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An Overview of The Recent Progress and Challenges in Nano Aerial Vehicles (NAVs)

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Abstract

Unmanned aerial vehicles (UAVs) offer a variety of uses that make them suitable for both military and civilian use. The increasing need for intelligence operations has led to the development of UAVs, such as micro, nano, and pico air vehicles (MAV, NAV, and PAV). Nano aerial vehicles are extremely small and lightweight, smaller than 7.5 cm, and weighing less than 10 grams. Initially, the Nano Air Vehicle (NAV) had the capacity to execute challenging combat operations both indoors and outdoors. At the primary stage, some characteristics like lift generation and vehicle control, and analytical tools for low Reynolds numbers were developed, which led to construct a hummingbird-inspired prototype aircraft. In recent years, nano aerial vehicles have advanced significantly in terms of their design, flying characteristics, and navigation systems. The performance of NAV depends on some aerodynamic parameters such as lift, drag, thrust, and Reynolds number. Nowadays, both biomimicry and nanotechnology are used in NAVs. This paper is concerned with the evolution of NAV through the years and how it was developed day by day. NAV has become an autonomous vehicle and AI is used to improve its performance. Some other technologies are used, such as radar positioning, collision avoidance, obstacle detection, and 3D map and model creation by GPS and various sensors. This paper will encourage the researchers to conduct research in this area and they can gather knowledge about the NAV technology.

Keywords: Nano Aerial Vehicle (NAV), Biomimicry, Aerodynamic performance, Drag

1.Introduction

Nano Aerial Vehicles (NAVs) are a specialized type of small unmanned aerial vehicles (UAVs) which are designed for applications requiring great manoeuvrability, low visibility and operating in constrained places. DARPA initiated a program titled nano air vehicles, aimed at developing and demonstrating an exceptionally small (under 15 cm) and ultralight (under 20 g) aerial vehicle system capable of executing military operations both indoors and outdoors. NAVs are classified as small aircraft with an optimal flying altitude of around 100 meters, a maximum operational range of less than a kilometer, an endurance of under an hour, and a maximum takeoff weight of 25 grammes [1]. The advantages presented by NAVs, including their diminished safety requirements and risks due to their lightweight nature, are significantly relevant to the broader application of these technologies in agriculture [2]. They can be equipped with specialized sensors, including those for gas, radiation or other technologies employed to detect biological, nuclear, chemical, or more hazards. They can, for example, navigate within poisonous clouds to transmit data or retrieve samples for the base station, thereby offering critical information regarding the composition and size of gaseous clouds and enhancing danger assessment [1]. A smell-sensitive nano-drone can be utilized in various uses, including environmental surveillance, chemical, biological, radiological, and nuclear (CBRN) defence, and explosive detection, among others [3]. Nano drones equipped with cameras provide unique perspectives for photography and cinematography. They may achieve stunning aerial photography and filmmaking that was once unachievable [4]. In the early 1990s, MIT Lincoln Laboratory devised a concept to construct a small aircraft with a wingspan of 74 mm capable of accommodating a miniature electro-optical reconnaissance equipment. Subsequently, in 1997, DARPA launched the nano air vehicle project. The existing literature indicates the evolution of three NAVs. Their names are AeroVironment Nano Hummingbird, Robobee, and Samarai. The Nano Hummingbird was conceived and engineered by AeroVironment. This flapping-wing NAV operates at a velocity of 5 m/s and manoeuvres across three axes of motion. The object possesses a form like an authentic

hummingbird, featuring a wingspan of 160 mm, an overall weight of 19 g, a wing length of 74 mm, and a flight endurance of 4 minutes. Harvard University created Robobee, which does tethered flight. The propulsion mechanism of Robobee is a piezoelectric actuator. Robobee weighs 8 grams and possesses a wingspan of 30 millimeters, representing the smallest man-made wingspan capable of sustained flight [5].
Numerous empirical studies have concentrated on NAV; however, there are very few literatures that summarize all kinds of studies and experiments on NAV. The work in [6] focused on developing control mechanisms and effective flight control tactics inspired by insect. Additionally, for wing construction and enhancing performance, natural concepts were used. The work in [1] presented the challenges associated with the design and manufacture of NAV. The main structure, control, communication and use of micro and nano-technology on NAV was reviewed. In the reviewed literature, the recent progress on NAV and the challenges it will face in future was not included as one of them is not very recent. Furthermore, there was not enough information about recent modifications. Therefore, this study is focused on the evaluation of NAV from the early stages to recent years and the challenges one will face in designing an NAV. Besides recent advancement of NAV in technologies and their advantages are briefly discussed. In addition, the enhancements that NAV must accomplish in the future are introduced.



