UÇAK-HAVACILIK-UZAY MÜHENDİSLİĞİ DEĞERLENDİRMELERİ

Editör: Dr.Öğr.Üyesi Ahmet ŞUMNU

yaz
yayınları

Akademik Perspektiften Uçak-Havacılık-Uzay Mühendisliği

Editör

Dr.Öğr.Üyesi Ahmet ŞUMNU

yaz yayınları

2025

Uçak-Havacılık-Uzay Mühendisliği Değerlendirmeleri

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E_ISBN 978-625-5838-90-2

Ekim 2025 – Afyonkarahisar

Dizgi/Mizanpaj: YAZ Yayınları

Kapak Tasarım: YAZ Yayınları

YAZ Yayınları. Yayıncı Sertifika No: 73086

M.İhtisas OSB Mah. 4A Cad. No:3/3 İscehisar/AFYONKARAHİSAR

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İÇİNDEKİLER

A REVIEW OF ACTIVE AND PASSIVE FLOW CONTROL APPLICATIONS

Ahmet ŞUMNU[1]

1. INTRODUCTION

Energy conservation has become increasingly critical due to the finite nature of global energy resources. As a result, maximizing energy efficiency is a key objective across various engineering applications. One significant contributor to energy or fuel consumption in vehicles exposed to airflow is aerodynamic drag. Reducing this drag is essential for improving overall energy efficiency. To address this challenge, various flow control techniques—both active and passive—have been developed to manipulate airflow and enhance aerodynamic performance.

Drag force may be classified into two categories: skin friction drag and pressure drag. The majority of the total drag stems from pressure drag when flow separation occurs. Hence, flow can be controlled to prevent separation from the surface in the boundary layer. The boundary layer control aims to reduce drag on air vehicles by controlling the flow in the boundary layer. It may be provided by blowing fluid to the boundary layer through a porous wall or a jet placed on the surface. This increases fluid energy or momentum to keep it attached to its wall. Eventually, pressure drag is reduced since flow separation is suppressed or the wake size occurring on air vehicles is decreased thanks to flow

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control devices. In Figure 1, the flow separation around a wing is represented.

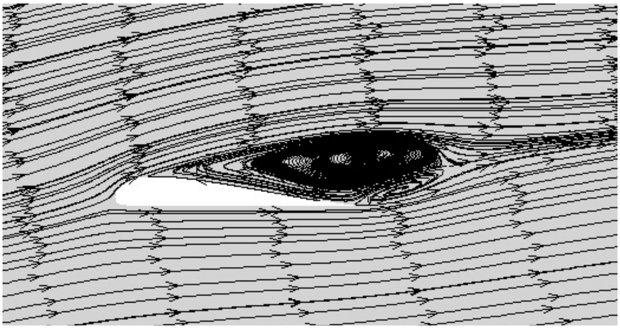

Figure 1. Flow separation around a wing (Adapted from ref. Şumnu, 2025)

This paper presents a brief review of recent developments in the exciting field of active and passive flow control methods for enhancing aerodynamic performance through open- and closed-loop control. Active flow control requires an energy input to manipulate airflow during motion, typically by increasing momentum in the boundary layer via open- or closed-loop systems. In contrast, additional mechanical structures are placed on the surface to prevent flow separation in the boundary layer using passive control devices. These methods are commonly used to delay or suppress stalls on wings or aircraft. However, limited research has explored the integration of open/closed-loop control with passive devices, such as activating mechanical structures like active vortex generators. This review highlights current techniques and proposes directions for future research in this area. The following section presents previous studies on various flow control methods and their application areas.

2. FLOW CONTROL

Flow control can be performed using various methods and devices. Active flow methods utilize devices that impart energy to the boundary layer, thereby increasing flow momentum and preventing flow separation. Passive flow methods use additional mechanical structures to prevent or suppress flow separation in the boundary layer by increasing momentum. Flow methodologies are shown in Figure 2. In this section, previous studies related to active and passive flow control methods are examined.

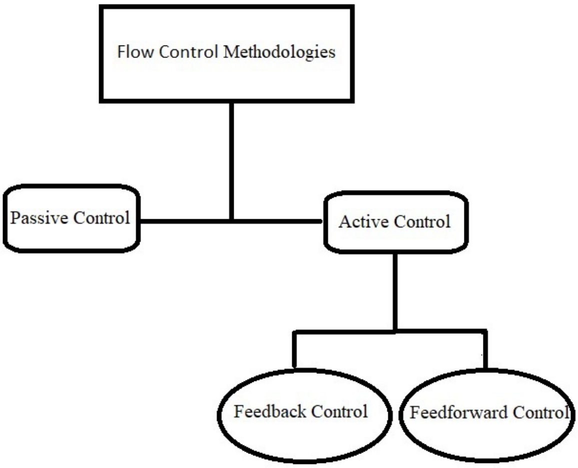

Figure 2. Flow Methodologies (Adapted from ref. Kral, 2000)

2.1. Active Flow Technique

The active flow method can be applied to improve lift and drag characteristics using energy-requiring devices such as synthetic jets, plasma actuation and pulsed blowing. It is also carried out by applying both suction and blowing. Thanks to active control devices, these applications may reduce pressure drag stemming from flow separation. Extensive research has been conducted on active flow separation control using both experimental and computational approaches.

2.1.1. Applied Control Jets

In the boundary layer, blowing jets are used to increase flow momentum and obtain turbulent flow. Synthetic jet actuators are devices that produce a jet of fluid by alternating suction and expulsion of the surrounding fluid through an orifice, without net mass addition. This is typically achieved using a vibrating diaphragm or piston within a cavity (Ho et al., 2024). The literature contains many studies that used control jets.

