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MAINTENANCE ASPECTS OF UKRAINIAN DRONES

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Drones become part of our life, having a huge impact on it. What was beyond our imagination yesterday, becomes true today and will be even better tomorrow. Nowadays, with the help of drones we are able to detect in agriculture the parcels that require herbicides and fertilizer, develop researches in the atmosphere, monitor pollution and dangerous areas, have a better reconnaissance of the domestic infrastructure or obtain an easier victory in conflicts.

The purpose of this paper is to briefly analyze the maintenance required by drone systems - going through a short history of drones, their evolution and classification, their use in the ongoing Russian-Ukrainian conflict as well as the key aspects of their maintenance process. This article aims to provide a concise analysis of the maintenance needs for drone systems. It will cover the drone's brief history, classification and evolution, use in the ongoing Russian-Ukrainian conflict, and important maintenance procedures. Unmanned aerial vehicles have a very small tendency to be maintained in the same way as conventional aircraft (only by qualified aircraft maintenance personnel guided by complete maintenance procedures) due to differences in the personnel, equipment to be maintained, practices, and technical documentation, especially in a combat environment. In fact, untrained operators or maintainers without prior training in aviation maintenance constitute even the staff engaged.

Keywords: *drones; military; maintenance; reliability, operator; unmanned; aircraft.*

Introduction

The expanding selection of drones by a wide set of companies, open administrations and business visionaries guarantees a progressive cost-effective jump forward within the efficiency and execution of businesses, ranging from civilian logistics or infrastructure projects to the military domain. The conceivable outcomes

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for the use of drones can be found today in all divisions of a society. Within the open domain of society drones can be operated for the avoidance of wrongdoing (heat sensors detect unauthorized access on ranches or on border crossings during the night), in countering catastrophes, for governmental civil engineering projects, geographical studies, countering violations of human rights, guarding borders, and for environmental and agriculture assessments. Within the private domain of society there is potential for video surveillance applications (aerial photos and videos), for the assessment and avoidance of neighborhood wrongdoing. There are also various potential applications for drones with different payloads – carrying supplies for helpful purposes or pesticides used in agriculture. Within the military domain, drones are engaged for domestic purposes and in military operations abroad in theaters of operations.

1. A Brief History of Drones

Drones, as defined by the Merriam-Webster dictionary, are uncrewed aircrafts or vessels (performing in air, on water or underwater) guided by remote control or onboard computers. Abbreviations often used when there are topics related to drones are:

− UAVs - Unmanned Aerial Vehicles (used in the industry is the most frequent term, for recreational and professional civilian applications, speeds are quite fast, could reach difficult-to-access areas);

− UAS - Unmanned Aircraft System (describe the entire equipment: the aircraft, the control aparatus and the wireless data link and it is used by American and British organizations as Federal Aviation Administration (FAA – United States), Unmanned Aerial Vehicle Systems Association (UAVSA) – UK and so on);

− RPAS - Remotely Piloted Aircraft System (formal term used by international agencies as the International Civil Aviation Organization (ICAO), the European Aviation Safety Agency (EASA) and so on);

− USV - Uncrewed Surface Vessel is a ship (boat) that performs on the surface of the water not having a crew;

− UUVs - Unmanned Undersea Vehicles (speeds are low, long duration is required but it is affected by high sea currents).

The French language speaking countries use the term “drone” associated with military technology (AltiGator 2024).

The first case recorded in the history of the use of drones (not similar to what is available nowadays in the drone field) was on 1849 in Venice, Italy, during the war for independence when Austrian soldiers attacked the city with approximately 2200 balloons caring small bombs (weighing between 11 kg and 14 kg).

In 1907, brothers Jacques and Louis Bréguet, with the help of French Physiologist Professor Charles Richet, built a gyroplane which was similar to a modern day quadcopter and performed the first rise of a vertical-flight aircraft which reached a height of 0.6 meters. The flight was not considered a free flight because four men were needed to maintain the aircraft steady during the flight.

In 1916 the first pilotless aircraft named Ruston Proctor Aerial Target was built, serving as a military drone, using a radio guidance system developed by British engineer Archibald Low. The aircraft was launched from the back of a truck using compressed air but later the British military leadership did not follow the path discovered by Archibald Low. It is worth mentioning that very soon an aircraft similar to an aerial torpedo using gyroscopic controls was constructed and it was named Kettering Bug. After the first item the US Air Force produced 50 platforms.

In the 1930 a radio-plane called OQ-2 was developed by British actor Reginald Denny and engineer Walter Righter which later became the first mass-produced drone in the U.S with approximately 15,000 drones being produced.

