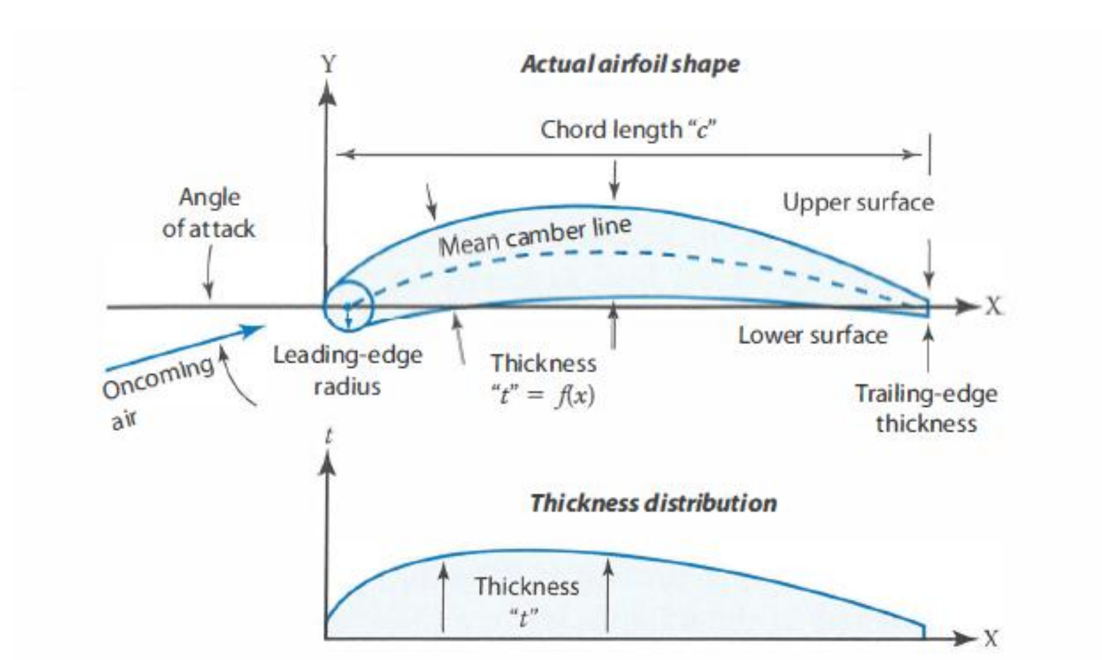


Figure 49: Geometry of an airfoil (D. P. Raymer, 2018, p. 55)

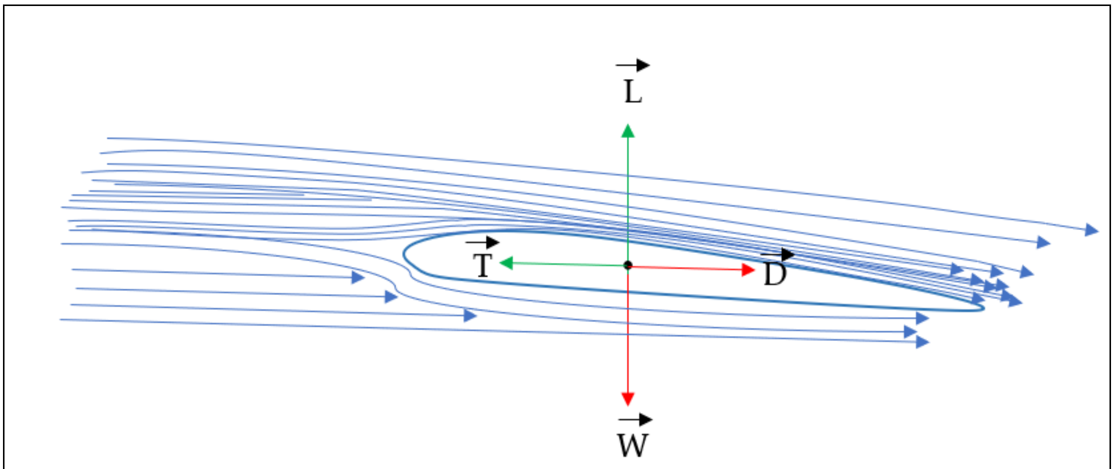


Figure 50: Forces acting on an airfoil during flight

Any change in the Angle of Attack, would result in vertical motion of the flying object, so in a change of altitude. This is explained by Newton's 3rd Law, where every action has an equal and opposite reaction. A flying object's movement through space, is the result of a surface's change of angle. Those surfaces that control the motion of flight, are called "control surfaces" and are divided in primary and secondary[3]. Secondary control surfaces are additional control mechanisms that assist in refining the handling and performance of an aircraft or a fixed – wing drone.

[3] Loitering munitions and smaller UAVs in general, do not typically use secondary control surfaces, since they are designed with the least complex way possible, they do not fly at a very high speed and LMs are designed to be destroyed after impact.

1. **Primary**:

- **Elevators:** These control surfaces are located at the rear of an aircraft or a fixed – wing UAV and control the pitch, which is the nose – up and nose – down movement around the lateral axis that affects the altitude. These control surfaces are presented in Figure 52.
- **Rudder:** This control surface is usually located in the vertical tail and controls the side – to – side movement of the nose around the vertical axis, also known as yaw. Many types of manned and unmanned aircraft, use two or more rudders, in order to enhance their capabilities in performing this type of turn. Figure 53 shows this primary control surface.
- **Ailerons:** These control surfaces are located in the main wings and are responsible for making the aircraft or UAV roll and turn, as presented in Figure 54.

2. **Secondary:**

- **Flaps:** These secondary control surfaces are mounted on the trailing edge of the wing, closer to the fuselage than the ailerons. Their purpose is to increase the lift, generated by the wing at lower speeds, especially during takeoff and landing.
- **Slats:** They are mounted on the leading edge of the wing. They are movable surfaces that improve the airflow over the wing at high Angles of Attack.
- **Spoilers:** They are located on the upper surface of the wing and through deployment, they increase drag and reduce lift, forcing the aircraft to slow down.
- **Trim tabs:** These are small adjustable surfaces attached to the trailing edge of ailerons, elevators or rudders.

The following Figures show a 3D model of a Switchblade 300, along with its primary control surfaces.

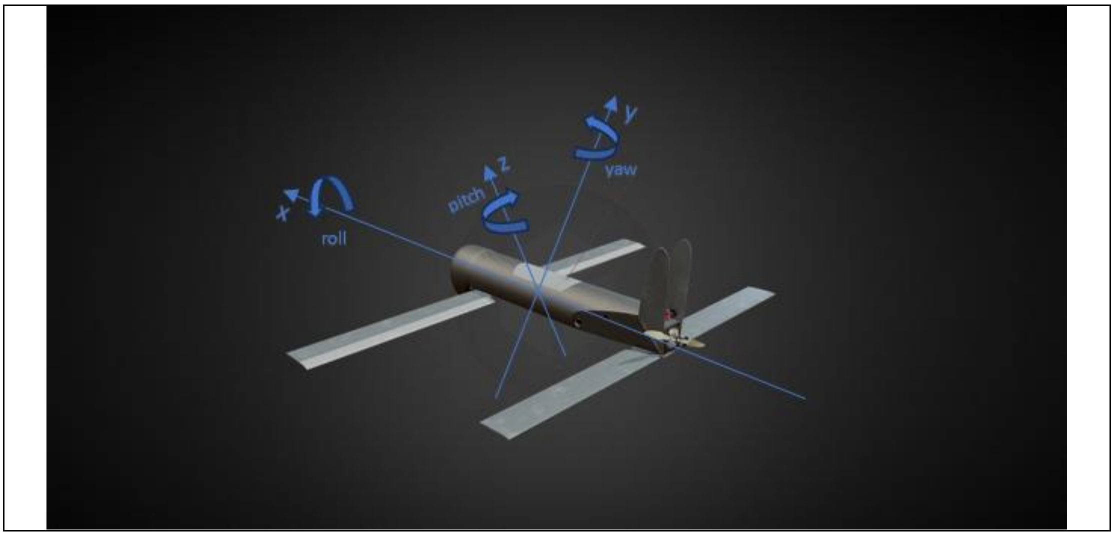


Figure 51: The six degrees of freedom in aviation[4]

Figure 52: Elevators and pitch

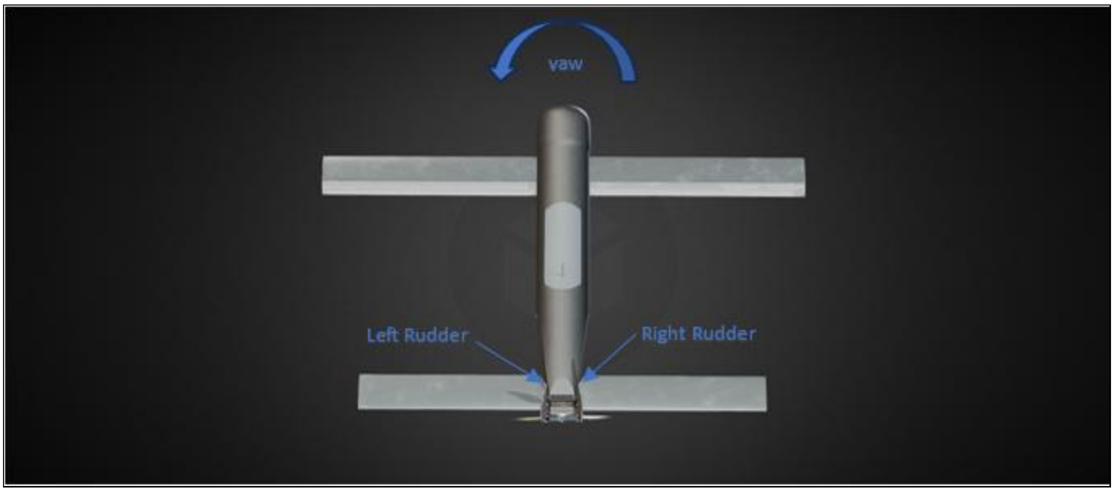


Figure 53: Rudders and yaw

[4] Available at https://sketchfab.com/3d-models/aerovironment-switchblade-300-539d82faa75b463298328c7095e72aef

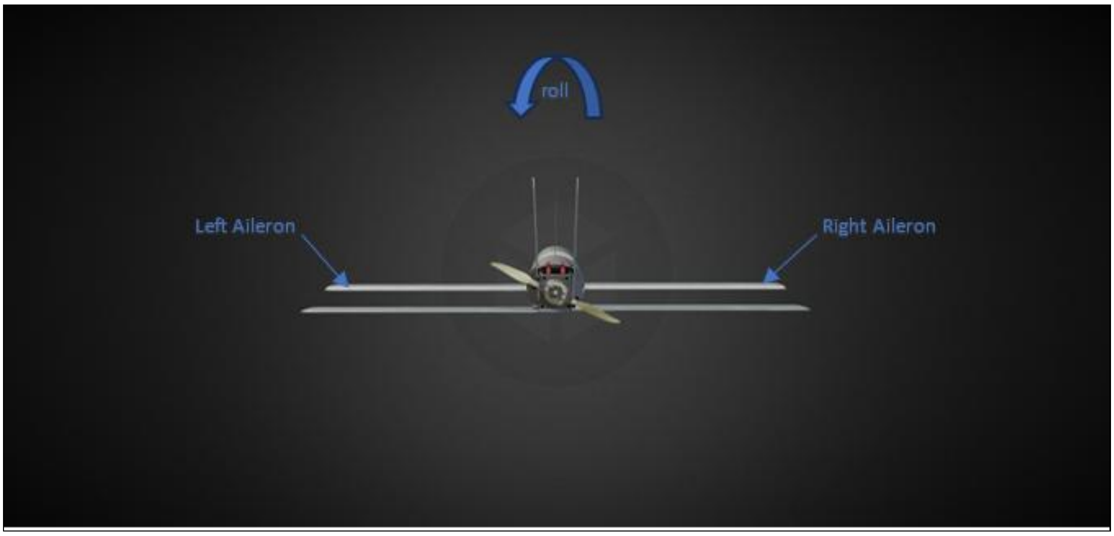


Figure 54: Ailerons and roll

The center of gravity (c.g.) for a manned or unmanned aircraft, is a point where the entire weight of the aircraft is considered to be acting (SKYbrary, n.d.). Pitch, yaw and roll movements occur about this point. The distance between the center of gravity and the primary control surfaces plays a key role to the aircraft's moments that are created. The center of pressure (c.p.) is the average location of all the pressure acting upon a body moving through a fluid (SKYbrary, n.d.). It is not a fixed point and can move forward or backward, depending on the amount of lift that is being created.

With an increase in the AoA, the lift increases and the c.p. moves forward. The opposite thing happens when the AoA decreases. In order for an aircraft to be stable during flight, the c.g. has to be in front of the c.p. (Positive Static Stability). In that way, the aircraft can resist external disturbances and come back to its initial attitude. If the c.g. and the c.p. are in the same position, then the aircraft doesn't return to its original attitude after any disturbance (Neutral Static Stability). If the c.p. is in front of the c.g. the aircraft tends to deviate from its initial attitude, after any disturbance (Negative Static Stability).

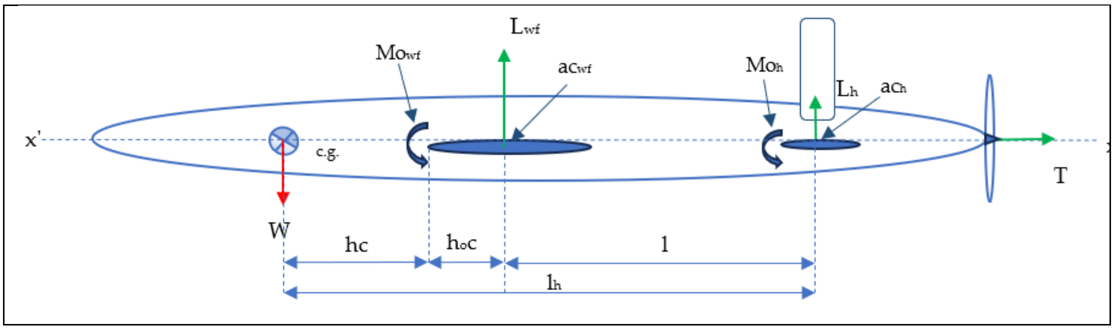


Figure 55: Positive static stability

Where:

$M_{o_{wf}}$: The wing/fuselage aerodynamic pitching moment (The factor "o" indicates that the aerodynamic moment is measured relatively to the aerodynamic center)

M_{o_h}: The horizontal tail aerodynamic pitching moment

ac_{wf}: The wing/fuselage aerodynamic center

ac_h: The horizontal tail aerodynamic center

hc: The distance between the center of gravity and the leading edge (acts as a reference point)

$h_o c$: The distance between the wing/fuselage aerodynamic center and the leading edge

l: The distance between the wing/fuselage aerodynamic center and the horizontal tail aerodynamic center

l_h: The distance between the center of gravity and the horizontal tail aerodynamic center

Chapter 5

§5.0 Mission analysis

§5.1 Concept of Operations (ConOps)

Class 1 loitering munitions are lightweight, man – portable systems, designed for tactical – level operations (from squad to battalion), providing small units with organic precision – strike capabilities. Their Concept of Operations emphasizes rapid deployment, ease of use and flexibility in both offensive and defensive missions. Typically operated by a single soldier or a small team, Class 1 loitering munitions can be launched from the ground or from lightweight launchers, requiring minimal infrastructure (E. Karatzas, V. Kostopoulos and V. Lappas, 2023). Their dimensions are suitable for launch by a catapult, a mortar or even a recoilless rifle and a grenade launcher. Once deployed, the munition can loiter over an area for a predetermined period of time, providing real – time intelligence, surveillance and reconnaissance (ISR) capabilities. The primary mission profile includes targeting enemy personnel, light vehicles or command – and – control systems, allowing ground forces to neutralize threats before they escalate. These systems are especially valuable in environments where conventional air or artillery support is unavailable or delayed. They can autonomously search for targets within their designated area or be manually guided, offering precision strike capability with minimum collateral damage. Overall, the Concept of Operations of Class 1 loitering munitions, focuses on enhancing situational awareness, increasing lethality and providing immediate firepower in tactical engagements.

§5.2 Flight plan

When designing a new aircraft, either manned or unmanned, it is truly important to consider all the different parameters that affect its flight. From its empty weight and the necessary payload to the total flight time, from takeoff to landing, an aeronautical engineer is responsible to predict and be prepared for any kind of situation. The only way to think of any possible scenario, is to analyze the mission that the aircraft is made for. This analysis is done by dividing the mission to smaller segments, where each segment represents a sub-mission. The aircraft has to be able to achieve all of its sub-missions, in order to be effective and go into production. In the case of UAVs and more specifically of kamikaze drones, one of the key parameters that must be taken into consideration, is the loiter time. Unlike other UAVs, loitering munitions are made for striking targets, so they have a different set of initial requirements. For example, no landing gear is needed, so there is no worry for finding extra space in the fuselage for storage. Those small aircraft are not designed to return and land. However, if the loitering munition is running out of power and no target has been acquired, there are some methods for emergency landing, such as the belly landing or the use of a net, which is used more often. The following Figure, depicts a loitering munition's mission profile, where all the different phases are presented.

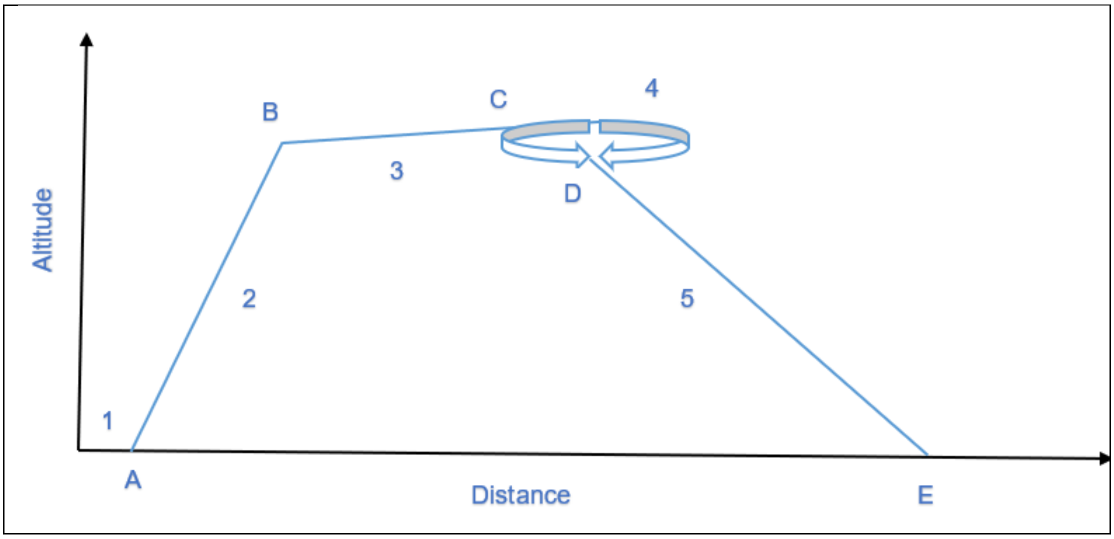


Figure 56: Mission phases

Transition points	Mission phase
A. Launch	1.Takeoff
B. Reaching operational altitude	2. Climb
C. Reaching target	3. Cruise
D. Start loitering	4. Loiter
E. Start descending	5. Strike

Table 13: Mission segments

During phase 1, the loitering munition is launched from a grenade launcher and in phase 2, it starts climbing, until the soldier takes control. With the use of a tablet or a smartphone, he will be able to fly the kamikaze drone and guide it to the target area. This was phase 3. In phase 4, the UAV will loiter around the target, waiting for the command to strike. In phase 5, a high-speed dive will be performed in order to destroy the target. After the impact, the soldier can reload and fire another loitering munition, to take out other possible threats, following the exact same procedure.

For the estimation of time, we will use the equations that D. P. Raymer proposes.

$$t_{loiter} = E\ (hours) \qquad \text{(eq. 5.2.1)}$$

$$t_{cruise} = \frac{R}{V_{cr}}\ (hours) \qquad \text{(eq. 5.2.2)}$$

$$t_{climb} = \frac{h_c}{V_{V_c}} * 0{,}000277777778\ (hours) \qquad \text{(eq. 5.2.3)}$$

$$t_{descent} = \frac{h_d}{V_{V_d}} * 0{,}000277777778\ (hours) \qquad \text{(eq. 5.2.4)}$$

The total time (t_{total}) for the mission, calculated by the designer is

$$t_{total} = t_{takeoff} + t_{climb} + t_{cruise} + t_{loiter} + t_{descent} + t_{strike}\ (hours) \Rightarrow \qquad \text{(eq. 5.2.5)}$$

⇨ $t_{total} = 0.43\ h$ (or 25.8 min)

It is necessary at this point to mention that the units that are being used play a crucial role to the calculations.

The following Table presents the requirements, regarding time of flight (E), altitude (h), speed (V) and range (R), that will be used later, to provide the completed initial set of requirements.

Variable	Symbol	Estimation
Desired Flight Endurance (h)	E	0.27
Desired Flight Range (km)	R	8
Desired MTOM (kg)	W	2.5
Desired Payload weight (kg)	W_{PL}	0.5
Desired Cruise speed (km/h)	V_c	60
Desired Max speed (km/h)	V_{max}	80
Desired Speed of climb (km/h)	V_{CL}	7
Desired Speed of descent (km/h)	V_D	7
Desired Stall speed (km/h)	V_s	>30
Desired Max altitude (m)	h_{max}	500

Table 14: Mission requirements

In a hypothetical scenario where the target is located at a distance of 4 km, the estimated time is calculated with the equations (5.2.1 – 5.2.5)

Mission Phase	Estimated time (h)
Takeoff	0.0027

Climb	0.07
Cruise	0.13
Loiter	0.16
Strike	0.07

Table 15: Estimation of time

§5.3 Market analysis

Since our goal is to develop a low-cost loitering munition, the use of cheap and yet appropriate materials is necessary. Polymer composites are quite often used in aerospace for many reasons, some of which are the value of money, their simple use and the mechanical qualities they offer. Composites are mixtures of two or more different materials that combine the advantages of each material such as the effectiveness, the durability or the flexibility and have replaced traditional metals that are heavier and less effective. Through market analysis, we search for the right materials from various manufacturers, in order to find the most suitable parts at the best possible price. In 2022, the global commercial drone market size, reached over 18.000.000.000 € and is estimated to increase rapidly, with a rate of growth of 13.9% until 2030. The following Figure, presents the estimated growth rate of U.S. commercial drone market.

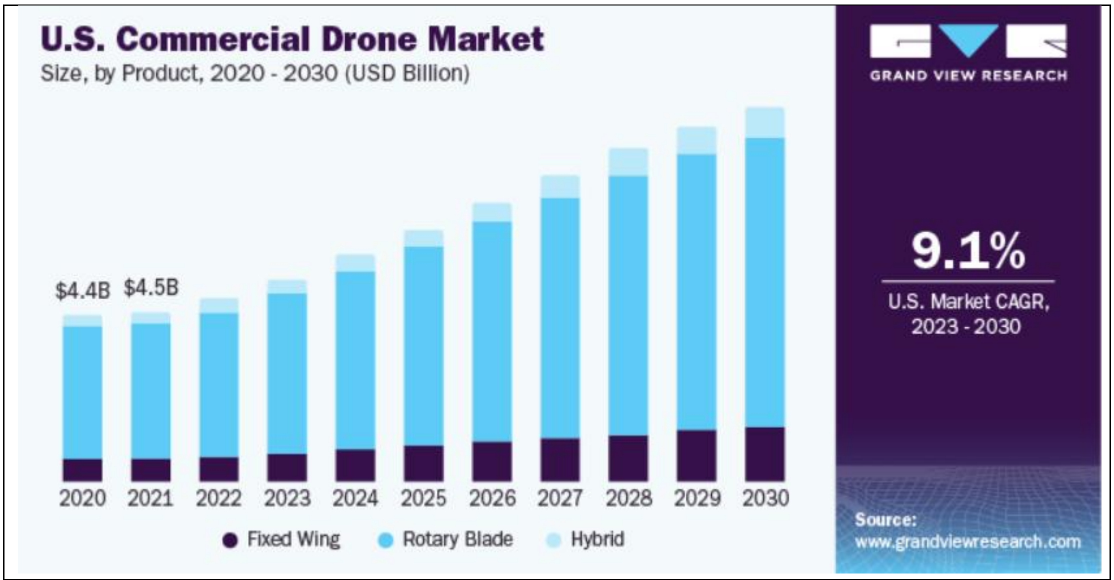


Figure 57: U.S. commercial drones market rate of growth (Grand View Research, n.d.)

This increase in demand, also increases the number of the different manufacturers and diversifies at the same time the price. By searching online, a client who looks for a cheap but durable airframe for a fixed – wing FPV drone, could notice that some of the manufacturers, along with the price of their product are the following, as shown in the Table below:

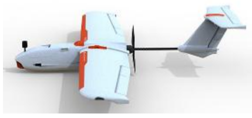
Airframe				
No	Site	Manufacturer	Price (€)	Figure
1	www.drone-fpv-racer.com	VCI	189.90	
2	eu.robotshop.com	SONICMODELL	61.93	
3	www.buildyourowndrone.co.uk	FINWING Sabre Deluxe ARF	269.50	

Table 16: Search for airframe

As for the parts, through the same process of searching in various websites, the collected data is presented in the following Tables:

Battery					
No	Site	Manufacturer	Price (€)	Features	Figure
1	www.drone-fpv-racer.com	TATTU 1400 MAH LiPO Battery	46.90	Minimum Capacity: 1400mAh Configuration: 4S1P / 14.8V / 4Cells Discharge Rate: 130C Max burst discharge rate: 240C Net Weight(±10g): 158g Dimensions: 75mm x 38mm x 28mm (L x W x H) Charge Plug: JST-XHR-5P Discharge Plug: XT60	

2	www.drone-fpv-racer.com	DJI 1800 MAH Li-ION Battery	39.90	Voltage: 7-9V (1.5A) Capacity: 1800mAh Energy: 18Wh Weight: 122g Dimensions: 76.04*40.96*26mm Connectors: USB-C Autonomy: ~2h	
3	www.copters.eu	MAVIC Mini Intelligent Battery 2400 MAH	45	Provides up to 30 minutes of flight time Model: MB2-2400mAh-7.2V Rated Capacity: 2400 mAh Battery Type: Li-ion 2S Rated Voltage: 7.2 V Limited Charge Voltage: 8.4 V Max Charging Power: 24 W Charging Temperature: 5° to 40°C	

Table 17: Commercial batteries

ESC				
No	**Site**	**Manufacturer**	**Price (€)**	**Figure**
1	www.getfpv.com	Tiger Motors 75 AMP	32.90	
2	www.myhelis.com	TY1TW 50 AMP	58.74	
3	www.dronex.gr	Hobbywing Skywalker 40AMP	18.90	

Table 18: Commercial ESCs

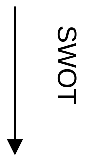
From the Tables above, it is obvious that a drone can be easily built by anyone, because everyone has access in the market. Commercial drones are also used by the Army and serve as loitering munitions, as mentioned in Chapter 2. Military experts in drones can order all the necessary parts from different websites and manufacturers and assemble the drone by themselves. The most important factor that affects their choice, is the price. Through Market Analysis a client is able to gather information and compare the specifications of each part of the drone among various manufacturers.

§5.4 SWOT analysis

This kind of strategic analysis (Durasiewicz, Arkadiusz, Noworol-Luft, Elizabeth, Mucha, Katarzyna, 2008) is performed, in order to better understand and evaluate key parameters and potential challenges, associated with the use of a project, business or technology. These include:

Strengths

Weaknesses



Opportunities

Threats

In Chapter 4, we analyzed in detail the advantages and disadvantages of all the different configurations of UAVs. Taking this into consideration, a SWOT analysis of any type of UAV would be similar to this of Figure 58.

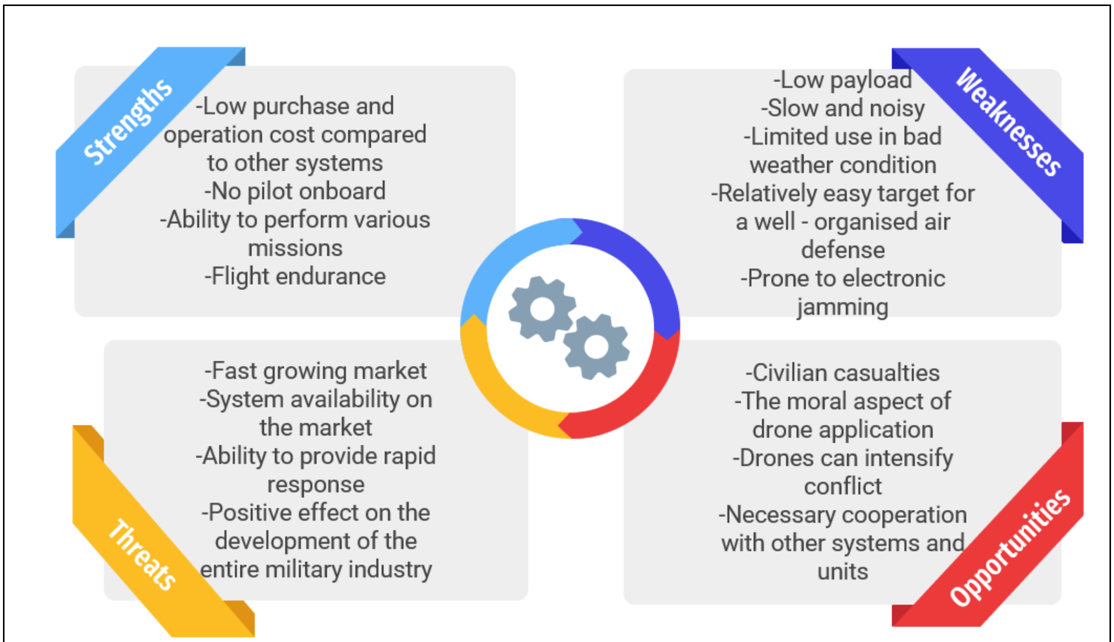


Figure 58: SWOT analysis for a commercial UAV (Damir Ilić, 2020)

In our case, the fixed-wing loitering munition would have the following SWOT analysis:

Strengths	Weaknesses
Loitering endurance	Low wing loading (W/S)

Aerodynamic efficiency	Prone to gust
Folding capability	Complex folding mechanism
High maneuverability	
Opportunities	**Threats**
Technological advancements – use of AI	Emerging anti – drone technologies
Cost reduction and mass production	Regulatory and ethical challenges
Development of autonomous capabilities	Proliferation risks
Integration with Network-Centric Warfare	Cybersecurity vulnerabilities
	Escalation of conflict dynamics

Table 19: SWOT analysis of a conventional kamikaze drone

§5.5 Initial specifications

After having conducted a brief Market Analysis and taking into account the Concept of Operations and the mission profile of the Class 1 loitering munition, it is time to come up with a set of initial requirements, necessary for the mission to be successful. Table 20 presents some of the initial specifications that the designer must pay great attention to.