To obtain sufficient lift force for an air vehicle, some complex high-lift devices can be used. However, active flow control devices can provide superior performance in terms of aerodynamic characteristics. Chng et al. (2009) used three different jet momentums to show the effect on flow control for an airfoil by applying both injection and suction. Han et al. (2010) conducted an optimization study to enhance aerodynamics over an airfoil using synthetic jet parameters and to show improvement of the flow field; the baseline case, controlled case, and optimal case were compared. The results showed that flow separation was delayed, especially for optimal cases. Haucke and Nitsche (2013) performed an experimental study employing pulsed jets to improve the performance of the flap system, and a numerical simulation was also carried out for the validation process by comparing the obtained experimental data. The experimental study was presented to investigate the contribution of active flow control by Ciobaca et al. (2013). The results showed that aerodynamic performance was enhanced by utilizing the pulsed blowing flow control technique. Monir et al. (2014) focused on flow control to prevent flow separation using tangential synthetic jets at different oscillating frequencies and blowing ratios.

By changing the jet parameters that are frequency, angle, and amplitude, it was shown which parameters were effective on aerodynamic performance. An experimental study investigating active flow control was conducted by Gul et al. (2014) through the deployment of synthetic jet actuators to prevent flow separation. Skarolek and Karabelas (2016) conducted an active flow method using NACA 0015 wing by taking into consideration energy efficiency. Liu and Zha (2016) performed active flow control for a transonic supercritical airfoil utilizing a Co-flow jet via RANS equations for the RAE2822 airfoil. Svorcan et al. (2017) performed 2-D flow solution to improve the performance of the airfoil utilizing an active flow control method using three different airfoils and different URANS turbulence models. Fisher et al. (2017) also presented active flow control using bidirectional synthetic jets by means of RANS simulation in a 2D model.

There is the theoretical limit of maximum lift coefficient for an airfoil however, it can exceed this thanks to active flow control techniques. Yang and Zha (2017) investigated C_{Lmax} value utilizing Co-Flow jet using CFD simulation at high AoA, and it was concluded that there was no limit for $C_{Lmax,}$ and it was based on the amount of energy that is added to the flow by active flow devices. An active flow control technique was also used to increase efficiency and thrust for a wing in fan configuration, and the solution was performed using three three-dimensional, unsteady RANS solvers. Results showed that aerodynamic enhancement was achieved, and this study also supported to search for VTOL (Vertical Takeoff and Landing) (Sheng and Zhao, 2017). Boukenkoul et al. (2017) investigated 2-D flow analyses for the NACA0015 airfoil to enhance the lift coefficient using a synthetic jet actuator. The study was presented to reduce the circumferential velocity that occurs wing tip vortex thanks to active flow control using synthetic jets for NACA 0012 airfoil by Dghim et al. (2018). The objective of Halawa et al. (2018) was to show the effect of active flow control using an active slat through the OpenFOAM solver for incompressible, unsteady, low Reynolds number flow, and the optimum excitation frequency was obtained using Fast Fourier Transform (FFT). Zhang et al. (2018) also used Co-Flow jet to enhance aerodynamic performance for NACA 0012 airfoil with and without flap. The results showed that CFJ usage substantially reduced net energy cost and increased lift coefficient. A similar study was also presented to reduce the wing tip vortex using five different active control configurations for NACA 0012 airfoil by Dghim et al. (2020). The active flow control study was conducted via CFD simulation for NACA 0012 airfoil with and without flap by applying blowing and suctions by Fatahian et al. (2019). Ramos et al. (2019) studied active flow control to alleviate dynamic stall. For this aim, at the leading edge region, blowing and suction were implemented by applying different spanwise arrangements of actuators. Dolgopyat and Seifert (2019) presented an active flow control study that included both suction and blowing to prevent and separate flow over an airfoil. Active flow control with a co-flow jet was investigated for the S809 airfoil, and an optimization study was performed to find maximum efficiency by Xu and Zha (2020).

The experimental study was conducted to enhance performance and prevent flow separation for trailing edge flaps using microjet (Aley et al., 2020). Lehmkuhl et al. (2020) studied active flow control for micro air vehicles using a synthetic jet. The result showed that stall prevention was successfully achieved at high angles of attack. Aldabash et al. (2021) performed numerical and experimental studies to delay stall formation over NREL S822 aerofoil employing blowing and suction techniques. The results showed that the aerodynamic characteristic was improved with increasing blowing and suction volume flow rate. Singh et al. (2021) used NACA 23012 airfoil to perform active flow control using hybrid jets. Tousi et al. (2021) carried out CFD simulations for the SD7003 airfoil to improve aerodynamic efficiency by utilizing synthetic jets and performing optimization techniques at different angles of attack. Abbasi and Yazdani (2021) used synthetic jet to prevent or control dynamic stall at high angles of attack by means of 2D numerical solution for NACA 0015 airfoil. Marouf et al. (2022) applied a hybrid control technique that includes chambered flap and Zero Net Mass Flux (ZNMF) methods for enhancing aerodynamics, solving three-dimensional CFD simulations utilizing RANS/LES turbulence models. Abbasi (2022) investigated the effect of blowing jet parameters to control flow over NACA 0012 airfoil at various blowing velocities, jet angles, and jet locations. The results revealed that aerodynamic improvement was especially achieved at a 30° blowing angle. Abbasi and Esmailzadeh Vali (2022) simulated active flow control for NACA 0012 airfoil by applying both blowing and suction. The results showed that aerodynamic improvement was significantly achieved at the vertical suction position and blowing flow control at 30° where the velocity was approximately half the free stream velocity. Both suction and blowing flow were operated over NACA 0015 airfoil employing a synchronized actuator by Sonkaya et al. (2022). The results showed that flow separation was prevented at high angles of attack and especially at high frequencies. Çanlıoğlu and Kara (2023) used an active flow control method to improve aerodynamic efficiency, and the results showed that a loudspeaker-type synthetic jet actuator enhanced the lift-to-drag ratio at low and moderate Reynolds numbers. Gupta et al. (2023) presented a numerical study by employing incompressible, unsteady, RANS equations and the SST k-ω turbulence model to show active flow control performance using a delta wing. For this, a blowing jet was placed at different locations, and it was concluded that maximum performance was observed at location 3.24% of the root chord from the leading edge. Luo et al. (2023) also presented active flow control by using sweeping jets for a supercritical airfoil. Different momentum coefficients were used to analyze the flow over the flap, and the influence of flow rate on aerodynamic performance was also investigated. The results showed that maximum lift was increased by about 33%.