In 1937 the US Navy Curtiss developed the N2C-2 Drone, a radio-controlled aircraft, and in 1935 the British developed "Queen Bee," a radio-controlled target drone, which is also believed to have led to using the term "drone" for radio-controlled unmanned aircraft.

In WW2 the German Army developed the V-1 "Doodlebugs", the first cruise missile used against London. The equipment used an autopilot for altitude control and airspeed through the force of pressurized air, gyroscopes for yaw and pitch, a magnetic compass for the azimuth and a barometric device for altitude. Afterwards, same capabilities were used by the US who designed the TD2D-1 Katydid and Curtiss KD2C drones.

The Vietnam War (1955-1975) between the communist government of North Vietnam against South Vietnam and its main ally, the United States, witnessed the use of the drones equipped with cameras for reconnaissance and the new purposes for drones in operations such as decoys in combat, launching missiles against fixed targets and the dropping of leaflets against communist propaganda in psychological operations. The Lightning Bugs drone was used in combat missions over North Vietnam and southern China, the flights being controlled by the Strategic Air Command (SAC) from Monkey Mountain Facility in South Vietnam.

Invented in 1947, the transistor technology had a peak in 1960 with its presence inside the drones' mechanisms, especially of the miniaturized radio-controlled components and an increase in radio-controlled planes during the same decade. Thanks to that, planes began to appear in kit form, allowing people to build and fly RC aircraft indoors or outdoors contributing to the development of commercial RC technology.

A drawback in the military domain was considered the price of drones and the lack of trust in the outcome, however, the victory in 1982 of the Israeli Air Force against the Syrian Air Force using drones brought a change in people's minds and a revolution in the use of drones for military purposes (Vyas 2023).

Abraham Karem, born in 1937, is considered today the person who invented the drones. His occupation was designer of fixed and rotary-wing unmanned aircraft and he built his first drone that was used during the Yom Kippur War (between October 6th and 26th, 1973) and from that moment on, the Israeli Air Force began to develop unmanned aerial systems, an example being the presence against the Syrian air fleet jamming communications and providing accurate reconnaissance.

Some milestones to be considered: in 1974 Abe Karem designed the Predator, in 1986 Israel and American military start using the Pioneer, in 1993 monitoring of climate and environment began, in 1999 Predators were used for surveillance and combat in Kosovo, Yugoslavia, Afghanistan and in other conflict areas. In 2007, the Reaper was used in combat missions in Iraq and Afghanistan.

After 2010, we are witnessing an increase in the use of drones as tech toys in non-military fields and an increase of military drone budget, at least in the US, especially under President Barack Obama who ordered a lot more counter-terror strikes than George W Bush (Attard 2024).

2. Drones Classification

Basically, a drone is a flying equipment that can be controlled from a distance or that can fly independently using onboard systems (sensors, a global positioning system, etc.).

There are two types of drones: Rotor type - single-rotor and multi-rotor (such as tricopters, quadcopters, hexacopters and octocopters), and Fixed-wing that could be a regular type and hybrid type with vertical takeoff and landing (abbreviation used is VTOL) –no runways required.

Explicitly, components of a drone are:

- frame (chassis) - the main structure which holds all the parts together;
- motors - fundamental parts that help keep the drone in the air and running;
- drone propellers – comprised by standard propellers and propellers attached to the drone motor making onward movement possible;
- battery - provides power and makes all actions and reactions possible;
- flight controller board - the brain of the drone - responsible for navigation, flight control, communication, etc.;
- electronic speed controller - a device used to control the speed of an electric motor;
- radio transmitter - responsible for the transmission of the radio signals from the controller to the drone to command the flight;
- radio receiver - receives the signal from the drone controller;
- sensors - Position and movement sensors give information about the location of the drone;

− camera - for aerial photography or aerial filming;

− 3 axis gimbal - maintains the drone still and stabilized – a motor is placed on the 3 different axes around the camera);

− GPS - is responsible for providing longitude, latitude and elevation points;

− software-based interface - with the purpose of data collection and analysis using mobile devices or computers;

− software - a collection of algorithms for guidance, navigation and control for autonomous drones or autopilot software used in drone applications;

− remote control - because the use of the radio frequency needed to establish a communication between the remote operator and the drone, remote control signals from the operator's side can be provided from: ground control systems, (a human operating a radio transmitter, smartphone, computer or other similar control systems, remote network systems, (satellite bidirectional communication - can send and receive signals at the same time or wireless data transmission) and another aircraft serving as a mobile control station (relay);

− payload - equipment (even ammunition) able to be carried by the drone to perform a specific mission.