Requirements	Specifications
Type	Loitering munition
Configuration	Conventional
Launch method	Portable launch from small tube or handheld system – grenade launcher (minimum setup required)
Landing Method	Destruction over impact, belly landing or use of a net. Not equipped with parachute
MTOM	Less than 2 kg (man portable – ease of transport by a single operator)
Range	Effective range of 7 – 8 km (LOS)
Endurance	25 min (around 16 min loiter)
Aspect Ratio	Around 6
Speed	Cruise speed of 60 km/h Max speed of 80 km/h
Length	180 mm
Width	40 mm (fits within an M320 grenade launcher)
Height	46 mm
Type of engine	Electric (BLDC motor)
Power source	Battery (LiPO)
Payload	Small warhead capable of neutralizing personnel, light vehicles or soft targets
Wing mechanism	Deployable wings
Guidance system	GPS/INS with manual override and target tracking capabilities via electro – optical/infrared (EO/IR) sensor
Autonomy	Autonomous flight and target acquisition with operator intervention if needed

Targeting capability	Day/night capability with real – time video feed for ISR and precision strike
Operational altitude	500 m above ground level (AGL), depending on terrain and mission
Communications	Secure data link for command and control within line of sight (LOS)
Environmental resilience	Operable in adverse weather conditions (wind, light rain)
Mobility	Rapid deployment and recovery (system packed in a backpack or carried by an individual)
Cost	Low cost for expendability in tactical operations
Stealth	Low acoustic and visual signature
Survivability	Ability to avoid detection and interception from enemy air defenses

Table 20: Initial set of requirements

Although this Table represents the initial set of requirements, some of them may change later during the design process. The following Figure, presents an initial layout of how the loitering munition will look like at the end of the design process.

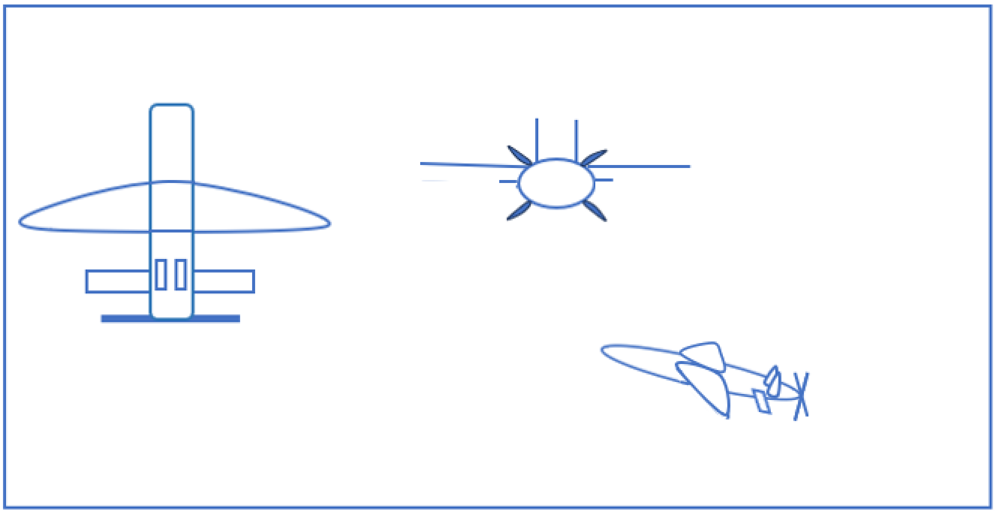


Figure 59: Initial layout of the loitering munition

Now, we can move on to the description of the design process itself.

Chapter 6

§6.0 Loitering munition design

§6.1 Parts of the Class 1 loitering munition

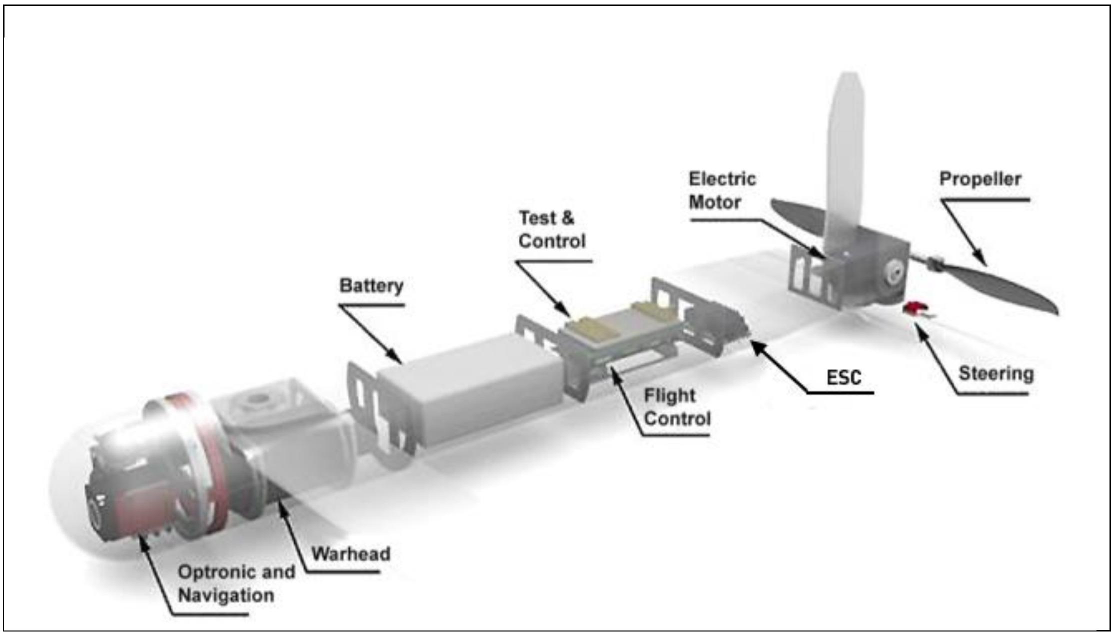


Figure 60: Parts of a loitering munition (EDR ON-LINE, 2022)

Loitering munitions, just like other UAVs, commonly known as drones, are sophisticated machines that combine advanced technology, engineering and warheads, to operate without a human pilot on board. Whether used for surveillance or high precision strikes, loitering munitions are composed of several critical components that work together to enable flight, navigation and control. Understanding these parts is essential for appreciating how these lethal weapons function and the complexity behind their operation. Below, the key components of a UAV are presented. The main difference between a typical UAV and a loitering munition, is the payload. Loitering munitions are equipped with warheads that explode when striking their target.

1. Airframe:

The main body of the UAV that houses all the components. It can be fixed wing, rotary-wing (like quadcopters), or a hybrid design. The airframe is designed to provide structural support and as technology advances, new materials are on demand that are lightweight, don't cost as much as traditional ones and offer structural stability. The innovative solution to these demands is the use of composite materials, that optimize performance and reduce cost. The Composite Affordability Initiative (CAI) is funded by the Air Force, the Navy and industry (Boeing, Lockheed Martin and Northrop Grumman) (National Research Council, 2000). Its goal is to "develop the tools, methodologies and technologies, necessary to design and manufacture a composite airframe using revolutionary design and manufacturing practices to enable breakthrough reductions in cost, schedule and weight. (Department of Defense, 1999)" The weight savings of composite materials over metals can be around 20 – 25%. We can divide them into the following categories (IJARESM, 2022):

I. Composites

- Carbon Fiber Reinforced Polymer (CFRP): Used in structural frames and arms, carbon fiber provides excellent strength-to-weight ratio and stiffness, essential for stability and durability. It's most common in higher-end small drones where performance and durability are prioritized.
- Glass Fiber Reinforced Polymer (GFRP): Often used as a more affordable alternative to carbon fiber. While not as lightweight or strong, it provides sufficient durability for consumer and recreational UAVs, especially those where budget constraints are more crucial.
- Kevlar composites: Kevlar is less common in small UAVs due to cost but may be used in military drones for enhanced impact resistance.

II. Plastics and Polymers

- ABS (Acrylonitrile Butadiene Styrene): Widely used in consumer drone frames and housings, ABS is lightweight, impact-resistant and easily 3D-printed, making it ideal for prototyping and custom UAV builds.
- Polycarbonate (PC): Known for transparency and toughness, polycarbonate is often used in propellers, canopies or parts that need to be lightweight yet impact resistant.
- Nylon (Glass-Filled): It is durable, flexible and strong, commonly used in propellers, gears and motor mounts.
- Polyethylene (PE) and Polypropylene (PP): Lightweight and inexpensive, these polymers are sometimes used for non-load-bearing parts in recreational drones, though they may lack the strength needed for heavy-duty applications.

III. Lightweight metals

- Aluminum (often Alloy 6061 or 7075): Aluminum is common in structural components such as arms, motor mounts and connection points. For small UAVs, aluminum strikes a good balance between weight, strength and cost.
- Magnesium Alloys: They offer weight savings in comparison to aluminum, but are not so commonly used, due to the higher flammability.
- Foams and lightweight fillers
- Expanded Polypropylene (EPP): A resilient lightweight foam that can withstand impact without breaking.
- Expanded Polystyrene (EPS): Very lightweight and provides adequate strength for body structure.

2. Propulsion System

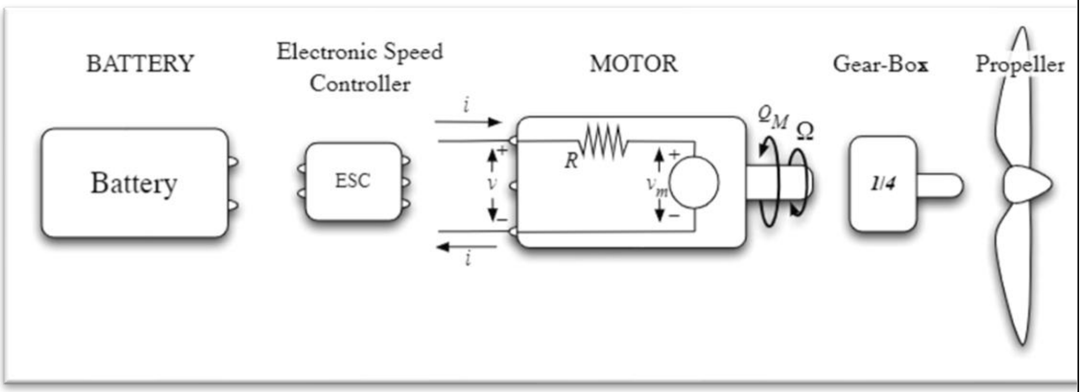


Figure 61: Electric propulsion system architecture (HAL, 2014)

The propulsion system is a critical part of any UAV, as it provides the necessary thrust to achieve and maintain flight. Loitering munitions usually use one of the following propulsion systems, as presented in the Table below.

Propulsion System	Pros	Cons	Example
Electric propulsion	Quiet operation Lightweight and compact Simple maintenance and reduced logistics	Limited endurance due to battery capacity Lower thrust compared to fuel – based systems	Switchblade 300

Internal Combustion Engine	Greater endurance and range compared to electric propulsion Higher power to weight ratio (P/W)	Noisy operation (affects stealth capability) More complex mechanical systems, requiring more maintenance	Harop

Table 21: Types of propulsion systems for loitering munitions

In fact, a large number of UAVs and the majority loitering munitions, use Electric Propulsion Systems, because they are small, lightweight, reliable and do not waste too much space in the fuselage. Electric motors can be placed closer to the propeller, so the existence of a shaft (mechanical component that transfers the rotational motion and torque generated by the motor to other mechanical parts or systems) might not be necessary. An energy efficiency of around 90% is attained, in contrast to typical gasoline engines that reach almost 20% (D. P. Raymer, 2018, p. 739). They are also a "green" solution, since they do not pollute the environment through emissions when flying. These types of systems use batteries as a power source, which keep their weight steady during flight, and sometimes they might also use fuel cells. In the case of batteries, the weight remains the same, comparing to fuel which is burnt and the aircraft becomes lighter, so its center of gravity (c.g.) changes. Electric Propulsion Systems use motors, attached to propellers. There are two main categories of motors for UAVs, the Direct Current (DC) and the Brushless (BLDC). The second option is by far more commonly used, because of the longer endurance, (since the brushes are not damaged from friction as the motor spins), the higher power and the reduction of noise. The following Table presents the main differences in terms of function of these two types of motors.

DC motor	BLDC motor
Brushed DC Motors have mechanical brushes and a commutator to switch current in the windings, producing rotational motion	Brushless DC Motors eliminate the need for brushes and a commutator by using electronic controllers to manage current switching
The rotor contains the windings and the stator has permanent magnets	The stator has the windings and the rotor contains the permanent magnets
Brushes wear out over time, requiring maintenance	No mechanical contact is needed for commutation, reducing wear out and increasing reliability

Table 22: DC Motors vs BLDC Motors function

Figure 62: BLDC Motor for drones (Drone FPV Racer, n.d.)

- Electronic Speed Controller (ESC) (T-Drones, 2023): Regulates the speed of the motors, which directly affects the drone's flight characteristics. In multirotor, the number of ESCs depends on the number of motors, since each motor is connected to an ESC. The flight controller sends commands to each ESC to adjust motor's speed, determine rotation and convert three – phase electricity, allowing the UAV to perform maneuvers like hovering, yawing and climbing. In fixed – wing drones and loitering munitions, the ESC controls the speed of the propeller. Figure 63 shows a commercial ESC without BEC[5].

Figure 63: No BEC ESC (T-Drones, 2023)

[5] ESCs are divided to two main categories BEC and No BEC. BEC stands for Battery Elimination Circuit and can convert the voltage of the battery (it's usually high in LiPo batteries) to a lower and more stable voltage, suitable for sensitive electronics.

3. **Flight Controller**

The "brain" of the UAV, responsible for stabilizing the drone. It collects data from all the existing sensors of the UAV (gyroscope, accelerometer, GPS, optical sensors and any other available sensor) and the commands from the remote control and sends the necessary signals to the servos and the motor(s) of the UAV. The following Figure shows a Flight Controller for a fixed – wing drone.

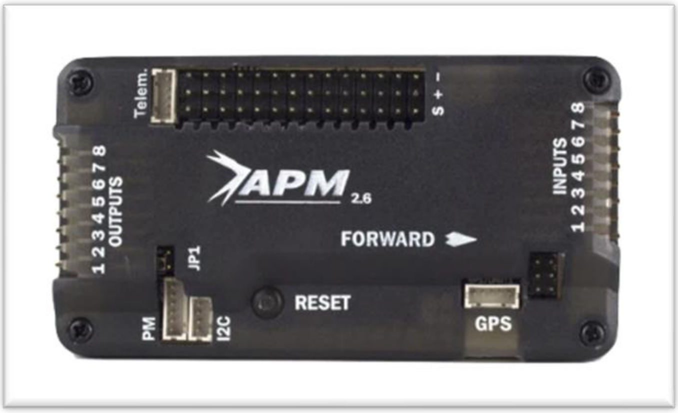


Figure 64: APM 2.6 Flight Controller (Flying Tech, 2024)

4. **Power Supply**

- Battery: Batteries convert stored chemical energy into electrical power (Jay Gundlach, 2012, p. 322). Nowadays, the most commonly batteries are the Lithium-Polymer (LiPo) and Lithium-Ion (LiIon), that provide the necessary power to the UAV's systems and can maintain it airborne for a longer period of time, in contrast to Nickel Cadmium batteries that were previously used (E. Karatzas, V. Kostopoulos and V. Lappas, 2023). In Figure 65, a commercial multi-copter battery is shown.

Figure 65: Li-Po battery for UAV (Made in China, 2024)

- Power Distribution Board (PDB): Its role is to handle the power management. The PDB distributes power from the battery to various components of the drone, such as the ESCs, flight controller, camera and many more.

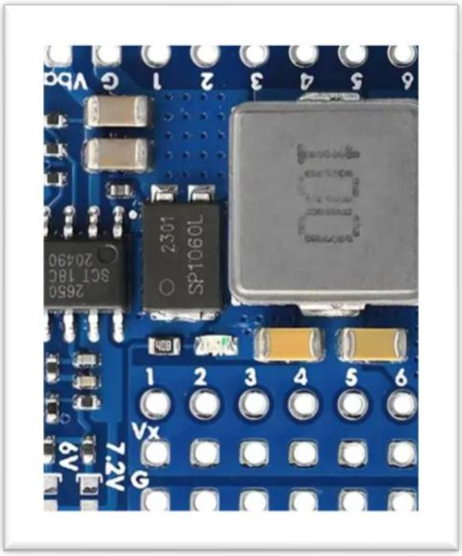


Figure 66: Power Distribution Board (Getfpv, 2024)

5. Sensors

- GPS module: Provides positioning data for navigation and autonomous flight. A GPS receiver, like those in smartphones, cars and many other devices, receives signals from satellites and uses the time it takes for the signals to reach it, to calculate the distance to each satellite. The receiver needs three satellites to compute latitude, longitude and altitude and triangulate its position. A fourth satellite is necessary, in order to measure the ranges from these signals, so, in other words, to calculate time and also avoid the use of an atomic clock. Without the existence of a fourth satellite, an atomic clock, synchronized with the GPS is essential for the measurement of ranges (Dederal Aviation Administration, n.d.). In Figure 67, a UAV detects its position, with the use of four satellites and at the same time, transmits data to another UAV, whose location is unknown.

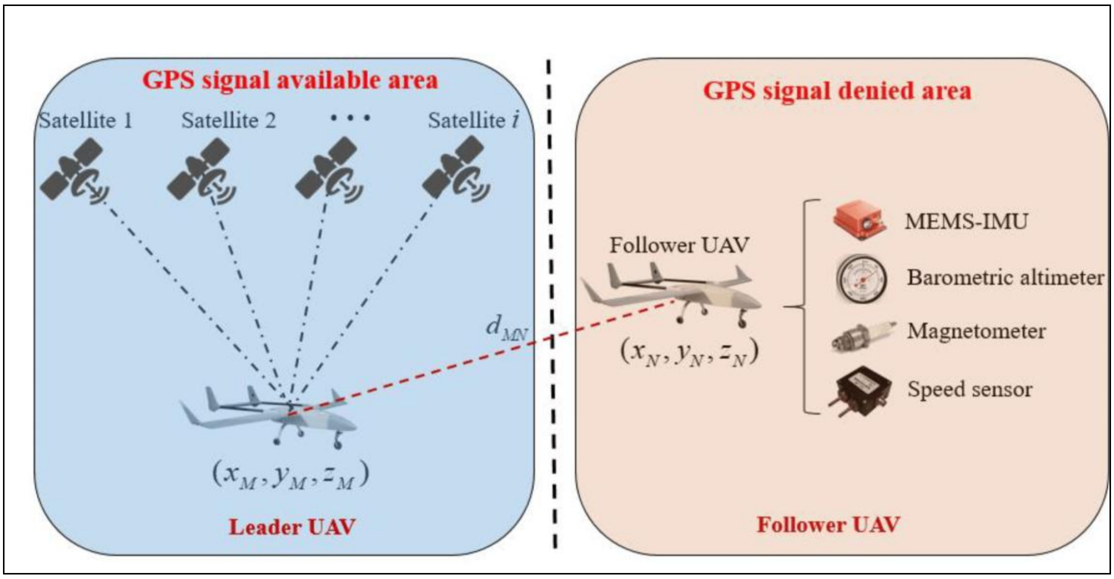


Figure 67: GPS triangulation of Leader UAV (Energies, 2022)

- Inertial Measurement Unit (IMU): It includes accelerometers and gyroscopes to measure orientation, speed and movement. Accelerometers measure linear accelerations (a_x, a_y, a_z) and gyroscopes measure the angles (θ, ψ, φ) (Jay Gundlach, 2012).

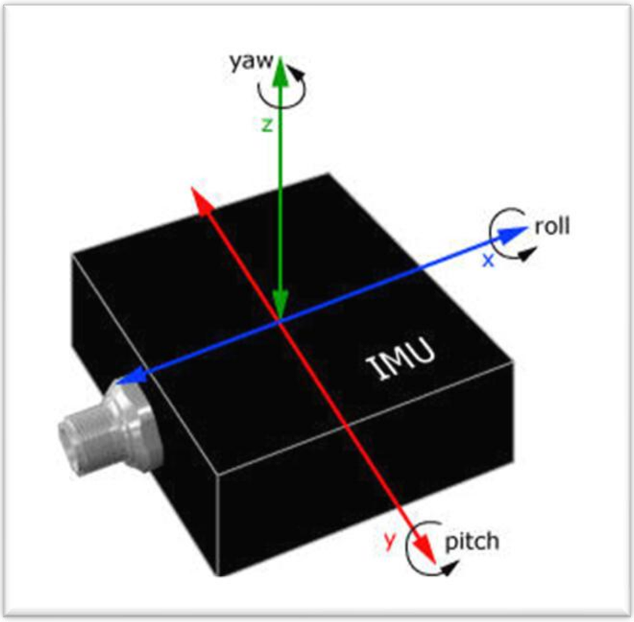


Figure 68: IMU orientation (6 degrees of freedom) (USGS, 2020)

- Barometric altimeter: Measures altitude by detecting air pressure changes. As height increases, pressure drops and vice versa.

Figure 69: Radar altimeter (AeroExpo, 2024)

- Magnetometer: Often referred to as digital compass, it detects the Earth's magnetic field and helps determine the drone's heading (its orientation relative to the magnetic north). In the Figure below, a digital PNI (Positioning Navigation Intelligence) magnetic compass for target location is presented.

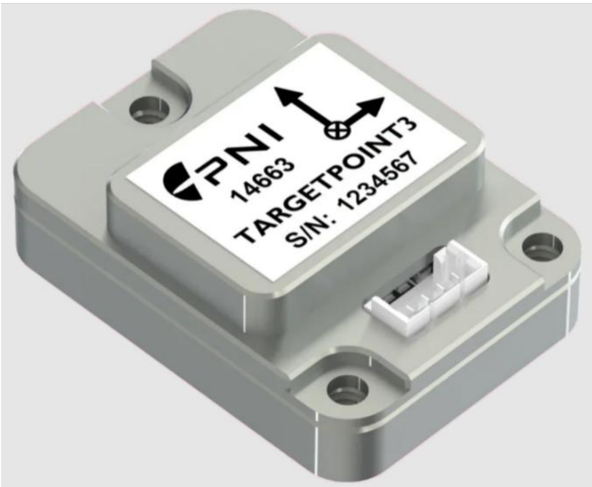


Figure 70: Digital magnetic compass for a UAV (PNI, 2024)

6. Communication System

Communication Systems in UAVs are critical for controlling the vehicle, transmitting data and ensuring mission success. These systems enable the UAV to interact with the Ground Control Station, other UAVs and aircraft and also satellites (Satellite Communication – SATCOM), with the use of antennas. The transmitter and receiver modules, the antennas and all the subsystems necessary for data transmission, are connected and relayed to the Data Processing Unit (DPU) This unit serves as the central hub where all sensor data is collected, processed and then relayed to other subsystems, including the communication module and navigation systems. The DPU is a powerful onboard computer, potentially equipped with Digital Signal Processors (DSPs) or Field-Programmable Gate Arrays (FPGAs) that process raw sensor data and turn it into usable information. Northrop Grumman RQ – 4B Global Hawk is a strategic UAV and the pride of the USAF in terms of communications, since it bears a radar in its fuselage for managing SATCOM and contributing to successful transmission of data from satellites to the GCS and back (downlink – uplink). The transmission of data is wireless, both for direct line – of – sight (LOS) and beyond – line – of – sight (BLOS) and possible through Radio – Frequency (RF) waves. The following Figures present the structure of a Communication System.

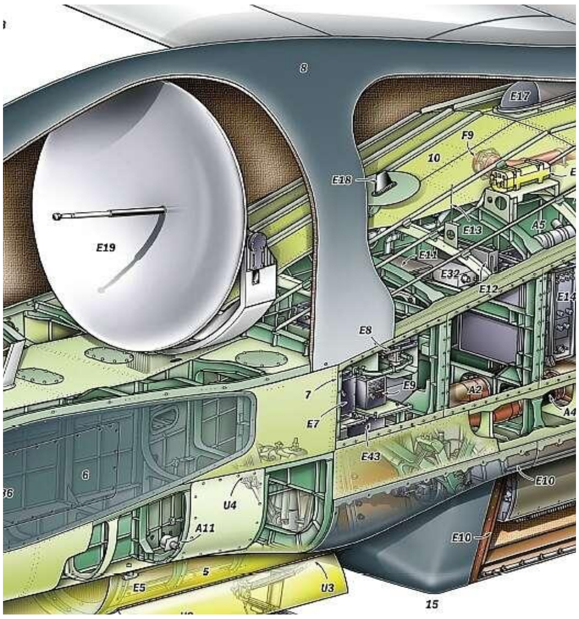


Figure 71: SATCOM radar of RQ – 4B Global Hawk (EDN, 2013)

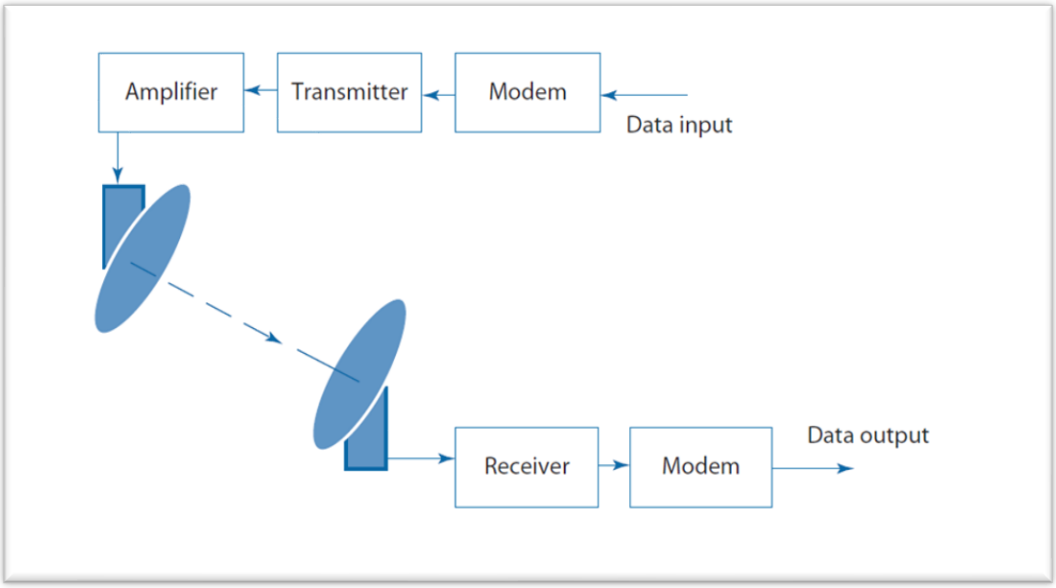


Figure 72: Block diagram of a communication system (Jay Gundlach, 2012, p. 474)

- Telemetry system: It sends real-time data back to the operator, such as altitude, speed, battery status, environmental data, system health information. The operator of a loitering munition uses telemetry data, along with live video feeds to loiter over a designated area and acquire a target.

Figure 73: Telemetry data (EDR ON-LINE, 2021)

- Command, Control and Communications (C3): In the context of UAVs, C3 represents an integrated system that allows the effective operation of the UAV, so as to operate autonomously or semi – autonomously, while maintaining a strong link with the ground control station and the operators.

7. Camera

Loitering Munitions use highly advanced EO/IR cameras, that provide high – resolution images and video both in the visible light spectrum and in low – light conditions or at night. These cameras can focus on targets at specific ranges of angles, independently of the drone's movement, providing smooth footage. A typical example is presented in the Figure below, which shows the camera of a Switchblade 300 loitering munition.

Figure 74: The Switchblade's EO/IR camera (TopWar, 2023)

8. Autopilot system

Software and hardware that enable autonomous navigation without manual input, following pre-set waypoints. The autopilot system handles critical tasks such as flight stabilization, trajectory control and mission execution without requiring continuous human intervention. Advanced sensors, onboard computers and specific algorithms allow these munitions to loiter over a designated area, scan for potential targets and autonomously execute missions when commanded or when a target is identified. Figure 75 presents an autopilot for Loitering Munitions.

Figure 75: Veronte autopilot for Loiter Munitions (EMBENTION, 2024)

9. Warhead

The existence of a warhead is the main difference between typical UAVs and Loitering Munitions and that's what makes kamikaze drones expendable. Located at the front part of the fuselage, warheads are responsible for the explosion and the destruction of the target, right after impact or even before it, as the warhead can be armed manually and explode after a specific period of time. There are many different types of warheads like (Institute for Science and International Security, 2024):

- High Explosive Fragmentation (HEFRAG): It creates a large number of fragmentation when detonated.
- Fuel Air Explosive (FAE) or Thermobaric Explosive: It uses high – temperature blast waves to create intensive overpressure, making them highly effective in enclosed spaces like bunkers or buildings.
- High Explosive Anti – Tank (HEAT): It uses directed explosive force to penetrate armored vehicles, such as tanks.
- High Explosive (HE): It causes blast damage to structures, vehicles or personnel.

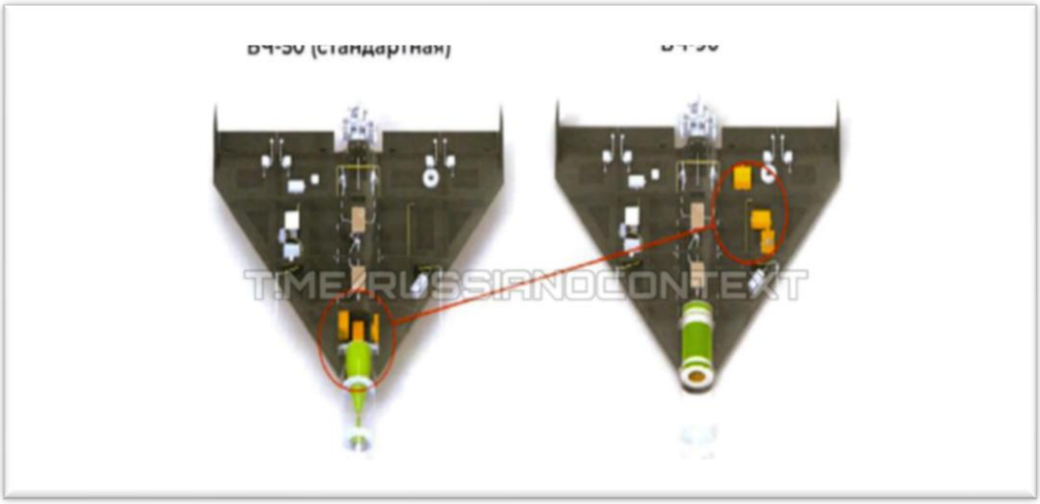


Figure 76: Installation of the warhead 90 (ISIS, 2024)

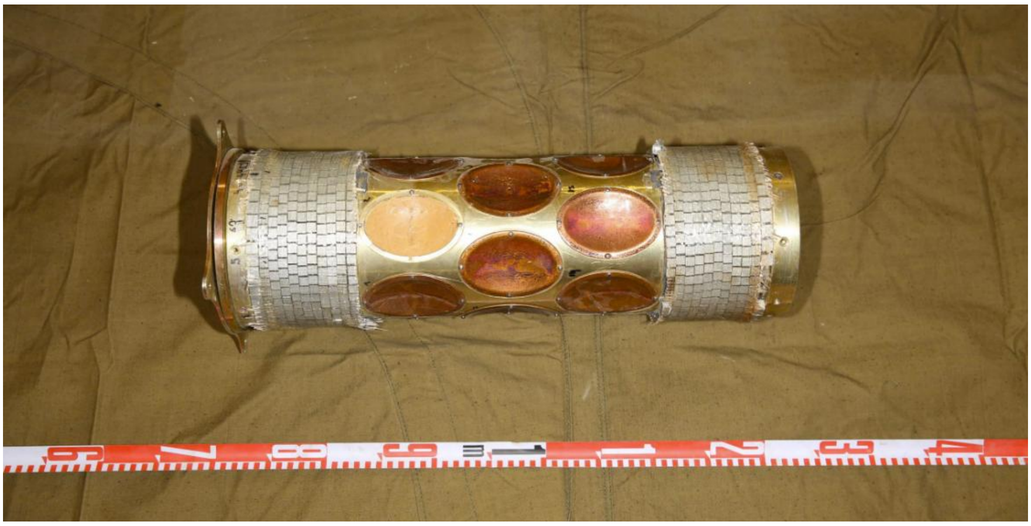


Figure 77: Warhead for the Shahed – 131 kamikaze drone (ISIS, 2024)

10. Ground Control Station (GCS)

Serving as the interface between human operators and the drone, the GCS enables real – time control and monitoring of the UAV's flight, navigation, sensors and mission systems. Equipped with advanced software, communication links and control interfaces, the GCS allows the operator to have the necessary telemetry data. The GCS can either be portable or stationary. In the case of smaller drones and loitering munitions, a smartphone, a tablet, or a small case that can be carried inside a bag can be used, like in Figures 78 and 79.