2.1.2. Plasma Actuation and Fluidic Oscillators

Fluidic actuators and synthetic jet actuators are both devices that manipulate fluid flow, but they differ significantly in their design, operation, and applications.

Plasma actuators, particularly dielectric barrier discharge (DBD) types, utilize high-voltage alternating current to ionize air between electrodes separated by a dielectric material. This ionization creates an electrohydrodynamic (EHD) force that accelerates nearby air, influencing the boundary layer to delay flow separation, reduce drag, and improve lift (Erfani, 2012; Iranshahi et al., 2024).

Fluidic actuators utilize pressurized fluids—either gases or liquids—to generate mechanical motion. They are commonly found in systems like hydraulic or pneumatic cylinders, where the fluid's pressure is converted into linear or rotary motion. Recent advancements include the development of curved fluidic oscillators, which enable the placement of sweeping jets near the leading edge of airfoils, thereby enhancing flow control capabilities. Fluidic oscillators are devices that produce oscillating jets of air without moving parts, leveraging the Coandă effect and internal feedback loops. These oscillating jets can effectively control flow separation over surfaces like airfoils and turbine blades. Their simplicity and lack of mechanical components make fluidic oscillators attractive for applications requiring reliable and maintenance-free operation (Liu et al., 2022; Baghaei and Bergada, 2019).

Timor et al. (2007) also carried out active flow control using 14 piezo-fluidic actuators and it was concluded that this application improved the rolling moment, and a lift increment was achieved. Agate et al. (2018) performed both numerical and experimental studies to control laminar separation bubble flow using a DBD plasma and blowing/suction simulation active flow device. Çobanoğlu et al. (2022) performed an experimental study to show the effect of active flow control using DBD plasma actuator and passive flow control at various angles of attacks, and the results showed that the active flow control method had superior performance compared to the passive control method.

David and Seifert (2012) explored an innovative approach to generate yawing moments without relying on traditional moving control surfaces. They employed active flow control (AFC) techniques using piezo-fluidic actuators to manipulate aerodynamic forces asymmetrically across an airfoil. Pack Melton (2014) performed wind tunnel experiments and focused on flow control separation using fluidic actuators at the trailing edge flap and the flap shoulder. The actuator momentum, freestream velocity, and trailing edge flap deflection were varied when performing the study. Using fluidic oscillators, flow separation was tried to prevent for the vertical tail model by Andino et al. (2019). The investigation of the fluidic oscillator was performed for flow control applications by Woszidlo et al. (2019). The results of the examination showed that the jet entrainment is at least four times higher than in a steady jet. Otto et al. (2019) presented an experimental study to show differences between the steady jet and fluidic oscillators. The results showed that the performance of fluidic oscillators is better than steady jet since it has a larger jet spreading angle and stronger coherent streamwise vortices.

The high-lift airfoil was investigated for Fowler and simple flaps, and fluidic oscillators were placed at the leading edge to improve aerodynamic performance by DeSalvo et al. (2020). The experimental study using an oscillatory bump to reduce the drag of an airfoil was performed by Hochhäusler and Erfort (2022), and a numerical simulation was also compared.

The results showed good agreement with the experimental results. Khalil et al. (2022) presented a study to alleviate wind load through an active flow control technique by simulating 2-dimensional, steady, RANS equations. The investigated result showed that the fluidic flow control technique was successfully implemented for the gust load alleviation system.

2.2. Passive Flow Technique

Passive flow control (PFC) encompasses aerodynamic techniques that enhance flow characteristics without relying on external energy sources or active systems. These methods are integral in various applications, including aviation, automotive engineering, and wind energy, aiming to reduce drag, delay flow separation, and improve overall performance. The vortex generators (VG), riblets and grooves, dimples and trip strips, tubercles, and vortilons can be used for PFC devices. Figure 3 represents the wing with VG and the wing equipped with leading edge tubercles. The recent studies have been presented in the following.

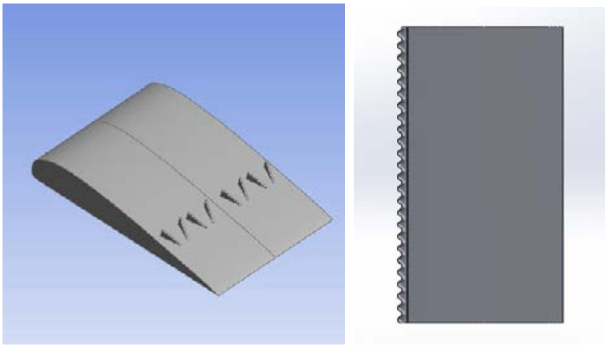

Figure 3. a: Wing with VG (Adapted from ref. Şumnu, 2025) b: Wing equipped with leading edge tubercles (Adapted from Johari et al. 2007)

Both passive and active flow control methods were employed, and the study's results showed that active flow control was more effective than the passive control method when compared with the baseline case for the NACA 0012 airfoil, as reported by Shan et al. (2008). Mai et al. (2008) used vortex generators to improve aerodynamics for the rotor blade at the leading edge. The results revealed that the negative pitching moment was reduced while the overall time average lift significantly increased, thanks to the leading edge vortex generators. Coutu et al. (2011) focused on morphing wings by applying both open-loop and closed-loop control under cruise flight conditions in a wind tunnel, and the results showed that aerodynamic improvement was achieved by about 15% and 13.7% for closed-loop and open-loop control, respectively. Both experimental and numerical investigations were performed for AUV using vortex generators to obtain maximum lift, and it was observed that maximum achievement was implemented when VG was placed closer to the separation region, and rectangular shape and curved-edge VG showed better performance than triangular one (Zhen et al., 2011). Pehlivanoglu and Yagiz (2011) focused on an optimization study using both active and passive control parameters. At the end of the study, aerodynamic enhancement was achieved by about 575.8%.

