Research of the creation and development of unmanned aerial vehicles

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Abstract. Drones were created back in the USSR. Many believe that UAVs - unmanned aerial vehicles, otherwise known as drones, appeared only at the beginning of the 21st century. However, this is not the case: since the 60s of the last centuries, Soviet and American engineers have been building supersonic unmanned reconnaissance aircraft for the armies of their countries. In addition, drones are actively used for environmental purposes. They are called "eco-drones". They are no different from ordinary ones, the prefix is designed to emphasize their purely peaceful, scientific purpose.

1 Introduction

Let us consider the history of the issue.

Work on the creation of drones began during the First World War. For example, Germany produced more than 100 wire-guided gliders, which were launched both from the ground and from airships, and could carry torpedoes and bombs weighing up to 1,000 kg. Similar work was carried out in the United States, but none of the parties could use UAVs in hostilities.

Interest in the UAV did not disappear in the 1920-1930s. The first radio-controlled flight in September 1924 was made by the American seaplane Curtiss F-5L. Moreover, designers from the USA and Great Britain in the pre-war decades focused on the creation of strike unmanned aircraft and target aircraft, which were used in trainings.

German designers worked in the same vein: the now well-known V-1 (V-1) projectile they created is considered the forerunner of modern cruise missiles and UAVs, but, however, a simplified version for today (Figure 1).

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Fig. 1. The V-1 (V-1) projectile is considered the forerunner of modern cruise missiles and UAVs.

Its low combat effectiveness was due to the lack of remote piloting and automatic navigation systems. Appropriate technologies did not yet exist, and if they did, there would be much more victims among the population of England. The Germans began shelling the British Isles with V-1 in June 1944.

2 Main part

At the end of World War II, the championship in the creation of UAVs passed to the United States. In the early 1950s, the United States Navy used a link of six F6F-5K Hellcat UAVs to bomb strategic targets in the DPRK (Korean War 1950-1953). The destruction of the U-2 high-altitude spy plane over the territory of the USSR on May 1, 1960, and then the loss of another U-2 during the Cuban Missile Crisis, forced the United States to begin the accelerated development of unmanned reconnaissance aircraft. The result was the appearance of the RyanModel 147A "FireFly" aircraft with a flight range of up to 1.729 km in 1963. Ryan Aeronautical produced them until the beginning of the 21st century. And the drone made its first flight in April 1962 - it was in time for the beginning of the Vietnam War.

Almost simultaneously with the Americans, drones for reconnaissance began to be developed in the USSR. On the basis of the La-17 flying target, Semyon Lavochkin's design bureau created the La-17R unmanned reconnaissance aircraft, which made its first flight in 1963. Subsequently, a modernized version of the unmanned reconnaissance aircraft La-17RM was developed. (Figure 2).

Fig. 2. Unmanned reconnaissance aircraft La-17R made its first flight in 1963.

By the early 1980s, theobsolete La-17R and La-17RM were replaced by more modern UAVs, work on which began at A.N. Tupolev design department in the late 1950s.

On May 1, 1960, an American high-altitude reconnaissance aircraft U-2, piloted by pilot Gary Francis Powers, was shot down over the Urals by a missile of the Soviet S-75 air defense system. This incident had consequences not only in international politics. The Americans realized that the USSR could shoot down aircraft at altitudes of more than 20 kilometers, which put an end to their intelligence program.As a result, the CIA had an idea - to launch unmanned vehicles instead of aircraft, risking losing experienced pilots. So, in October 1962, Lockheed (Figure 3) received a contract to develop the D-21 high-speed unmanned reconnaissance aircraft. The project amazed the imagination - the camera mounted on the drone filmed the Earth's surface with a resolution of up to 15 centimeters, and the speed of the reconnaissance was three times the speed of sound!This is where the difficulty arose. The D-21 could not start from the airfield. That is why it was decided to launch it in the air from a carrier aircraft. At that time, work was going in the United States to create a high-altitude supersonic reconnaissance aircraft SR-71 Blackbird ("Blackbird"). The plane itself was not readyyet, but its prototype, the A-12, was already flying. On its basis, a machine, called the M-21was built. It was supposed to be launched from it.

Fig. 3. UAV Lokheed D-21.

At the same time, the reconnaissance drone itself was a disposable device. After completing the task, the compartment with the camera and films was shot back by parachute somewhere over neutral waters, and a self-destruct device was triggered on board the drone. It was decided to carry out the first reconnaissance flights over China, since the Chinese air defense at that time was incomparably weaker than the Soviet one. However, as they say, something went wrong. On November 1969, D-21 with tail number 517, having completed the task, did not lie down on the return course, but continued flying, reaching the territory of the Kazakh SSR. There he ended up falling.

The relevant Soviet services found the wreckage of the D-21 in the steppe and delivered it to Moscow. The Tupolev Design Bureau was instructed to study the find. The reason was that just at that time the Tupolev team was in full swing developing similar reconnaissance drones. The trophy was called object "P" and carefully studied in the Tupolev Design Bureau. Acquaintance with the American model turned out to be very useful for Soviet designers. The D-21 had a tailless aerodynamic design with a thin swept wing. The drone was welded from titanium, on top of which lay a porous mass of thermal insulation, and on top everything was covered with a special elastic film. In the end, everything turned out clean and beautiful.Of course, from the point of view of modernity, many technological solutions would now cause a smile. So, almost the entire navigation system to protect against overheating in flight (after all, the speed was Mach 3.3, and, accordingly, the entire fuselage of the reconnaissance aircraft was very hot) was inside the fuel tanks and was cooled by fuel - aviation kerosene. However, for that period it seemed like a breakthrough.