Figure 78: Portable Ground Control Station (Unmanned Systems Technology, n.d.)


Figure 79: LM's GCS (BlueBird AeroSystems, n.d.)

The Portable Ground Control Station (PGCS) comes with the following elements:

- Ground Data Terminal (GDT): It facilitates data transmission between the UAV and the GCS, by both sending commands from the ground to the drone and receiving telemetry and video data from it.

Figure 80: Ground Data Terminal (BlueBird AeroSystems, n.d.)

- Remote viewing terminal (RVT): It provides the operator with real – time live imagery, taking advantage of the loitering munition's high – tech cameras and enhances the situational awareness of the commanders. The following Figure presents the latest configuration of the RVT, the "SPOT" adopted by the U.S. Army (TEXTRON Systems, 2024). SPOT stands for Soldier Portable OSRVT.

Figure 81: One System Remote Video Terminal (OSRVT) (TEXTRON Systems, 2024)

- Locating Transmission Unit (LTU): This device is used to transmit the position or location data of the loitering munition, to the receiving station or monitoring system.

Figure 82: Locating Transmission Unit (BlueBird AeroSystems, n.d.)

- Emergency Transmission Unit (ETU): This critical component is designed to send status signals under certain emergency conditions, such as system malfunctions, mission aborts, or to relay critical data before the loitering munition completes its mission.

Figure 83: Emergency Transmission Unit (BlueBird AeroSystems, n.d.)

No	Component	Function
1	Fuselage	Payload accommodation
2	Wing	Generation of lift

3	Horizontal tail	Longitudinal stability
4	Vertical tail	Directional stability
5	Engine	Generation of thrust
6	Control surfaces	Control/Maneuverability
7	Autopilot	Control, guidance and navigation
8	Ground Control Station	Control and guidance of the UAV
9	Tube	Launch

Table 23: Major components and their function

§6.2 Calculation of weight

The very first step in manned and unmanned aircraft design is the weight calculation. It's a part of the Sizing process, a process that determines the key physical and performance characteristics of an aircraft during the early stages of its design. It involves calculating the aircraft's dimensions, weight and performance specifications to meet specific mission requirements such as payload capacity, range, speed or altitude (D. P. Raymer, 2018, pp. 41-42). Through this process, the main objective is to determine the Takeoff Gross Weight (Wo), which is the summation of the following groups of weights:

- W_{struct}: The weight of the structures
- W_{subs}: The subsystems weight
- W_{prop}: The propulsion system weight
- W_{avion}: The avionics weight
- $W_{payload}$: The payload weight
- W_{batt}: The battery's weight (for electric powered drones)

(W_{struct}, W_{subs}, W_{prop}, W_{avion} } W_e)

To sum up, the total weight (MTOM) of the loitering munition, will be:

$$m = m_e + m_p + m_b \qquad \text{(eq. 6.4.1)}$$

The specifications for this part of the analysis are already presented in Table 14 in 5.2. Furthermore, we will also need data from the following Table:

Aircraft type	A_{factor} (metric)	C_{factor}
Sailplane-unpowered	0.83	-0.05
Sailplane-powered	0.88	-0.05
Homebuilt-metal/wood	1.11	-0.09
Homebuilt-composite	1.07	-0.09
General aviation-single engine	2.05	-0.18
General aviation-twin engine	1.4	-0.1
Agricultural aircraft	0.72	-0.03
Twin turboprop	0.92	-0.05
Flying boat	1.05	-0.05
Jet trainer	1.47	-0.1
Jet fighter	2.11	-0.13
Military cargo/bomber	0.88	-0.07

Jet transport	0.97	-0.06
UAV-tac recce & UCAV	1.47	-0.16
UAV-high altitude	2.39	-0.18
UAV-small	0.93	-0.06

Table 24: Empty weight vs total weight (D.P. Raymer, 2018, p. 31)

For a small UAV, A_{factor} = 0.93 and C_{factor} = -0.06

We are going to use the Battery Mass Fraction (BMF) methodology for electric aircraft initial sizing (D. P. Raymer, 2018, pp. 757-760).

This methodology, takes into account 4 cases, where different amounts of energy are consumed.

- BMF, Known Run-Time:

$$BMF_{KNOWN\ RUN\ TIME} = \frac{m_b}{m} = \frac{W_b}{W_0} = \frac{1000 \cdot E_{runtime}}{E_{sb} \cdot n_{b2s}} \cdot \left(\frac{P_{used}}{m}\right)cr, \quad \text{(eq. 6.4.2)}$$

Where:

$E_{runtime}$ = ttotal: Total flight time (h)

n_{b2s}: Total system efficiency from battery to motor output shaft

E_{sb}: Battery specific energy (Wh/kg)

P_{used}: Average power used during that period of time (kW)

- BMF, Climb:

$$BMF_{CLIMB} = \frac{m_b}{m} = \frac{W_b}{W} = \frac{h\_c}{3{,}6 \cdot V_{V_V} \cdot E_{sb} \cdot n_{b2s}} \cdot \left(\frac{P_{used}}{m}\right)cl \quad \text{(eq. 6.4.3)}$$

- BMF, Cruise:

$$BMF_{CRUISE} = \frac{m_b}{m} = \frac{W_b}{W} = \frac{R \cdot g}{3{,}6 \cdot E_{sb} \cdot n_{b2s} \cdot n_p \cdot \frac{L}{D}} \quad \text{(eq.6.4.4)}$$

Where:

R: Range (km)

g: Acceleration of gravity (g = 9.81 m/s^2)

- BMF, Loiter:

$$BMF_{LOITER} = \frac{m_b}{m} = \frac{W_b}{W} = \frac{E \cdot V \cdot g}{3{,}6 \cdot E_{sb} \cdot n_{b2s} \cdot n_p \cdot \frac{L}{D}}, \quad \text{(eq. 6.4.5)}$$

Where:

n_p: Propeller efficiency

E: Loiter time (hours)

As for the required Power, according to D. P. Raymer, P_{used} is the necessary power for climbing and the maximum constant power, provided by a specific engine. A propeller mounted drone, gets the most efficient loiter at a speed that corresponds to an L/D of 86.6% of the maximum L/D (D. P. Raymer, 2018, p. 41).

$$(\frac{P_{used}}{m})_{cruise} = \frac{T}{W} = \frac{10^{-3}}{L/_D} \ (\frac{kW}{kg}), \qquad \text{(eq. 6.4.6)}$$

$$(\frac{P_{used}}{m})_{climb} = \frac{T}{W} = \frac{10^{-3}}{0{,}866(L/_D)} \ (\frac{kW}{kg}), \qquad \text{(eq. 6.4.7)}$$

The Lift-to-Drag ratio (L/D), is a critical metric in aerodynamics that measures the efficiency of an aircraft or a UAV, including loitering munitions. It represents the amount of lift, generated per unit of drag. A higher L/D ratio, means that the vehicle is more aerodynamically efficient, requiring less power to maintain altitude and velocity, which is crucial for maximizing endurance and range. The maximum value for L/D is equal to:

$$\frac{L}{D_{max}} = K_{LD}\sqrt{\frac{A}{(S_{wet}/S_{ref})}}, \qquad \text{(eq. 6.4.8)}$$

Where:

K_{LD}: A constant* (D. P. Raymer, 2018, p. 40)

A: Aspect ratio

S: Reference area (m^2)

S_{wet}: Wetted area (m^2)

For the estimation of this ratio, D. P. Raymer proposes a historical data-based method. The following Figures are used during the estimation of S_{wet}/S_{ref} and A.

Aircraft type	**K_{LD}**
Civil jets	15.5
Military jets	14
Retractable prop aircraft	11
Non retractable prop aircraft	9
High-aspect-ratio aircraft	13
Sailplanes	15

Table 25: K_{LD} values for various types of aircraft

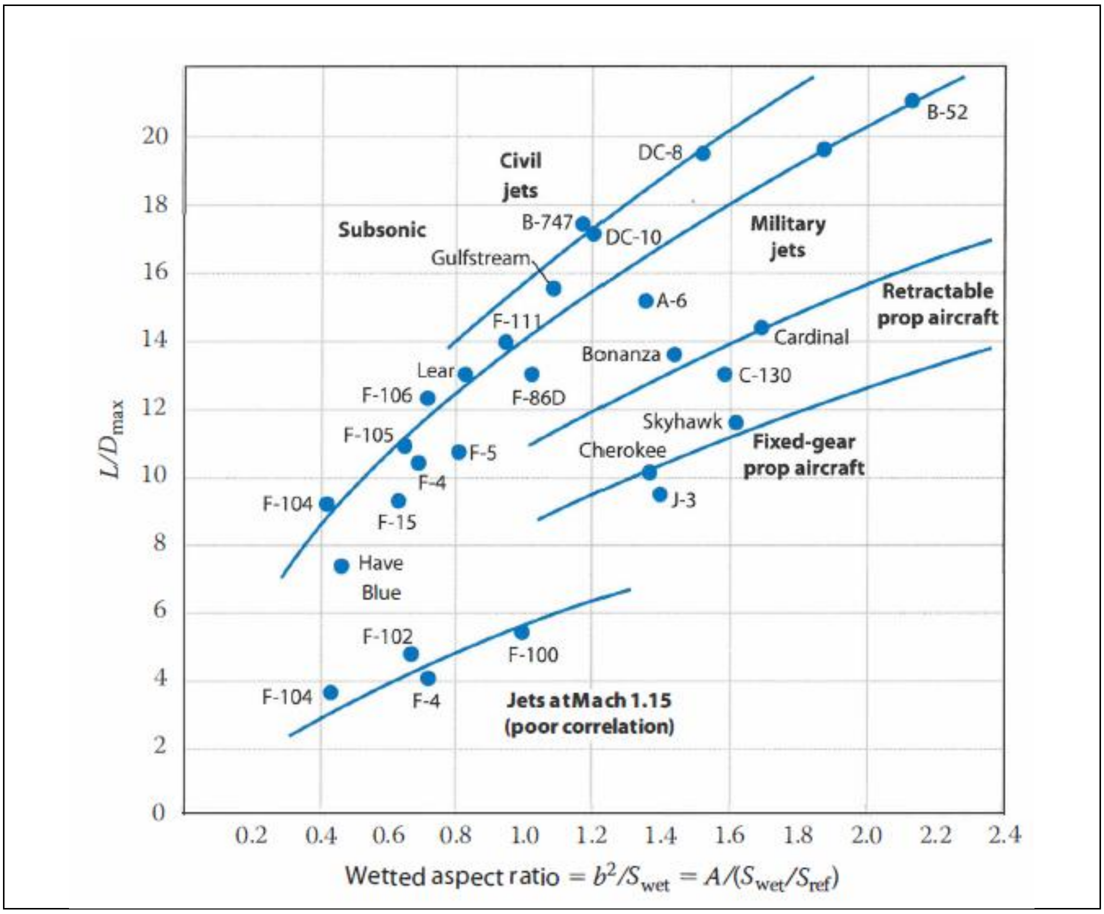


Figure 84: Maximum lift-to-drag ratio trends (D. P. Raymer, 2018, p. 39)

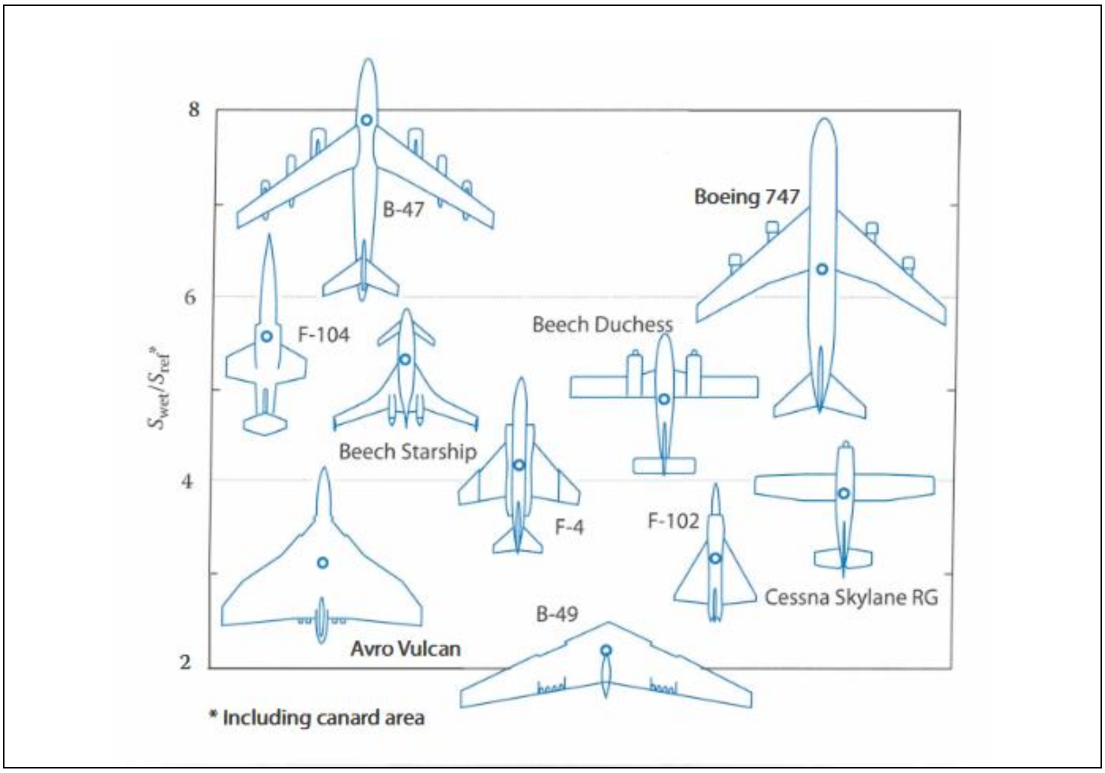


Figure 85: Wetted area ratios (D. P. Raymer, 2018, p. 40)

Propeller Aircraft	Equivalent Aspect Ratio
Homebuilt	6.0
General aviation – single engine	7.6
General aviation – twin engine	7.8
Agricultural aircraft	7.5
Twin turboprop	9.2
Flying boat	8.0
Micro UAV (Class 1)	<1.0
Mini UAV (Class 1)	1 to 3
Small UAV (Class 1)	4.0 to 8.0

Table 26: Aspect ratio (D. P. Raymer, 2018, p. 78)

To calculate the BMF_{TOTAL}:

$$BMF_{TOTAL} = BMF_{KNOWN\ RUN\ TIME} + BMF_{LOITER} + BMF_{CRUISE} + BMF_{CLIMB}, \qquad \text{(eq. 6.4.9)}$$

$$BMF_{available} = \frac{m_0 - m_e - m_{payload}}{m_0} = \frac{W_0 - W_e - W_{payload}}{W_0}, \qquad \text{(eq. 6.4.10)}$$

From (eq. 6.4.1) and (eq. 6.4.10):

$$W_{calculated} = \frac{W_{payload}}{1 - BMF - \frac{W_e}{W_0}}\ (kg), \qquad \text{(eq. 6.4.11)}$$

From Figure 85, we assume that the configuration of our loitering munition will look like the Beech Duchess or the Cessna Skyline RG model. For a conventional configuration and non-retractable prop aircraft, we have:

$S_{wet}/S_{ref} = 5$

$A = 6$ and $K_{LD} = 11$

During the design process, there might be some changes that will affect our initial assumptions, such as the aspect ratio, the surface area or the wingspan.

From (eq. 6.4.8):

$$\frac{L}{D_{max}} = K_{LD}\sqrt{\frac{A}{(S_{wet}/S_{ref})}} = 11\sqrt{\frac{6}{5}} = 12.045$$

So, from (eq. 6.4.6) and (eq. 6.4.7):

$$\left(\frac{P_{used}}{m}\right)_{cruise} = \frac{T}{W} = \frac{10^{-3}}{L/D} = \frac{10^{-3}}{12.045} = 8.3 * 10^{-5}\left(\frac{kW}{kg}\right)$$

$(\frac{P_{used}}{m})_{climb} = \frac{T}{W} = \frac{10^{-3}}{0,866(^{L}/_{D})} = \frac{10^{-3}}{0,866*12.045} = 9.5 * 10^{-5} \left(\frac{kW}{kg}\right)$

In a prop driven aircraft and UAV, the propeller can be assumed as a wing, hence it generates lift. Taking into account the drag that is created, a propeller cannot reach its 100% efficiency, so we assume that its efficiency is about 75 – 85% (Mohammad H. Sandraey, 2013, p. 456).
As a result:

$n_p = 0.75$ and $n_{b2s} = 0.85$

Where:

n_p : Propeller efficiency

n_{b2s} : Total system efficiency from battery to motor output shaft

As for the battery efficiency, we can consult the following Table that contains three types of LiPO batteries that could be used for our drone and calculate the average efficiency of them.

No	Battery	Price (€)	Features	E_{sb} (Wh/kg)*
1	Turnigy Heavy Duty 5200mAh 3S 60C LiPo Battery Pack w/EC5	26.30	Capacity: 5200mAh Configuration: 3S1P/11.1V/3 Cell Discharge: 60C/120C (Burst) Dimension: 160x46x25mm Weight: 404g	57.72
2	Turnigy Heavy Duty 6200mAh 3S 60C LiPo Battery Pack w/XT90	38.26	Capacity: 6200mAh Voltage: 3S1P / 3 Cell / 11.1V Discharge: 60C/120C Burst Weight: 465g Dimensions: 160x46x30 mm	68.82
3	Turnigy Graphene Panther 1200mAh 6S 75C Battery Pack w/XT60	23.35	Capacity: 1200mAh Cell Count: 6 Voltage: 22.2V Constant Discharge: 75C Peak Discharge (3s): 150C Battery Size: 75x35x45mm Weight: 232g	26.64

Table 27: Types of LiPO batteries

*For the calculation of E_{sb}, we use the equation below:

$$Energy\ (Wh/kg) = Voltage\ (V) \times\ Capacity\ (Ah) \qquad \text{(eq. 6.4.12)}$$

Average efficiency: E_{sb} = 51.06 Wh/kg

Considering that we have chosen the third battery, in order to fit in the fuselage, we have:

$W_{battery}$ = 0.232 kg and E_{sb} = 26.64 Wh/kg

As for the BMF_{total}, from (eq 6.4.9):

BMF_{total} = 157.7 * 10^{-5} + 3534 * 10^{-5} + 10657 * 10^{-5} +30.03 * 10^{-5} =>

- ⇨ BMF_{total} = 0.1437873

From eq. (6.4.1):

$m = m_e + m_p + m_b$ =>

- ⇨ $W_e = W_o - W_b - W_p$
- ⇨ $\frac{We}{Wo} = 1 - \frac{Wp}{Wo} - \frac{Wb}{Wo}$ (eq. 6.4.13)

For the initially selected value of W_0 = 2.5 kg, the empty weight fraction is equal to 0.707, so we can approximately consider:

$\frac{We}{Wo} = 0.71$

The value is close to the value proposed by Raymer in p. 30 from (D. P. Raymer, 2018).
From eq. (6.4.11), for W_o = 2.5 kg:

$W_{calculated}$ = 3.42 kg (>2.5)

The calculated weight is bigger than the predetermined, so we need to change our assumption about W_o. At this point, we have to calculate the fraction $\frac{We}{Wo}$ and start guessing the value for W_o, using the equation (6.4.13). Then, from eq. (6.4.11), we will calculate the weight of the loitering munition. We will continue this process, until we reach our initial requirement (2.5 kg).

$W_{o,guess}$ (kg)	W_e/W_o	$W_{calculated}$ (kg)
1.5	0.512	1.45
1.6	0.542	1.59
1.7	0.569	1.74
1.8	0.593	1.89
1.9	0.614	2.06
2	0.634	2.25
2.1	0.651	2.43
2.2	0.667	2.64

Table 28: Weight calculation data

From the process above, we see that for $W_{o,guess}$ = 2.1 kg, we have the $W_{calculated}$ that we want. (2.43 ≈ 2.5). Alternatively, we could use a special Excel Sheet, created to simplify this process by using data and creating charts that help us visualise the results (E. Karatzas, V. Kostopoulos and V. Lappas, 2022).

The results of the process above, for the selected battery, are the following:

Wh/kg	BMF_{total}	We/Wo	$W_{payload}$ (kg)	$W_{o\ guess}$ (kg)	$W_{o\ calculated}$ (kg)
26.64	0.1437873	0.65	0.5	2.1	2.5

Table 29: Results from the weight calculation process

§6.3 Calculation of W/S and W/P

W/S and W/P are referred to as wing loading and power loading respectively. To begin with, we are going to need the following tables:

The International Standard Atmosphere

Elevation - z - (m) (ft)	Temperature - T - (K) (°F) (°C)	Pressure - p - (bar) (psi) (kPa)	Relative Density - ρ/ρ_o - Density - ρ (Kg/m3)	Kinematic Viscosity - ν - x 10^{-5} (m^2/s)	Thermal Conductivity - k - x 10^{-2} (W/m K)	Speed of Sound - c - (m/s)
-2000	301.2 28.2	1.2778 128	1.2067 1.48	1.253	2.636	347.9
-1500	297.9 24.9	1.2070 121	1.1522 1.41	1.301	2.611	346.0
-1000	294.7 21.7	1.1393 114	1.0996 1.35	1.352	2.585	344.1
-500	291.4 18.4	1.0748 107	1.0489 1.28	1.405	2.560	342.2
0	288.15 15.1	1.01325 101	1.0000 1.23	1.461	2.534	340.3
500	284.9 11.9	0.9546 95.5	0.9529 1.17	1.520	2.509	338.4
1000	281.7 8.7	0.8988 89.9	0.9075 1.11	1.581	2.483	336.4
1500	278.4 5.4	0.8456 84.6	0.8638 1.06	1.646	2.457	334.5
2000	275.2 2.2	0.7950 79.5	0.8217 1.01	1.715	2.431	332.5
2500	271.9 -1.1	0.7469 74.7	0.7812 0.957	1.787	2.405	330.6
3000	268.7 -4.3	0.7012 70.1	0.7423 0.909	1.863	2.379	328.6
3500	265.4 -7.6	0.6578 65.8	0.7048 0.863	1.943	2.353	326.6
4000	262.2 -10.8	0.6166 61.7	0.6689 0.819	2.028	2.327	324.6

Table 30: The International Standard Atmosphere (ISA) (The Engineering Toolbox, 2020)

Aircraft type	$C_{L\ max,CLEAN}$	$C_{L\ max,TO}$	$C_{L\ max,L}$
Home-built	1.2-1.8	1.2-1.8	1.2-2.0
Single engine prop	1.3-1.9	1.3-1.9	1.6-2.3
Twin engine prop	1.2-1.8	1.4-2.0	1.6-2.5
Agricultural	1.3-1.9	1.3-1.9	1.3-1.9
Business	1.6-1.8	1.6-2.2	1.6-2.6

Turbo-Prop	1.5-1.9	1.7-2.1	1.9-3.3
Transport Jet	1.2-1.8	1.6-2.2	1.8-2.8
Military training	1.2-1.8	1.4-2.0	1.6-2.2
Fighters	1.2-1.8	1.4-2.0	1.6-2.6
Military Patrol, Bomb and Transports	1.2-1.8	1.6-2.2	1.8-3.4
Flying Boats, Amphibious, Float Airplanes	1.2-1.8	1.6-2.2	1.8-3.4
Supersonic cruise	1.2-1.8	1.6-2.0	1.8-2.2

Table 31: Coefficients of lift for different aircraft types (Roskam, 1985, p. 91)

Aircraft type	C_{Do}
Jet transport	0.0015-0.02
Turboptop transport	0.018-0.024
Twin-engine piston prop	0.022-0.028
Small GA with fixed landing gear	0.02-0.03
Small GA with fixed landing gear	0.025-0.04
Agricultural	0.04-0.07
Sailplane/glider	0.012-0.015
Supersonic fighter	0.018-0.035
Home-built	0.025-0.04
Microlight	0.02-0.035
Fixed-wing UAV-Retractable landing gear	0.02-0.03
Fixed-wing UAV-Fixed landing gear	0.03-0.045

Table 32: Zero drag coefficients for different aircraft types (Polymers, 2023) and (Sandraey, 2020, p. 45)

Wing loading is a measure of how much weight a wing must support per unit area. It affects flight characteristics like lift, drag, takeoff distance and maneuverability. It is defined as the following ratio:

$$\frac{w}{s} = \frac{Total\ weight\ of\ the\ aircraft}{Wing\ area} \quad \text{(eq. 6.5.1)}$$

Power loading is a ratio that represents the amount of weight an aircraft has relative to its available power. It affects flight characteristics like thrust, acceleration and rate of climb. It is also known as weight-to-power ratio and defined as:

$$\frac{w}{P} = \frac{Total\ weight\ of\ the\ aircraft}{Power\ Output} \quad \text{(eq. 6.5.2)}$$

The basic parameters for this step are the following (Mohammad H. Sandraey, 2013, p. 114):

- Stall speed (V_s)
- Maximum speed (V_{max})
- Maximum rate of climb (ROC_{max})
- Ceiling (h_c)

For level flight with specific airspeed, the Lift force is equal to Weight and the Thrust is equal to Drag:

$$L = W = qSC_L = \frac{1}{2}\rho V^2 SC_L$$ (eq. 6.5.3)

$$T = D = \frac{1}{2}\sigma\rho_{SL} V^2 SC_D$$ (eq. 6.5.4)

Where:

q: The dynamic pressure (kg/m^2)

V: Velocity (m/s)

S: The surface area (m^2)

ρ: The air density depending on the altitude (kg/m^3)

Divided by the surface area (S), eq. (6.5.3) gives:

$$\left(\frac{W}{S}\right)_{Vs} = \frac{1}{2}\rho V_{stall}^2 C_{L_{max}}$$ (eq. 6.5.5)

The Power is given by:

$$P = \frac{TV}{n_p}$$ (eq. 6.5.6)

- **Stall speed**

In a very light aircraft, according to (Mohammad H. Sandraey, 2013, p. 120), the stall speed lies within the following restrictions:

Vs ≤ 61 knot or 31.38 m/s (FAR 23) (eq. 6.5.7)

Vs ≤ 45 knot or 23.15 m/s (EASA-CS VLA) (eq. 6.5.8)

We assume that our loitering munition has even lower stall speed (V_s):

V_s = 40 km/h (or 11.11 m/s)

$$V_{stall} = \sqrt{\frac{2(\frac{W}{S})}{\rho C_{L_{max}}}} =>$$ (eq. 6.5.9)

$$=>\left(\frac{W}{S}\right)_{Vs} = \frac{1}{2}\rho V_{stall}^2 C_{L_{max}} = \frac{1}{2} * 1.17 * 123.21 * 1.2 =>$$

=> $\left(\frac{W}{S}\right)_{Vs}$ = 86.649 N/m²

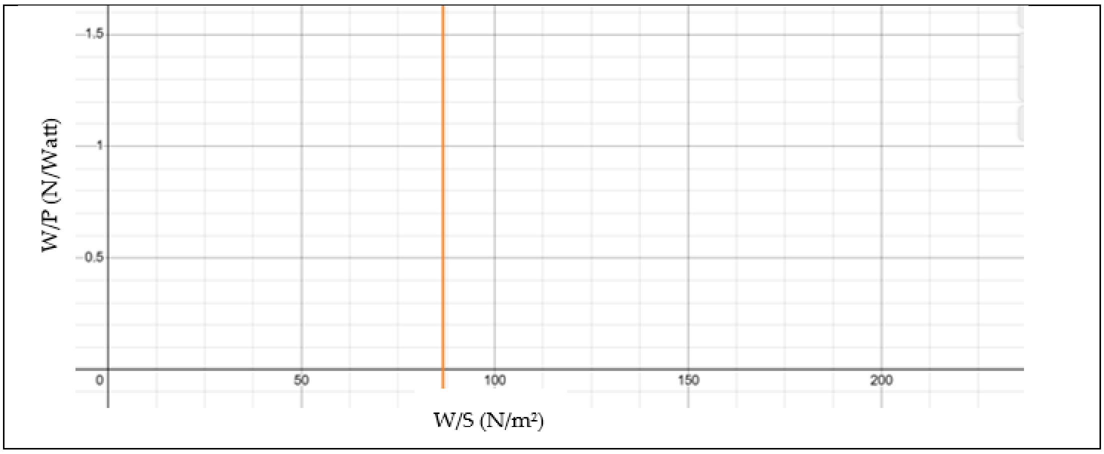


Figure 86: Stall speed contribution in constructing the matching plot

- **Maximum speed (V_{max})**

$$\left(\frac{W}{P}\right)max = \frac{np}{\frac{1}{2}*\rho o*V_{max}^3*C_{Do}*\frac{1}{\left(\frac{W}{S}\right)}+\frac{2*K}{\rho*\sigma*V_{max}}*\left(\frac{W}{S}\right)} \quad \text{(eq. 6.5.10)}$$

Where:

ρ_o: air density at sea level (ρ_o = 1.225 kg/m³)

V_{max}: maximum speed

C_{Do}: zero-lift drag coefficient (From Table 32, we assume that C_{Do} = 0.025)

σ: relative air density at flight altitude ($\sigma = \frac{\rho}{\rho o} = \frac{1.17}{1.225} = 0.95$)

K: induced drag factor ($K = \frac{1}{\pi*e*A} = \frac{1}{3.14*0.8*6} = 0.066$)

e: Oswald span efficiency factor $0,7 \leq e \leq 0.95$ (We assume that e = 0.8)

According to (Mohammad H. Sandraey, 2013, p. 126), we assume that the maximum speed is 20 – 30% greater than the cruise speed, because in prop – driven aircraft, cruise speed is calculated at 75 – 80% power. So,

V_{max} = 1.2 V_{cr} to 1.3 V_{cr} (eq. 6.5.11)

By inserting the values to (eq. 6.5.10):

$$\left(\frac{W}{P}\right)max = \frac{np}{\frac{1}{2}*\rho o*V_{max}^3*C_{Do}*\frac{1}{\left(\frac{W}{S}\right)}+\frac{2*K}{\rho*\sigma*V_{max}}*\left(\frac{W}{S}\right)} = \frac{0.75}{\frac{1}{2}*1.225*10970.64*0.025*\frac{1}{\left(\frac{W}{S}\right)}+\frac{2*0.066}{1.17*0.95*22.22}*\left(\frac{W}{S}\right)} =$$

$$\frac{0.75}{167.97*\frac{1}{\left(\frac{W}{S}\right)}+\frac{0.132}{24.69}*\left(\frac{W}{S}\right)} => \left(\frac{W}{P}\right)max = \frac{0.75}{167.97*\frac{1}{\left(\frac{W}{S}\right)}+0.0053*\left(\frac{W}{S}\right)} \quad \text{(eq. 6.5.12)}$$

The equation above, gives the following chart:

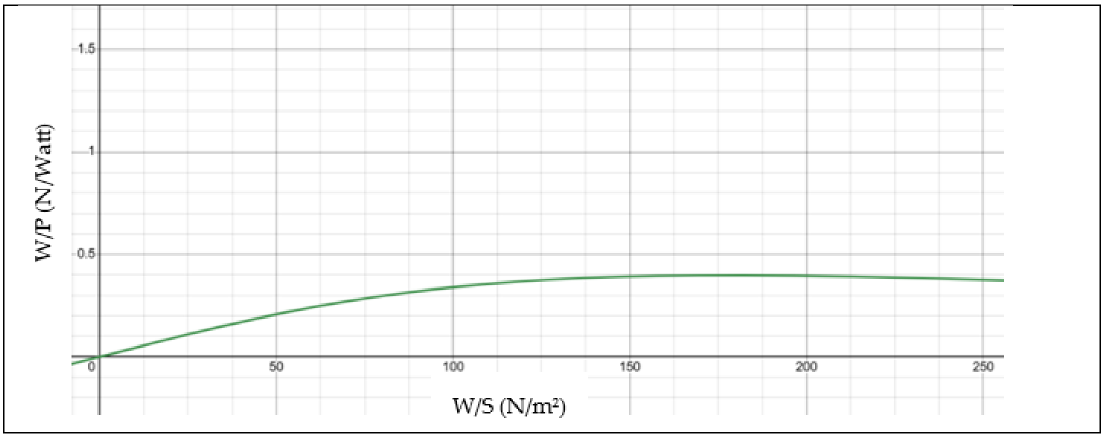


Figure 87: Maximum speed contribution in constructing the matching plot for a prop-driven aircraft

- **Rate of climb (ROC)**

The Rate of climb refers to the speed at which an aircraft gains altitude. Every aircraft type, has to meet specific requirements in terms of this rate. The equation that describes that rate is the following:

$$\left(\frac{W}{P}\right) Roc = \frac{1}{\frac{ROC}{np} + \sqrt{\frac{2}{\rho * \sqrt{\frac{3CDo}{K}}} * \left(\frac{W}{S}\right)} * \frac{1.155}{(\frac{L}{D})max * np}} \quad \text{(eq. 6.5.13)}$$

For $\left(\frac{L}{D}\right) max$ = 12.045 and ROC = V_{cl} = 7 km/h = 1.94 m/s, (eq. 6.5.13) becomes:

$$\left(\frac{W}{P}\right) Roc = \frac{1}{\frac{1.94}{0.75} + \sqrt{\frac{2}{1.17 * \sqrt{\frac{3 * 0.025}{0.066}}} * \left(\frac{W}{S}\right)} * \frac{1.155}{12.045 * 0.75}} = \frac{1}{2.58 + 1.26 * \sqrt{(\frac{W}{S})} * \frac{1.155}{8.03375}} = \frac{1}{2.58 + 0.16 * \sqrt{(\frac{W}{S})}} , \quad \text{(eq. 6.5.14)}$$

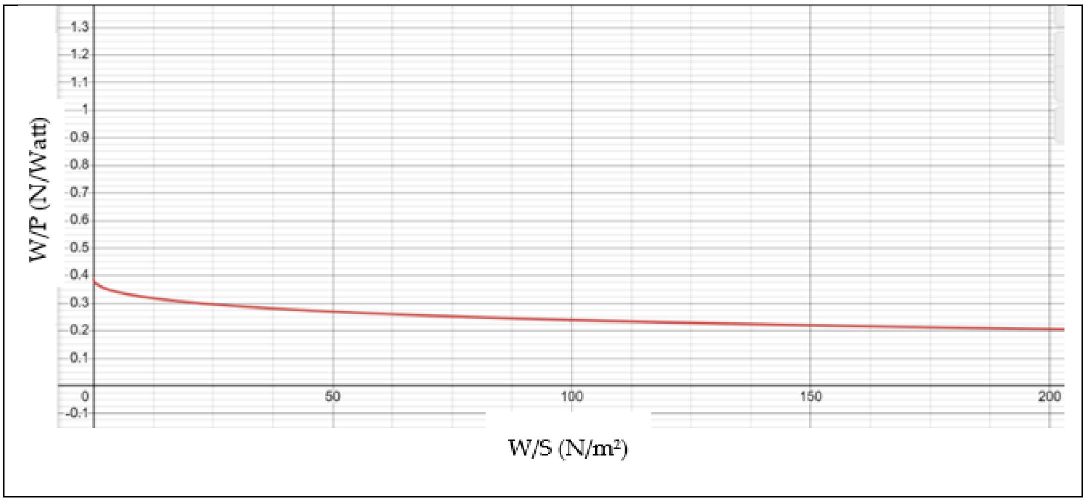


Figure 88: Rate of climb contribution to constructing the matching plot for a prop-driven aircraft

- **Ceiling**

The ceiling is defined as the highest altitude that an aircraft can safely have a straight level flight. Another definition is the highest altitude that an aircraft can reach by its own engine and have sustained flight (Mohammad H. Sandraey, 2013, p. 140). There are four types of ceiling:

- Absolute ceiling (h_{ac}): The maximum altitude an aircraft can reach where its rate of climb drops to zero.
- Service ceiling (h_{sc}): The altitude where an aircraft can maintain a climb rate of 100 ft/min.
- Cruise ceiling (h_{cc}): The altitude at which an aircraft can climb with a rate of 300 ft/min.
- Combat ceiling (h_{cc}): The altitude at which an aircraft can climb with a rate of 500 ft/min.

The power loading at the absolute ceiling (h_{ac}), where (ROC_{AC}) = 0, can be calculated if we eliminate the first term of the denominator of equation (6.5.13):

$$\left(\frac{W}{P}\right)_c = \frac{\sigma}{\sqrt{\frac{2}{\rho\sqrt{\frac{3CDo}{K}}}*\left(\frac{W}{S}\right)}*\left(\frac{1.155}{\left(\frac{L}{D}\right)\max*np}\right)} \quad \text{(eq. 6.5.15)}$$

After the calculations, eq. (6.5.15) becomes:

$$\left(\frac{W}{P}\right)_c = \frac{0.95}{1.265*\sqrt{\left(\frac{W}{S}\right)*0.127}} = \frac{0.95}{0.16*\sqrt{\left(\frac{W}{S}\right)}} \quad \text{(eq. 6.5.16)}$$

The equation above, gives the following chart:

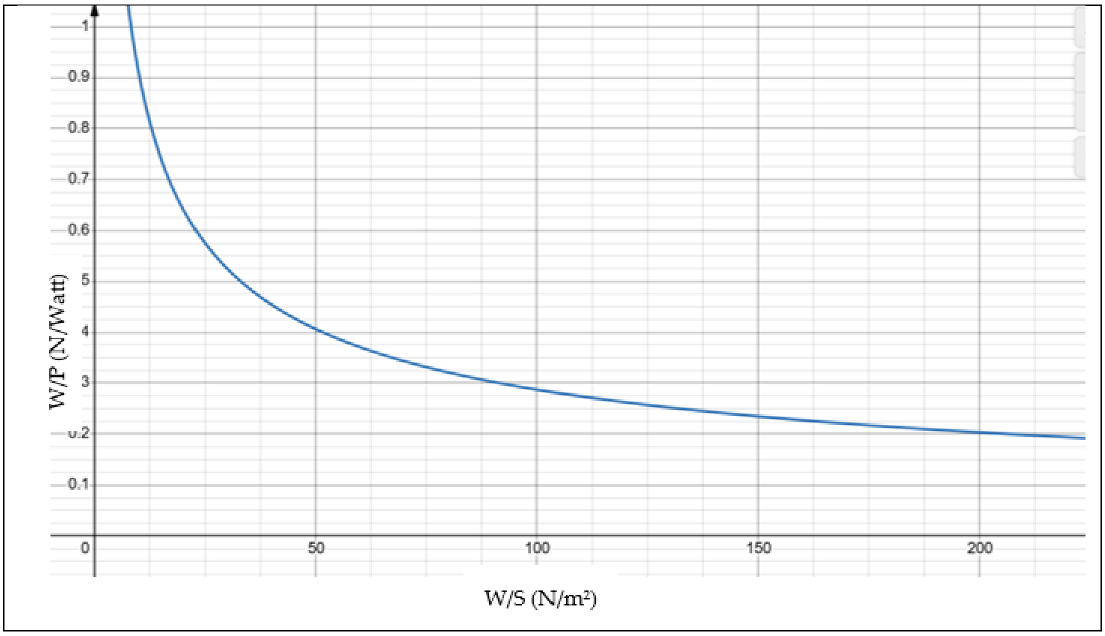


Figure 89: Ceiling contribution in constructing the matching plot for a prop-driven aircraft

In the (S.I.) system, the unit of measurement for the ROC is (m/s), for W is (N), for P is (W), for S is (m^2) and for ϱ is (kg/m^3).

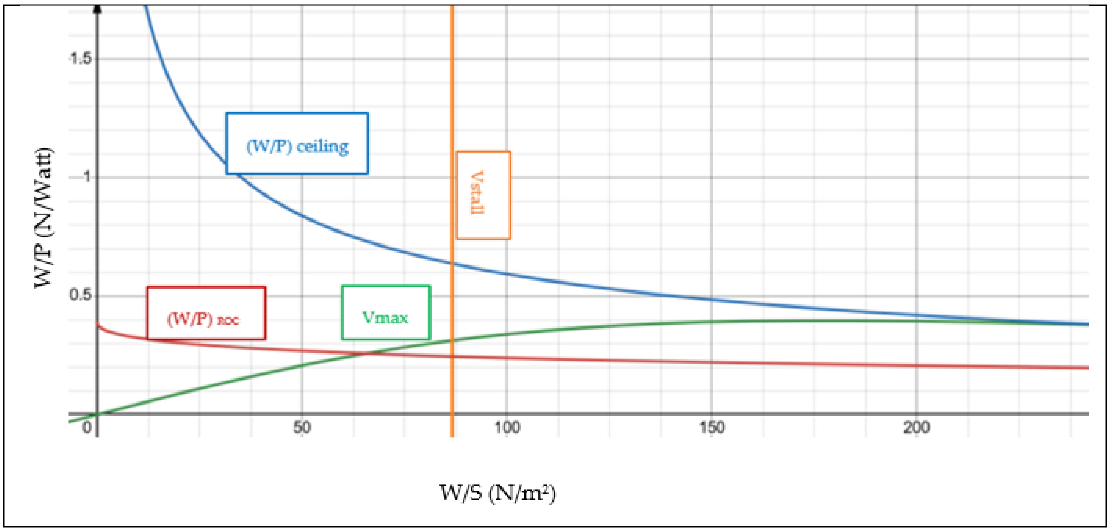


Figure 90: Matching plot

After the construction of the matching plot, which is a combination of Figures 86, 87, 88 and 89, we can define the area that fulfills our requirements. In each graph, the region below the graph, is satisfying the performance requirements. In Figure 86, the region on the left side of the equation $y = 86.649$, is allowable, hence, the region below the maximum speed, the ceiling and the ROC, is the target area. In this region, we are looking for the smallest engine (lowest power) that has the lowest operating cost. The desired point is the highest point of this region and is designated in the Figure below:

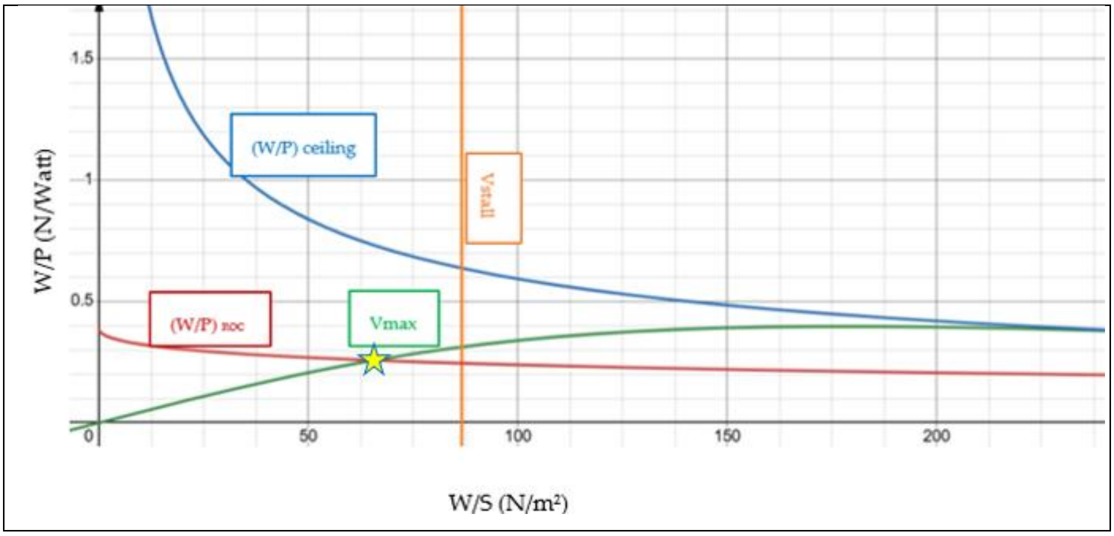


Figure 91: The design point

From the Figure above, we can see that at the design point:

$\frac{W}{P} = 0.257984\ N/Watt$

$\frac{W}{S} = 65.63094\ N/m^2$

We have already calculated W_{TO} = 2.5 kg, so we can find the wing area (S) and the power of the engine (P).

$W_{TO} = m_{TO} * g = 2.5 * 9.81 = 24.525$ N

$S = \frac{W_{TO}}{\frac{W}{S}} = 0.3736804623\ m^2$

$P = \frac{W_{TO}}{\frac{W}{P}} = 95.0640349789$ Watt

§6.4 Wing Design

The first part of an aircraft or a fixed – wing drone that is being designed, is the wing. It is the part that generates lift and allows the air vehicle to fly. The designer has to take into consideration a variety of different parameters, such as the number of wings, the reference area (S_w), the vertical position and many more. According to M. H. Sandraey, these key parameters are the following:

Parameters
Wing reference area (S_w)
Number of wings
Vertical position relative to the fuselage
Horizontal position relative to the fuselage

Cross-section
Aspect ratio (A)
Taper ratio (λ)
Tip chord (C_t)
Root chord (C_r)
Mean aerodynamic chord (MAC or $\bar{C}$)
Wingspan (b)
Twist angle (or washout) (a_t)
Sweep angle (Λ)
Dihedral angle (Γ)
Incidence (iw)
High-lifting devices such as flap
Aileron
Other wing accessories

Table 33: Wing design parameters (Mohammad H. Sandraey, 2013, p. 162)

After the definition of the parameters, the wing design procedure is presented in the Figure below:

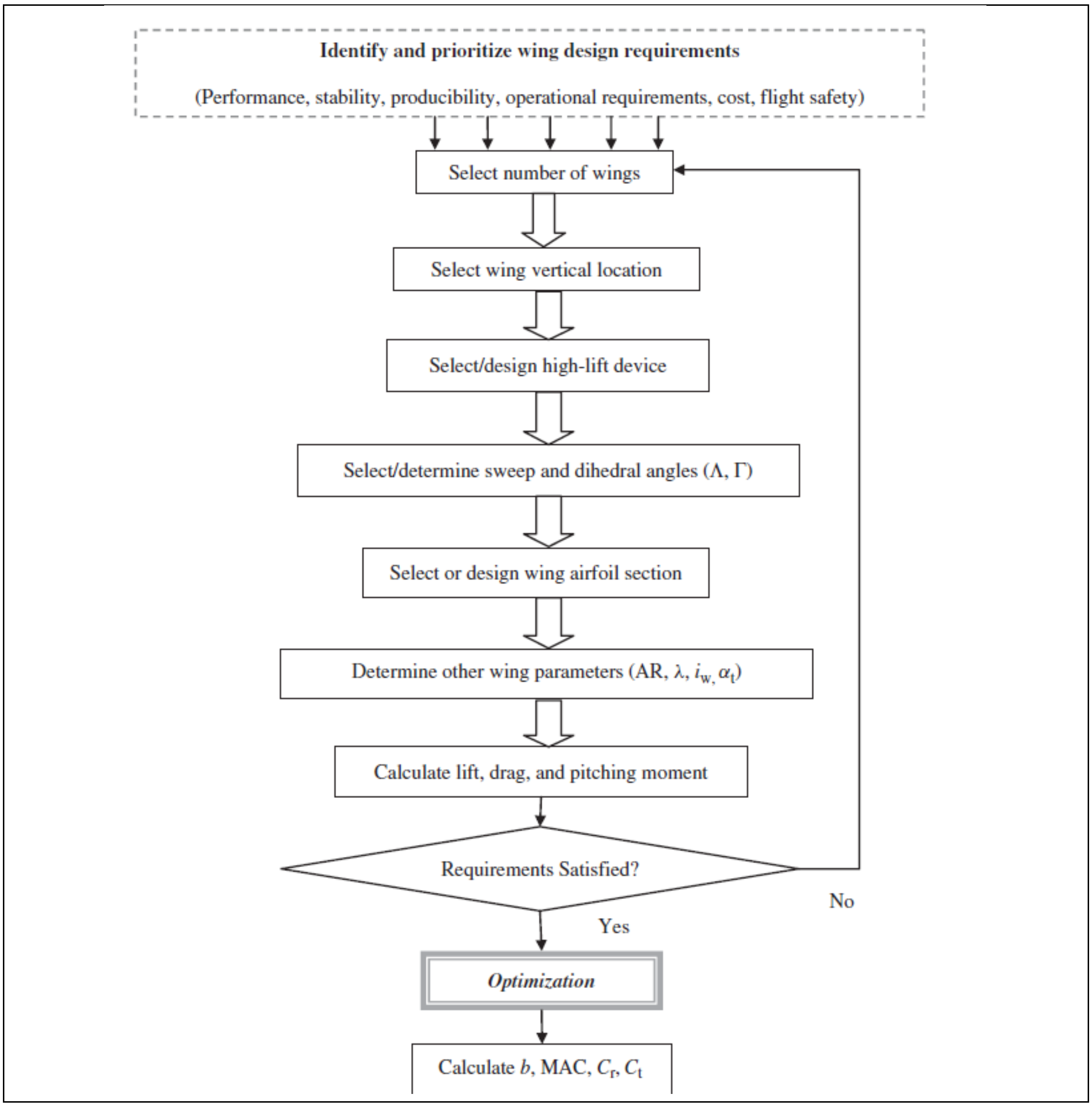


Figure 92: Wign design process (Mohammad H. Sandraey, 2013, p. 163)

1. **Wing reference area (S_w)**

   The AR is already assumed as 6

2. **Number of wings**

For the conventional configuration of the loitering munition, a single wing that includes both left and right section is the best option. The front view of a monoplane is depicted below:

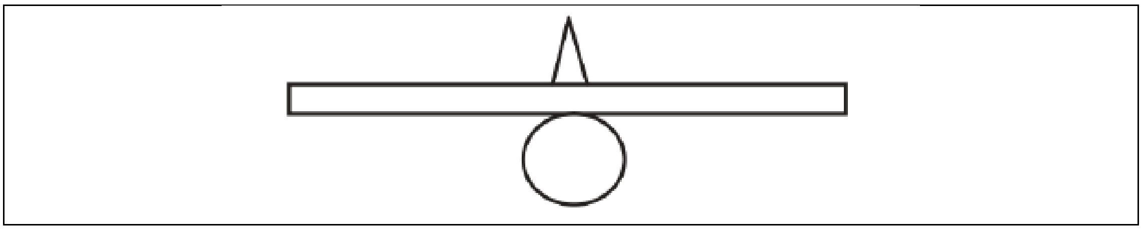


Figure 93: One main wing (Mohammad H. Sandraey, 2013, p. 164)

3. Vertical position relative to the fuselage

The position of this main wing could be either on top of the fuselage, right at the center of it, or at the bottom, as presented in the Figure below:

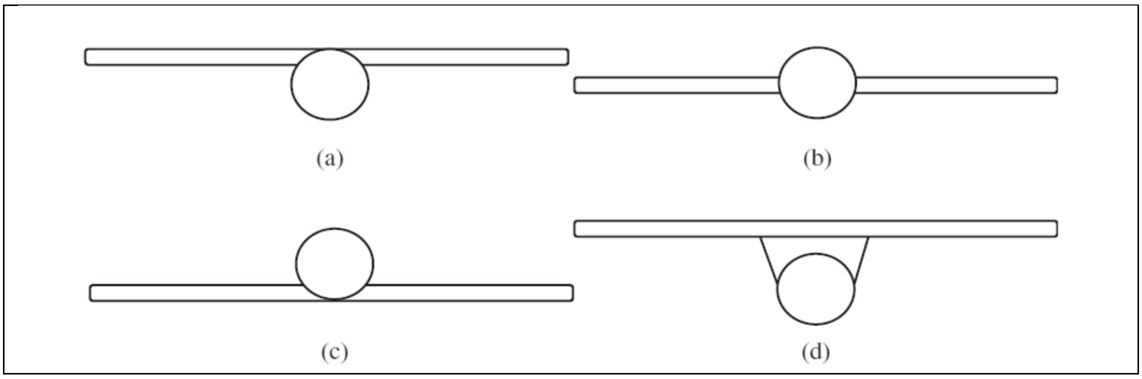


Figure 94: Vertical position of the main wing: (a) High-wing, (b) Mid-wing, (c) Low-wing, (d) Parasol-wing (Mohammad H. Sandraey, 2013, p. 165)

In order to decide which vertical position would be more suitable for our loitering munition, a further analysis of the advantages and disadvantages of each option should be conducted, with respect to the initial requirements that fulfill the design objectives.

Design objectives
Cost
Foldability
Stability
Maneuverability
Space inside fuselage
Lift
Drag

Table 34: Design objectives for wing vertical position

- **Cost**

  Our main objective is to develop a cheap platform, that could come to wide production easily.

  - **High-wing:** Medium cost

    It is a relatively simple design, but may need some structural reinforcement to sustain the stress during flight.

  - **Mid-wing:** Relatively low cost

    An option that stands between high-wing and low-wing

  - **Low-wing:** Relatively high cost

    The complexity of manufacture increases the cost of production

- **Foldability**

  The key feature of the loitering munition, will be its ability to fit in a grenade launcher, with its wings folded. A special mechanism is necessary, that allows the wings to fold and pop out immediately after launch.

  - **High-wing:** High level of foldability

    These configurations are very common in loitering munitions, since they provide the drone with enough space inside the fuselage.

  - **Mid-wing:** Low level of foldability

    It's the most challenging configuration to manufacture, so it is not usually met in loitering munitions.

  - **Low-wing:** High level of foldability

    Just like the high-wing configuration, low-wing configuration is highly met in case of loitering munitions.

- **Stability**

  It is very important for the operator to fly an easily controllable drone, that allows him to lock on a target and strike with precision.

  - **High-wing:** High level of stability

    This configuration maximizes stability and is often recommended for surveillance and reconnaissance UAVs.

  - **Mid-wing:** Medium level of stability

    This configuration combines stability with maneuverability.

  - **Low-wing:** Low level of stability

    This level of stability is a result from the increase in maneuverability.

- **Maneuverability**

  The more stable an air vehicle is, the less maneuverable it is going to be and vice versa, unless it is equipped with advanced avionics that maintain stability during aerobatic maneuvers, like in manned military aircraft.

  - **High-wing:** Low level of maneuverability

    With this configuration, the drone is more stable.

  - **Mid-wing:** Medium level of maneuverability

    It combines high-wing and low-wing characteristics.

  - **Low-wing:** High level of maneuverability

    This configuration offers maximum maneuverability, but sacrifices stability.

- **Space inside fuselage**

The placement of the wings, along with their folding mechanism, affects the availability of space inside the fuselage. All the necessary components are stored inside with a specific order, in order to achieve optimal weight distribution.

- **High-wing:** High volume of space

  This configuration offers more space, since the wings do not interfere with the fuselage. They are placed above it.

- **Mid-wing:** Low volume of space

  The folding mechanism, along with the wings, occupy too much space inside the fuselage.

- **Low-wing:** Medium volume of space

  This design also limits the available space inside the fuselage, but not to a great extent.

- **Lift**

  It is the force that allows the aircraft to fly and each configuration affects the amount of lift generated by the wings, in a different way.

  - **High-wing:** High amount of lift

    At this position, more lift is generated, as there is a better interaction between the airflow and the wings.

  - **Mid-wing:** Medium amount of lift

    In a mid-wing aircraft, the wing is mounted at the center of the fuselage. This configuration provides a balanced lift-to-drag ratio, suitable for maneuverability and stability.

  - **Low-wing:** Low amount of lift

    In a low-wing design, the wing is mounted beneath the fuselage. This configuration allows for a slightly lower center of gravity, which results in less natural lift compared to medium and high-wing configurations.

- **Drag**

  It is the resistance force experienced by an aircraft or UAV, moving through the air.

  - **High-wing:** Low amount of drag

    This configuration reduces interference drag, by generating more natural lift. The aircraft or UAV can operate at a lower angle of attack than low-wing configuration, to achieve the same lift and is also more efficient at slower speeds and in lower altitudes.

  - **Mid-wing:** Medium amount of drag

This configuration tends to experience moderate drag forces, across various types of drag, striking a balance between the stability of high-wing designs and the speed-focused efficiency of low-wing designs.

- **Low-wing:** High amount of drag

  The interference drag is increased due to the placement of the wings beneath the fuselage. The induced drag is also increased, as a result from the lower natural lift.

The following Table summarizes the effects of the different configurations, regarding the design objectives:

Design objectives	Weight (%)	Low	Medium	High
Cost	(30)	Mid-wing (10)	High-wing (15)	Low-wing (25)
Foldability	(35)	Mid-wing (10)	Low-wing (20)	High-wing (34)
Stability	(10)	Low-wing (2)	Mid-wing (5)	High-wing (9)
Maneuverability	(10)	High-wing (3)	Mid-wing (6)	Low-wing (8)
Space inside fuselage	(5)	Mid-wing (1)	Low-wing (3)	High-wing (4)
Lift	(5)	Low-wing (1)	Mid-wing (3)	High-wing (4)
Drag	(5)	High-wing (1)	Mid-wing (2)	Low-wing (4)
Summation	(100)	Low-wing (58)	Mid-wing (37)	High-wing (69)

Table 35: Configurations and their effect on the design objectives

As we can see from the Table above, high-wing configuration offers an overall higher ranking in terms of the design objectives and maintains a relatively low cost. None of the existing configurations can meet up with all the desired objectives at once, so every time that a designer has to design a UAV or an aircraft, specific objectives should be predetermined, according to the mission profile.

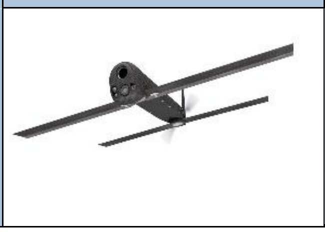
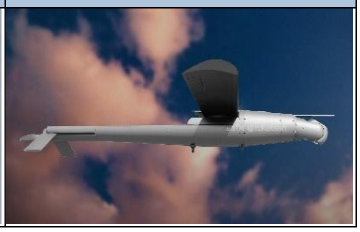
	Low-wing	Mid-wing	High-wing
Configurations			

Table 36: Loitering munitions with different wing configurations (Left: Switchblade 300, Middle: SkyStriker, Right: Alpagut)

4. High-lift device

High-lift devices (HLDs) are components of an aircraft or UAV that enhance the lift coefficient (C_L) during critical phases of flight, such as takeoff and landing. These devices enhance the performance of the wings by changing their shape or increasing the effective surface area, to provide more lift at lower speeds. Two main types of high-lift devices are flaps and slats.

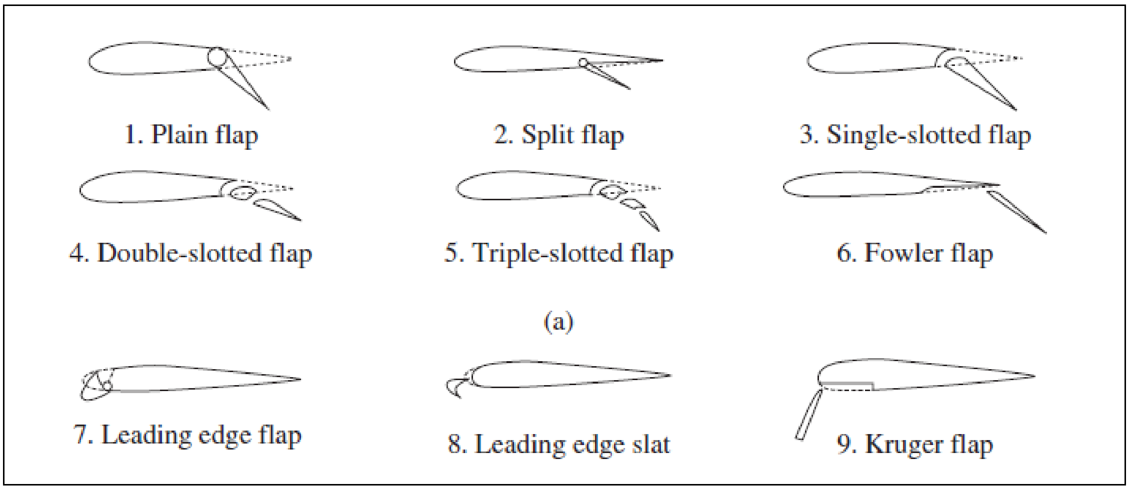


Figure 95: Hogh-lift devices (Mohammad H. Sandraey, 2013, p. 233)

Since our loitering munition will be launched by a canister and will not reach high velocities, no high-lift device is necessary.

5. Sweep angle (Λ)

The sweep angle (Λ) of an aircraft or UAV, refers to the angle between the semispan of the wing's leading edge or any other specified reference line (like the quarter-chord line) and a line perpendicular to the aircraft's longitudinal axis. This angle is a key design feature at high speeds, since it improves aerodynamic performance, by reducing drag. The following Figure, illustrates five cases of different sweep angles.

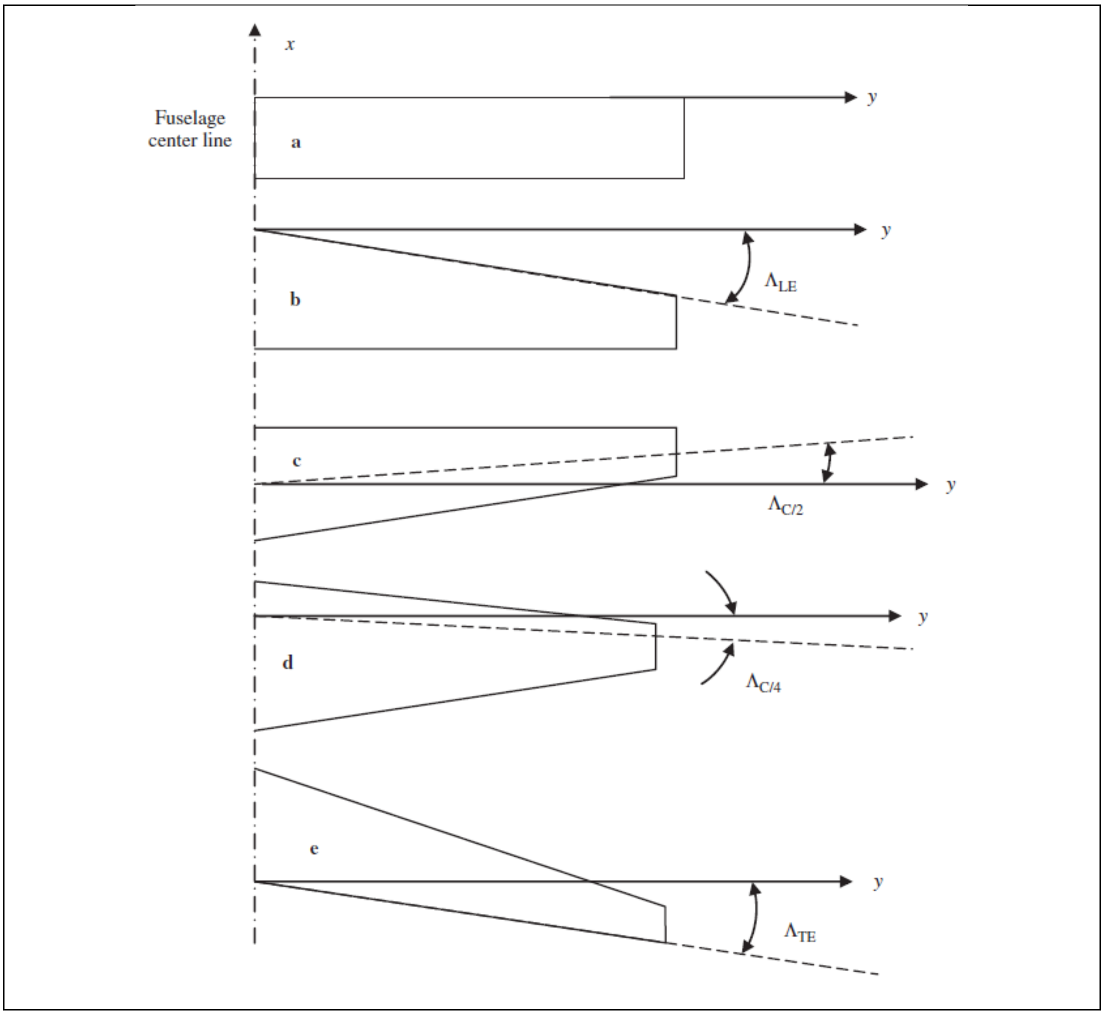


Figure 96: Five wings with different sweep angles (Mohammad H. Sandraey, 2013, p. 210)

The first wing (a) has no sweep angle, so Λ = 0. The second wing (b) has a leading-edge sweep, while the fifth wing (e) has a trailing-edge sweep. The fourth wing (d) has a quarter-chord sweep and the third wing (c) has a 50% chord sweep. Our loitering munition will fly at low speed, so no sweep angle is needed (Λ = 0).