Le Pape et al. (2012) presented dynamic stall control using vortex generators located at the leading edge for an airfoil that operated a helicopter blade. The vortex generators could be changed in height, frequencies, and phases with respect to airfoil oscillation. The results showed that static stall and negative pitching moment reduction were achieved. Heine et al. (2013) used cylinders that were mounted leading edge to control dynamic stall conditions for OA 209 wing profile. The experimental results showed that the negative pitching moment effect was reduced, and aerodynamic performance was improved. Namura et al. (2016) used a passive control device to control and improve the flow field over a supercritical infinite wing. The multi-objective genetic algorithm was performed to optimize the vortex generator using five design parameters, and aerodynamic performance was investigated using appropriate design variables. Fouatih et al. (2016) performed experimental study using vortex generators that was placed on NACA 4415 airfoil and optimization study was also carried out to find optimal vortex generator parameters for efficiency increment. Joshi and Gujarathi (2016) investigated both active and passive flow control methods, and the results revealed that the active flow control method shows superior performance according to passive devices.

Li et al. (2019a) presented an experimental and numerical study to demonstrate the effect of vortex generator installation angle, and the effect of vortex generator spacing on flow separation was also investigated by the same authors (Li et al., 2019b). The design optimization was carried out for a swept transonic wing, and it was concluded that a higher length-to-height ratio showed superior performance, and drag was reduced by about 50% thanks to optimally designed vortex generators (Namura et al., 2019). Using winglets and vortex generators (triangular and rectangular shapes), aerodynamic performance was enhanced for various angles of attack by Hasan et al. (2020).

De Tavernier et al. (2021) performed to demonstrate vortex generator effectiveness for unsteady flow conditions. The results showed that height and mounting position of VG significantly affected for delayed and suppressed dynamic stall. Dhileep et al. (2022) focused on morphing concepts to investigate aerodynamic characteristics using two different finite-volume solvers and a panel method. The result revealed that the morphed aerofoil showed good performance for moderate and high-lift necessities. Gönül et al. (2022) used a passive control device to enhance heat transfer capacity and pressure loss for micro channel and vortex generator parameters were optimized using a Genetic Algorithm. Li and Qin (2022) proposed a review paper to show flow control methods, especially under gust wind conditions. Rana et al. (2022) designed morphing aerofoil to enhance performance using NACA 0012. CFD analysis was performed under steady conditions at various angles of attack and transonic speeds. It was concluded that the morphing case showed superior performance when compared with the un-morphing case. Wang et al. (2022) performed optimization study using turbine aerofoil and vortex generators. They established a mathematical model for the wind turbine aerofoil with VG to optimize parameters and improve aerodynamic performance. Özden et al. (2023) presented an experimental study using single and double vortex generators. VG was mounted at different locations on the airfoil, and the results showed that both suction and pressure surface or double VG application increased the lift coefficient by gaining energy and momentum at the wake region. Esmaeili and Sousa (2023) also used hybrid flow control techniques that include active and passive control devices to improve aerodynamic performance for micro air vehicle wings.

In summary, passive flow control offers a cost-effective and efficient means to enhance aerodynamic performance across various sectors. By leveraging simple yet effective design modifications, PFC contributes to improved stability, reduced drag, and increased efficiency without the need for active systems. According to investigation results, few studies have observed the integration of open- or closed-loop control with passive devices, such as the activation of mechanical structures like active vortex generators.

3. OPEN AND CLOSED-LOOP CONTROLLER FOR ACTIVE FLOW CONTROL

An open-loop control system operates without feedback; the output does not influence the control action. The system functions solely based on the input, without monitoring the actual output. The application is easy to design and implement. However, since open-loop control systems lack feedback mechanisms, they cannot adapt to disturbances or correct errors, resulting in reduced accuracy (Chopra, and McCloud, 1983; Borovic et al. 2005). Figure 4 shows the chart of open-loop control system.

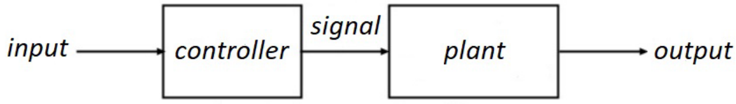

Figure 4. Open-loop control system (Adapted from ref. Kuo, 1967)

A closed-loop control system**,** or feedback control system, continuously monitors its output and adjusts its input to achieve the desired result. The system uses feedback to compare the actual output with the desired output and minimize the error. The system comprises additional components and features a sophisticated design, enabling it to maintain the desired output despite disturbances (Chopra, and McCloud, 1983; Borovic et al. 2005). Figure 5 represents the chart of a closed-loop control system.

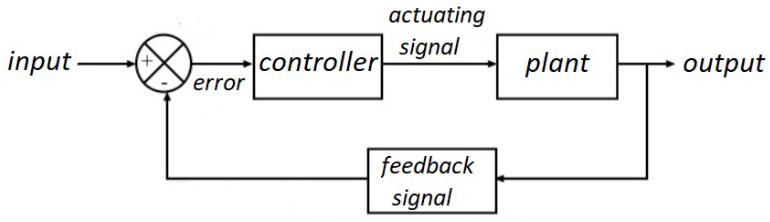

Figure 5. Closed-loop control system (Adapted from ref. Kuo, 1967)

The adaptive feedback control with light actuation system was reviewed to show aerodynamic efficiency and the effect of unsteady flow conditions on flapping wing flyers (Ho et al., 2003). The closed-loop controller was also performed by means of piezoceramic actuators to minimize vortices on the airfoil

(Zhang et al., 2006). The wind tunnel experimental study was implemented to control the position of the wing using a closed-loop control method by Kutay et al. (2007). Brzozowski et al. (2008) carried out the experimental study using active flow devices, and a closed-loop feedback controller was used for dynamic characteristic control. In order to control the flow separation employing closed-loop feedback control, the experimental study was conducted by Pinier et al. (2007).