A drone could serve different purposes such as:

− *in the civilian field*: reconnaissance, search and rescue, traffic and weather monitoring, firefighting, personal use drone-based photography and video, and for different services (especially in the logistics domain);

− *in the military field*:

• Intelligence (Signals Intel-SIGINT alludes to data determined from collected electronic transmissions of all sorts, counting catching communications between gadgets such as phones, radios, and computers. Data obtained through SIGINT sensors can be utilized to distinguish, find, and recognize targets for future strikes);

• Surveillance (Wide-Area Surveillance detects military targets within an area of interest thousands of times larger than the coverage of Full Motion Video);

• Reconnaissance – operating at high altitudes with extended endurance (up to 5 hours) covering large areas and collecting high-resolution imagery and data used to identify the location of threats and instantly communicate adequate measures;

• Search and rescue - provide capabilities that are leveraged by emergency situations in an enemy area, operate effectively in various terrains, ranging from dense forests to urban environments;

• Target Practice – drones are used for target practice or for training to develop a better accuracy. The software of a drone able to detect and respond to targets' presence automatically is a real help;

• Force protection – drones carrying explosives are extremely dangerous and effective as weapons and a reliable counter drone system (drone detection, jamming and also kinetic drones capability) are very important to track, identify, mitigate or destroy hostile drones entering in airspace denied to everyone because ongoing operations;

• Combat (offensive and defensive capabilities), target tracking and acquisition (the method by which a target is identified, recognized, and followed in planning for an accurate strike by another military weaponized platform);

• Buddy lasing – drone's operator points a capable laser label at the target making an impact named "sparkle" and another flying vehicle at that point discharges a laser-guided rocket, bomb);

• Artillery spotting – operations by which an observer located within visual range of a target provides information about the target back to artillery located beyond visual range, also performing fire correction enables actions for adjustment of aim after a first shot);

• Battle damage assessment (because drones are able to fly lower than manned aircraft, used for collecting profitable data amid minimal climate conditions or in profoundly challenged ranges as tactical air reconnaissance to provide information for post-strike analysis and re-strike decisions),

• Communications Relay – a drone provides the link between two or more military manned entities which are not able to communicate with each other directly);

• Electronic attack (EA) (the use of a variety of non-kinetic measures to break apart, degrade, or destroy weapons systems belonging to the enemy);

• Logistics in the military domain – drones can be used for transportation and for contribution in delivering supplies, equipment and ammunition or to evacuate injured military personnel.

In 2020 unarmed drones were more numerous than armed drones according to research by Dan Gettinger in The Drone Databook – 12 out of 95 countries with active military drone inventories confirmed to operate weaponized unmanned aircraft (The U.S., which possessed the biggest inventory, confirmed military operations were more numerous for unarmed drones than armed ones) (Michel 2020).

3. Drones in Ukraine

Because Ukrainians can attack and surveil Russian military troops and equipment using drones, there is a very restricted exchange of technical data concerning them. Using only publicly available data, the following is a brief list of the drones that the Ukrainian military uses:

1. Reconnaissance drones

− Leleka – a Ukrainian-made drone, in service since 2021, speed - 120 km/h, and maximum flight time - 2.5 hours;

− Shark - a Ukrainian reconnaissance drone in service since 2022. It is used for surveillance and fire control, maximum speed - 150 km/h, and the combat radius is 60 km, flight time - 4 hours;

− DJI Mavic-3 – a civilian quadcopter which is the most popular model because of its versatility. Flight time - 46 minutes, maximum altitude - 6 km. Equipped with high-quality optics, it can observe the enemy from above.

2. Reconnaissance drone with thermal imagery

− Mavic-3T – performs surveillance at night, equipped with a thermal equipment.

3. Drones for dropping

− Mavic-3/Mavic-3T – civilian drones, such as the Mavic-3, are equipped with systems for dropping explosives, in trenches or on enemy equipment.

4. Kamikaze drones have a built-in weapon system. They can stay in the air above a target for a period of time and then attack the target at the operator's command.

− Switchblade 300 – an American kamikaze drone with a speed of 160 km/h and flight time of 50 minutes at a distance of 600 meters.

− Pegas – Ukrainian-made drones with a speed of 50-75 km/h, about 400 meters, capable of dropping weapons weighing up to 20 kg.

− First Person View "Goida"" (and related craft names "Bavovna", "Nort Varta") - transmits video in real-time using a camera installed in the front;

− Foxeer – in February 2022 a Ukrainian Foxeer kamikaze drone striked a Russian Grenadier air defence system in Shebekino, Belgorod region, Russia.