6. Dihedral angle (Γ)

According to M. H. Sandraey, when looking an aircraft from the front, the angle between the chord line plane of a wing with the xy plane is referred to as the wing dihedral (Γ). The following Figure presents a positive (dihedral) and a negative angle (anhedral).

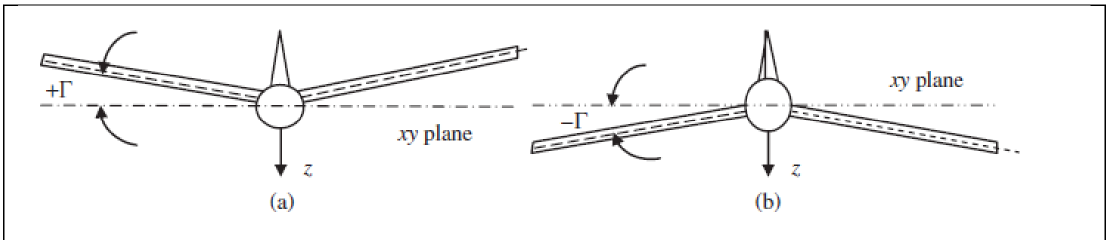


Figure 97: Dihedral angle (a) and anhedral angle (b) (Mohammad H. Sandraey, 2013, p. 226)

For our loitering munition, we will not use any of these angles (Γ = 0), for simplicity reasons.

7. Airfoil selection

At this point of the design, we can either choose an already existing airfoil, or we can design a new one, after a series of calculations and simulations. The design of a new airfoil requires deep knowledge of aerodynamics and it is a very complex, time-consuming and expensive procedure, that requires many tests in wind tunnels. For those reasons, we are going to use one of the existing airfoils. The following Figure shows various typical airfoils that are widely used in aircraft design.

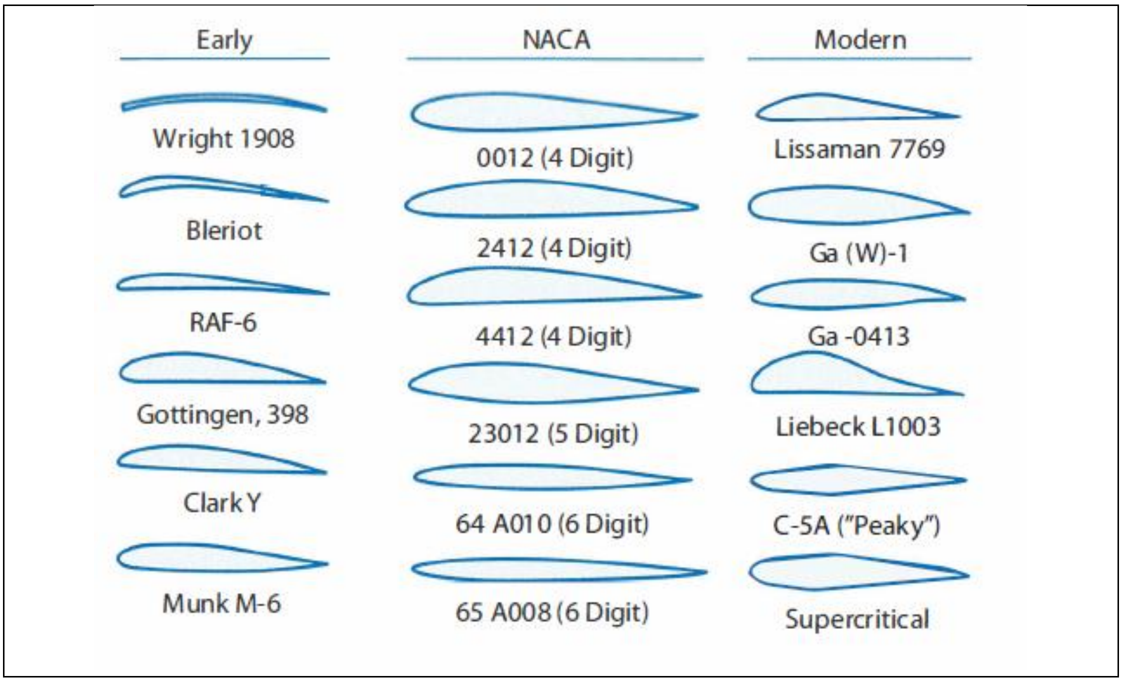


Figure 98: Typical airfoils (D. P. Raymer, 2018, p. 63)

The criteria that must be taken into consideration for the selection of an airfoil, are the following:

No	Criteria
1.	The airfoil with the highest maximum lift coefficient (C_{lmax}).
2.	The airfoil with the proper ideal or design lift coefficient (C_{ld} or C_{li}).
3.	The airfoil with the lowest minimum drag coefficient (C_{dmin}).
4.	The airfoil with the highest lift-to-drag ratio ((Cl/Cd)max).
5.	The airfoil with the highest lift curve slope ($C_{l\alpha max}$).
6.	The airfoil with the lowest (closest to zero; negative or positive) pitching moment coefficient (C_m).

7.	The proper stall quality in the stall region (the variation must be gentle, not sharp).
8.	The airfoil must be structurally reinforceable. The airfoil should not be so thin that spars cannot be placed inside.
9.	The airfoil must be such that the cross-section is manufacturable.
10.	The cost requirements must be considered.

Table 37: Airfoil selection criteria (Mohammad H. Sandraey, 2013, p. 182)

The methodology for airfoil section selection proposed by M. H. Sandraey (Mohammad H. Sandraey, 2013, pp. 188-193) consists of the following steps:

- Determine the average weight of the UAV (W_{avg}) in cruising flight:

  $W_{avg} = W_o$ (eq. 6.6.1)

- Calculate the UAV's ideal cruise coefficient (C_{Lc}):

  $C_{L_C} = \frac{2Wo}{\rho S V_{cr}^2}$ (eq. 6.6.2)

  Where:

  V_{cr}: The cruise speed

  ρ: The air density at cruising altitude

  S: The wing planform area

- Calculate the wing cruise lift coefficient (C_{Lcw}):

  $C_{L_{C_W}} = \frac{C_{L_C}}{0.95}$ (eq. 6.6.3)

- Calculate the wing airfoil ideal lift coefficient (C_{li}):

  $C_{l_i} = \frac{C_{L_{C_W}}}{0.9}$ (eq. 6.6.4)

- Calculate the UAV's maximum lift coefficient (C_{Lmax}):

  $C_{L_{max}} = \frac{2WTo}{\rho S V_s^2}$ (eq. 6.6.5)

  Where:

  V_s: The stall speed

  ρ: The air density at sea level

  W_{TO}: The UAV's maximum takeoff weight (m_{TO}*g)

- Calculate the wing maximum lift coefficient ($C_{Lmax,w}$):

  $C_{L_{max_W}} = \frac{C_{Lmax}}{0.95}$ (eq. 6.6.6)

- Calculate the wing airfoil gross maximum lift coefficient ($C_{Lmax,gross}$):

  $C_{l\_max\_gross} = \frac{C_{L_{max_W}}}{0.9}$ (eq. 6.6.7)

- Calculate the wing airfoil net maximum lift coefficient (C_{lmax}):

$C_{lmax} = C_{lmax_{gross}}$ - ΔC_{lHLD} (eq. 6.6.8)

Since there is no high-lift device, $\Delta C_{lHLD} = 0$

The results of the equations above, are presented in the following table:

C_{L_C}	$C_{L_{C_W}}$	C_{l_i}	$C_{L_{max}}$	$C_{L_{max_w}}$	$C_{l\_max\_gross}$	C_{lmax}
0.404	0.452	0.502	0.908	0.956	1.06	1.06

Table 38: Calculated lift coefficients

The wingspan (b) is given by the following equation:

b = $\sqrt{A * S}$ => b = 1.5 m

The Mean Aerodynamic Chord (MAC or $\bar{C}$) and the characteristic length of the chord (l):

L = $\bar{C} = \frac{S}{b}$ = 0.25 m

At this point, we see that the wingspan and the MAC are not suitable for a loitering munition with an 18 cm fuselage length and a 4 cm diameter. The chord of the wing should be smaller than 4 cm and the semispan not bigger than the length of the fuselage, because the wings won't bε able to fold. So, we have to perform trade studies and change the stall speed and the maximum speed, since they affect the W/S ratio and also the maximum and cruise lift coefficients, according to eq. (6.6.5) and (6.5.10) respectively. We could also change the size of the wing surface area, but it would affect the aspect ratio. So, we end up choosing a different wingspan and we will start the process from the beginning.

We assume that with the wings folded, the length of the wing (semispan) is equal to 0.12 m, so:

$\frac{b}{2}$ = 0.12 =>

⇨ b = 0.24 m

This changes the surface area, so:

b = $\sqrt{A * S}$ =>

⇨ S = 0.0096 m^2

From the equation that we calculated the wing surface area in chapter (6.5), we have:

S = $\frac{W_{TO}}{\frac{W}{S}}$ =>

⇨ $\frac{W}{S} = \frac{24.525}{0.0096} = 2554.6875 \text{ N/m}^2$

From eq. (6.5.9):

$$V_{stall} = \sqrt{\frac{2\left(\frac{W}{S}\right)}{\rho C_{L_{max}}}} = \sqrt{\frac{2*2554.6875}{1.17*1.2}} =>$$

⇨ $V_{stall} = 60.32\ m/s$

The total increase of the speed is:

$V'_{stall} = V_{stall} + xV_{stall}$

Where:

V_{stall}: The initial stall speed

V'_{stall}: The new stall speed

x: The percentage of increase (%)

So:

60.32 = 60.32 + x*60.32 => x = 4.43 %

We assume that this amount of increase has affected all the types of speed.

$V'_{max} = V_{max} + xV_{max}$ = 22.22 + 4.43*22.22 => V'_{max} = 120.65 m/s

$V'_{cr} = V_{cr} + xV_{cr}$ = 16.66 + 4.43*16.66 => V'_{cr} = 90.46 m/s

We observe that those speeds are maybe too high, but, for now, those are the values that satisfy our requirements. Further analysis should be conducted concerning the endurance of the materials used for the loitering munition at these speeds.

The new diagram for the stall speed is presented below:

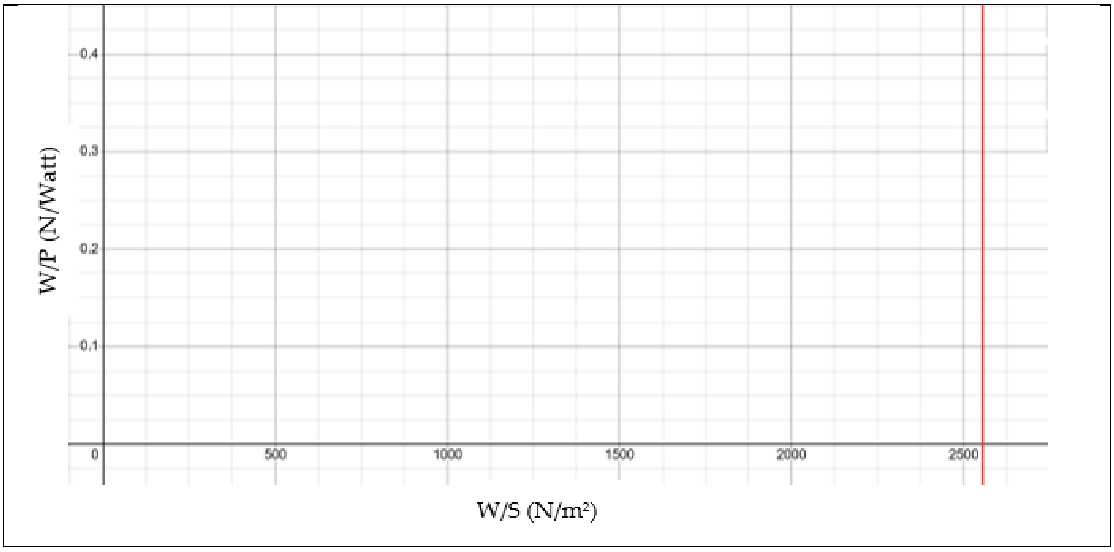


Figure 99: The new stall speed graph for the matching plot

For the $(\frac{W}{P})max$, we have:

$$(\frac{W}{P})max = \frac{np}{\frac{1}{2}*\rho o*V_{max}^{3}*C_{Do}*\frac{1}{(\frac{W}{S})}+\frac{2*K}{\rho*\sigma*V_{max}}*(\frac{W}{S})} = \frac{0.75}{\frac{1}{2}*1.225*(120.65)^{3}*0.025*\frac{1}{(\frac{W}{S})}+\frac{2*0.066}{1.17*0.95*120.65}*(\frac{W}{S})} =>$$

$$\Rightarrow \left(\frac{W}{P}\right) \text{max} = \frac{0.75}{26892.3*\frac{1}{(\frac{W}{S})}+0.001*(\frac{W}{S})} \quad \text{(eq. 6.6.9)}$$

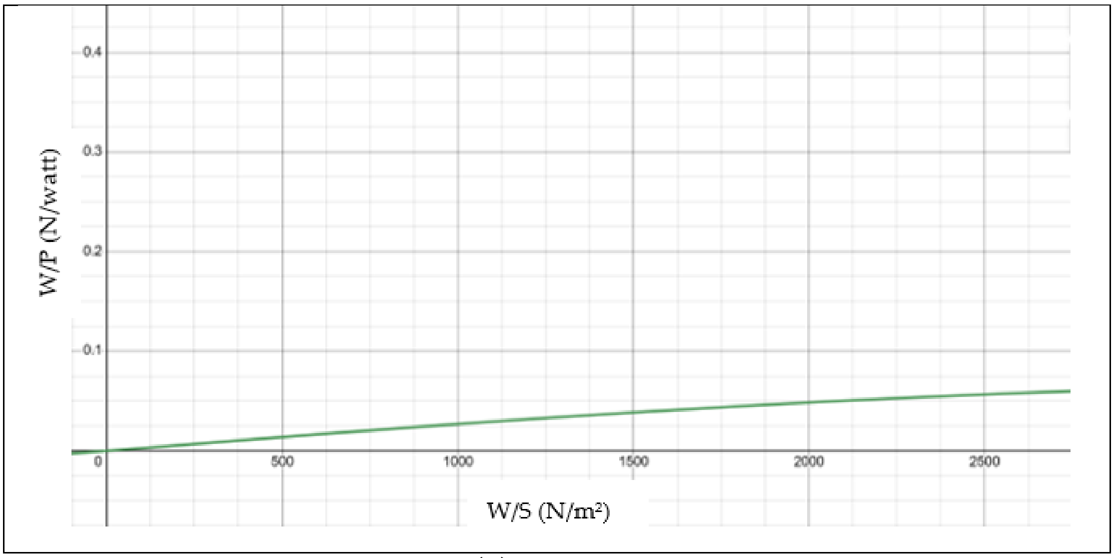


Figure 100: The new $\left(\frac{W}{P}\right)max$ graph for the matching plot

For the rate of climb:

$$\left(\frac{W}{P}\right)Roc = \frac{1}{\frac{ROC}{np}+\sqrt{\frac{2}{\rho*\sqrt{\frac{3CDo}{K}}}*\left(\frac{W}{S}\right)}*\frac{1.155}{(\frac{L}{D})max*np}} = \frac{1}{\frac{10.53}{0.75}+\sqrt{\frac{2}{1.17*\sqrt{\frac{3*0.025}{0.066}}}*\left(\frac{W}{S}\right)}*\frac{1.155}{12.045*0.75}} = \frac{1}{14.04+0.164\left(\frac{W}{S}\right)} \quad \text{(eq. 6.6.10)}$$

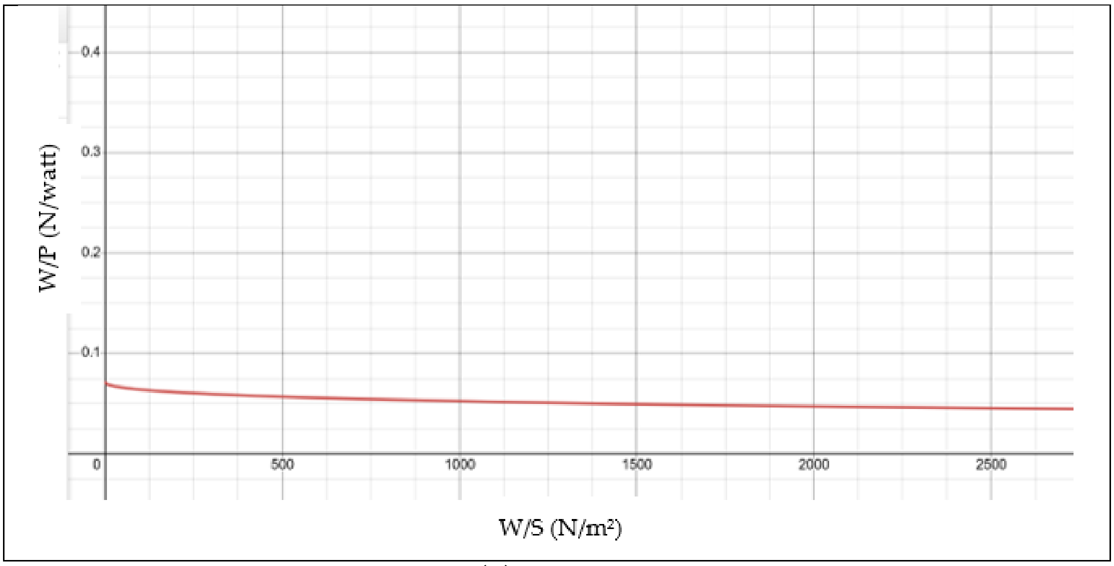


Figure 101: The new $\left(\frac{W}{P}\right) Roc$ graph for the matching plot

The ceiling (W/P) ratio remains the same:

$$\left(\frac{W}{P}\right)_c = \frac{\sigma}{\sqrt{\frac{2}{\rho\sqrt{\frac{3CDo}{K}}} * \left(\frac{W}{S}\right) * \left(\frac{1.155}{\left(\frac{L}{D}\right) \max * np}\right)}} = \frac{0.95}{0.16 * \sqrt{\left(\frac{W}{S}\right)}} \qquad \text{(eq. 6.6.11)}$$

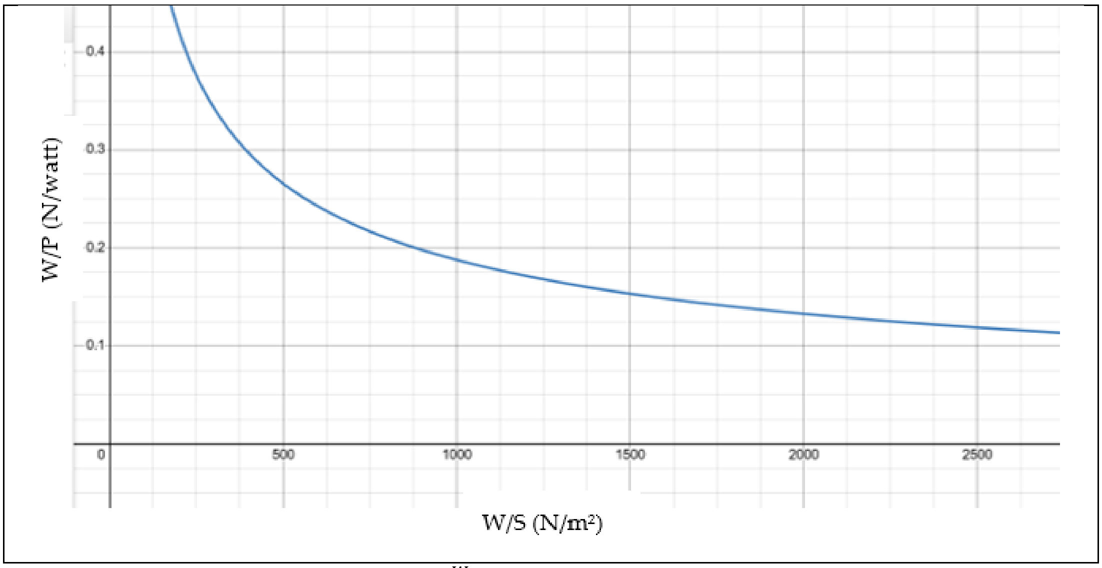


Figure 102: The $\left(\frac{W}{P}\right)_c$ ratio graph fot the matching plot

By combining all the above graphs, we get the new mathing plot and the desired point.

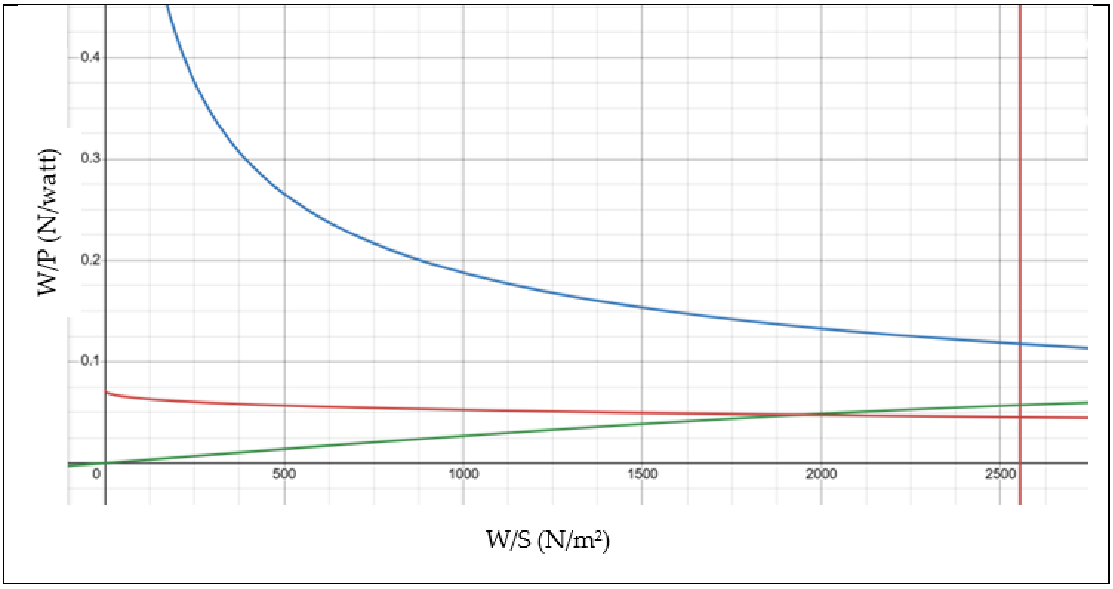


Figure 103: The new matching plot

The desired point is pointed again with a star, as presented in the Figure below.

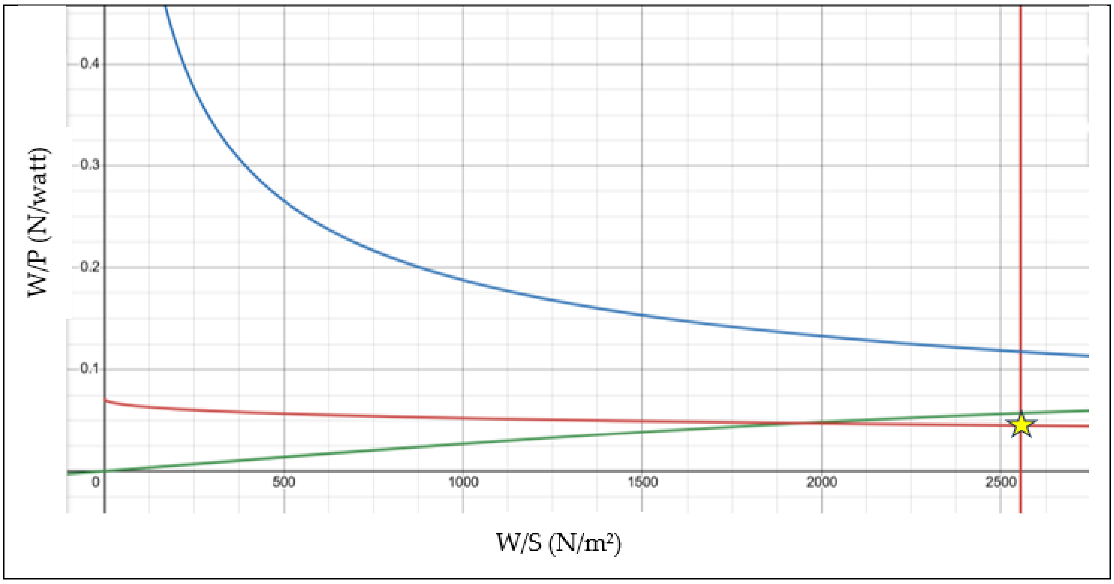


Figure 104: The new design point

At this point:

$\frac{W}{P} = 0.0451936\ N/Watt$

$\frac{W}{S} = 2554.68\ N/m^2$

The Reynolds number (Re) is a dimensionless quantity, used to predict the flow regime in fluid dynamics, indicating whether the flow is laminar, transitional or turbulent. It is calculated using the equation below (D. P. Raymer, 2018, p. 418):

Re = $\frac{\rho V l}{\mu}$ (eq. 6.6.12)

Where:

ρ: The air density at flight altitude

V: Cruise velocity

l: The characteristic length of the airfoil (We assume that l = MAC)

μ: dynamic viscosity of the fluid (At 25^0 C, μ = 0.00001837)[6]

$$MAC = \frac{S}{b} = \frac{0.0096}{0.24} = 0.04\ m$$

So, Re = 230458.79150789

At this Reynolds number there are specific airfoils that match and can be found with tests and the use of XFLR5, a software tool primarily used for the aerodynamic analysis and the design of airfoils, wings and airplanes in low-speed regime.

[6] From The Engineering Toolbox website

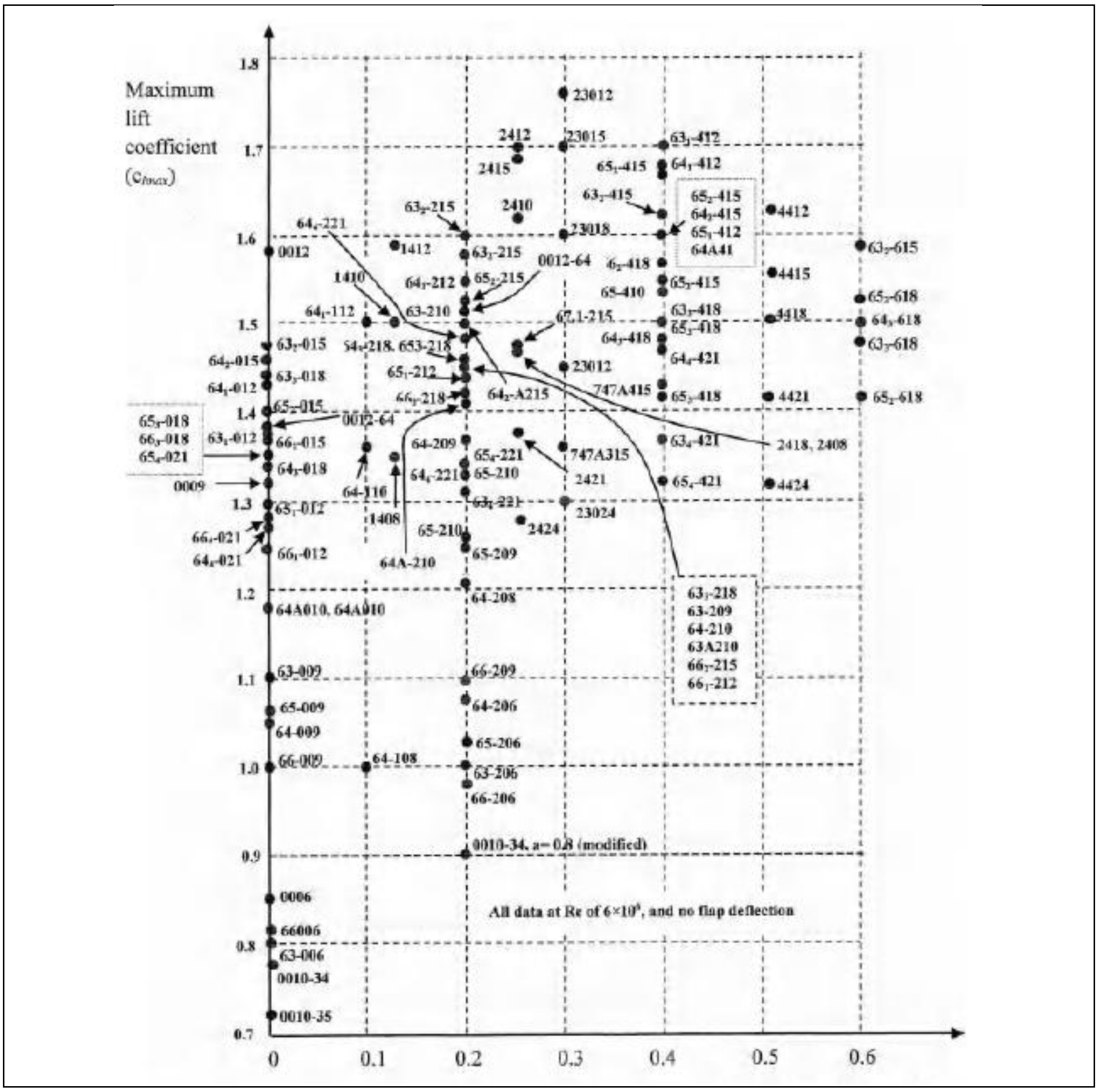


Figure 105: Maximum lift coefficients for several NACA airfoils (Mohammad H. Sandraey, 2013, p. 192)

The criteria that are used for an airfoil selection, are the following (Mohammad H. Sandraey, 2013, p. 182):

No	Criteria of the airfoil	Symbol
1	Highest maximum lift coefficient	C_{lmax}
2	Proper ideal or design lift coefficient	C_{ld} or C_{li}
3	Lowest minimum drag coefficient	$C_{d_{min}}$
4	Highest lift-to-drag ratio	$\left(\frac{C_l}{C_d}\right)_{max}$
5	Highest lift curve slope	C_{lamax}
6	Lowest (close to zero; negative or positive) pitching moment coefficient	C_m
7	Highest stall angle	a_s
8	Highest zero lift angle of attack	a_o

9	Must be such that the cross-section is manufacturable	-
10	The cost requirements must be considered	-
11	Other design requirements must also be considered. For example, a warhead is going to be placed inside our loitering munition, so sufficient space must be left inside the fuselage for this purpose.	-

Table 39: Criteria for airfoil selection

Our new requirements concerning the airfoil selection process, are the following:

C_{L_C}	$C_{L_{C_W}}$	C_{l_i}	$C_{L_{max}}$	$C_{L_{max_w}}$	$C_{l\_max\_gross}$	C_{lmax}
0.533	0.561	0.623	1.146	1.2	1.34	1.34

Table 40: New airfoil selection criteria

We are going to compare some of the airfoils that already exist (NACA airfoils, Eppler, Selig, Sd, etc.), providing a brief example of the conceptual design procedure. In some cases, new airfoils can be designed using the pattern of an airfoil whose database is known, but this is beyond the scope of this thesis. The following table, contains three different airfoils of the NACA series and one Eppler airfoil:

Airfoil	Cl_i	a_i (deg)	Cd_{min}	Cm_i	$(Cl/Cd)_{max}$	a_o (deg)	Cl_{max}	a_s (deg)	$(t/c)_{max}$ (%)
NACA 0008	0.3	2.25	0.008	-0.011	41.06	3.25	0.78	7.8	8
NACA 0009	0.4	2.25	0.009	-0.0291	45	2.5	0.9	10	9
NACA 0012	0.03	0.25	0.01	-0.0004	47.43	5	1.11	12.25	12
Eppler 212	0.541	0.47	0.0068	-0.123	104.86	-3.460	1.365	12	10.56

Table 41: NACA and Eppler airfoils comparison[7]

From Table 41, we can see that the Eppler 212 airfoil has characteristics close to our expectations. Its ideal and maximum lift coefficient are similar to those we are looking for.