Fig. 1. Application of NAV in different sectors

2. Design method and challenges

The design and development of a NAV encounter obstacles such as aerodynamic uncertainty at low Reynolds numbers (below 100,000) and the NAV's sensitivity to atmospheric turbulence [7]. NAVs are capable of flying at low altitudes (i.e., below 150–200 m) over localized geographic areas in real time while maintaining economical running expenses [3].The NAVs are classified into fixed-wing, flapping wing, and rotary wing categories. Fixed-wing aircraft require a thrust-to-weight ratio of less than 1, as wings generate supplementary lift. The total weight is divided by the lift-to-drag (L/D) ratio, resulting in a lower power requirement for flight compared to a helicopter of equivalent weight in a hovering state, when the weight is entirely counterbalanced by the motor thrust [1]. Flapping wing NAVs are predominantly utilized for indoor operations and low Reynolds number applications. Owing to their instability in windy situations, they are unsuitable for outdoor use. Flapping wings have excellent manoeuvrability but possess limited endurance and range capabilities. During flight, a flapping wing experiences four primary forces: lift, drag, thrust, and weight, with lift and thrust counterbalancing weight and drag, respectively. In hovering mode, the sole force generated is a lift, which counteracts the weight of the flapping wing NAV. The average lift value is sufficient to support the intended NAV. The instantaneous forces and mechanical power fluctuate during the upstroke and downstroke actions. Enhancing the flapping frequency yields elevated average values of aerodynamic forces, including lift, thrust, and mechanical power, while concurrently lowering the thrust-to-power ratio [8].

3. Evolution through years

Early stage

The DARPA launched a two-phase program in October 2005. Four contractors were included initially.

Draper Laboratory

The demand for large-aircraft manoeuvrability and control capability during an outdoor flight in adjusting winds and huge impulses that are typical around structures motivated the development of this unique vehicle configuration. It was predicated on a coaxial helicopter with various distinctive features. The rotors were positioned at each end of the fuselage, accommodating the electronics and battery. The rotor-blade motors were integrated with the rotor hubs, and piezoelectric actuators were employed to tilt the rotors. Furthermore, Draper developed a point-tracking algorithm for visual navigation, a mission-assessment instrument, and a strategy for interaction and management throughout the entire NAV operation. Figure 2 shows the conceptual view of the proposed NAV.

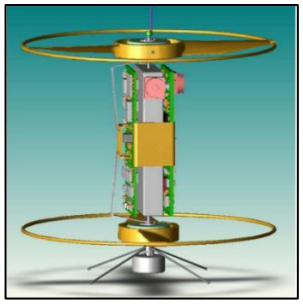


Fig.2.Draper Laboratory coaxial helicopter concept [9].

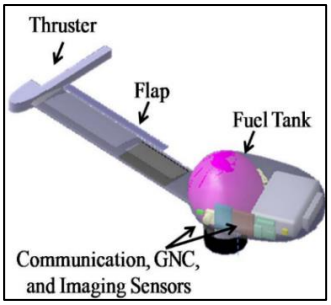


Fig. 3. Conceptual design of Lockheed Martin SAMARAI NAV [9].

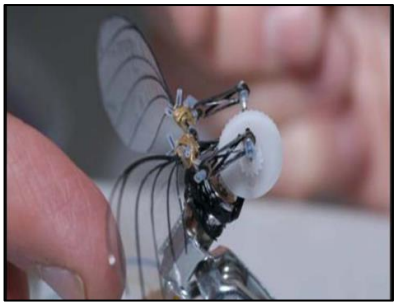


Fig. 4. Flapping system prototype [9].