− "Falcon Avenger" – an FPV drone transmits video in real-time using a camera installed in the front;

− RAM II – Ukrainian-made strike drone based on the Leleka drone with battle range of 30 km, flight time -1 hour (Molfar 2024).

5. Long Range Attack Drones

− Mugin-5 – available drones such as the Chinese built Mugin-5 (aka Skyeye 5000) - attack the Black Sea Fleet headquarters in Sevastopol, Crimea;

− Tu-143 Reys/Tu-141 Strizh – a Soviet era jet-powered reconnaissance drone still in the inventory of Ukrainian military was weaponized in 2022 and used as cruise missile;

− UJ-22 Airborne – a single engine drone which can either carry an internal warhead or several air-dropped bombs. Payload is up to 20 kg, range - 800 km;

− Morok – carrying a small warhead of 3 kg that has a range of 300 km. It is launched with the aid of a rocket and speed of 290 kmph.

− UJ-25 Skyline – a weaponized development of the Ukrajet UJ-23 Topaz target drone;

− UJ-26 Beaver – has a distinctive canard layout with sleek fuselage and inverted tail. Starting with 2023, it has been built in mass production. It has a range of 1,000 km and payload of 20. This type was used to attack Moscow and other targets in Russia.

− Lyutyy – has resemblance to the Turkish-made Bayraktar TB2 but not in detail.

− AQ-400 Scythe – The Terminal Autonomy AQ-400 Scythe is a volunteer project which has entered serial production. It has a range of max 750 km and payload between than 32 kg and 70 kg (Sutton 2024).

A lot of drones have been reconfigured and upgraded in the last year but the outcome has not been revealed to the public. The President of Ukraine, Volodymyr Zelensky, announced on August 24th in Ukrainska Pravda, an online publication that covers Ukrainian politics, that a new long-range weapon, a combination of missile and drone, called "Palianytsia" after a popular bread brand, had been developed domestically with the intention of striking deep into Russian territory without first requesting authorization from allies to use Western long-range missiles.

Mykhailo Fedorov, Ukraine's minister for digital transformation, told Reuters agency in 2024 that Ukrainian production in 2023 was 300,000 drones and one-third of those were made available to combat forces. Moreover, an additional large number was delivered to the soldiers from different sources.

In regards to the future of Ukrainian drones, we will present some lessons identified. It is obvious that Ukrainians did not obtain an operational or strategic advantage due to the drones utilized in the war because the majority of drones were commercial and the technical characteristics were available to anyone, thus any improvements were known also by the enemy. Even the fact that Ukraine used at first the first-person view (FPV) drones in kamikaze attacks creating do-it-yourself (DIY) cheap kamikaze drones allowed the enemy to quickly adapt to the improvement developing their own type of drones.

Ukraine was the best at utilizing commercial drones in a wartime setting. The Ukrainians were not able to leverage technologies and software advancement to impose the drone supremacy because, at the beginning of the war, the enemy had a large inventory; and, in 2023, the implementation of war production drones domain creates a larger capability on disposal.

Ukraine did not have long-range cruise or ballistic missiles in service and the capability to strike long range targets inside Russia and Crimea was accomplished through drones. Because Russian long-range cruise or ballistic missiles are very expensive, this capability was upgraded with Russian drones trying to surpass the Ukrainian air-defence. In the Ukraine war, both sides have been using counter drone methods. Starting with the end of 2023, Electronic Warfare (EW) has been the most efficient method to block drones through jamming procedures, especially on the path pointing the military area of interest. The use of wire nets as barriers and the attack against drone operators (situated in the proximity of the battlefield) did not provide spectacular results.

Using the artificial intelligence warfare, the Ukrainian drones tried to operate close to the concept of swarms with numerous army units that acted autonomously and coordinated their operations but in fact the result was a stack behavior with a lot of army operators on the battlefield using traditional means of communication or civilian (commercial) communications platforms.

To sustain the aforementioned opinion, in February 2024, a report from the Center for a New American Security released serious doubts regarding the use of AI in warfare. Stacie Pettyjohn defence program director stated the fact that: "Both parties claim to be using artificial intelligence to improve the drone's ability to hit its target, but likely its use is limited" (Pettyjohn 2024).

Bureaucratic defence procurement system did not allow for sufficient investment to increase the drones production projects. Strong community of Defense Tech foreign stakeholders who benefit from exchanging expertise and opportunities was created to help production and implementation of military technolgy.

Army of Drones project became the driving force behind the UAF's drone activity - 10,000 drone operators received the neccesary training and the aquisition process brought into inventory thousands of drones.