Cl_i	a_i (deg)	Cd_{min}	Cm_i	$(Cl/Cd)_{max}$	a_o (deg)	Cl_{max}	a_s (deg)	$(t/c)_{max}$ (%)
0.541	0.47	0.0068	-0.123	104.86	-3.460	1.365	12	10.56

Table 42: Data for the selected Eppler 212 airfoil

8. Wing parameters

- Aspect ratio (A)

[7] For more details, visit http://www.airfoiltools.com

For a tapered wing ($0 \leq \lambda \leq 1$) aspect ratio is defined as the span squared divided by the wing area, while for an untapered wing ($\lambda = 1$), it is defined as the wingspan divided by the chord (D. P. Raymer, 2018, p. 75).

$A = \frac{b^2}{S}$,   ($0 \leq \lambda \leq 1$)   (eq. 6.6.13)

$A = \frac{b}{S}$,   ($\lambda = 1$)   (eq. 6.6.14)

- High Aspect Ratio (Long, Narrow wings): It provides lower drag, more efficient lift generation and better performance at high altitudes and low speeds. However, the UAV is less maneuverable and its long wings require reinforcement due to structural challenges.
- Low Aspect Ratio (Short, Wide wings): It provides better maneuverability and strength for high-speed lift. However, at lower speeds the drag is higher.

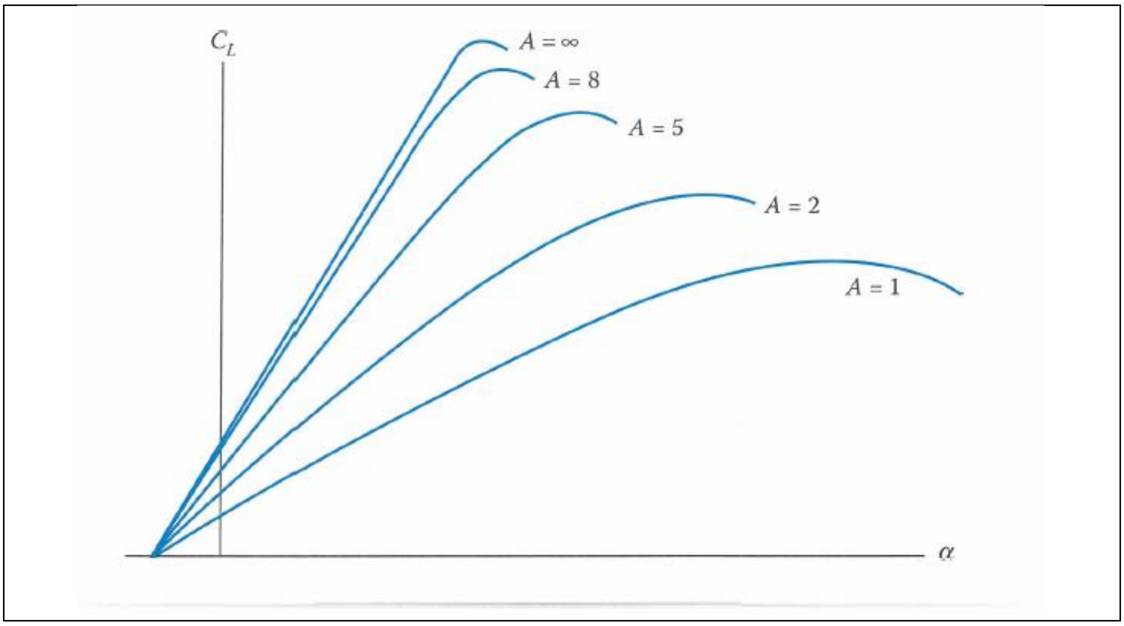


Figure 106: Aspect ratio and lift coefficient (D. P. Raymer, 2018, p. 77)

- Taper ratio (λ)

Wing taper ratio is the ratio between the tip chord and the centerline root chord (D. P. Raymer, 2018, p. 82).

$\lambda = \frac{Ctip}{Croot}$ (eq. 6.6.15)

The following Figure presents the effect of taper ratio on lift distribution:

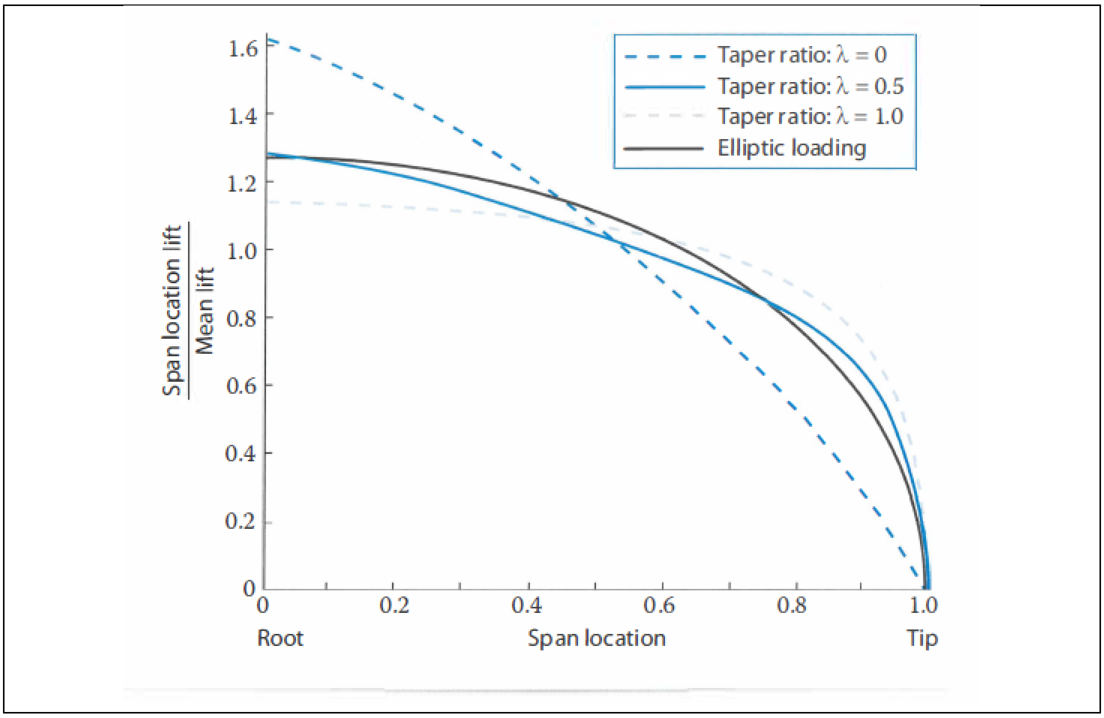


Figure 107: Taper and lift distribution (D. P. Raymer, 2018, p. 84)

- Aerodynamic efficiency: A tapered wing reduces induced drag (drag due to lift) by distributing the lift more efficiently across the wing span, improving performance and fuel efficiency.
- Structural weight: Tapered wings often reduce weight by using less material at the wing tip, where it has less structural loading.
- Stability and control: The taper ratio also affects how lift is distributed along the wing, influencing stall characteristics. Proper taper can help make an aircraft more stable or give better control at lower speeds.

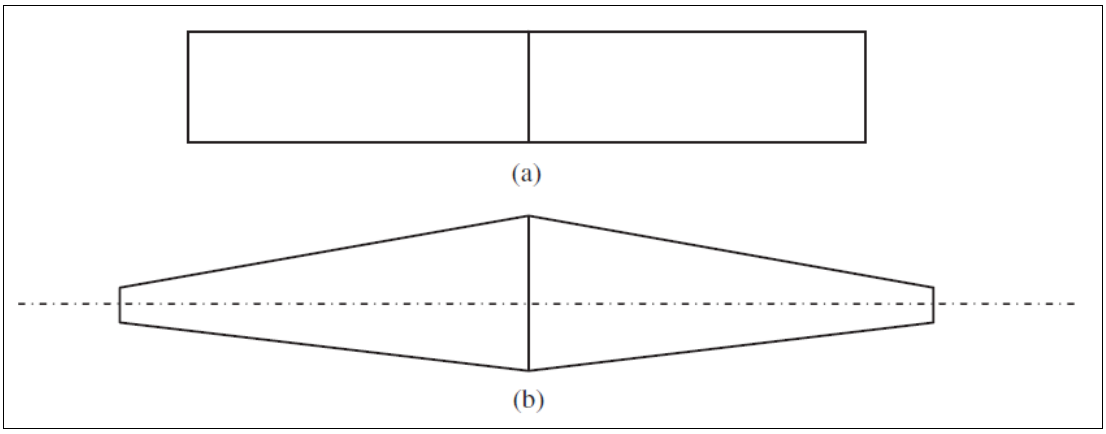


Figure 108: Untapered wing (a) and tapered wing (b) (Mohammad H. Sandraey, 2013, p. 204)

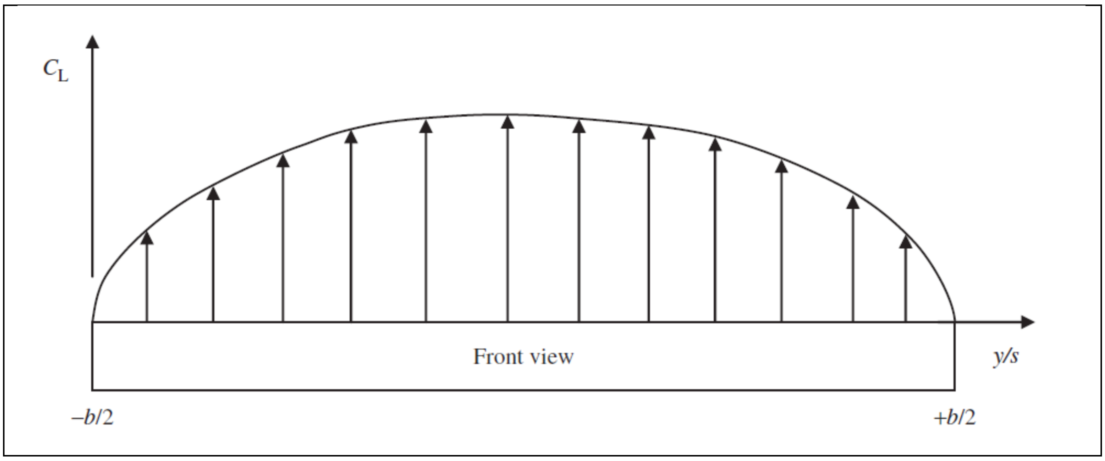


Figure 109: Lift distribution of an elliptical wing (Mohammad H. Sandraey, 2013, p. 207)

The elliptical lift distribution is the optimal for a wing, while wing taper, plays a crucial role that affects the way lift forces are distributed. The value of taper ratio is selected after the determination of the lift distribution requirements.

The advantages of the elliptical lift distribution are the following:

- If the wing tends to stall (CL_{max}), the wing root is stalled before the wing tip ($CL_{root} = CL_{max}$ while $CL_{tip} < CL_{max}$).
- The center of an elliptical load distribution is closer to the wing root, thus it leads to a lower bending moment, which results in less bending stress and less stress consentration at the wing root.
- The center of gravity of each wing section for an elliptical load distribution is closer to the fuselage center line.
- The downwash is constant over the span for an elliptical lift distribution.
- For an elliptical lift distribution, the induced angle of attack is also constant along the span. An elliptical lift distribution also yields the minimum induced drag.
- The variation of lift over the span for an elliptical lift distribution is steady (gradually increasing from tip (zero) to root (maximum)).

- Wing incidence (i_w)

  The wing incidence (i_w) is the angle between the fuselage center line and the wing chord line at its root (Mohammad H. Sandraey, 2013, p. 195).

  The incidence angle directly impacts the amount of lift the wing generates. By increasing the incidence angle, the wing can produce more lift at lower speeds. However, a very high incidence angle, could result in stall.

  $i_w = a_i$(Eppler 212) = 0.47 deg

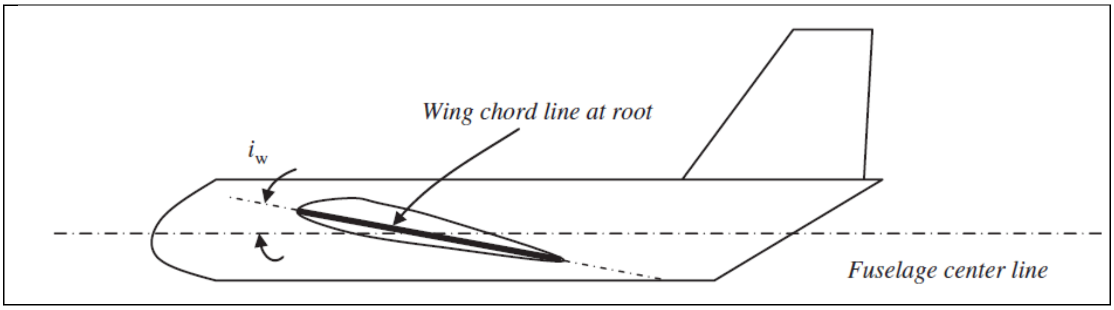


Figure 110: Wing incidence angle (Mohammad H. Sandraey, 2013, p. 196)

- Twist angle (a_t)

The wing twist, refers to the gradual change in the angle of incidence from the root of the wing to the tip. The angle of the twist can be either negative or positive. In a negative twist or "washout", the root has a higher angle of incidence than the tip. In a positive twist or "wash-in", the angle of incidence increases gradually from the root to the tip. If the angles of incidence of the root and tip are different, then the wing has "geometric" twist. If the tip airfoil section and root airfoil section are not the same, the twist is called "aerodynamic" twist.

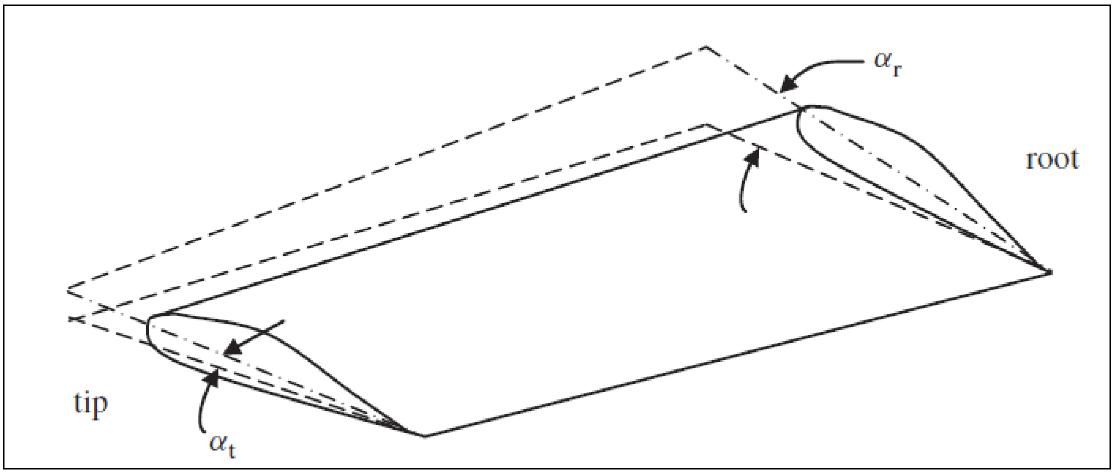


Figure 111: Washout twist (Mohammad H. Sandraey, 2013, p. 223)

By employing the twist in the wing design proecss, our main objective is to avoid tip stall before root stall and to achieve an elliptical lift distribution. The equation that is used for the twist angle is the following:

$$|\,a_t| + i_w \geq \,|\,a_o| \Rightarrow \qquad \text{(eq. 6.6.16)}$$

⇨ $a_t \geq 2.99\ deg$

- Lifting-line theory

Using this technique, we can achieve our design goals and determine the parameters for the wing, solving several equations, without using a CFD software. The steps that we follow are presented below (Mohammad H. Sandraey, 2013, p. 242):

- Divide one half of the wing (semispan) into several (N) segments.

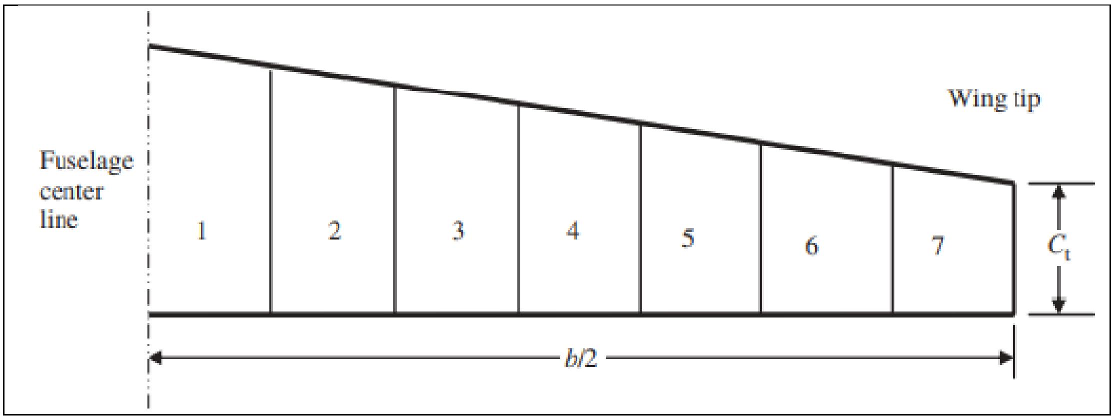


Figure 112: Wing divided to several sections (Mohammad H. Sandraey, 2013, p. 243)

- Calculate the corresponding angle (θ) for each section. Each angle (θ) is defined as the angle between the horizontal axis and the intersection between the lift distribution curve and the segment line. In fact, we originally assume that the lift distribution along the semispan is elliptical. This assumption will be corrected later.

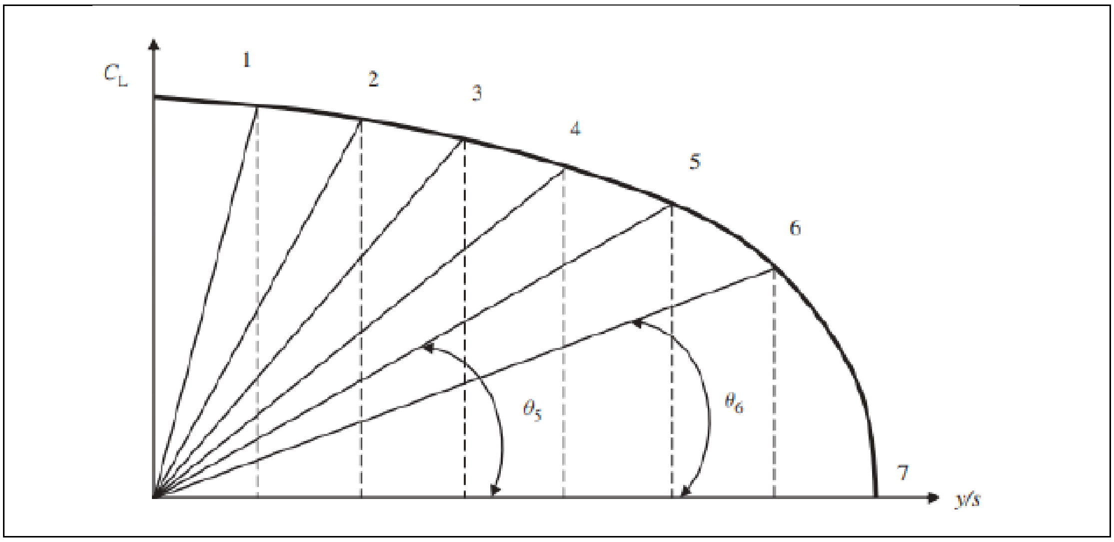


Figure 113: Angles corresponding to each section

- Solve the group of the following equations to find A1 to An:

$\mu(\alpha_o - \alpha) = \sum_{n=1}^{N} A_n \sin\left(n\Theta(in\ radians)\right)\left(1 + \frac{\mu n}{\sin(\theta(n\ radians))}\right)$ (eq. 6.6.17)

Where:

N: number of segments

α: segment's angle of attack

α_o: segment's zero-lift angle of attack

A_n: intermediate unknown coefficients

μ: $\mu = \frac{\bar{C} C_{l_a}}{4b}$

$\overline{C_i}$: segment's MAC

C_{l_a}: segment's lift curve slope (1/rad)

b: wingspan

If the wing has a twist, the twist angle must be applied to all segments linearly. Thus, the angle of attack for each segment is reduced by deducting the corresponding twist angle from the wing setting angle.

- Determine each segment's lift coefficient using the following equation:

$C_{Li} = \frac{4b}{\bar{C}_i} \sum A_n \sin(n\theta)$ (eq. 6.6.18)

- Determine the wing total lift coefficient using the following equation:

$C_{L_W} = A\pi A_1$ (eq. 6.6.19)

The lifting-line theory has other useful features, but they are not covered or used here.
Since we are looking for elliptical lift distribution and sufficient lift produced by the wing, the wing total lift coefficient has to be equal or higher than the wing cruise lift coefficient. So:

$C_{L_W} = 0.561$

At this point, Sandraey presents a MATLAB code at his book for the application of the lifting-line theory. Many trials and errors are needed.

```
clc
clear
N = 9; % (number of segments - 1)
S = 0.0096; % m^2
```

```
AR = 6; % Aspect ratio
lambda = 1; % Taper ratio
alpha_twist = 2.99; % Twist angle (deg)
i_w = - 0.47; % wing setting angle (deg)
a_2d = 6.3; % lift curve slope (1/rad)
alpha_0 = - 3.46; % zero-lift angle of attack (deg)
b = sqrt(AR*S); % wing span (m)
MAC = S/b; % Mean Aerodynamic Chord (m)
Croot = (1.5*(1+lambda)*MAC)/(1+lambda+lambda^2); % root chord (m)
theta = pi/(2*N):pi/(2*N):pi/2;
alpha = i_w+alpha_twist:-alpha_twist/(N-1):i_w;
% segment's angle of attack
z = (b/2)*cos(theta);
c = Croot * (1 - (1-lambda)*cos(theta)); % Mean Aerodynamics
Chord at each segment (m)
mu = c * a_2d / (4 * b);
LHS = mu .* (alpha-alpha_0)/57.3; % Left Hand Side
% Solving N equations to find coefficients A(i):
for i=1:N
for j=1:N
B(i,j) = sin((2*j-1) * theta(i)) * (1 + (mu(i) * (2*j-1)) /
sin(theta(i)));
end
end
A=B\transpose(LHS);
for i = 1:N
sum1(i) = 0;
sum2(i) = 0;
for j = 1 : N
sum1(i) = sum1(i) + (2*j-1) * A(j)*sin((2*j-1)*theta(i));
sum2(i) = sum2(i) + A(j)*sin((2*j-1)*theta(i));
end
end
CL = 4*b*sum2 ./ c;
CL1=[0 CL(1) CL(2) CL(3) CL(4) CL(5) CL(6) CL(7) CL(8) CL(9)];
y_s=[b/2 z(1) z(2) z(3) z(4) z(5) z(6) z(7) z(8) z(9)];
plot(y_s,CL1,'-o')
grid
title('Lift distribution')
xlabel('Semi-span location (m)')
ylabel ('Lift coefficient')
CL_wing = pi * AR * A(1)
```

Figure 114: MATLAB code for the application of the lifting-line theory (Mohammad H. Sandraey, 2013, p. 245)

We previously calculated the length of the MAC and since the diameter of the fuselage will be 0,04 m and the length of the C_{root} also 0.04 m, we will use untapered wing.

$\lambda = 1$

$\bar{C} = \frac{2}{3}\, C_r (\frac{1+\lambda+\lambda^2}{1+\lambda})$ => (eq. 6.6.20)

⇨ $C_r = 0.04\ m$

From eq. (6.6.15): $C_t = 0.04\ m$

For the sweep angle, we assume that the 50% chord line sweep angle is zero. From the figure below, we can calculate the leading edge, trailing edge and quarter chord sweep angles, using the triangle law in the triangle ABC.

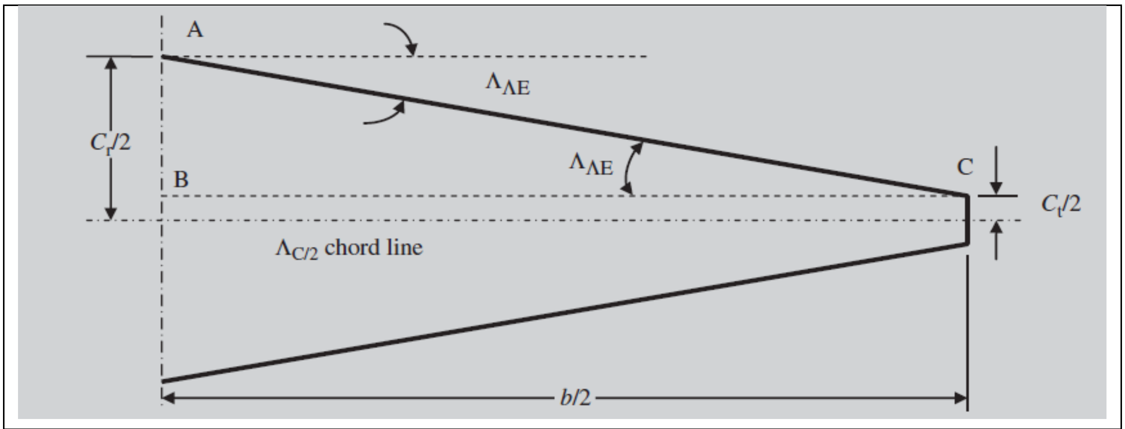


Figure 115: Sweep angles of the wing from the example of (Mohammad H. Sandraey, 2013, p. 219)

$\tan(\Lambda_{LE}) = \frac{AB}{BC}$ =>

⇨ $\Lambda_{LE} = \tan^{-1}(\frac{\frac{Cr}{2} - \frac{Ct}{2}}{\frac{b}{2}})$ (eq. 6.6.21)

⇨ $\Lambda_{LE} = 0\ deg$

$\Lambda_{TE} = -\Lambda_{LE} = 0\ deg$ (eq. 6.6.22)

$\Lambda_{\frac{c}{4}} = \tan^{-1}(\frac{\frac{Cr}{4} - \frac{Ct}{4}}{\frac{b}{2}})$=> (eq. 6.6.23)

⇨ $\Lambda_{\frac{c}{4}} = 0$ deg

The folllowing Table contains the specifications for the wings:

Parameter	Value
S	0.0096 m^2
A	6
b	0.24 m
MAC	0.04 m
λ	1
C_r	0.04 m
C_t	0.04 m
a_t	2.99 deg

i_w	-0.47 deg
Γ	0 deg
$\Lambda_{C/2}$	0 deg
$\Lambda_{C/4}$	0 deg
Λ_{LE}	0 deg

Table 43: Specifications for the wigngs

§6.5 Tail design

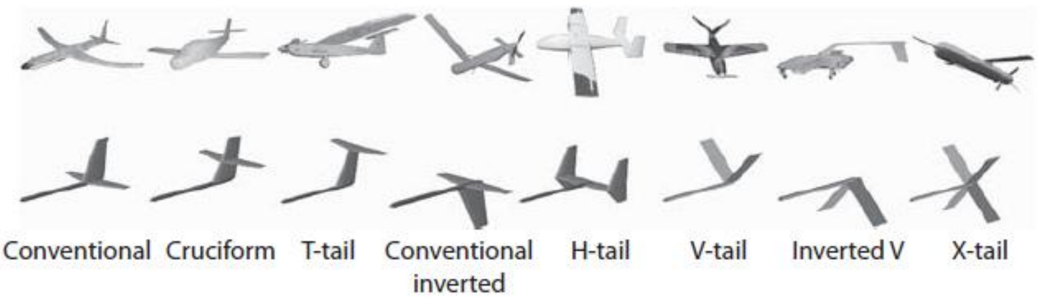


Figure 116: Tail configurations for UAVs (Jay Gundlach, 2012, p. 128)

As years went by, aeronautical engineers came up with plenty of different tail configurations and each one comes with its own advantages and disadvantages. Some of these tails have already been presented in chapter 4.

The tail of a UAV or an aircraft, is the structure at the rear, that provides stability, control and steering during flight. Along with the wings, the vertical and horizontal tail, are referred to, as lifting surfaces (Mohammad H. Sandraey, 2013, p. 265). The tail's functions are the following, as already mentioned in *Aerodynamics and Flight Dynamics*, in paragraph (4.7):

- Trim
- Stability
- Control

The methodology that is going to be followed is the one proposed by M. H. Sandraey. After the determination of the tail geometry, the design parameters that must be taken into consideration, are the following:

Horizontal tail	Vertical tail
Planform area (S_h)	Planform area (S_v)
Tail arm (l_h)	Tail arm (l_v)
Airfoil section	Airfoil section
Aspect ratio (A)	Aspect ratio (A)
Taper ratio (λ_h)	Taper ratio (λ_v)
Tip chord (C_{htip})	Tip chord (C_{vtip})
Root chord (C_{hroot})	Root chord (C_{vroot})

Mean aerodynamic chord (MAC_h)	Mean aerodynamic chord (MAC_v)
Span (b_h)	Span (b_v)
Sweep angle (Λ_h)	Sweep angle (Λ_v)
Dihedral angle (Γ_h)	Dihedral angle (Γ_v)
Tail installation	Tail installation
Incidence (i_h)	Incidence (i_v)

Table 44: Design parameters for horizontal and vertical tail (Mohammad H. Sandraey, 2013, pp. 266-267)

In a conventional tail configuration, longitudinal stability is achieved when:

$$\sum M_{cg} = 0 \;\; =>$$

⇨ $M_{o_{wf}} + L_{wf}(h\bar{C} - h_o\bar{C}) + L_h l_h = 0$ (eq. 6.7.1)

$$\sum F_z = 0 =>$$

⇨ $W = L_{wf} + L_c$ (eq. 6.7.2)

Where:

$M_{o_{wf}}$: The wing/fuselage pitching moment

$M_{L_{wf}}$: The wing/fuselage pitching moment due to lift

- Tail arm

Tail arm is defined as the distance (l or l_h) between the tail aerodynamic center and the center of gravity (Mohammad H. Sandraey, 2013, p. 298).