A morphing airfoil study to control stall using dielectric barrier discharge (DBD) actuators was implemented through the medium of closed-loop control (Poggie et al., 2010). A morphing wing model was tested to improve aerodynamic performance using open loop architecture in the wind tunnel by Popov et al. (2010). Adaptive flow control using dielectric barrier discharge was presented at a low Reynolds number, which resulted in sensitive flow separation (Cho and Shyy, 2011). The closed-loop controller was used to improve flight control for an aircraft wing by taking into account aerodynamic force computed using the Panel method (Blower et al., 2012). The morphing wing application was carried out employing a 6-DoF mechanism, and its motion control was proposed by Moosavian et al. (2013). A wind tunnel test was conducted to apply closed-loop control for a half-model designed civil aircraft (King et al., 2013). Computational and experimental investigation was performed to prevent stalls occurring leading edge by means of a synthetic jet using PID controller (Lee et al., 2013). The closed-loop dynamic control to delay stall was carried out by means of a plasma actuator by Lombardi et al. (2013). The closed-loop control was used for a thick turbulent airfoil to recovery degraded surface quality by Troshin and Seifert (2013). Chabert et al. (2014) focused on flow separation that occurs flap using closed-loop control. The feedback control method was used to control separation by means of machine learning control that is based on genetic programming by Gautier et al. (2015). Wu et al. (2015) performed an experimental study for airfoil aerodynamics using an extended Kalman filter in a closed-loop system to decrease convergence time. Lepage et al. (2017) investigated buffet control on 3D wings performed using both open and closed-loop controllers and their experimental studies at transonic flow. Williams and King (2018) discussed and reviewed closed-loop flow control systems for obtaining useful models and enhancing aerodynamic performance. The active flow control system with dense wireless sensors was presented to reduce the drag produced, especially separation flow region (Sámano et al., 2018). Nogar et al. (2018) also focused on closed-loop control for flapping-wing micro air vehicles. Choi et al. (2018) proposed adaptive control system to enhance aerodynamic performance by preventing flow separation using pressure sensors and piezoelectrically driven synthetic jet for the NACA 64A210 airfoil.

Stalewski and Krzysiak (2019) proposed a closed-loop control system to improve flow conditions and protect against flow separation by locating pressure sensors at the flap trailing edge and controlling the air blown. The active flow control and flight control were performed by means of a PID controller for morphing unmanned aerial vehicles by Kanat et al. (2019). The schematic diagram of the PID controller is presented in Figure 6. Obeid (2020) proposed an active flow control study with a closed-loop feedback controller using synthetic jet actuators for a flapped airfoil. Akhter and Omar (2021) presented a review study on flow control devices for both passive and active methods to observe their contribution for aerodynamic and structural improvement. Nekoo and Ollero (2023) implemented a dynamic model of flapping wings for closed-loop control.

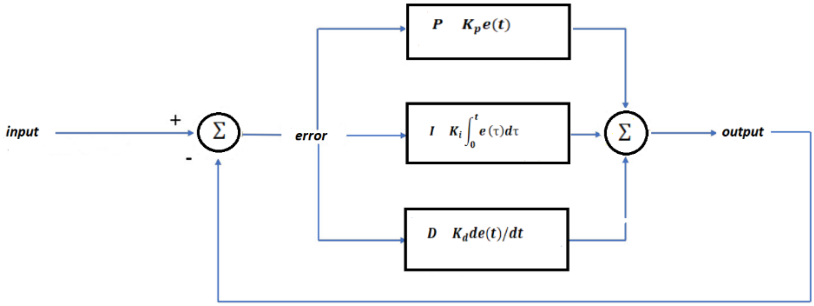

Figure 6. Schematic diagram of the PID algorithm (Adapted from ref. Kuo, 1967)

4. CONCLUSION

This paper summarizes the development and implementation of flow control strategies, highlighting key advancements and methodologies. Active and passive flow control methods have been investigated, and closed/open loop control systems have also been explored for the active control technique. Separation of the boundary layer over a wing causes an increase of adverse pressure gradients and resulting in a reduction of lift to drag ratio. Recent studies have demonstrated that flow control methods can significantly enhance aerodynamic performance by preventing or delaying flow separation and reducing pressure drag.

Among the investigated techniques, active flow control (AFC) methods generally outperform passive flow control (PFC) in terms of effectiveness. However, active control requires an energy input, and their systems are complex. In contrast, PFC methods do not need additional energy and are typically integrated into the air vehicle's structure. Although passive control increases drag forces in some cases, the aerodynamic performance of the applied system or vehicle improves, as evidenced by a higher lift force than drag force and a lift-to-drag ratio, indicating that aerodynamic performance is enhanced. Notably, some studies have proposed innovative approaches to PFC by introducing actuation capabilities to otherwise passive devices. For instance, vortex generators with adjustable positions and angles, responsive to vehicle motion, can further enhance aerodynamic efficiency. Additionally, hybrid flow control systems combining passive structures with active mechanisms have shown promise in boosting overall performance and energy efficiency.

In conclusion, emphasis on energy efficiency, system reliability, and adaptability will be crucial in advancing flow control technologies across various engineering domains. Furthermore, incorporating control strategies such as PID controllers to modulate passive devices could pave the way for more responsive and effective flow control technologies across various engineering applications.

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COMMUNICATION SECURITY IN UAV SWARM NETWORKS: VULNERABILITIES, COUNTERMEASURES, AND FUTURE DIRECTIONS

Cemal ISILAK[1]

1. INTRODUCTION

The concept of swarm technology is fundamentally rooted in self-organization, defined as the emergence of macroscopic behaviors from the nonlinear interactions of multiple entities within a group and their environment [1]. With the rapid advancements in sensors, processors, and communication modules, small unmanned aerial vehicles (UAVs) are now capable of performing tasks that were previously achievable only with larger, more resourceful platforms. Consequently, the deployment of multiple UAVs—commonly referred to as UAV swarms—has emerged as an attractive solution for executing complex missions that exceed the limitations of a single aerial vehicle [1].