AI should become the next step in improving the identification of the enemy's location more rapidly, determining and transmitting the coordinates to the commander of the striking capability, to make the decision and to destroy the enemy by sending the order to the tool of destruction.

"From the dozens of systems that were in service in early 2022, the Armed Forces of Ukraine used 70 different types of unmanned aerial systems and more than 20 types of ammunition for attack drones at the end of 2023. About 200 companies that manufacture drones in Ukraine produce about 50,000 unmanned aerial systems per month. Plans for 2024 are even more ambitious: to increase the production of FPV drones to 1 million units per year, medium-range attack drones to 10,000 units per year, and long-range attack drones to 1,000 units per year. This number should ensure asymmetric parity with Russia, which is also trying to maximise drone production" (Samus 2024).

In terms of the programs that have driven the UAF's drone activities, one of these programs is the Army of Drones project, part of the national crowdfunding initiative, United 24. Through this project, thousands of drones have been acquired, and over 10,000 drone operators have been trained. Additionally, the United 24 campaign initiated the development of maritime drones, which evolved into a separate state-level program for maritime platforms. Ukraine's advancements in maritime drone technology have significantly impacted the Russian Black Sea Fleet, creating an unexpected strategic situation (Samus 2024).

Despite losing its naval capabilities, Ukraine has successfully used maritime drones to force the Russian Black Sea Fleet to relocate to the eastern Black Sea, avoiding the western areas due to substantial losses inflicted by these drones. Several types of maritime drones have been developed, initially funded by volunteers and later by the Ministry of Defence and other security and intelligence agencies. Currently, Ukrainian defence forces employ various surface and underwater maritime drones, continually enhancing their features and effectiveness. These drones have inflicted considerable damage on the Russian Black Sea Fleet, its bases, and infrastructure, including the Kerch Bridge. Notably, the Ukrainian drone Magura V522, the primary naval unmanned platform of the Defence Intelligence of Ukraine, sank two landing boats in Chornomorske, Crimea, on November 10, while one was loading a BTR-82, prompting the relocation of the Black Sea Fleet to Novorossiysk (Samus 2024).

In 2023, Ukraine unveiled its first underwater maritime drone, the Marichka. This drone is designed to target ships, bridges, coastal fortifications, and submarines. It can be adapted to carry military or civilian cargo instead of explosives and can also function in a reconnaissance role. The large-scale production of these underwater drones could significantly change the dynamics in the Black Sea, as the Russian Black Sea Fleet may struggle to detect and counter them, posing a substantial threat to Russian warships (Samus 2024).

Additionally, an advanced underwater drone, the Toloka, has been developed with various modifications. The TLK 1000, for instance, has a range of 2,000 kilometers and can carry up to 5,000 kg of explosives. Its guidance system includes passive sonar for identifying and locating underwater and surface objects using hydrophones, as well as ultrasonic (active) sonar for close-range detection, tracking, and object identification by size (Samus 2024).

Organizational and doctrinal changes have also been made, with the Ukrainian Navy creating a naval drone brigade. This brigade is the first naval combat unit of its kind to be equipped with naval drones. These drones are used not only by the Ukrainian Navy but also by the SBU and the Defence Intelligence of Ukraine, working in close coordination at the operational level (Samus 2024).

Russia's war in Ukraine has revealed how important drones are in today's warfare. NATO needs to adapt rapidly. More and higher quality assets are needed regarding drones because the war in Ukraine stressed the fact that "if you haven't invested in sufficient unmanned aircraft capabilities, you're likely to have serious deficiencies against someone who has made the investment" (Federico Borsari and Gordon B. "Skip" Davis 2023).

4. Drones Maintenance Aspects

A drone (military, except kamikaze and civilian), should be kept in proper condition to perform outstandingly and to avoid expensive repairs. There are numerous components that can influence the operability and functionality of a drone such as climate, utilization, capacity, and software overhaul. The main problems could appear on:

− Battery – swelling, leaking, overheating, or losing capacity. To avoid these problems, it is mandatory to utilize the proper charger and to follow the manufacturer's instructions. Also, store the batteries in a cool, dry and ventilated area and check the battery level before and after each flight (it should be changed when signs of wear or damage appear);

− Propeller – propeller damage by collisions, debris, or wear and tear which can reduce the efficiency and stability of the drone causing vibrations, noise, or even crashes. To avoid this problem, the recommendation is to check the propellers before and after each flight to determine the changes in its condition. The propellers should be cleaned periodically (they should be changed when signs of wear or damage appear because they are difficult to repair in an area of operation);