Tupolev personally listened to the report of the commission that studied D-21. He liked the technical data of the "R" product: speed over Mach 3, flight altitude 23-27 kilometers, flight range - over 4 thousand kilometers with a launch weight of just over 6 tons. As a result, the commission of the Presidium of the Council of Ministers of the USSR on military-industrial issues instructed the Tupolev Design Bureau to create a long-range supersonic strategic reconnaissance aircraft "Voron". Outwardly, the "Voron» was very similar to the D-21. He was supposed to start from the Tu-95K, later - from the Tu-160.Since these aircraft, subject to refueling, had an unlimited flight range, the Raven could also operate anywhere in the world. If not for one "but" ... Soviet optics then could take high-quality, suitable for decoding pictures only during the day and in relatively good weather conditions. In addition, reconnaissance satellites were already on the way. As a result, the authorities decided to collapse the project.

Here one could say: they say, an ill-conceived decision deprived the Soviet army of an advanced type of weaponry. But it's not true. The fact is that by that time domestic drones already existed. Back in 1960, the development of a heavy reconnaissance drone began at the Tupolev Design Bureau. On May 23, 1964, the Tu-123 Yastreb long-range unmanned photo and radio reconnaissance system was adopted by the Soviet Army (Figure 4).

Fig. 4. UAV Tu-123 "Yastreb".

The Tu-123 was launched from a launcher based on a car trailer (Figure 4).

Fig. 4. Long-range supersonic unmanned reconnaissance aircraft Tu-123 "Yastreb" was adopted by the USSR Air Force on May 23, 1964.

"Yastreb» had impressive dimensions: length - 27.83 m, wingspan - 8.41 m, height - 4.78 m; maximum takeoff weight - 35.610 kg. The flight altitude at the beginning of the march

section was 22.800 m and 19.000 m at the end of the march section, and the practical range was 3.560-3.680 km.

At the same time, the drone operation scheme was similar to the American one - having completed the task, "Yastreb», upon reaching the landing area, passed under the control of ground controls, after which it climbed, drained the remaining kerosene from the tanks and turned off the turbojet engine. Then the braking parachute was released, the compartment with reconnaissance equipment was separated from the device and descended to the ground on a rescue parachute, where it was picked up and used again after maintenance. The central and tail parts of the drone were destroyed by hitting the ground and were not suitable for further use. A total of 52 reconnaissance drones were released. "Yastreb" was equipped with the western military districts of the USSR - it was decommissioned in 1979 after the Air Force was equipped with MiG-25R aircraft. "Yastreb» was the first, but far from the last, Soviet drone.

DBR-1 was designed to conduct aerial photo and radio reconnaissance at a distance of up to 3,200 km: airfields, missile launch complexes, military industrial facilities, naval bases and ports, the location of troops, ships, air defense and missile defense systems, as well as to control results of the use of weapons of mass destruction. The complex was in service with the Air Force intelligence units stationed in the western border military districts. Soviet intelligence officers could perform tasks over the entire Central and Western Europe, although, of course, real flights were not carried out.

At the same time, the launches of drones during exercises and inspections have repeatedly confirmed their high reliability and declared flight performance. The DBR-1 complexes gradually began to be decommissioned after the appearance in the Air Force units of the MiG-25R supersonic high-altitude reconnaissance aircraft.

On August 30, 1968, a resolution of the Council of Ministers of the USSR on the development of the Reis tactical intelligence complex was issued. It included the Tu-143 unmanned reconnaissance aircraft. In 1976, the complex was put into service. 950 devices were produced. Moreover, the " Reis" were in service not only with the Soviet army, but also with the armies of the Warsaw Pact countries, as well as other allies of the USSR. "Reis" provided reconnaissance to a depth of 450 kilometers. It also had a special modification, called the Tu-141 "Strizh" (Figure 5). “Strizh” was somewhat larger than the Reis and had a flight range of 1,000 kilometers, reaching a speed of 1,100 kilometers per hour.

Fig. 5. UAV Tu-141 "Strizh".

The development of a new unmanned tactical reconnaissance complex "Reis" (VR-3) and the unmanned reconnaissance aircraft Tu-143 included in it began in the Soviet Union with a decree of the Council of Ministers of the USSR of August 30, 1968. The complex was

created on the basis of the previously developed UAV VR-2 "Strizh", but in a lightweight and reduced version, and was intended for tactical low-altitude reconnaissance in the front line at a depth of 60-70 km by photo and telereconnaissance of area targets and individual routes, as well as for monitoring the radiation situation along the flight route. State tests "Flight" was held in 1976 and was put into service.

The UAV was made according to the "tailless" scheme. In front of the fuselage there was equipment, in the middle part - a fuel tank, in the rear - a power plant (Figure 6).

Fig. 6. Tu-143 "Reis" - a Soviet reconnaissance unmanned aerial vehicle, was put into service in 1976.

The aircraft was mass-produced in two versions: a photographic reconnaissance aircraft with information recording on board and a television reconnaissance version with information transmitted over a radio channel to ground command posts. In addition, the reconnaissance aircraft could be equipped with radiation reconnaissance equipment with the transmission of materials on the radiation situation along the flight route to the ground via a radio channel.