Lockheed Martin

The development of this device was based on the concept of a single wing with multiple innovative technologies. This device included a jet situated at the wingtip, which was chemically powered, a system for fuel supply, a mechanism to fulfil the purpose of launching, a quick wing-flap for control, and a module for navigation and vision connected to a continuously spinning hub. The primary inspiration for the design was the better range and manoeuvrability of a chemically fueled vehicle in contrast to a battery-powered system. On the airfoil and control surface configurations, comprehensive wind tunnel analyses were conducted, yielding the requisite lift and maneuverability required for flight. The conceptual design of the Lockheed Martin aircraft is shown in Fig. 3.

MicroPropulsion

From the desire to look like a naturalistic creature, MicroPropulsion was built by using the concept of cicada. The MicroPropulsion team primarily focused on enhancing the comprehension of fluid mechanics in flapping flight, simulating, and modeling mechanisms for flapping, analyzing the flapping flight's control and stability aspects, and constructing flapping mechanisms prototypes. The team not only constructed and tested prototype flapping mechanisms but also created wing designs, unique actuators, and initial control schemes for both aircraft stability and long-range navigation. Fig. 4. shows the prototype Micropropulsion.

AeroVironment

AeroVironment was the only idea which was selected for the next phase of DARPA program. The engineers took hummingbird as their inspiration and created a prototype whose mechanism of flapping and wings for both onward and hovering flight ensured thrust, controllability and efficiency. In phase 1, AV enhanced the wing-flap-control system to facilitate more accurate control, hence providing precision-hover capabilities, to withstand gusts manoeuvrability was increased, and the capacity to fly ahead at speeds exceeding 5 meters per second. In phase 2, a significant advancement was the creation of small wing modulation and propulsion systems for control and thrust to facilitate efficient wing actuation. A sophisticated system for actuation was designed and implemented on a succession of prototype vehicles, enabling slight deflection at the wing roots to produce significant aerodynamic effects. Fig. 5. shows the final NAV.

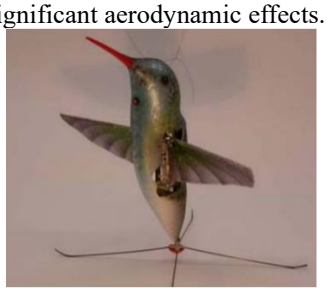


Fig. 5. AeroVironment NAV demonstrator [9].

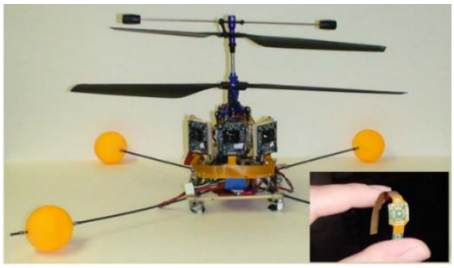


Fig. 6. Phase 1 of CentEye [9].

CentEye

A human operator could maneuver a vehicle which was controlled remotely with solely the information of optical-flow, rather than conventional video data was the objectives of this program. Besides, optical-flow data were used to combine inputted human orders and autonomously controlled action and develop the flight control system. Sensors were created for optical flow which were developed and for flight testing these sensors were integrated in the NAV. Fig. 6. shows the CentEye of phase 1.

Recent progress

In recent years, NAV has been advanced in various fields. Some of them are mentioned below:

Bug 4.1

The most recent version, the Bug 4.1, weighs around 350 grams and possesses a range of 3 kilometers. The UAV is manually launched and retrieved. The lossless HD zoom camera features thermal imaging functionality, with data relayed to the operator through a secure WiFi connection or an encrypted SD card. Supplementary payload choices comprise a microphone/listening device, loudspeaker, assorted lights (white/red/infrared), a mapping system, and a diverting device. Sensor data can be concurrently delivered to several locations; eligible receivers comprise cellphones, laptops, tablets, and the Android Team Awareness Kit (ATAK). A comprehensive GPS follow-the-leader kit equips the Bug 4.1 for UAV swarm deployment. The flight duration is 30 minutes at a maximum velocity of 80 km/h; however, the potential mission endurance is significantly extended as the drone can land at its target location and continue transmitting sensor data for several hours. Fig. 7. shows the Bug 4.1.