− Motor – responsible for rotating the propellers and controlling the speed and direction can be affected. Unfortunately, they can suffer from issues such as overheating, burning, or jamming. To mitigate these issues, the flights should occur in dust-free environments, to avoid extreme temperatures moderate temperatures are preferred, bearings should be lubricated and the vents should remain clean (they should be changed when signs of wear or damage appear);

− Camera – photos and videos could be affected by poor settings to light or weather conditions or by malfunction caused by gimbals system resulting in distortions of color (lens should be changed when signs of wear or damage appear);

− GPS – errors, such as weak signals, interference, or drift of the Global Positioning System create an impediment for the drone to locate itself and to navigate and return home. These problems are avoided if the flight occurs in open and clear areas with no interference and the drone is in proper technical condition (the firmware is updated), the GPS module and the IMU (inertial measurement unit) calibrated. The operator should also maintain secure flight lines, avoiding power lines, high-rise obstacles and areas with different bodies of water that cause interference with GPS signals;

− Firmware – software that runs on drone when it is updated to improve performance or to add new features could create compatibility problems, which can affect its functionality. To avoid these issues, the manufacturer's instructions should be implemented with accuracy and the drone should be checked after each update first in a secure area, close to the operator (Vineeth Jacob Anthony n.d.).

The primary distinction between maintaining a conventional aircraft and an unmanned aerial system that the UAS technician is accountable for the entire system, which includes the flying apparatus and a variety of ground-based apparatus (a new set of requirements specific to UAS maintenance is introduced by maintaining ground-based components, desktop and laptop computers are now considered airworthy products). The technician must not only make sure that every component of the system is operating as intended, but also that the links connecting the various systems are operating as intended.

Drone systems, military or civilian, require almost the same logistics support as most manned aircraft including the unmanned aircraft and the ground control station. Research and development has an objective to design a system with a reduced logistical footprint, characterized by fast deployment and high mobility with a reasonable maintenance program. Because drones are more and more complex and composed by many sub-systems which perform in the same time it is more difficult to maintain a large drone fleet without a *Maintenance Program*. To provide more safety and confidence to drone operators (to fulfill the mission) there are available *Maintenance Programs* composed of three types of adaptive maintenance (according to the daily flight hours and environment of action) and a recommended maintenance cycle.

In the most basic terms, drone maintenance is the act of inspecting, mending, and replacing any malfunctioning components and generally speaking, there are three primary types of maintenance: preventative, ongoing, and emergency. The kind of drone maintenance that should constantly be performed is the preventative one since it keeps minor problems from becoming major ones – long-term maintenance costs are decreased, and the operator is confident that the drone will operate constantly in the air. In terms of expenses and downtime, ongoing maintenance is comparable to preventative maintenance – even though there might not be a problem with the drone, it is still advisable to carry out the maintenance after a number of flight hours to make sure all the components are in good operating order. After a component breaks down or the drone malfunctions in some other way, emergency maintenance is necessary, but it usually is more expensive and takes longer than preventative maintenance (Spires 2021).

The controller of the drone should respect the user manual regarding the maintenance regime:

− the pre-flight and post-flight inspections are mandatory;

− Operational (Basic) Maintenance: includes changing propellers, carrying out firmware updates and test flights, and calibrations, etc., which will be recorded in the maintenance logbooks;

− Intermediate (Routine) Maintenance: a more detailed inspection or repair will be performed by producer technical personnel when local maintainers are not authorized – it could include components replacement because wear and tear;

− Depot-Level Maintenance: maintenance beyond the capabilities and/or facilities of the field will also consist in verifying the Line Replaceable Unit malfunction, isolation and repair of part(s). Activities could require overhaul, upgrading, or rebuilding of parts, assemblies, or subassemblies and could include the replacement of propulsion system (Vachtsevanos 2015).

Although it may seem tedious, drone maintenance keeps them operating longer and guarantees safe, effective (for the intended purpose) flights. Regular inspections and prompt replacement of broken components stop additional deterioration and reduce the need for expensive repairs or component replacements. Over time, preventive maintenance reduces costs – by reducing the likelihood of catastrophic failures, preventive measures and early problem detection can save money on repairs and downtime when operational needs are paramount. Tracking a drone's long-term history may lose significance if the most important system components, such as wings or engines, are replaced but real-time data and sophisticated analytics are essential for predictive maintenance - drone component performances and conditions monitoring allow for the early detection of faults before they happen. Algorithms evaluate the data collected by sensors and diagnostic instruments to forecast when maintenance needs to be done for maximizing drone availability while reducing unnecessary servicing. Data management is critical to the effectiveness of operations because it helps with maintenance planning, informed decision-making, and performance insights that enable operators to foresee and avert possible problems. The integration of technologies not only improves overall drone fleet reliability but also streamlines operations and considerably lowers maintenance expenses.