Flight performance characteristics of the Tu-143 UAV:

• Length - 8.06 m, wingspan - 2.24 m, height - 1.55 m, wing area - 2.9 square meters. m;

• weight - 1.230 kg;

• cruising speed - 950 km/h;

• practical range - 180 km, flight time - 13 minutes, service ceiling - 1,000 m, minimum flight altitude - 10 m;

• photo reconnaissance flight altitude - 200-1,000 m;

• flight altitude of conducting television reconnaissance - 300-1.000 m.

As you can see, already in 1976, Soviet UAVs could broadcast TV from theaters of war. The “Reis” complexes were combined into squadrons, each of which was armed with 12 Tu-143 reconnaissance UAVs, 4 launchers, and there were also means of preparation, launch, landing and evacuation, a command post, communication centers, a point for processing and decoding intelligence information and etc.

The direct combat use of the UAV was provided by means of a starting position, which included two vehicles based on BAZ-135MB tractors: the SPU-143 self-propelled launcher and the TZM-143 transport-loading vehicle. With the help of the SPU-143, the reconnaissance aircraft was aimed and launched, with the help of the TZM-143, it was transported from the landing and preparation site.

Tu-143 reconnaissance UAVs were in service with the USSR, Czechoslovakia, Iraq, Syria, Bulgaria, Romania, were used in Afghanistan (1979-1989), the Lebanese war (1982), and in the armed conflict in eastern Ukraine.

Later, another drone was developed - the Tu-300 “Korshun-U”. It was created not as a reconnaissance, but as an attack vehicle. Work on it began in 1982. Initially, he was instructed to develop the Sukhoi Design Bureau, then transferred to the Tupolev Design Bureau. The work was actively promoted until the mid-90s, but then due to lack of funding they were frozen. In 2007, they resumed, but, judging by the fact that other heavy drones were adopted by the Russian army, this project was not continued. Now the Russian army is armed with a whole line of aircraft and helicopter-type drones. Recently, the S-70 “Okhotnik” heavy strike and reconnaissance drone was announced. It should work in tandem with the fifth-generation Su-57 aircraft. In addition, the “Altius-U” heavy drone is in service. These machines are worthy heirs of the Tupolev drones of the twentieth century.

It should be noted that the American D-21 attracted the attention of not only Soviet engineers. Shortly after the incident with the loss of control of the drone and the fall on the territory of the USSR, a second similar incident occurred. This time the drone crashed into China. As a result, the CIA decided in 1971 to stop using these drones.

And on October 1, 2019, a Chinese supersonic reconnaissance drone was demonstrated at a parade in Beijing. Experts immediately noted that outwardly it is very reminiscent of the old American D-21. Of course, you can be sure that all the "stuffing" of the drone is made at the level of the 21st century - as you know, in the Celestial Empire they masterfully use other people's ideas and developments. It is likely that the idea of a supersonic high-altitude reconnaissance drone in China was considered promising. What will come of this will be clear in the near future.

UAVs and sea-based ones are being developed in Russia. The Ministry of Defense is working on a project for a special unmanned aerial vehicle (UAV) designed to search for and destroy enemy submarines. To perform such tasks, the military needs an unmanned aerial vehicle with a payload capacity of at least that of the S-70 Okhotnik (Figure 7).

Fig. 7. UAV S-70 " Okhotnik ".

In addition, the greatest efficiency of the use of such devices can be achieved by organizing "flocks" of such drones using elements of artificial intelligence.

Promising heavy drones should be equipped with both the means of detecting submarines and the means of destroying them.

Hunter drones should be able to take off from both ground airfields and surface ships. They can be controlled from both ship and air command posts.

Having detected an enemy submarine, the drones will be able to either strike on their own, or aim anti-submarine weapons at them from other carriers.

Unmanned aerial vehicles or drones of various purposes and sizes have played a very prominent role in the military conflicts of our time. But for some reason they are perceived

as a kind of "know-how". In fact, drones are peers of "large aviation", and in the 70s and 80s of the last century, the USSR generally held the lead in this aviation direction (Figure 8).

Fig. 8. Joint flight of the S-70 Okhotnik UAV and the Su-57 fighter.

2.1. Experience of foreign countries

For inexplicable reasons, in the 1990s, interest in the development of unmanned aerial vehicles in Russia was lost, while the United States, Israel, and then China increased their efforts in this direction. Speaking about Israel, we note that during the Lebanese war of 1982, the highest result of the combat use of the “Scout” UAV (Figure 9) and small-sized Mastiffs was recorded, when with their help (Operation "Artsav-19") a powerful striking blow was inflicted to the positions of Syrian air defense batteries in the Bekaa Valley.

Fig. 9. The highest result of the combat use of the Scout UAV was recorded during the 1982 Lebanon War.

And by the middle of the second decade of the 21st century, Israel had become one of the largest UAV manufacturers - in the period from 1985 to 2014, 60.7% of all exported unmanned aircraft in the world were produced in Israel, which was far ahead of the United States (23.9%) and Canada (6.4%).

The development of communication and navigation systems, primarily GPS global positioning systems (the Gulf War was the first conflict in which GPS was widely used) brought UAVs to a new level of combat effectiveness.