From the Table below, we choose the tail volume coefficient.

No	Aircraft	Horizontal tail volume coefficient ($\overline{V_H}$)	Vertical tail volume coefficient ($\overline{V_V}$)
1	Glider and motor glider	0.6	0.03
2	Home-built	0.5	0.04
3	GA signle prop-driven engine	0.7	0.04
4	GA twin prop-driven engine	0.8	0.07
5	GA with canard	0.6	0.05
6	Agricultural	0.5	0.04
7	Twin turboprop	0.9	0.08
8	Jet trainer	0.7	0.06
9	Fighter aircraft	0.4	0.07
10	Figher (with canard)	0.1	0.06
11	Bomber/military transport	1	0.08
12	Jet transport	1.1	0.09

Table 45: Tail volume coefficients (Mohammad H. Sandraey, 2013, p. 303)

The horizontal tail volume coefficient for home-built is equal to 0.5, so:

$\overline{V_H} = 0.5$

The horizontal tail aerodynamic center is located at the quarter chord of the horizontal tail's mean aerodynamic center, so:

$ac_h = (0.25*MAC_h) = 0.01$

The equation for calculating the optimum tail arm is the following:

$$l_{opt} = \mathrm{Kc}\sqrt{\frac{4\bar{C}S\overline{V_H}}{\pi D_f}} \qquad \text{(eq. 6.7.3)}$$

Where:

K_c: A correction factor

$\bar{C}$: Mean aerodynamic chord

S: Wing surface area

$\overline{V_H}$: Horizontal tail volume coefficient

D_f: The maximum diameter of the fuselage

Our loitering munition's diameter will be equal to the diameter of the M320 grenade launcher, so:

$D_f = 0.04$ m

The correction factor varies between 1 and 1.4, depending on the aircraft configuration. $K_c = 1$ is used when the aft portion of the fuselage has a conical shape. As the shape of the aft portion of the fuselage goes further away from the conical shape, the K_c factor is increased up to 1.4. We assume that the correction factor is equal to 1.2:

$K_c = 1.2$

As for the length of the fuselage, it should match the length of other 40 mm drones that are used for the grenade launcher. An example could be the Drone 40 from DefendTex:

$L_f = 0.18$ m

From Table (6.2) of (Mohammad H. Sandraey, 2013, p. 276):

$\frac{l}{L} = 0.45$

Where:

$l = l_{opt}$

$L = L_f$

So:

$l_{opt} = 0.081$ m

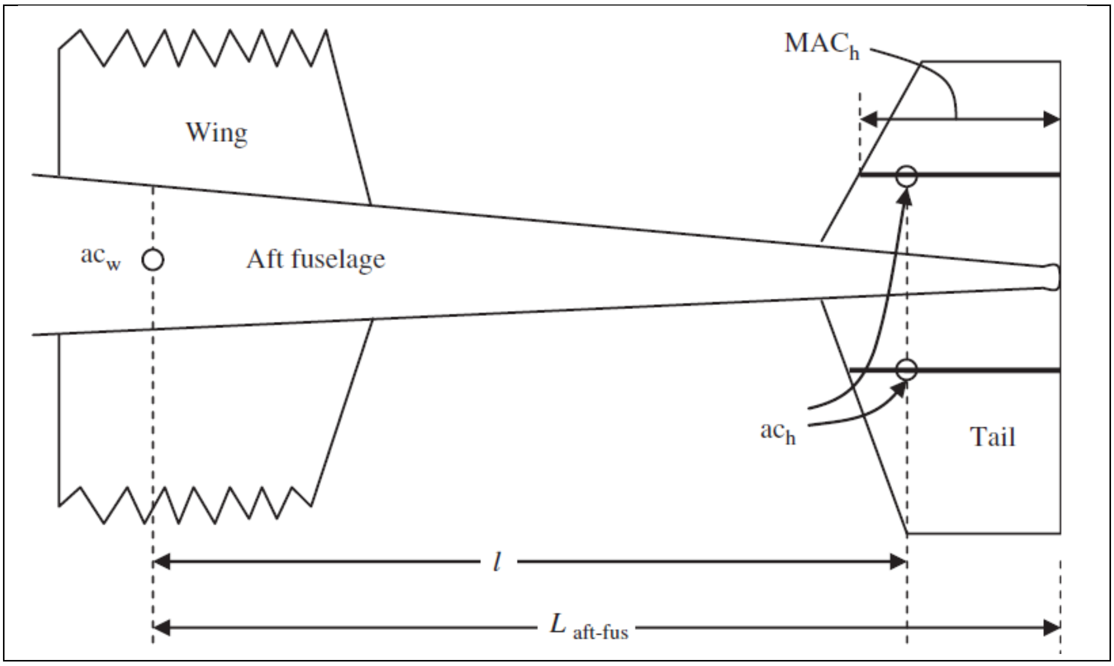


Figure 117: Top view of the optimum tail arm (l_h) (Mohammad H. Sandraey, 2013, p. 299)

To calculate the horizontal tail area S_h, we solve the following equation:

$\overline{V_H} = \frac{lS_h}{\bar{C}S}$ => (eq. 6.7.4)

⇨ $S_h = 0.0023703704$ m^2

To find the horizontal tail lift coefficient:

$C_{mo\_wf} + C_L*(h - h_o) - n_h*V_H*C_{Lh} = 0$ (eq. 6.7.5)

$C_{mo\_wf} = C_{maf}\frac{A\cos^2(\Lambda)}{A+2\cos(\Lambda)} + 0.01 * a_t$ (eq. 6.7.6)

Where:

C_{maf}: The wing airfoil section pitching moment coefficient ($C_{maf} = C_{mi(Eppler\ 212)} = -0.123$)

A: The aspect ratio

Λ: The wing sweep angle

a_t: The wing twist angle (in degrees)

From eq. (6.7.6):

$C_{mo\_wf} = (-0.123)\frac{6\cos^2(0)}{6+2\cos(0)} + 0.01 * 2.99 \Rightarrow$

⇨ $C_{mo\_wf} = -0.06235$

As already mentioned and shown in Figure 55, longitudinal stability is achieved when the center of gravity is in front of the aircraft's aerodynamic center.

$$h_o = \frac{x_{acwf}}{\bar{C}} \quad \text{(eq. 6.7.7)}$$

Where:

h_o: The position of the wing/fuselage (dimensionless)

x_{acwf}: The distance between the wing's leading edge and aerodynamic center

$$h = \frac{x_{cg}}{\bar{C}} \quad \text{(eq. 6.7.8)}$$

Where

h: The position of the center of gravity (dimensionless)

x_{cg}: The distance between the cg and wing's leading edge

If we assume that the aerodynamic center of the wing/fuselage is located at one quarter of the MAC and the distance between the center of gravity and the aerodynamic center is 10% of the MAC, then, using the equations (6.7.7) and (6.7.8) respectively, we have:

$x_{acwf} = \frac{1}{4}\bar{C} \Rightarrow h_o = 0.01$

$x_{cg} = x_{acwf} - 0.1\bar{C} \Rightarrow h = 0.0096$

The typical value of the tail efficiency (n_h) for an aircraft with a conventional tail varies from 0.85 to 0.95. We assume that:

$n_h = 0.9$

For $C_L = C_{Lc} = 0.533$, we can calculate from eq. (6.7.5) the horizontal tail lift coefficient:

$C_{Lh} = -0.1385084444$

Then, we can find the aspect ratio of the tail, the horizontal tail span, the tail MAC and the taper ratio:

$A_h = \frac{2}{3}A \Rightarrow A_h = 4$

$A_h = \frac{b_h^2}{S_h}$ => $b_h = 0.093$ m

Ah = $\frac{b_h}{\bar{C}_h}$ => $\bar{C}_h = 0.02325$ m

$\lambda_h = \lambda_w = 1$

As for the tail root chord:

$$\bar{C}_h = \frac{2}{3} C_{hroot} \left(\frac{1+\lambda_h+\lambda_h^2}{1+\lambda_h}\right) \quad \text{(eq. 6.7.9)}$$

$C_{hroot} = 0.02325\, m$

The tail tip chord (λ_h):

$\lambda_h = \frac{C_{htip}}{C_{hroot}}$ => $C_{htip} = 0.02325\, m$

The dihedral angle Γ_h is zero, as is the tail sweep angle at 50% of the chord.

$\Lambda_{hc/2} = 0$

$\Lambda_h = \Lambda_{LE} = 0$ deg

$\Lambda_{TE} = -\Lambda_{LE} = 0$ deg

$\Gamma_h = 0$

From eq. (6.6.12), we can calculate the Reynolds number for the horizontal tail, by using the $\bar{C}_h$:

Re = 133954.17256396

Using the same method, we will choose a symmetrical airfoil that corresponds better at this Reynolds number. The airfoil that is going to be used should be thinner than the main wing and stall after the wing. The drag coefficient should be the lowest possible.

For example, let's use the NACA 0006 airfoil.

Cl_i	a_i (deg)	Cd_{min}	Cm_i	$(Cl/Cd)_{max}$	a_o (deg)	Cl_{max}	a_s (deg)	Cl_a (1/rad)	$(t/c)_{max}$ (%)
0	0	0.0066	0	41.20	0	0.7	8	5.92	6%

Table 46: Data for NACA 0006 airfoil

As for the tail setting angle (i_h):

$$C_{L_{\alpha\_h}} = \frac{C_{l_{\alpha\_h}}}{1+\frac{C_{l_{\alpha\_h}}}{\pi A}}$$ eq. (6.7.10)

Where:

$C_{l_{\alpha\_h}}$: tail lift curve slope for NACA 0006 airfoil

$C_{l_{\alpha\_h}} = 5.92 \left(\frac{1}{rad}\right)$ (from Table 46)

From eq. (6.7.10):

$C_{L_{\alpha\_h}} = 4.027\ (1/rad)$

During cruise, the angle of attack of the tail, is:

$$\alpha_h = \frac{C_{L_h}}{C_{L_{\alpha_h}}}$$ (eq. 6.7.11)

$\alpha_h = -0.072$ rad (or -4.138 deg)

The horizontal tail setting angle is given by the following equation:

$$i_{w_h} = a_h - a_f + \varepsilon$$ (eq. 6.7.12)

Where:

i_{w_h}: The tail setting angle

a_h: The angle of attack of the horizontal tail

a_f: The angle of attack of the fuselage (we assume that $a_f = 0$)

ε: The downwash (in deg)

The downwash is calculated by:

$$\varepsilon = \varepsilon_o + \frac{\partial\varepsilon}{\partial\alpha}\alpha_w$$ (eq. 6.7.13)

Where:

ε_o: The downwash at zero angle of attack (in deg)

$\frac{\partial\varepsilon}{\partial\alpha}$: The downwash slope

α_w: The angle of attack of the wing

For the downwash at zero angle of attack:

$$\varepsilon_o = \frac{2C_{L_C}}{\pi A} \quad \text{(eq. 6.7.14)}$$

$$\frac{\partial \varepsilon}{\partial \alpha} = \frac{2C_{L\alpha}}{\pi A} \quad \text{(eq. 6.7.15)}$$

From the equations above, we get:

$\varepsilon_o = 0.0843949045\ rad$ (or 4.835472 deg)

$\frac{\partial \varepsilon}{\partial \alpha} = 0.6412420382$ (deg/deg)

Since, $\alpha_w = i_w = -0.47\ deg$, we have:

$\varepsilon = 4.835472 - 0.3008 = 4.534672\ deg$ (or 0,0791449569 rad)

The tail setting angle can be calculated from the following equation:

$$\alpha_h = \alpha_f + i_h - \varepsilon \quad \text{(eq. 6.7.16)}$$

So:

$i_h = 4.534672 - 4.138 = 0.396672$ deg (or 0.0069232325 rad)

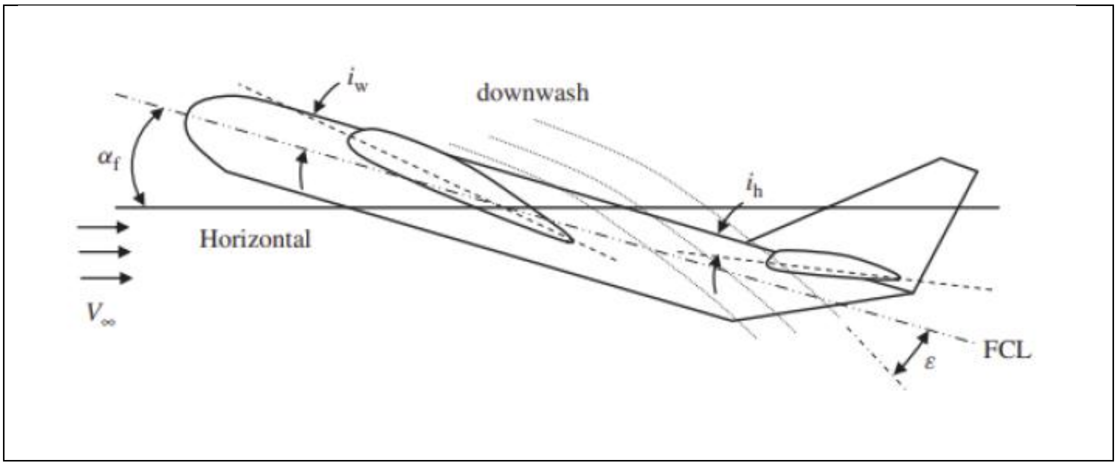


Figure 118: Horizontal tail effective angle of attack (Mohammad H. Sandraey, 2013, p. 311)

Just like in the wing design process, there is a MATLAB code that Sandraey presents in his book.

```
clc;
clear all;
close all;
N = 9; % (number of segments-1)
S = 0.0023703704; % m^2
AR = 4; % Aspect ratio
lambda = 1; % Taper ratio
alpha_twist = 0; % Twist angle (deg)
a_h = -4.138; % tail angle of attack (deg)
a_2d = 4.027113605; % lift curve slope (1/rad)
alpha_0 = 0; % zero-lift angle of attack (deg)
b = sqrt(AR*S); % tail span
MAC = S/b; % Mean Aerodynamic Chord
Croot = (1.5*(1+lambda)*MAC)/(1+lambda+lambda^2); % root chord
theta = pi/(2*N):pi/(2*N):pi/2;
alpha=a_h+alpha_twist:-alpha_twist/(N-1):a_h;
% segment's angle of attack
z = (b/2)*cos(theta);
c = Croot*(1-(1-lambda)*cos(theta)); % Mean Aerodynamics chord at each segment
mu = c*a_2d/(4 * b);
LHS = mu.*(alpha-alpha_0)/57.3; % Left Hand Side
% Solving N equations to find coefficients A(i):
for i=1:N
for j=1:N
B(I,j)=sin((2*j-1)*theta(i))*(1+(mu(i)*(2*j-1))/sin(theta(i)));
end
end
A=B\transpose(LHS);
for I = 1:N
sum1(i) = 0;
sum2(i) = 0;
for j = 1 : N
sum1(i) = sum1(i) + (2*j-1) * A(j)*sin((2*j-1)*theta(i));
sum2(i) = sum2(i) + A(j)*sin((2*j-1)*theta(i));
end
end
CL_tail = pi * AR * A(1)
```

Figure 119: MATLAB code for the application of the lifting-line theory for tail design (Mohammad H. Sandraey, 2013, p. 333)

Moving on with the vertical tail, its volume coefficient ($\overline{V_V}$) is given by:

$$\overline{V_V} = \frac{l_v S_v}{bS} \qquad \text{(eq. 6.7.17)}$$

Where:

S_v: The tail planform area

b: The wingspan of the main wing

S: The surface of the main wing

We use the data from Table 45:

So, $\overline{V_V} = 0.04$

The following figure, presents the parameters of the vertical tail:

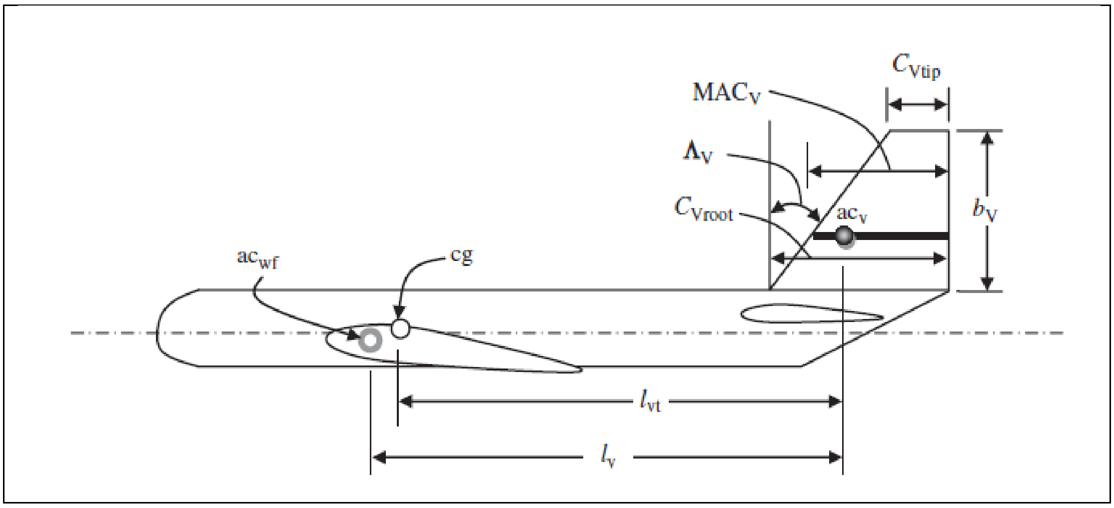


Figure 120: The vertical tail parameters (Mohammad H. Sandraey, 2013, p. 319)

The vertical tail moment arm (l_v) is assumed to be equal to the horizontal tail moment arm (l_{opt}):

$l_v = l_{opt} = 0.081$ m

The vertical tail planform area (S_v) is calculated by equation (6.7.17):

$\overline{V_V} = \frac{l_v S_{v,total}}{bS}$ =>

⇨ $S_{v,total} = 0.001137$ m^2

However, our loitering munition will have twin vertical tail configuration, so:

$S_v = \frac{S_{v,total}}{2} = 0.0005685$ m^2

To find the aspect ratio of the vertical tail (A_v) we choose the same as the horizontal tail, but since we have a twin vertical tail, we will continue our calculations using the semispan, so:

$A_v = A_h/2 = 2$

In terms of airfoil type selection, we want to achieve symmetry, high value of lift curve and thinner MAC, in relation to the wing airfoil section. For these reasons, we could select the same airfoil as the horizontal tail, hence, the NACA 0006.

For the setting angle, just like in equation (6.7.10):

$C_{L_{\alpha\_v}} = \frac{C_{l_{\alpha\_v}}}{1+\frac{C_{l_{\alpha\_v}}}{\pi A}}$ =>

- ⇨ $C_{L_{\alpha\_v}}$ = 3.049 (1/rad), since $C_{l_{\alpha\_v}} = C_{l_{\alpha\_h}}$ = 5.926 (1/rad)

The vertical tail efficiency (n_v) is the ratio between the dynamic pressure of the aircraft and the dynamic pressure of the vertical tail.

$n_v = 0.9 = n_h$

The parameter K_{f1}, represents the contribution of the fuselage to the aircraft static directional stability and the acceptable values are 0.65 – 0.85. We assume that:

$K_{f1} = 0.8$

As for the sweep angle of the vertical tail, we assume that:

$\Lambda_{vc/2} = 0$

$\Lambda_v = \Lambda_{vLE} = \Lambda_{hLE} = 0$ deg

$\Lambda_{vTE} = 0$ deg

The vertical tail span (b_v) is equal to:

$A_v = \frac{b_v^2}{S_v}$ =>

- ⇨ $b_v = 0.033$ m

Also, the MAC of the vertical tail is calculated from the following equation:

$A_v = \frac{b_v}{\bar{C}_v}$ =>

- ⇨ $\bar{C}_v = 0.01685$ m

The taper ratio is the same as the previously calculated taper ratios, of horizontal tail and wing:

$\lambda_v = 1$

For the vertical tail root chord, we use the equation below:

$\bar{C}_v = \frac{2}{3}\, C_{vroot}\,(\frac{1+\lambda_h+\lambda_h^2}{1+\lambda_v})$ =>

- ⇨ C_{vroot} = 0.01685 m

Since $\lambda_v = \frac{C_{vtip}}{C_{vroot}}$, $C_{vtip} = 0.01685$ m

We will choose zero-degree angles for the dihedral and the incidence angle, so:

$\Gamma_v = 0$ deg and $i_v = 0$ deg

We also assume that the sidewash gradient is equal to zero, so:

$\frac{d\sigma}{d\beta} = 0$

At this point, we can calculate the static directional stability derivative C_{n_β}, which shows if the loitering munition is statically stable or not. If $C_{n_\beta} > 0$, then we have static directional stability.

$$C_{n_b} = K_{f1} C_{L_{\alpha_v}} \left(1 - \frac{d\sigma}{d\beta}\right) \eta_v \frac{l_{vt} S_v}{bS} \qquad \text{(eq. 6.7.18)}$$

Where:

K_{f1}: A parameter that represents the contribution of the fuselage to the aircraft's static directional stability (For conventional aircraft, the typical value is around 0.65 – 0.85. We assume that $K_{f1} = 0.8$)

$C_{L_{\alpha_v}}$: Indicates the vertical tail lift curve slope

$\frac{d\sigma}{d\beta}$: The vertical tail sidewash gradient

η_v: The dynamic pressure ratio at the vertical tail

By inserting the values, we have:

$C_{n_b} = 0.3954219$ (1/rad) > 0, so static directional stability is achieved.

The following Table presents the horizontal and vertical tail specifications:

Specifications	Horizontal tail	Vertical tail
Volume coefficient	$\overline{V_H} = 0.5$	$\overline{V_V} = 0.04$
Optimum moment arm	$l_{opt} = 0.081$	$l_{opt} = 0.081$
Surface area	$S_h = 0.0023703704$ m^2	$S_v = 0.0005685$ m^2
Lift coefficient	$C_{Lh} = -0.1385084444$	-
Aspect ratio	$A_h = 4$	$A_v = 2$
Wingspan	$b_h = 0.093$ m	$b_v = 0.033$ m
MAC	$\bar{C}_h = 0.02325$ m	$\bar{C}_v = 0.01685$ m
Taper ratio	$\lambda_h = 1$	$\lambda_v = 1$
Root chord	$C_{hroot} = 0.02325$ m	$C_{vroot} = 0.01685$ m
Tip chord	$C_{htip} = 0.02325$ m	$C_{vtip} = 0.01685$ m
Sweep (LE)	$\Lambda_{vLE} = 0$ deg	$\Lambda_{hLE} = 0$ deg

Sweep (LE/2)	$\Lambda_{hc/2} = 0$	$\Lambda_{vc/2} = 0$
Dihedral angle	$\Gamma_h = 0$ deg	$\Gamma_v = 0$ deg
Angle of attack	$\alpha_h = -0.072$ rad (or -4.138 deg)	-
Downwash angle	$\varepsilon = 4.534672\ deg$ (or 0,0791449569 rad)	-
Incidence angle	$i_h = 0.0069232325$ rad (or 0.396672 deg)	$i_v = 0$ deg

Table 47: Tail specifications

§6.6 Fuselage design

It's the central body of our loitering munition and it is the part in which all the components, including the warhead will be stored. In our case, the dimensions of the fuselage play a crucial role, since our loitering munition is going to be launched from a grenade launcher, so its shape is going to be cylindrical. According to (Mohammad H. Sandraey, 2013, p. 372), two of the main fuselage parameters are the fuselage length (L_f) and the maximum diameter (D_f). The fuselage optimum length-to-diameter (or slenderness) ratio may be determined based on a number of design requirements. The design objectives may be to determine the fuselage length-to-diameter ration such that it:

- Results in the lowest zero-lift drag
- Creates the lowest wetted area
- Delivers the lightest fuselage
- Provides the maximum internal volume
- Generates the lowest mass moment of inertia
- Contributes the most to aircraft stability
- Requires the lowest cost to fabricate

The optimum slenderness ratio for lowest f_{LD}:

$$C_{D_{O\_f}} = C_f f_{LD} f_M \frac{S_{wet}}{S_{ref\_fus}} \quad \text{(eq. 6.8.1)}$$

Where:

f_{LD}: function of the fuselage length-to-diameter ratio

S_{wetf}: fuselage wetted area

$$f_{LD} = 1 + \frac{60}{\left(\frac{L}{D}\right)^3} + 0.0025\left(\frac{L}{D}\right) \quad \text{(eq. 6.8.2)}$$

To determine the optimal value for the length-to-diameter ratio, we take the lowest value for the function f_{LD}.

$$\frac{df_{LD}}{d\left(\frac{L_f}{D_f}\right)} = 0 \Rightarrow$$

$$\Rightarrow \left(\frac{L}{D}\right)_{opt} = 16.3 \qquad \text{(eq. 6.8.3)}$$

Another influential parameter in the fuselage drag is the fueslage wetted area (S_{wetf}). When this parameter is inserted into the differentiation, the optimal value changes:

$$\left(\frac{L}{D}\right)_{opt} = 5.1 \qquad \text{(eq.6.8.4)}$$

According to M. H. Sandraey, a cylindrical fuselage with minimum surface (wetted) area, has a length equal to its diameter, so:

$$\left(\frac{L}{D}\right)_{opt} = 1 \qquad \text{(eq. 6.8.5)}$$

This ratio is also the same, when we try to minimize the weight of the fuselage.

From equations (6.8.3 – 6.8.5), the ($\left(\frac{L}{D}\right)_{opt}$) ranges between [1, 16.3]

We have already calculated the length and the diameter of the fuselage and they are equal to:

$L_f = 0.18$ m

$D_f = 0.04$ m

If we divide them, we take:

$\frac{L}{D} = 4.5$ (within the range of the accepted values)

The following Table presents the specifications of the fuselage:

Parameter	Value
Length	0.18 m
Diameter	0.04 m
Height	0.046 m
Geometry	Rounded (40 x 46 mm)

Table 48: Specifications of the fuselage

§6.7 Computer-aided design (CAD)

OpenVSP (Open Vehicle Sketch Pad) is an open-source parametric aircraft geometry modeling tool primarily used in the aerospace industry, introduced by NASA. It enables users to create 3D models of aircraft designs for conceptual and preliminary analysis. Developed by NASA, OpenVSP is widely used for aerodynamic analysis, structural studies and general design optimization in aerospace engineering. The Figures below, present the design steps, as mentioned above, in the right order and contain also the initial specifications for our loitering munition. The results are the following:

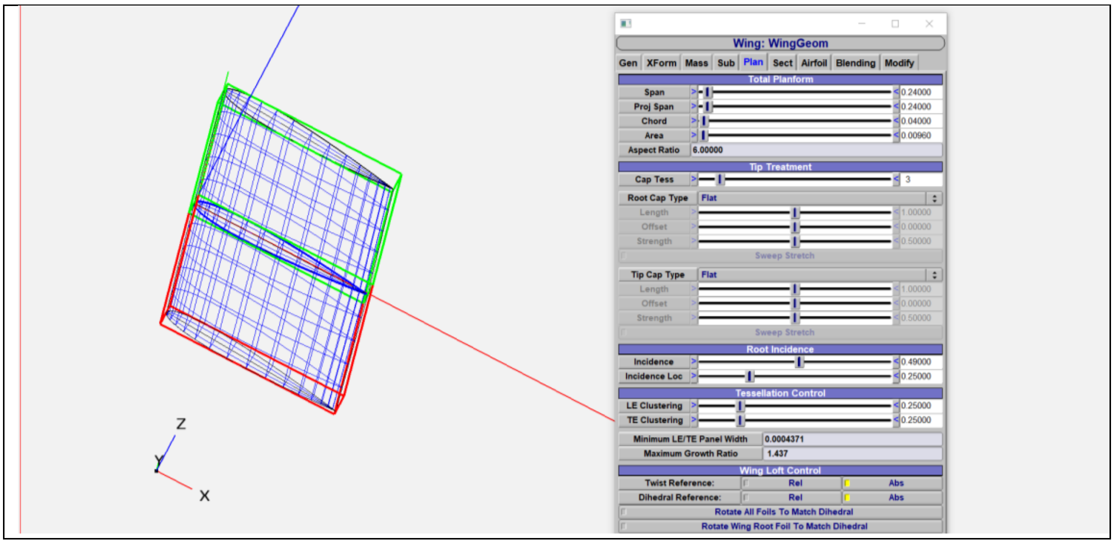


Figure 121: Main wing

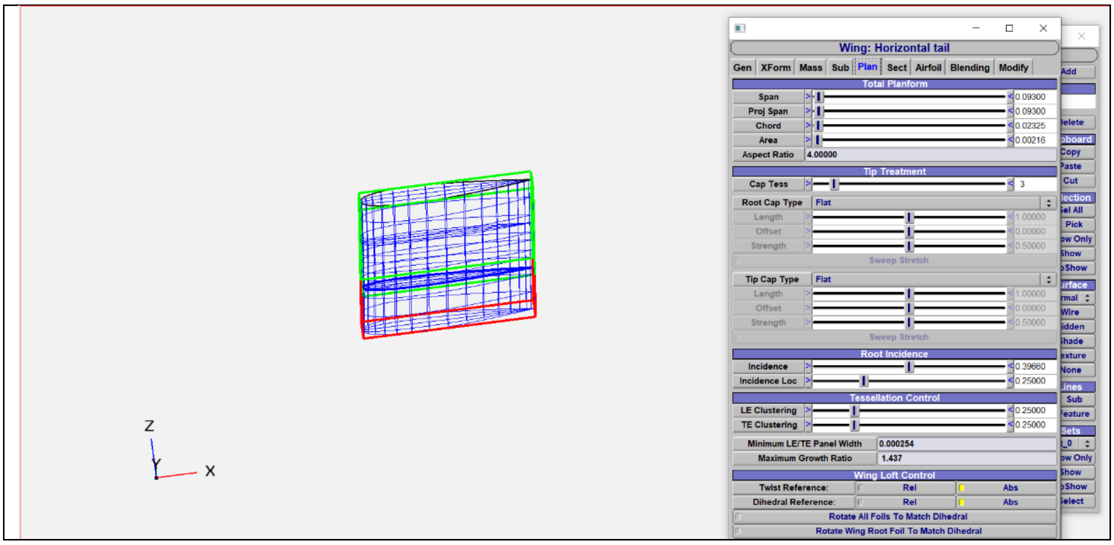


Figure 122: Horizontal tail

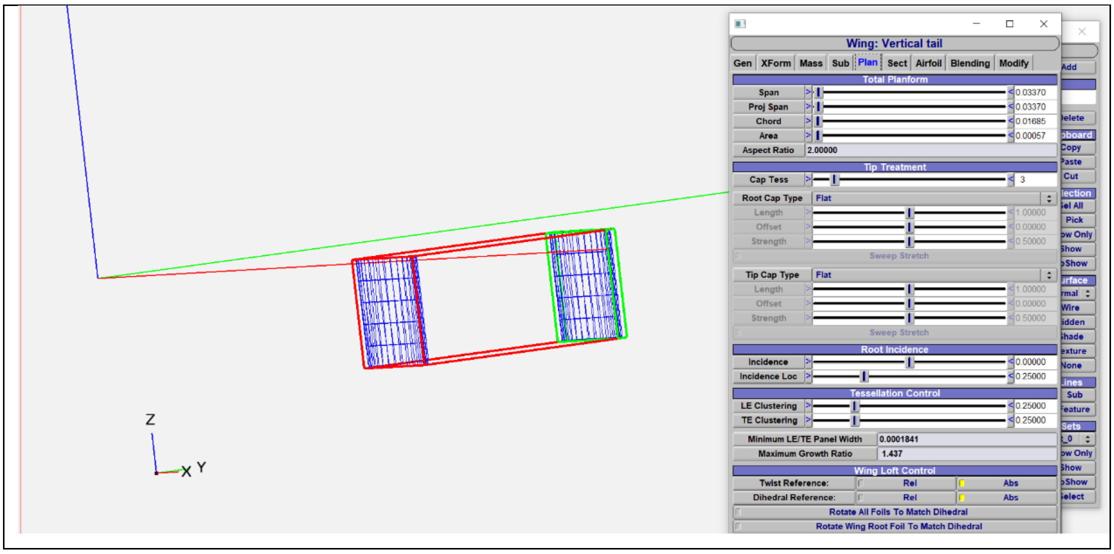


Figure 123: Vertical tail

This loitering munition will serve as an ammunition for the M320 grenade launcher, so its dimensions play a crucial role, as it has to be able to fold and fit in the tube (40 x 46 mm). We have to take into consideration the thickness of the main wing, the horizontal tail and the vertical tail, their twist angles and their incidence angles, in order to leave enough space for the folding. The length of the fuselage is also predetermined and equal to 180 mm.