The maintenance teams are composed of multiskilled personnel; they do all the ground work, including assembly, flight planning, and in-flight operations (small drones often have a single owner or operator who handles all maintenance and other duties). Within the military drone domain, there is typically a two-tier system that distinguishes between major repairs and routine operating maintenance. Simple preventative maintenance, refueling, servicing, daily inspections, and replacing line-replaceable units are all included in basic operational maintenance performed by military personnel and structural repairs, overhauls, and the diagnosis and correction of complex faults - major repairs are the responsibility of the manufacturer personnel.

Logistic support elements could be described by:

− primary systems characteristics: reliability, availability, maintainability and safety;

− support system elements: maintenance, training, spares, tools, transport, availability of technical publications.

R.A.M.S. refers to "Reliability, Availability, Maintainability, and Safety". Reliability, availability, maintainability and safety are connected together, but a drone could not be available not only because unfinished maintenance, but also because of different causes. The availability of a drone is a measured probability that the drone would not fail or it would not undergo a maintenance action when it needs to be used. In the field of maintenance, availability depends on maintainability, on the maintenance organization capability (sizing, skills of maintenance personnel, availability of technical documentation, tools used, amount of spare parts available). It is important to not forget that Integrated Logistic Support requests that the logistic support system has to be designed at the same time with the design of the primary system in order to not have future problems of compatibility and to obtain efficiency.

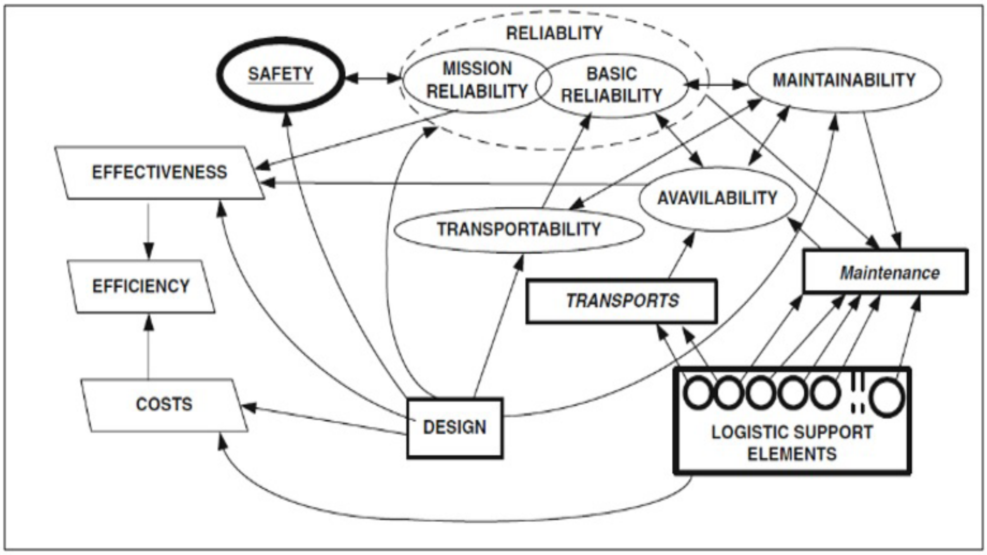

Figure no. 1: Relationship between R.A.M.S., logistic support elements, design and other related issues (Vachtsevanos 2015)

The values of safety, reliability and maintainability are obtained by the design of the product itself. Maintainability, the probability that a failed technical system will be restored to a specified condition in a specified period of time when maintenance is performed in accordance with the producer procedure imposes automatic diagnostics. Reliability deals with the risk of failures in an equipment focusing on equipment availability, performing the task, and the cost involved.

The commercial aviation failure rate is about 1/105 flight hours, while for commercial (civilian) drones, it has been identified at about 1/103 flight hours (Enrico Petritoli 2018).

Even in the case of drones, it is necessary to define the criteria for the level of reliability:

− catastrophic failures: a crash of the drone;

− severe failures: heavy damages to the drone – the probability of being in service again is very low or it requires high costs in the adjacent area of production costs;

− moderate failures: a moderate degradation of the drone’s functions could lead to abortion of mission;

− soft failures: light degradation of the drone’s functions, does not request to abort the mission.