A single UAV often faces inherent constraints such as limited endurance, payload capacity, and communication bandwidth over long distances. These limitations can severely hinder its performance in mission-critical scenarios. In contrast, a swarm of UAVs can collaboratively overcome these restrictions by leveraging distributed sensing, task allocation, and cooperative decision-making. Recent advances in collision avoidance,

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formation control, and path planning have further accelerated the feasibility of swarm deployment in both civilian and military applications [1,2].

UAV swarms can be classified as homogeneous—comprising identical platforms—or heterogeneous, consisting of UAVs with diverse configurations, sensor capabilities, and processing capacities. While homogeneous swarms are simpler and less computationally demanding, heterogeneous swarms offer greater flexibility and enhanced mission effectiveness in scenarios that require diverse sensor modalities or specialized payloads [1]. For instance, large-scale environmental monitoring or disaster response operations often necessitate heterogeneous UAV fleets to achieve robust and adaptable sensing [3].

The application domains of UAV swarms are extensive and multifaceted. In the civilian sphere, swarms have been employed in precision agriculture for crop monitoring and spraying, in disaster management for search-and-rescue operations, in infrastructure inspection for assessing structural integrity, and in environmental surveillance such as forest fire detection and monitoring [3]. Militarily, UAV swarms are envisioned for tasks such as reconnaissance, border surveillance, electronic warfare, and autonomous strike missions, where resilience, scalability, and distributed intelligence provide significant operational advantages [1].

While the swarm paradigm offers immense potential, its success relies heavily on secure and reliable communication mechanisms among UAVs and between UAVs and ground control stations (GCS). Effective coordination, task allocation, and situational awareness all require seamless communication links that are resilient to disruptions and cyberattacks. However, the reliance on wireless channels inherently exposes UAV swarms to a broad spectrum of vulnerabilities. Addressing these challenges necessitates the development of robust communication security frameworks tailored specifically to UAV swarm networks.

This chapter provides a comprehensive exploration of communication security in UAV swarm systems. It begins by reviewing swarm control architectures and inter-UAV communication models, followed by an in-depth discussion of vulnerabilities and attack vectors targeting UAV networks. The chapter then introduces countermeasures and defense mechanisms while highlighting emerging trends and research directions aimed at ensuring resilient and secure UAV swarm communication in the face of evolving cyber-physical threats.

2. CONTROL ARCHITECTURES IN UAV SWARMS

The control of multi-UAV systems, particularly in the domains of path planning and task allocation, has been extensively studied in the literature. Two primary approaches dominate these studies: centralized architectures and decentralized/distributed architectures [1]. Each comes with unique advantages and limitations, directly influencing swarm robustness, scalability, and operational resilience.

2.1. Centralized Control Architecture

In a centralized architecture, the UAV swarm operates with relatively low levels of autonomy. The UAVs themselves do not communicate directly with each other; instead, an operator or ground control station (GCS) receives information from each UAV, coordinates their behavior, and assigns mission tasks in advance [1].

This approach offers the benefits of simplified coordination and easier optimization, as decision-making is consolidated at a single control point. However, the reliance on a single controller reduces redundancy and makes the system vulnerable to failures in communication or the central UAV. If the central node or communication link is disrupted, the entire swarm may fail.

2.2. Decentralized (Distributed) Control Architecture

In contrast, a decentralized (or distributed) architecture relies on high levels of autonomy within each UAV. In this model, UAVs actively communicate, share information, and make local decisions, reducing the operator's role to supervisory or mission-level management [1].

The strength of decentralized systems lies in their robustness and flexibility. Since tasks and information are distributed among UAVs, the system can adapt dynamically to changing environments and tolerate individual UAV failures without compromising overall mission success. Furthermore, the swarm's collective behavior emerges from localized cooperation, allowing UAVs to adjust more effectively to real-time conditions such as unexpected obstacles or communication delays.

Despite these advantages, decentralized systems are inherently more complex to design and implement. They require sophisticated communication protocols, advanced decision-making algorithms, and strong resilience against cyber and physical threats. Until recent years, these systems were rarely feasible due to the lack of sufficient onboard computational capacity and reliable inter-UAV communication technologies.

2.3. Deployment Strategies of UAV Swarms

The deployment of UAV swarms depends on mission requirements and environmental conditions. Generally, three types of swarm deployments are identified: static, dynamic, and hybrid swarms [4].

2.3.1. Static Swarms

A static swarm is the simplest form of deployment. The members of the swarm are determined in the pre-mission assignment phase, and no new UAVs are allowed to join during flight. Communication security, mutual trust, and collaboration are established prior to takeoff, typically enforced by the ground control system. Any UAV not belonging to the swarm is treated as an external entity.

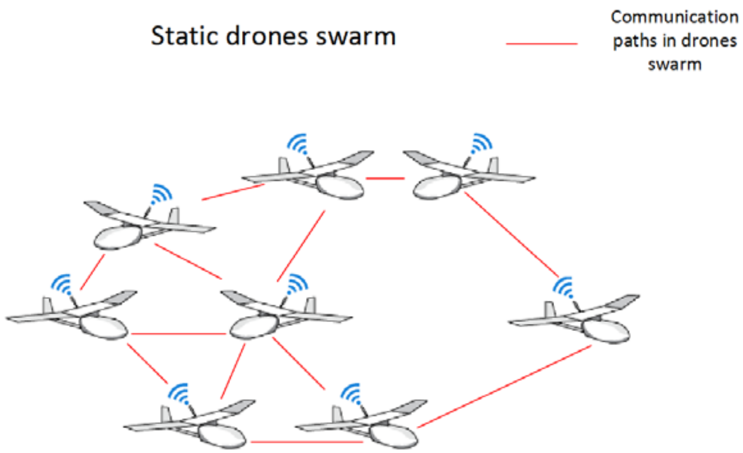

Figure 1. Illustrates a static swarm structure, where UAV membership remains fixed throughout the mission [4].

2.3.2. Dynamic Swarms

Unlike static swarms, dynamic swarms allow UAVs to join or leave the swarm during the mission. Two subcategories exist:

Closed-dynamic swarms, in which only UAVs from the same organization are allowed to join.

Open-dynamic swarms, in which UAVs from third-party organizations can be integrated into the swarm.