During operation “Desert Storm”, coalition UAVs made 522 sorties, the total combat raid amounted to 1.641 hours - at any time during the operation there was at least one unmanned vehicle in the air. An important task of the UAV was target designation and coordination of fire for B-52 strategic bombers, F-15 fighters and artillery of ships stationed in the Persian Gulf. In the future, UAVs were successfully used during the US and NATO aggression against Yugoslavia and in other military conflicts.

The American systems MQ-1 "Predator", MQ-9 "Reaper" and RQ-4 "Global Navk" (Figure 10) are currently the most used American UAVs of reusable applications.

Fig. 10. RQ-4 Global Hawk is the most used American UAV.

Drones have become an important part of military strategy in the PRC. Currently, China produces a full range of UAVs, including multi-purpose drones with high technical and flight characteristics.

2.2. The state of Russian UAVs today

Russia demonstrated the capabilities of its UAVs only in the second decade of the 21st century (recall that the USSR was one of the leaders in the production of UAVs). In 2010, the Russian company Oboronprom, which was part of the state corporation Rostec, created a joint venture with the Israeli company IAI, signing a contract for the purchase and production of reconnaissance UAVs (the Israeli side refused to supply strike UAVs under pressure from the United States. - Auth.). And in 2014, the first detachment of“Forpost” drones was formed in Russia. There is already a “Forpost-R”, assembled on the basis of domestic components (Figure 11).

Fig. 11. Attack drone "Forpost R".

Launched from a catapult, the “Forpost” is capable of carrying up to 120 kg of payload. Optoelectronic sensor units provide the possibility of reconnaissance at any time and in any

weather, and a 47 hp engine allows the device to reach speeds of up to 200 km / h. Flight range - 250-400 km. Duration - up to 18 hours.

Since 2010, the Russian army has begun using the ” Orlan-10” multifunctional short-range unmanned complex, designed to monitor objects in hard-to-reach areas (Figure 12).

Fig. 12. UAV "Orlan-10".

After a series of exercises, including "Kavkaz-2012", "Orlan-10" was highly appreciated by the leadership of the Ground Forces and the Airborne Forces and was put into service. To date, more than 1,000 such devices have been delivered to the troops. "Orlan-10" is part of the tactical link control system (ESU TZ) and can broadcast targets for destruction by all combat vehicles (self-propelled guns, tanks, infantry fighting vehicles, air defense vehicles) connected to the ESU TK. Its maximum takeoff weight is up to 18 kg, the practical flight range is up to 600 km, the practical ceiling is 6,000 m. The UAV was actively used during the military operation of the Russian Aerospace Forces in Syria.

It is known that the development of the “Orion” drone with a maximum take-off weight of 5,000 kg and a ceiling of 12,000 m is already underway (Figure 13).

Fig. 13. Orion UAV.

The unmanned aerial vehicle "Orion" (export version "Orion-E") passed combat tests in Syria and confirmed the declared characteristics. "Orion" allows not only to stake off, but also to strike. The maximum takeoff weight of the device is 1,000 kg, the UAV can carry a payload of 200 kg - four bombs or missiles. The drone is equipped with an optoelectronic system that is capable of surveying space in the optical, infrared and thermal ranges, automatically detecting targets and highlighting them with a laser designator.

2.3. The use of drones for environmental purposes

Their advantages lie in the fact that they can be closer to the object under study, unlike aircraft or satellites, they can interact with the surrounding space. UAVs have been used in the environmental sphere in Russia and in the world for more than a year. They help to survey waste storage sites, water bodies, assess the consequences of natural disasters, and much more. As part of the article, we will consider five eco-directions in which drones can be useful.

2.3.1. The fight against environmental pollution

Here, environmental monitoring is possible at the oil spill sites. The first step in oil spill cleanup is to localize the contaminated area, prevent the spread of the oil slick, and collect as much spilled oil as possible. The thickness of the contamination layer in the first hours after the spill is still quite large, which makes it easier to separate oil from water and land. Therefore, it is very important to determine the location of the spill on the ground and its size in time.

Aerial photography technologies are also excellent for quickly assessing the condition of oil pipelines.

Environmental monitoring is also widely carried out to prevent pollution of natural resources by garbage (Figure 14).

Fig. 14. Helicopter-type drone for monitoring the level of soil and water pollution.

2.3.2. Disaster management

For example, after large forest fires, drones help the forestry to get the most complete picture of the situation that arose after a natural disaster. Based on aerial photography data, the forest management service can assess the damage and draw up an action plan: first clear roads from the wind blow, and then the forest area in order to protect the remaining living forest from pests and fires.

2.3.3. Animal observation, counting, condition and behavior study

In Russia, copters were used for reconnaissance, searching for walrus and polar bear rookeries, counting animals, studying their condition and behavior. The expeditions conducted surveys on the Greater Oransky Islands, the northernmost group of islands in the Novaya Zemlya archipelago in the Barents Sea. Drones make it possible to conduct research

without disturbing the habitats of animals and without frightening them, which is important for maintaining ecological balance.

2.3.4. Assessment of the state of water bodies

Using aerial photography with the help of UAVs, scientists determine the degree of destruction of the coast, dump sites and popular locations for recreation. Based on photographic materials, they collect information about the state of ecosystems and vegetation, determine the recreational load on the territory and other factors that affect the coast (Figure 15):

Fig. 15. Monitoring of water bodies.