Commercial Drone (a)			
System Description	λ_p System FIT (F/10^6 hrs)	MTBF (hours)	Incidence (%)
Ground Control System	2.00	500,000.0	6.62%
Mainframe	2.77	360,984.8	9.16%
Power plant	9.94	100,603.6	32.88%
Navigation system	9.41	106,269.9	31.13%
Electronic system	5.01	199,600.8	16.57%
Payload	1.10	909,090.9	3.64%
λ TOTAL =	30.23	FIT	
MTBF (R_{Total}) =	33,079.50	Hours	
	1378.31	Days	
	49.23	Months	

Military Drone (b)			
System Description	λ_p System FIT (F/10^6 hrs)	MTBF (hours)	Incidence (%)
Ground Control System	14.00	71,403.6	27.30%
Mainframe	2.77	360,984.8	5.40%
Power plant	21.08	47,428.7	41.10%
Navigation system	7.39	135,369.3	14.40%
Electronic system	3.44	290,942.9	6.70%
Payload	2.62	382,219.2	5.10%
λ TOTAL =	51.30	FIT	
MTBF (R_{Total}) =	19,493.18	Hours	
	812.22	Days	
	29.01	Months	

Figure no. 2: Comparison between the reliability of a commercial and a military drone (Enrico Petritoli 2018)

Due to its complexity, a military drone is inferior in terms of reliability to a commercial drone – MTBF (the average time between failures of a system) is smaller to military drones.

In 2022 the lifespan of military drones on the battlefield depended on the type of design:

- a fixed-wing drone lasted for about six flights;
- a rotary-wing drone (quadcopter) lasted for three flights (www.technology.org 2022).

Conclusions

The evolution and diverse applications of drones have revolutionized various sectors, ranging from civilian logistics and environmental assessments to military operations. The parts of a drone are occasionally put back together and taken apart before and after each flight in the battlefield areas. Regularly connecting and disconnecting electrical and other systems might raise the risk of malfunctions, damage and factors such as weariness, bad illumination, and the operating environment can all increase the likelihood of error but it underlines the need of trained and professional maintainers. The maintenance staff should be proficient in using a variety of technologies, such as computer software and hardware, autopilots, radio communication equipment, modems, and radio frequency interference dangers, in order to connect with and control the drone (very challenging to define in detail the skill and knowledge requirements for maintenance professionals in the small drone area due to its diversity and fast rate of change). In military operations the operating crew need the abilities and expertise required to comprehend how components work together, diagnose small malfunctions, and connect system aspects.

Maintenance of drones is crucial to ensure their optimal performance and longevity. Proper care of components such as batteries, propellers, motors, and cameras is essential to avoid malfunctions and costly repairs. The integration of advanced software and GPS technology further enhances the operational efficiency of drones. Military drones, in particular, require rigorous maintenance protocols and logistic support to maintain their reliability and effectiveness in various combat scenarios. Preventive maintenance is a key component in reducing drone maintenance expenses – frequent inspections and maintenance assist in identifying problems before they worsen and help save costly repairs. Human error and further expenses are decreased by automating maintenance inspections with software tools and on-board diagnostics. Purchasing affordable technology, drones with sophisticated sensors for self-surveillance can give real-time data and support predictive maintenance. This data-driven strategy guarantees effective resource allocation, further reducing expenses. By ensuring that operators and maintenance personnel are proficient in doing minor repairs and maintenance, training programs help to minimize downtime and reliance on professional technicians. Working together with outside maintenance companies can be advantageous as well, since they can provide resources and experience that are not always available inside.

The absence of repair facilities and issues with the supply chains that affect the scarcity of spare parts on the battlefield or in the surrounding areas have a significant impact on the entire maintenance process, which could become too sluggish to be viable. Waiting times for maintenance activities may increase due to logistical factors such as the location of spare parts remote from operating activities in Ukraine or overseas. These factors could be mitigated with effective management and local maintenance solutions.

In the context of the Ukraine conflict, drones have played a significant role, demonstrating both their potential and limitations in warfare. Ukrainian forces have utilized a range of drones for reconnaissance, combat, and logistical purposes. Despite the initial advantage, the widespread availability of commercial drone technology has allowed adversaries to quickly adapt and counter these capabilities. The use of drones for long-range strikes and maritime operations has provided strategic advantages, thus the effectiveness of counter drones measures like electronic warfare has highlighted the ongoing technological arms race.

Looking forward, the future of drone technology in Ukraine and beyond will likely hinge on advancements in artificial intelligence, improved maintenance practices, and strategic innovations in drone deployment. The lessons learned from the Ukrainian experience underline the importance of continuous development and adaptation to maintain a tactical edge. As drone technology evolves, its impact on both civilian and military domains will continue to expand, driven by innovation and strategic application.

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