Ninox 40 MT

This nano-UAV is the smallest variant of the Ninox family of nano/micro-UAVs, weighing under 250 grams and possessing a flying endurance of 35 minutes. Artificial intelligence governs the integrated day/night camera mechanism, facilitating the automatic monitoring of objects of interest. Sensor data is transmitted through a secure two-way datalink utilizing commercial-off-the-shelf (COTS) technology, with the launch capsule operating as the wireless router that links the drone to the tablet. To maintain functionality in signal-denied conditions, the navigation system integrates global navigation satellite system (GNSS) and inertial navigation system (INS) guidance. Mesh networking and swarm functionalities are essential to the system, encompassing the capability to transmit targeting data to Spear UAV's Viper loitering munitions. Fig. 8. shows the Ninox 40 MT

Black Hornet 4 PRS

This latest generation of the Black Hornet series boasts improved range, endurance, signature, and imagery data compared to earlier models. The 70 g UAV possesses a flight endurance of 30 minutes, a range exceeding 2 km, and can function in winds of 13 m/s (25 kn), with a maximum speed of 36 km/h. An upgraded battery and a novel obstacle avoidance technology augment flight performance, enabling operation in GNSS-denied conditions. The sensors on the current model have been enhanced. The Black Hornet 4 features five cameras that offer a total field of vision of 270°. The system comprises three low-resolution daytime cameras for navigation and obstacle detection, a new 12 MP forward-looking HD daytime camera with low-light capability and a 125° field of view, a thermal camera with a resolution of 650×512 and a 78° field of view (the smallest thermal camera globally, as stated by Teledyne FLIR), and an ultrasonic sensor. Fig. 9. shows the Black Hornet 4 PRS.



Fig.7. The Bug 4.1 nano-UAV [10].



Fig. 8. Ninox 40 MT [10].



Fig. 9. Black Hornet 4 PRS [10]

5. Technological advancement

From the early stages to the recent times, NAV has advanced in performance by using various technologies.

Biomimicry in NAV design

Biomimicry in nanotechnology vehicles entails utilizing nature as a source of inspiration for the design and engineering of these small flying objects. Engineers can develop more efficient, nimble, and complex nano-drones by analyzing the structures and systems of biological species, including the flying patterns of birds and the sensory systems of animals. For Example, Engineers have precisely created mosquito-inspired nanotechnology drones, accurately emulating the flying characteristics of their biological equivalents [11].

Autonomy and AI

Autonomous, nano unmanned aerial vehicles driven by artificial intelligence (AI) are revolutionary in the Internet of Things (IoT) sector. Smart sensors enhance their sensory and operational capabilities to autonomously navigate to areas where their presence is most beneficial, particularly close to humans [12].

Radar Positioning

Modern NAVs can function in both GNSS and non-satellite modes. Satellites utilize GNSS satellites upon the initial activation of the NAV. The NAVs radar technology verifies information on the control panel prior to flight, ensuring the conditions are appropriate for takeoff.

Collision avoidance and obstacle detection

NAVs are outfitted with collision avoidance devices to enhance safety. These systems comprise sensors that do not survey the environment but identify obstructions. Data from various sensors convert images into three-dimensional maps, enabling the flight controller to identify and dodge obstacles.

Gyro stabilization, IMU, and flight controllers

The gyroscope promptly reacts to fluctuating pressures affecting the NAV by supplying essential navigation data to the central flight controller. The IMU measures the current acceleration rate through the accelerometer and gyroscope to observe variations in rolling parameters, including pitch, roll, and yaw. The IMU incorporates a magnetometer to counteract drift during flight.

Ready-to-fly and no-fly-zone

Based on the compass calibration, when the drone initiates operation, it seeks the location of GPS satellites; upon detecting more than six satellites, the drone is deemed "ready-to-fly." To enhance flight safety and avoid incidents in limited locations, the "no-fly zone" feature is engaged, resulting in flying restrictions.

3D map and model creation

The NAV visualization employs hyperspectral, multispectral, LiDAR, and thermal sensors generated from 3D digital surface models (DSM) of structures, terrain, and landscapes, along with digital elevation models (DEM) of the ground. Time-of-Flight (ToF) is a 3D imaging and precision mapping technology that measures the rotation time of each camera sensor pixel by emitting a very brief pulse of infrared light. By measuring the distances within a captured scene Flash LiDAR time-of-flight cameras provide a diverse array of solutions [13]. Table 1 summarizes the following technological advancements with their advantages and usage.