2.3.5. Assessment of the state of ecosystems and vegetation

Carbon polygons are created. Such sites are intended for conducting experiments on measuring emissions and removals of greenhouse gases. To do this, the scientific staff of the site conducts ground and remote measurements to assess changes in the flows of climatically active gases (methane, carbon dioxide, nitrous oxide). There are currently 11 active carbon polygons in Russia (Figure 16):

Fig. 16. Heavy drone over a carbon polygon.

3 Conclusions

Be that as it may, drones have one significant drawback - the vulnerability of communication channels. The signals of GPS navigators, as well as any signals received and sent by an aircraft, can be jammed, intercepted and replaced; both conventional artillery mounts and

means of jamming control signals can be used to destroy UAVs. Nevertheless, according to most experts, the United States, NATO countries, China and Russia in possible military conflicts of the future will still rely on UAVs - reconnaissance and strike. It is possible that these will be not only controlled, but also thinking devices endowed with intelligence.

In addition to military purposes, unmanned aerial vehicles are increasingly used in peaceful economic activities. In particular, they are widely usedin the field of ecology to protect the environment.

References

1. S. Darvishpoor, J. Roshanian, A. Raissi, M. Hassanalian, Aerosp. Sci., **121**, 100694 (2021)
2. M. Hassanalian, D. Rice, A. Abdelkefi, Aerosp. Sci. **97**, 61–105 (2018)
3. M. Hassanalian, A. Abdelkefi, Aerosp. Sci. **91**, 99–131 (2017)
4. J. Shahmoradi, E. Talebi, P. Roghanchi, M.A. Hassanalian, Drones **4**, 34 (2020)
5. J. Shahmoradi, P. Roghanchi, M. Hassanalian, Int. J. Theor. Appl. Multiscale Mech. **4**, 58–82 (2022)
6. A. Mirzaeinia, J. Shahmoradi, P. Roghanchi, M. Hassanalian, *Autonomous Routing and Power Management of Drones in GPS-Denied Environments through Dijkstra Algorithm. In Proceedings of the 2019 AIAA Propulsion and Energy Conference* (Indianapolis, Indiana, 2019)
7. J. Shahmoradi, A. Mirzaeinia, M. Hassanalian, P. Roghanchi, *Monitoring of Inaccessible Areas in GPS-Denied Underground Mines Using a Fully Autonomous Encased Safety Inspection Drone. In Proceedings of the AIAA SciTech 2020* (Orlando, FL, USA, 2020)
8. S. Lanctot, J. Cooke, J. Montoya, B. Herkenhoff, A. Mostafanejad, M.A. Hassanalian, *Hybrid Vehicle System for Depositing Payloads in Extreme Environments Like Antarctica and Arctic. In Proceedings of the AIAA Propulsion and Energy 2021 Forum* (Virtual Event, 2021)
9. A.H. Louie, Axiomathes **20**, 495–509 (2010)
10. P. Borges, T. Peynot, S. Liang, et al., Field Robot **2**, 1567–1627 (2022)
11. S. Lanctot, B. Herkenhoff, M. Hassanalian, *Unmanned Launching & Landing Rover (ULLR) for Moon and Martian Missions on Ice-Caps. In Proceedings of the 2021 ASCEND Conference* (Las Vegas, NV, USA, 2021)
12. T.S. John, Int. J. Sci. Eng. Res. **2**, 1–6 (2011)
13. M. Ben-Ari, F. Mondada, *Robotic motion and odometry. In Elements of Robotics; Springer* (Cham, Switzerland, 2018)
14. J. Ni, J. Hu, C. Xiang, J. Automob. Eng. **235**, 1084–1100 (2021)
15. *Clearpath Robotics: Mobile Robots for Research & Development. Available online:* https://clearpathrobotics.com/ (accessed on 30 December 2022).
16. N.A. Olmedo, M. Barczyk, H. Zhang, et al., J. Unmanned Veh. Syst. **8**, 364–381 (2020)
17. P. Gonzalez-De-Santos, R. Fernández, D. Sepúlveda, E. Navas, M. Armada, *Unmanned ground vehicles for smart farms. In Agronomy-Climate Change and Food Security; Intech UK* (Horwich, UK, 2020)