While this flexibility offers scalability and adaptability, it introduces significant challenges in communication security, trust establishment, and cooperative behavior. Unauthorized or malicious UAVs could attempt to infiltrate the swarm, making authentication and data integrity critical concerns [4].

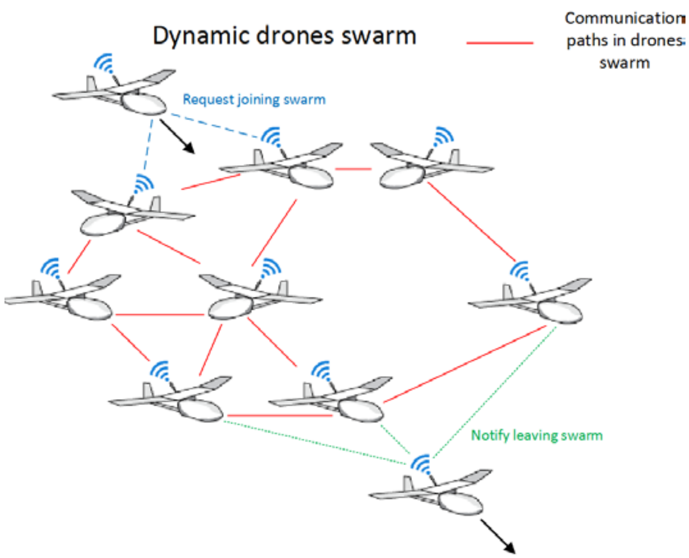

Figure 2. Demonstrates a dynamic swarm structure, showing the fluid nature of UAV membership [4].

2.3.3. Hybrid Swarms

Hybrid swarms combine the features of both static and dynamic deployments. At the core of the swarm lies a static subgroup, which remains consistent across missions and acts as the backbone of the operation. Around this static core, additional UAVs can dynamically join or leave, thereby forming an extended swarm.

The advantage of hybrid swarms is their ability to maintain a stable and secure core while still benefiting from the scalability and adaptability of dynamic structures. When cooperative learning, evaluation, and decision-making are required, the core swarm typically holds higher priority, ensuring mission continuity even if peripheral UAVs are compromised.

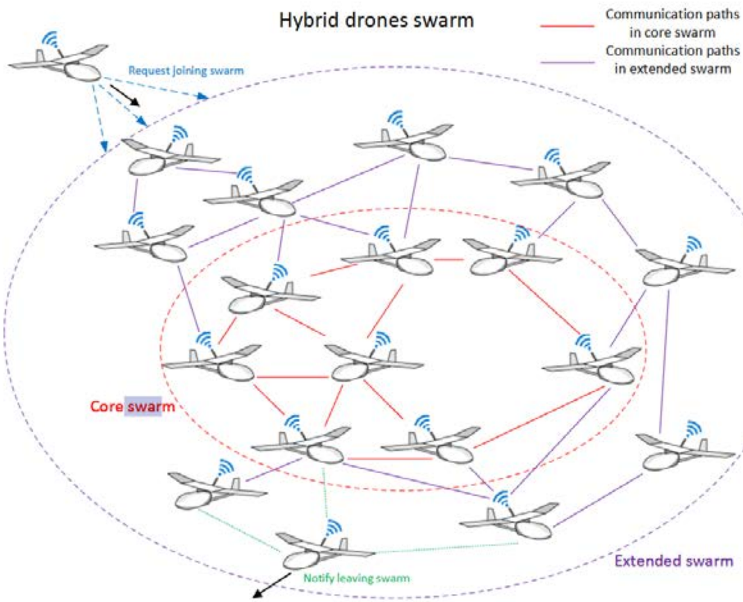

Figure 3. Provides an example of a hybrid swarm structure, where a central static group is augmented by dynamically attached UAVs [4].

3. INTER-UAV COMMUNICATION

Effective communication among UAVs is the cornerstone of coordination in swarm systems. In multi-agent environments, the ability of UAVs to exchange information reliably and efficiently directly impacts decision-making, situational awareness, and mission success. Since UAVs are highly mobile and operate in dynamic, often contested environments, communication strategies must be optimized to handle mobility, latency, and resilience challenges [5].

Wired communication is impractical due to UAV maneuverability and speed; therefore, UAV swarms rely predominantly on wireless communication mechanisms. These systems, however, are constrained by factors such as signal coverage, latency, interference, and energy consumption. Communication in UAV swarms can generally be categorized into direct and indirect methods [5].

3.1. Direct Communication

In direct communication, UAVs establish links with one another without the need for base stations or external infrastructure. Common technologies for direct communication include Wi-Fi, Bluetooth, and ZigBee.

- Advantages: Low power consumption, reduced latency, and relatively low cost.
- Limitations: Limited coverage range and susceptibility to interference, particularly in dense environments.

Direct communication is best suited for short-range coordination within compact swarm formations.

3.2. Indirect Communication

Indirect communication allows UAVs to connect through ground-based base stations or relay nodes, which may include mobile vehicles equipped with communication modules. This method extends the communication range to cover long-distance operations through technologies such as cellular networks (e.g., GSM, LTE) or satellite links.

- Advantages: Extended coverage and global accessibility.
- Limitations: Higher latency, increased power consumption, and higher cost.

Indirect communication is critical in scenarios where UAVs must maintain connectivity across large-scale operational theaters.

3.3. Communication Types at the Application Level

At the application layer, inter-UAV communication typically follows three paradigms:

1. Broadcast: A UAV shares its current status with all other members of the swarm.
2. Query: A UAV sends a request for status updates from other members.
3. Synchronization (Sync): A UAV (usually the leader) initiates a synchronization request, prompting all recipients to broadcast their states to the swarm.

This layered communication ensures that UAVs maintain situational awareness and temporal coordination, essential for tasks such as formation flying, cooperative sensing, and dynamic task allocation.