Table 1: List of different technological advancements, their advantages and usages of NAV

Category	Applications	Technologies Used	Advantages
Biomimicry in NAV design	Bio-inspired nano-drones for complex navigation in challenging environments.	Nanomaterials, biological structure analysis, flight mechanics.	Enhanced agility, improved stability in turbulent conditions, energy efficiency.
Autonomy and AI	Precision agriculture, search & rescue, smart cities, Human drone interaction (HDI), IoT integration.	AI algorithms, smart sensors.	Reduces human intervention, enhances decision-making, real-time data processing.
Radar Positioning	Navigation in GPS-limited environments, SAR (Search and Rescue), 3D mapping for terrain exploration.	GNSS (GPS, GLONASS), satellite constellation technology, radar, return-to home algorithms.	Precise navigation, reliability in various environments, accurate 3D mapping.
Collision avoidance and obstacle detection	Safe navigation in complex environments, urban surveillance, and industrial inspections.	LiDAR, vision sensors, ultrasonic sensors, ToF (Time-of-Flight) sensors, monocular vision sensors.	Prevents accidents, safer navigation in complex and crowded environments.
Gyro stabilization, IMU, and flight controllers	Smooth and stable flight control for tasks requiring precision, such as inspection or data gathering.	Gyroscopes, accelerometers, IMUs, magnetometers, flight controllers.	Enhanced stability, responsive flight control, smooth flight in turbulent conditions.
Ready-to-fly and no-fly-zone	Safety in regulated airspaces, no-fly zone enforcement for restricted areas such as airports, government buildings.	GPS, software for no-fly-zones.	Ensures compliance with airspace regulations, enhances safety by preventing unauthorized flight zones.
3D map and model creation	3D terrain modeling for agriculture, forestry, environmental monitoring, construction, and urban planning.	Hyperspectral sensors, multispectral sensors, LiDAR, thermal imaging, digital surface models (DSM), digital elevation models (DEM), 3D mapping software (Pix4D, ArcGIS, DroneDeploy).	Detailed analysis of terrain, large-scale environmental, and structural assessments.

6. Future challenges

Despite the enhanced capabilities of contemporary nano-UAVs compared to previous models, restrictions persist in terms of speed, endurance, range, and payload capacity. The two primary aspects that could affect these performance metrics are the improvement of the propulsion and energy systems, and the reduction of weight. Innovative composite materials are expected to enhance UAVs by reducing weight and increasing durability, allowing existing motors to carry more payloads or extend operational range and velocity. Batteries remain a significant weight consideration. A Recent study at MIT indicates that employing a solid ceramic electrolyte instead of a liquid electrolyte may yield solid-state lithium batteries with superior energy density compared to existing lithium-ion batteries, hence enhancing mission range and endurance for platforms utilizing them. Research undertaken at Monash University in 2023 indicates that Lithium-Sulphur (Li-S) batteries may offer a lighter and more effective alternative to Li-ion batteries. Mission systems provide numerous possibilities for performance improvement. The cameras in the previously mentioned NAVs exceed the capabilities of earlier-generation sensors. Furthermore, future advancements will include ongoing enhancements in sensor performance. Alongside video, thermal, and audio, supplementary sensor payloads such as NBC detection and signals intelligence capabilities may gain more popularity [10].

7. Conclusions

Nano Aerial Vehicles (NAVs) have emerged as a crucial technological advancement, driven by the demand for intelligence and military operations. This paper discussed the historical evolution, design methods, recent technological advancements, and future challenges faced by NAVs. From early prototypes inspired by biological organisms like hummingbirds to modern drones equipped with advanced AI, biomimicry, and sensor technology, NAVs have evolved significantly in terms of flight endurance, manoeuvrability, and application diversity. Key developments have occurred in navigation systems, propulsion mechanisms, and collision-avoidance technologies. Despite these advances, challenges persist, particularly in improving the propulsion systems and reducing overall weight. Future research will need to focus on overcoming these limitations, ensuring NAVs remain cutting-edge tools for both military and civilian applications.

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