18. M.R. Blackburn, R. Bailey, B. Lytle, In Unmanned Ground Vehicle Technology VI; Society of Photo Optical: Orlando, FL, USA **5422**, 124–134 (2004)
19. B. Sun, X. Jing, Robot. Biomim. **4**, 1–14 (2017)
20. W. Guo, J. Qiu, X. Xu, J. Wu, Sensors **22**, 1470 (2022)
21. B. Herkenhoff, S. Lanctot, T. Bjorkman, N. Serda, M. Hassanalian, *Preliminary Design Concept of Locust Inspired Jumping Moon Robot Swarm. In Proceedings of the AIAA Propulsion and Energy 2021 Forum* (Virtual Event, 2021)
22. A. Western, R. Cervantes, C. Dunning, et al., *Bioinspired Robot with Walking, Rolling, and Jumping Capabilities for Planetary Exploration. In Proceedings of the AIAA Aviation 2021 Forum* (Virtual Event, 2021)
23. B.K. Herkenhoff, S.I. Lanctot, J.M. Fisher, N. Serda, et al., In Proceedings of the Lunar and Planetary Science Conference, Online, 2754 (2021)
24. A. Western, M. Haghshenas-Jaryani, M. Hassanalian, Acta Astronaut **204**, 34–48 (2022)
25. S. Rezazadeh, A. Abate, R.L. Hatton, J.W. Hurst, IEEE Access **6**, 54369–54387 (2018)
26. E. Prada, Ľ. Miková, R. Surovec, M. Kenderová, *Complex kinematic model of snake-like robot with holonomic constraints. In Proceedings of the Mezinárodní Vědecká Konference k Problematice Technologických a Inovačních Procesů Technnológia Europea* (Hradec Králové, Czech Republic, 2012)
27. A. Crespi, A. Badertscher, A. Guignard, A.J. Ijspeert, Robot. Auton. Syst. **50**, 163–175 (2005)
28. *CDC—Mining Contract—Snake Robot for Mine Rescue—NIOSH. Available online: https://www.cdc.gov/niosh/mining/researchprogram/contracts/contract200–2009-30721.html* (accessed on 30 December 2022).
29. A. Menciassi, S. Gorini, G. Pernorio, L. Weiting, et al., *fabrication and performances of a biomimetic robotic earthworm. In Proceedings of the 2004 IEEE International Conference on Robotics and Biomimetics* (Shenyang, China, 2004)
30. M. Carlo, S.A. Metin, J. Bionic Eng. **3**, 115–125 (2006)
31. Saunders, A.; Goldman, D.I.; Full, R.J.; Buehler, M. The rise climbing robot: Body and leg design. In Proceedings of the Unmanned Systems Technology VIII, Kissimmee, FL, USA, 17–20 May 2006; pp. 401–413.
32. Uckert, K.; Parness, A.; Chanover, N.; Eshelman, E.J.; Abcouwer, N.; Nash, J.; Detry, R.; Fuller, C.; Voelz, D.; Hull, R.; et al. Investigating habitability with an integrated rock-climbing robot and astrobiology instrument suite. Astrobiology 2020, 20, 1427–1449.
33. The First Climbing Robot for Mars–Sciworthy. Available online: https://sciworthy.com/the-first-climbing-robot-for-mars/ (accessed on 30 December 2022).
34. Lanctot, S.; Montoya, J.; Dunaway, C.; Flores, C.E.; Barstow, J.; Janney, W.; Eisenberg, S.; Good, F.; Davis, N.S.; Zhang, S.; et al. Pillbug-Inspired Robot with Crawling and Rolling Locomotion Mechanisms for Use on the Lunar Surface. In Proceedings of the AIAA SciTech 2023 Forum, National Harbor, MD, USA & Online, 23–27 January 2023.
35. Liu, G.H.; Lin, H.Y.; Lin, H.Y.; Chen, S.T.; Lin, P.C. A bio-inspired hopping kangaroo robot with an active tail. J. Bionic Eng. 2014, 11, 541–555.

36. Yu, J.; Ding, R.; Yang, Q.; Tan, M.; Wang, W.; Zhang, J. On a bio-inspired amphibious robot capable of multimodal motion. IEEE/ASME Trans. Mechatron. 2011, 17, 847–856.
37. Han, S. A Guide to the Different Types of Drones & UAS. Everglades University. 5 March 2021. Available online: https://www.evergladesuniversity.edu/blog/guide-different-types-drones-unmanned-aerial-systems/ (accessed on 1 December 2022).
38. Carholt, O.C.; Fresk, E.; Andrikopoulos, G.; Nikolakopoulos, G. Design, modelling and control of a single rotor UAV. In Proceedings of the 2016 24th Mediterranean Conference on Control and Automation (MED), Athens, Greece, 21–24 June 2016; pp. 840–845.
39. Darvishpoor, S.; Jafar, R.; Morteza, T. A novel concept of VTOL bi-rotor UAV based on moving mass control. Aerosp. Sci. Technol. 2020, 107, 106238.
40. Mirkov, N.; Rasuo, B. Maneuverability of an UAV with coanda effect based lift production. In Proceedings of the 28th International Council of the Aeronautical Sciences (ICAS), Brisbane, Australia, 23–28 September 2012; pp. 1–6.
41. Barlow, C.; Lewis, D.; Prior, S.D.; Odedra, S.; Erbil, M.A.; Karamanoglu, M.; Collins, R. Investigating the use of the Coanda Effect to create novel unmanned aerial vehicles. Microsoft Word–MES_2009_Paper_coanda effect C Barlow D Lewis (soton.ac.uk). In Proceedings of the International Conference on Manufacturing and Engineering Systems, Huwei, Taiwan, 17–19 December 2009; pp. 386–391.
42. Lavars, N. Bizarre 'Bicopter' Drone Uses Two Tilting Rotors for 50-Minute Flights. Available online: https://newatlas.com/drones/v-coptr-falcon-drone-tilting-50/ (accessed on 20 December 2019).
43. Jin, H. Tricopter vs. Quadcopter 2022: Which Is Better for You. Available online: https://lucidcam.com/tricopter-vs-quadcopter/ (accessed on 27 April 2022).
44. Yoo, D.W.; Oh, H.D.; Won, D.Y.; Tahk, M.J. Dynamic modeling and control system design for Tri-Rotor UAV. In Proceedings of the 2010 3rd International Symposium on Systems and Control in Aeronautics and Astronautics, Harbin, China, 8 June 2010; pp. 762–767.
45. Lukow, S.; Sherman, M.; Gammill, M.; Hassanalian, M. Design and Fabrication of Electromagnetic Attachment Mechanism for a Hybrid Drone for Mars Exploration. In Proceedings of the 2021 AIAA SciTech Forum, Virtual Event, 11–15 & 19–21 January 2021.
46. Pilot Institute. Is a Drone with More Rotors Better? Available online: https://pilotinstitute.com/more-rotors-better/ (accessed on 30 December 2022).
47. Lenski, P. Design, Construction and Operation of a Pentacopter. Master's Thesis, Luleå University of Technology, Department of Computer Science, Electrical and Space Engineering, Luleå, Sweden, March 2017.
48. Foxtech. Blog–Foxtech Screamer Racing Pentacopter-Preorder. Available online: https://www.foxtechfpv.com/blog/0530-news/ (accessed on 30 December 2022).
49. Guitarbob. Dragonfly/Pentacopter Project. Available online: https://www.instructables.com/DragonflyPentacopter-Project/ (accessed on 30 December 2022).
50. RedDrone. The Red Drone. (Pentacopter Version.right-Top View). Available online: https://www.123rf.com/photo_37276849_the-red-dronepentacopter-versionrighttop-view.html (accessed on 30 December 2022).