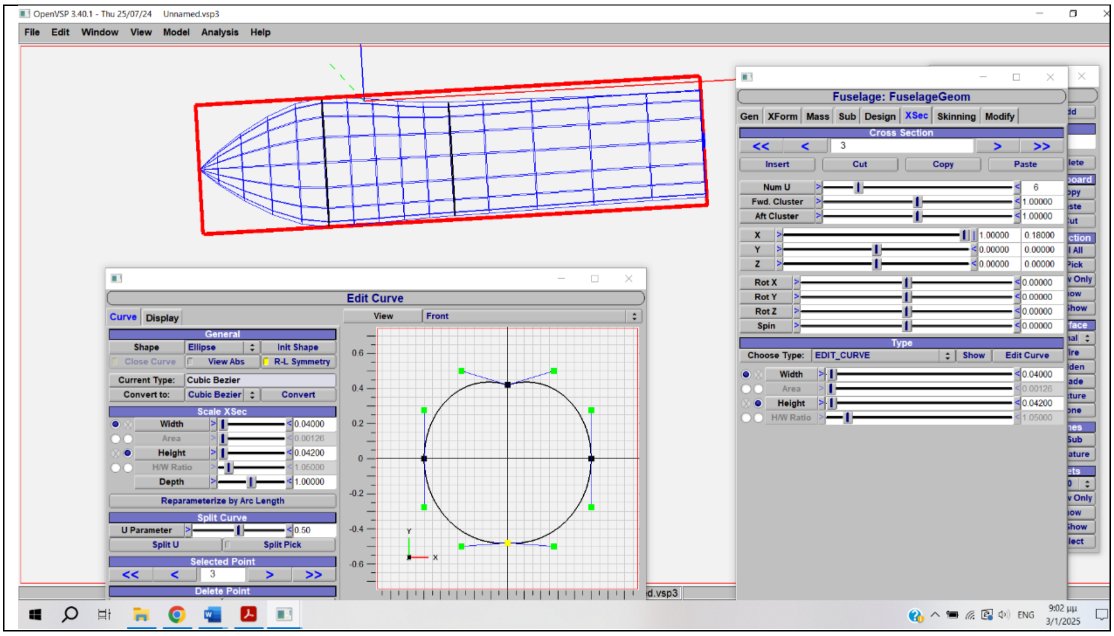


Figure 124: Fuselage calculations

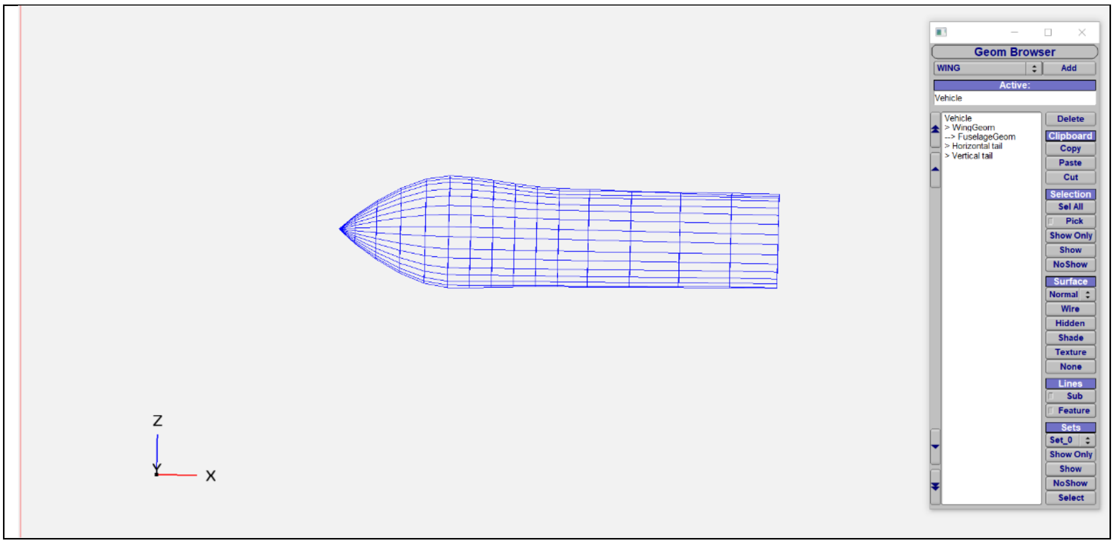


Figure 125: Fuselage shape

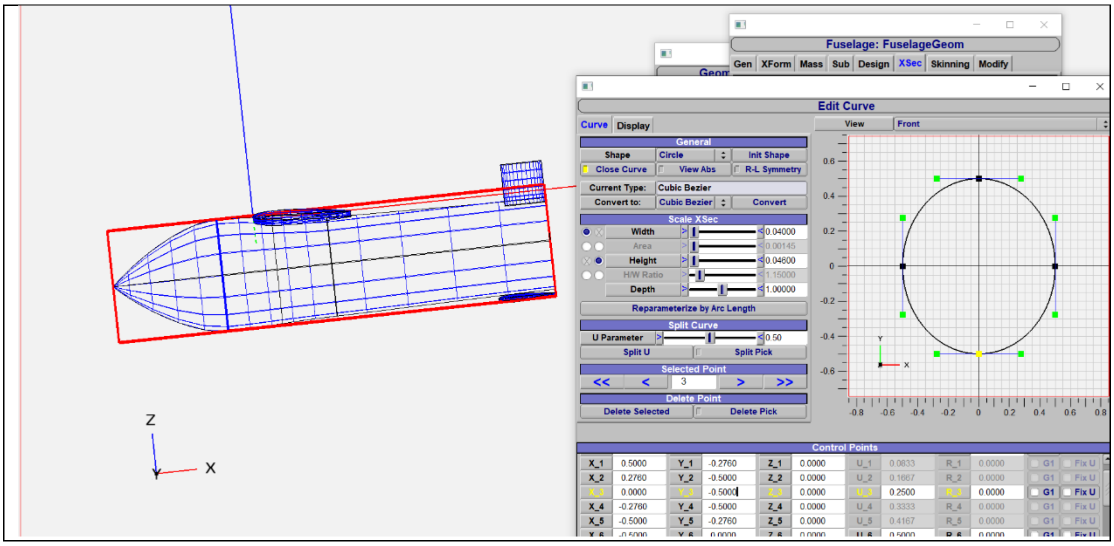


Figure 128: Fuselage height and width calculation

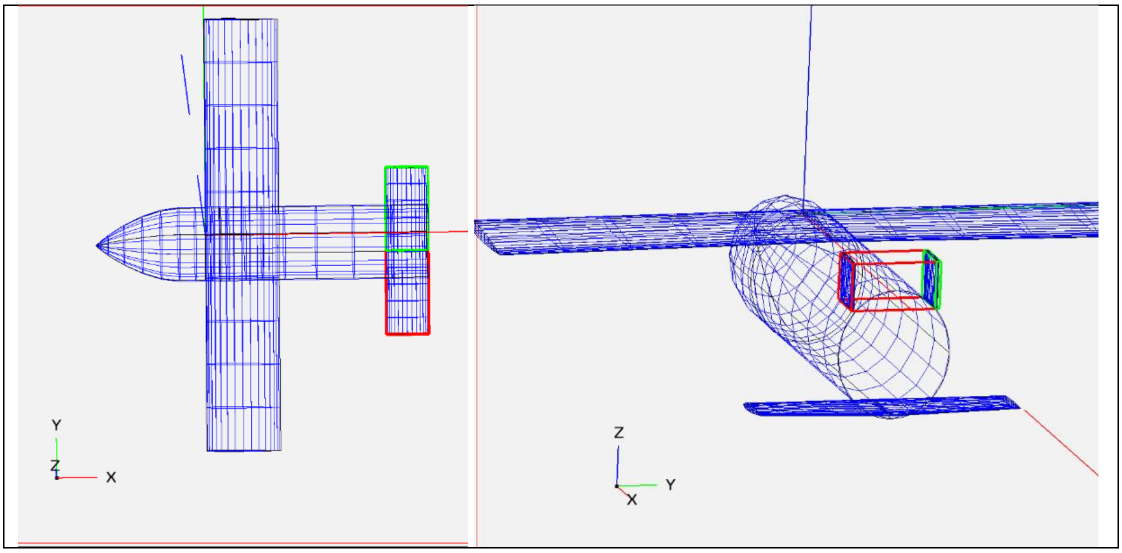


Figure 126: Our loitering munition unfolded (Top view on the left and back view on the right)

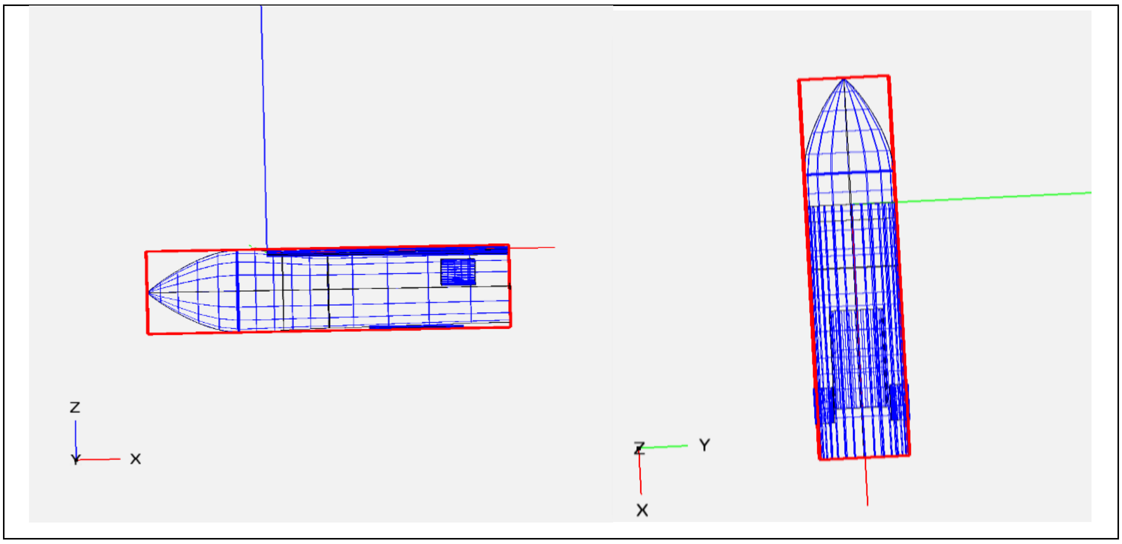


Figure 127: Our loitering munition folded (Side view on the left and top view on the right)

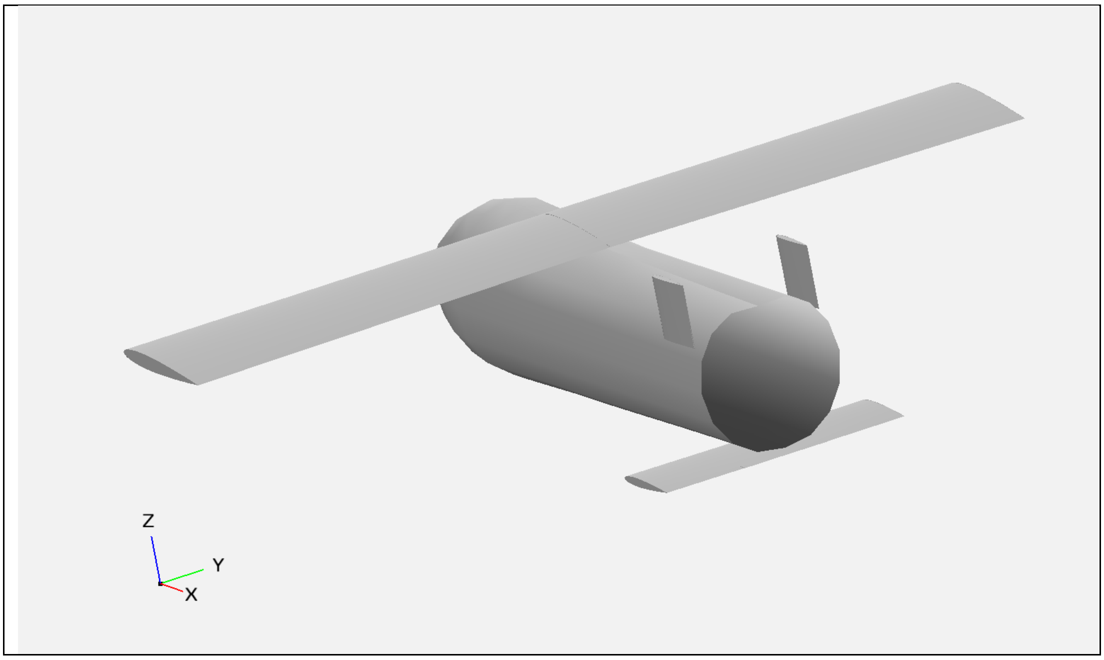


Figure 128: 3D model of our loitering munition (back view)

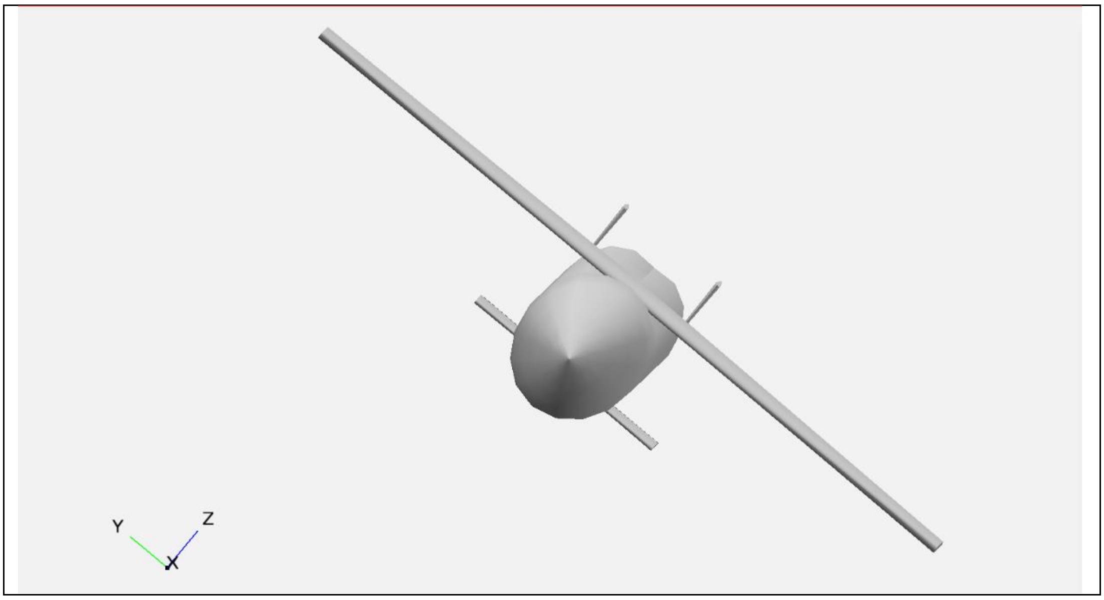


Figure 129: 3D model of our loitering munition (front view)

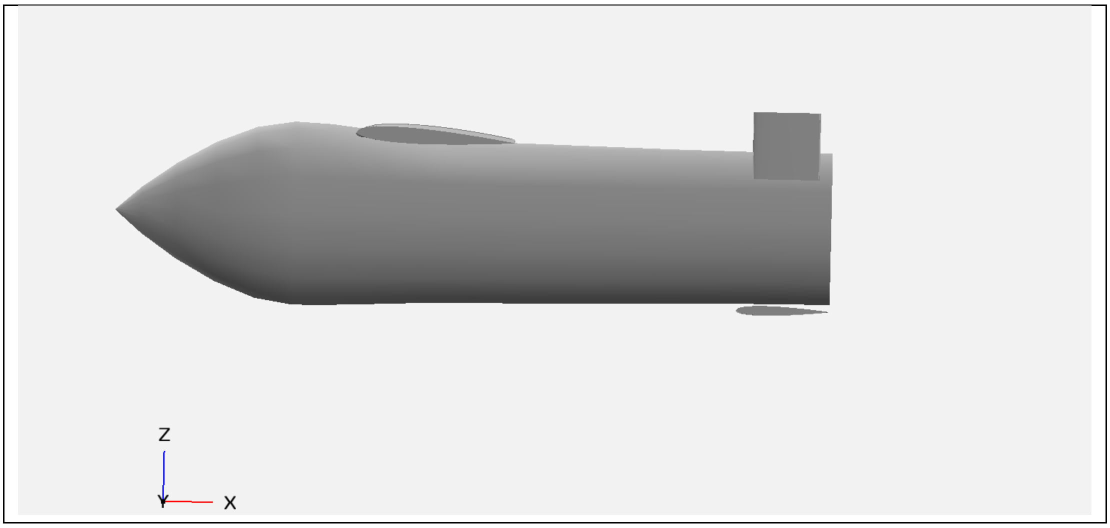


Figure 130: 3D model of our loitering munition (side view)

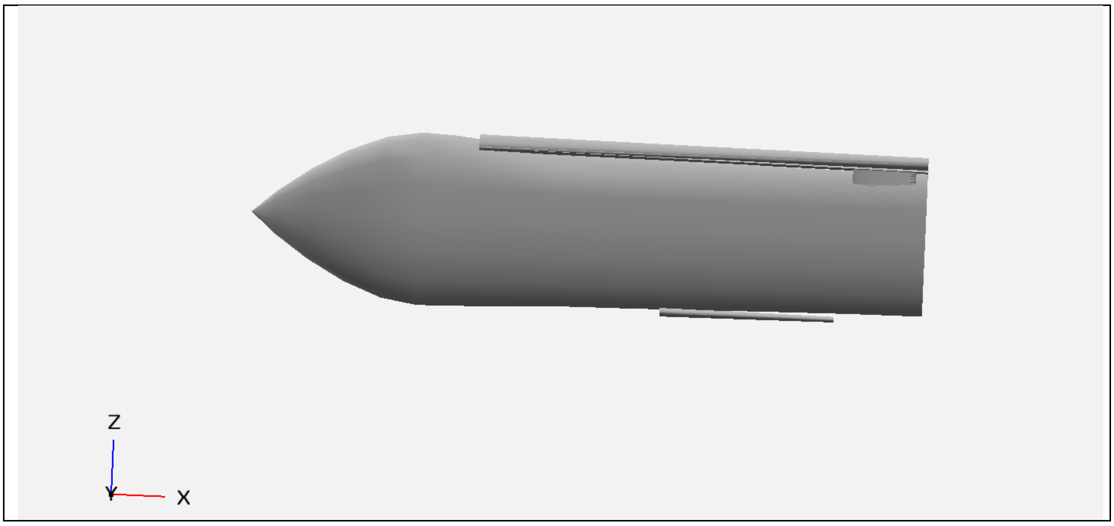


Figure 131: 3D model of our loitering munition (folded, side view)

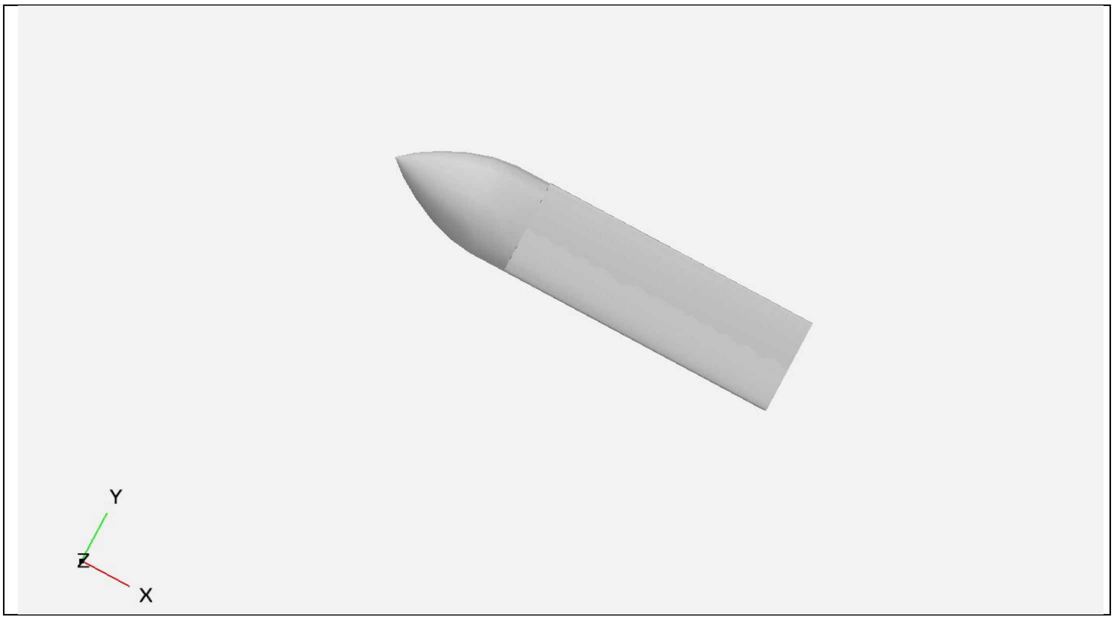


Figure 132: 3D model of our loitering munition (folded, top view)

Then, the propeller is added, but the analysis of the propeller blades and the propulsion system in general, is out of the scope of this thesis, so the conceptual design procedure will end here. It is a loitering munition, so no landing gear is required. All the parts, including the warhead that will be stored in the front of the fuselage, will be placed inside in a specific way, in order to achieve stability during flight, taking always into consideration the center of gravity (c.g.). An imbalance could deeply affect flight stability. At this point, the conceptual design analysis has come to an end. It is necessary to note that this thesis serves as an introduction to loitering munitions and the basic steps of conceptual design. Further analysis and testing should be conducted, in order to create, with the use of a 3D printer for example, a cheap loitering munition.

§6.8 The M320 grenade launcher

The M320 grenade launcher is a versatile, single-shot 40 mm grenade launcher, used by the U.S. military and other armed forces worldwide. It is designed to replace the older M203 grenade launcher, by enhancing the accuracy, the effectiveness and the grip. It can be used in the stand-alone configuration, but it can also be mounted on an M-16 series rifle, or an M-4 carbine, as presented in the Figure below:

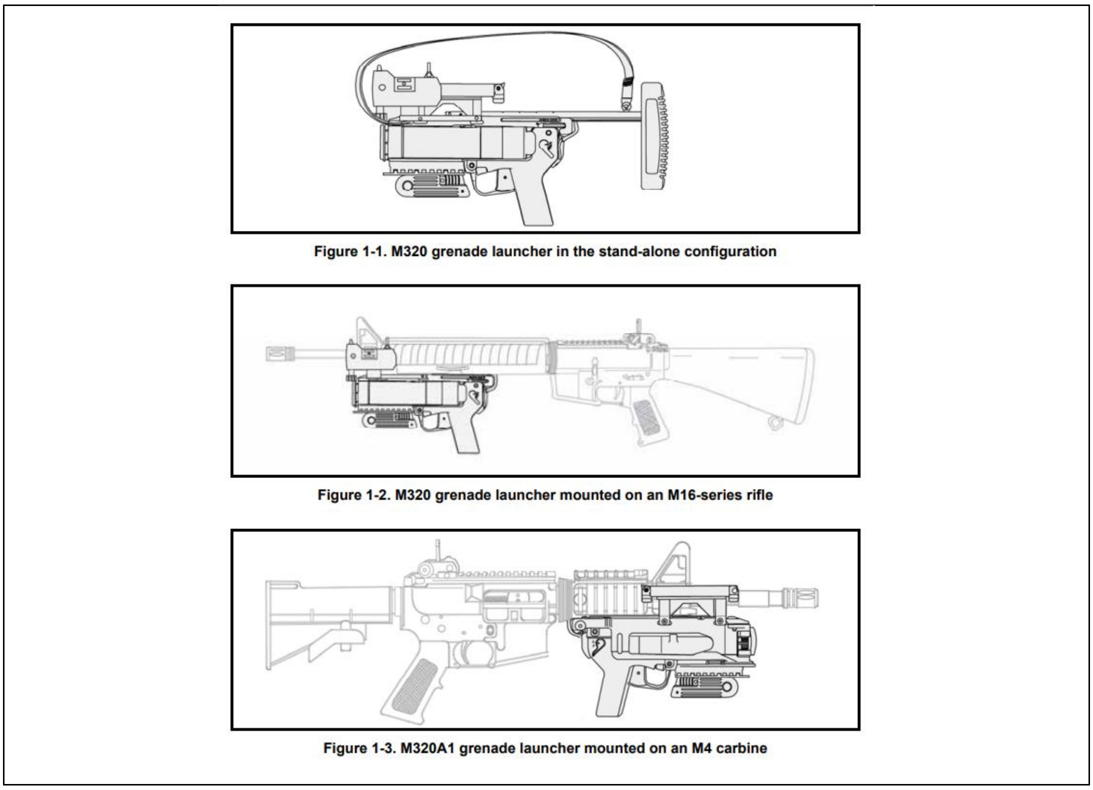


Figure 133: Different M320 configurations (TM 3-22.31 (FM 3-22.31), 2010, p. 2)

Amongst the advantages offered by this grenade launcher, military personnel came up with the idea of launching unmanned aerial systems, instead of conventional 40 mm grenades. This innovative solution, offers numerous advantages to the soldiers in the front line, as they can launch in no time, loitering munitions known as Grenade Launched Aerial Systems (GLUAS) and destroy the enemy with high-precision strikes.

Figure 134: A soldier is reloading an M320 grenade launcher (Task & Purpose, 2020)

These unmanned aerial systems have the dimensions of a 40 mm grenade (40 x 46 mm), because they have to fit and get launched through the same barrel with the conventional grenades. For this reason, their shape and look, are almost the same. There are some companies like the Spear or the DefendTex, that have innovated in the field, by producing these types of drones. The following Figure, presents the famous Drone-40, which is a 40 mm quadcopter, developed by DefendTex.

Figure 135: Drone-40 from DefendTex (Top War, 2021)

Our loitering munition however is fixed-wing, so it looks more like a Switchblade. Its wings and tail are folded and unfolded, using similar folding mechanism and the overall same philosophy. In the Figure below, we can see the launch of a Switchblade 300 and how its wings are unfolded.

Figure 136: The moment of launch of a Switchblade 300 (Wikipedia, n.d.)

The technical data for the M320 grenade launcher are presented below:

PHYSICAL CHARACTERISTICS		
Caliber		40 mm x 46 mm
Weight	Without buttstock	5.0 pounds
	With buttstock	7.0 pounds
Length	Without buttstock	11.18 inches
	With buttstock retracted	14.37 inches
	With buttstock extended	19.69 inches
	Barrel	8.46 inches
Height	Without sights or weapon adapters	6.38 inches
	With mechanical sights down	8.39 inches
	With mechanical sights up	12.05 inches
Width	With mechanical sights	3.62 inches
	Without mechanical sights	2.56 inches
Line of Sight		5.51 inches
Mechanical Features		Lands and grooves rifling
FIRING CHARACTERISTICS		
Muzzle Velocity		236.22 feet per second
Trigger Pull		11.25 to 15.75 pounds
Maximum Effective Range	Area target	350 m
	Point target	150 m
Maximum Range		400 m
Modes of Operation		SAFE and FIRE

Figure 137: Technical data (TM 3-22.31 (FM 3-22.31), 2010, p. 3)

Conclusions

This thesis focused on the use loitering munitions and the basic steps of the conceptual design of a Class 1 and fixed-wing loitering munition. These weapons have already changed the way wars are conducted and tend to affect many domains of modern societies, like the economy, the civilian's safety and world peace. From the spread of propaganda to terrorist attacks and military invasions, these small, lightweight drones form a new reality. In our case, the use of Class 1 loitering munitions designed for precision strikes, has transformed modern warfare. These systems offer numerous advantages, including cost-effectiveness, ease of deployment and high maneuverability, making them ideal for demanding operations, surveillance and precision targeting. Their ability to loiter over a target area before striking, allows for flexible and responsive decision-making, operational efficiency and reduction of collateral damage as the operator has the choice to abort and proceed to a new target. Moreover, Class 1 loitering munitions unlock advanced capabilities, enabling the conduction of joint operations between the Air Force, the Army and the Navy. In more advanced countries, like the United States, loitering munitions are massively used from squad to company level and exchange information with higher levels of command, in order for the squad to be more effective in harsh environments, like forests, towns and close-quarters battle (CQB). Their small dimensions, low heat signature and low noise, make them difficult to be detected. According to the recent announcement of the Greek minister of defense N. Dendias, by the year 2030, Greek camps will be equipped with small drones and will have the ability to counter drone attacks, a sign that indicates the importance of investing in UAS and especially in loitering munitions. This innovation is part of the "Agenda 2030", a program that will enhance the effectiveness of the Greek armed forces, in modern warfare. On top of that, some of these technologically advanced countries, use plenty of methods for deploying their loitering munitions, for example canisters or even grenade launchers. This last method for takeoff gives numerous advantages to the operators, as they can launch the loitering munition as if it was a grenade, hence rapidly and easily. For the operator, it is an innovative solution to strike targets. On the other hand, for the manufacturer could be a tough part to design the loitering munition, as it demands certain dimensions in order to fold and fit in the tube, specific weigh, warhead, engine and in general all the necessary calculations take time and many trials and errors are needed. We saw that during the conceptual design process, many changes are made, regarding the initial specifications, because there are numerous parameters and the smallest change leads to another change and this is why sizing is so important. Through trading studies, we recalculate and we eventually end up to a design that meets our requirements, but is maybe a little different from what we expected in first place.

Many questions are raised however, concerning the ethical part of these weapons. As we saw in the war in Ukraine, loitering munitions sometimes strike populated areas and there are collateral losses. The ethical issue is the challenge of distinguishing between military and civilian personnel, in complex dynamic environments. Loitering munitions often rely on semi-autonomous targeting systems or human operators, which can lead to lethal mistakes, particularly in urban or crowded areas. These errors can result in unintended civilian casualties, undermining the principles of proportionality and discrimination, outlined in international humanitarian law. Another concern is the accountability for these lethal decisions. As these systems can also operate autonomously, the line between human oversight and machine decision-making becomes blurred. This raises the question: "Who is responsible for the actions taken by an autonomous weapon system? The operator, the commander or the manufacturer?" These concerns will continue to grow, as technology will never stop evolving and new ways of striking will emerge. Either with the use of typical loitering munitions or the use of canister-launched loitering munitions with foldable wings, which are smaller and easier to deploy and operate. This is the new way of fighting and scientists and military personnel try to come up with innovative solutions for evolving the existing arsenal and defending their country, as each new weapon, demands a new way to counter it. Loitering munitions are already defining the future of modern warfare.

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