51. Night Hawk, Sky Rider. King Soopers—Sky Rider Night Hawk Hexacopter Drone with Wi-Fi Camera—Blue/Black, 1 CT. Available online: https://www.kingsoopers.com/p/skyrider-night-hawk-hexacopter-drone-with-wi-fi-camera-blue-black/0004732355700 (accessed on 30 December 2022).
52. Octocopter. Spreading Wings S1000—DJI. DJI Official. Available online: https://www.dji.com/spreading-wings-s1000 (accessed on 30 December 2022).
53. Throneberry, G.; Hassanalian, M.; Hocut, C.M.; Abdelkefi, A. Insights on the potential of vibratory actuation mechanism for enhanced performance of flapping-wing drones. Meccanica 2021, 56, 1–16.
54. Hassanalian, M.; Abdelkefi, A. Towards Improved Hybrid Actuation Mechanisms for Flapping Wing Micro Air Vehicles: Analytical and Experimental Investigations. Drones 2019, 3, 73.
55. Throneberry, G.; Hassanalian, M.; Abdelkefi, A. Insights into Sensitivity of Wing Shape and Kinematic Parameters Relative to Aerodynamic Performance of Flapping Wing Nano Air Vehicles. Drones 2019, 3, 49.
56. Ghommem, M.; Hassanalian, M.; Al-Marzooqi, M.; Throneberry, G.; Abdelkefi, A. Sizing process, aerodynamic analysis, and experimental assessment of a biplane flapping wing nano air vehicle. Inst. Mech. Eng. Part G. J. Aerosp. Eng. 2019, 233, 0954410019852570.
57. Hassanalian, M.; Abdelkefi, A. Methodologies for weight estimation of fixed and flapping wing micro air vehicles. Meccanica 2017, 52, 2047–2068.
58. Hassanalian, M.; Abdelkefi, A.; Wei, M.; Ziaei-Rad, S. A novel methodology for wing sizing of bio-inspired flapping wing micro air vehicles: Theory and prototype. Acta Mech. 2017, 228, 1097–1113.
59. Khan, M.M.; Gee, P.; Upshaw, J.; Hassanalian, M. Taxidermy Birds as Platform for Flapping Wing Drones: A Bioinspired Mechanism for Wildlife Monitoring. In Proceedings of the AIAA SciTech 2023 Forum, National Harbor, MD, USA & Online, 23–27 January 2023.
60. Martinez-Ponce, J.; Urban, C.; Armanini, S.F.; Agarwal, R.K.; Hassanalian, M. Aerodynamic Analysis of V-Shaped Flight Formation of Flapping-Wing Drones: Analytical and Experimental Studies. In Proceedings of the AIAA SCITECH 2022 Forum, San Diego, CA, USA & Online, 3–7 January 2022.
61. Timirgaleeva, R.R., Kazak, A.N., Filippov, D.M., Novikova, N.I., Lankovskaya, E.K Robotics in the hospitality sector of the Russian Federation, CEUR Workshop ProceedingsVolume 2914, 2021, Pages 493-5005th International Scientific and Practical Conference ""Distance Learning Technologies"", DLT 2020
62. Kazak, A.N., Oleinikov, N.N., Timirgaleeva, R.R., Ryndach, M.A., Gorobets, D.V. Service robotics development trends in the Russian Federation, AIP Conference ProceedingsVolume 2402, 15 November 2021, 070020, 3rd International Conference on Advanced Technologies in Materials Science, Mechanical and Automation Engineering, MIP: Engineering-III 2021
63. Kazak, A.N., Oleinikov, N.N., Ryndach, M.A.,Sergeeva, E.A. Potential and development of the Russian transport industry, IOP Conference Series: Materials Science and Engineering Volume 918, Issue 1, 6 October 2020, 012235, 8th International Scientific Conference Transport of Siberia 2020.
64. Erb, J.; Strauss, E.; Naghdi, M.; Hassanalian, M. Exploration of Venus' Upper Atmosphere Using an Aqua and Bacteria Inspired Aerial System. In Proceedings of the

AIAA SCITECH 2022 Forum, San Diego, CA, USA & Online, 3–7 January 2022; p. 2581.

65. Kawano, H. Study of path planning method for under-actuated blimp-type UAV in stochastic wind disturbance via augmented-mdp. In Proceedings of the 2011 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), Budapest, Hungary, 4 July 2011; pp. 180–185.
66. Shrestha, E.; Hrishikeshavan, V.; Benedict, M.; Yeo, D.; Chopra, I. Development of control strategies and flight testing of a twin-cyclocopter in forward flight. In Proceedings of the 70th annual national forum of the American Helicopter Society, Montreal, QC, Canada, 20 May 2014.
67. Tank Quadcopter Drone|Uncrate. Available online: https://uncrate.com/tank-quadcopter-drone/ (accessed on 30 December 2022).
68. Miniature Hybrid UAS/UGV Introduced|Unmanned Systems Technology. Available online: https://www.unmannedsystemstechnology.com/2020/01/miniature-hybrid-uas-ugv-introduced/ (accessed on 30 December 2022).
69. Shapeshifting Pegasus Drone Both Drives and Flies, Now Has Smart Radio (forbes.com). Available online: https://www.forbes.com/sites/sebastienroblin/2021/01/27/shapeshifting-pegasus-drone-both-drives-and-flies-now-has-smart-radio/?sh=6a295650795e (accessed on 30 December 2022).
70. Available online: https://dronehub.ai/we-are-proud-to-present-the-huuver-our-new-hybrid-drone-that-flies-and-rides/ (accessed on 30 December 2022).
71. Kim, K.; Spieler, P.; Lupu, E.S.; Ramezani, A.; Chung, S.J. A bipedal walking robot that can fly, slackline, and skateboard. Sci. Robot. 2021, 6, eabf8136.
72. Goldman, J. Parrot MiniDrone Rolling Spider Review: Inexpensive Drone Fun for Novice Flyers. Available online: https://www.cnet.com/reviews/parrot-minidrone-rolling-spider-review/ (accessed on 30 December 2022).
73. Mining & Technology: Drones to Map Underground Areas, Save Time & Improve Safety (mozambiqueminingpost.com). Available online: https://mozambiqueminingpost.com/2018/04/30/mining-technology-drones-to-map-underground-areas-save-time-improve-safety/ (accessed on 30 December 2022).
74. Ahmed, S.N. 3D scanning and mapping of underground mine workings using aerial drones. Phys. Can. 2018, 74, 103.
75. Biggs, T. Disney Research Creates Drone Car That Can Climb Walls. Available online: https://www.smh.com.au/technology/disney-research-creates-drone-car-that-can-climb-walls-20151231-glx6dd.html (accessed on 30 December 2022).
76. Panther. Advanced Tactics Panther Drone Has Completed First Aerial Package Delivery Test. Available online: https://uasweekly.com/2017/03/31/advanced-tactics-panther-drone-completed-first-aerial-package-delivery-test-safe-drive-doorstep-capability/ (accessed on 30 December 2022).
77. Moscaritolo, A. Airblock Drone Can Turn into a Hovercraft. Available online: https://www.pcmag.com/news/airblock-drone-can-turn-into-a-hovercraft (accessed on 30 December 2022).
78. Zhao, M.; Anzai, T.; Shi, F.; Chen, X.; Okada, K.; Inaba, M. Design, modeling, and control of an aerial robot dragon: A dual-rotor-embedded multilink robot with the ability of multi-degree-of-freedom aerial transformation. IEEE Robot. Autom. Lett. 2018, 3, 1176–1183.

79. Drone Can Transform into a Tiny Car to Slide under Small Gaps|New Scientist. Available online: https://www.newscientist.com/article/2204184-drone-can-transform-into-a-tiny-car-to-slide-under-small-gaps/ (accessed on 30 December 2022).
80. Falanga, D.; Kleber, K.; Mintchev, S.; Floreano, D.; Scaramuzza, D. The foldable drone: A morphing quadrotor that can squeeze and fly. IEEE Robot. Autom. Lett. 2018, 4, 209–216.
81. Miki, T.; Khrapchenkov, P.; Hori, K. UAV/UGV autonomous cooperation: UAV assists UGV to climb a cliff by attaching a tether. In Proceedings of the 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 20–24 May 2019; pp. 8041–8047.
82. Autonomous Drone-Launching Security UGV Under Development|Unmanned Systems Technology. Available online: https://www.unmannedsystemstechnology.com/2020/11/autonomous-drone-launching-security-ugv-under-development/ (accessed on 30 December 2022).
83. Russia's Autonomous Robot Tank Passes New Milestone (And Launches Drone Swarm). Available online: https://www.forbes.com/sites/davidhambling/2021/09/02/russias-autonomous-robot-tank-passes-new-milestone-and-launches-drone-swarm/?sh=2d9ae0ba21fa (accessed on 30 December 2022).
84. Spot Robot Dog Expands with Arm Attachment, Teams Up With Drone, and More!—Construction Junkie. Available online: https://www.constructionjunkie.com/blog/2020/12/15/spot-robot-dog-expands-with-arm-attachment-teams-up-with-drone-and-more (accessed on 30 December 2022).
85. Researchers Create Drone that Can Land on Moving Vehicle—Autoevolution. Available online: https://www.autoevolution.com/news/researchers-create-drone-that-can-land-on-moving-vehicle-video-85516.html (accessed on 30 December 2022).