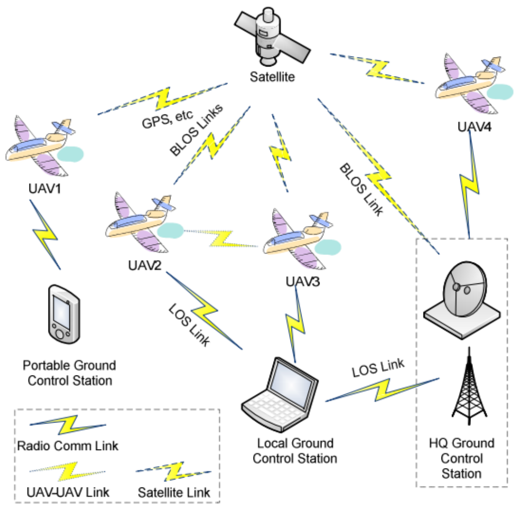

Figure 4 illustrates a typical UAV communication scenario involving diverse communication links, such as inter-UAV links, radio channels, and satellite connections [6]. Each link carries different types of data, including telemetry, command-and-control, GPS, and meteorological information.

3.4. UAV Communication Networks (UAVNet) and Security Considerations

Although researchers have extensively studied the security of wireless sensor networks (WSNs) and mobile ad hoc networks (MANETs), these models cannot be directly applied to UAV networks (UAVNets) due to the unique requirements of aerial platforms [6]. UAVNet security must address:

- Heterogeneous communication channels (short-range vs. long-range)
- Diverse devices with varying power requirements
- Multiple data types (command, video, voice, imagery)
- Integrity and confidentiality requirements

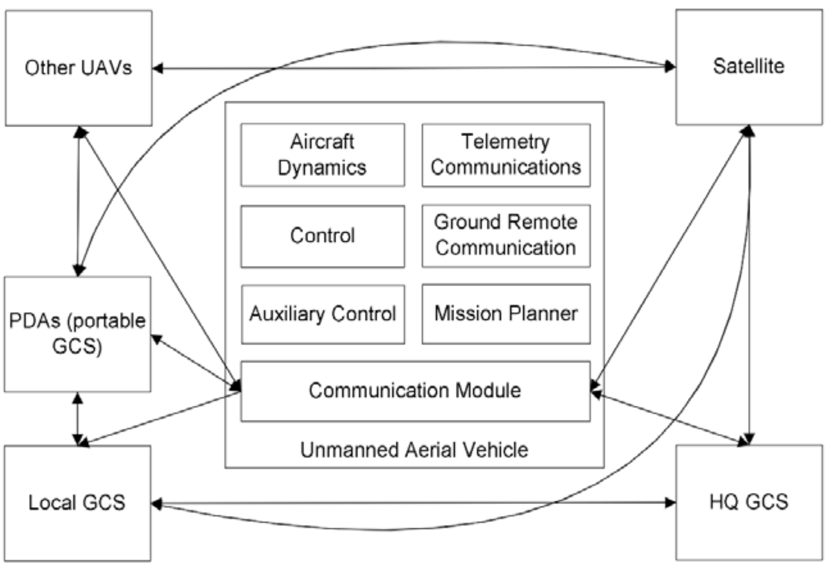

Figure 5 presents a UAV system architecture, highlighting different wireless channels and ground control station types [6]. These channels differ significantly in terms of their security vulnerabilities, ranging from line-of-sight (LOS) radio links to GPRS/EDGE-based communications.

3.5. UAV Control and Telemetry Systems

At the heart of UAV operations lies the flight controller (FC), often referred to as the “brain” of the UAV. The FC translates remote control inputs or mobile device commands into signals for electronic speed controllers (ESCs), thereby ensuring stable flight [7]. Typical components include:

- Inertial sensors (accelerometer, gyroscope)
- Environmental sensors (barometer, ultrasonic sensors)
- Navigation modules (GPS)

UAVs can be controlled in two primary ways:

1. Radio controllers, operating over the 2.4 GHz or 5.8 GHz bands.
2. Mobile applications, typically via Wi-Fi links.

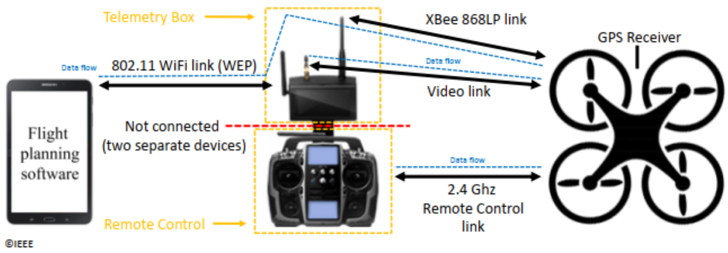

Figure 6 Shows a control and mission planning scheme, illustrating connections between remote controllers, telemetry units, and ground control applications [8].

Telemetry data (altitude, velocity, battery status, etc.) is critical not only for mission monitoring but also for establishing secure feedback loops between UAVs and operators.

3.6. Communication Security Requirements in UAV Swarms

The data exchanged in UAV swarms typically includes:

- Remote control commands (e.g., flight path adjustments)
- Telemetry data (e.g., UAV position, flight parameters, hardware status)
- Mission payload data (e.g., video, infrared imagery, or sensor outputs)

While command and telemetry data are relatively small in size (typically requiring transmission rates as low as 12.8 kb/s), they demand real-time, reliable, and error-free delivery. Payload data, on the other hand, is often bandwidth-intensive and highly sensitive to delays or interruptions.

The key security requirements in UAV communication include:

- Availability: Ensuring continuous service despite attacks such as denial-of-service (DoS). In this context, a study has shown that using UAVs as routers increased System-of-Systems (SoS) availability, and redundancy in the number of links between nodes helped mitigate cyber-caused link failures and add robustness in cases of induced data variability[9].
- Confidentiality: Protecting communication from unauthorized interception.
- Integrity: Guaranteeing that received information matches what was originally transmitted.
- Authentication: Verifying the legitimacy of communicating entities to prevent spoofing.

- Non-repudiation: Ensuring accountability for transmitted commands and data.

These requirements form the foundation of secure swarm communication frameworks, which must be designed to withstand adversarial threats while supporting the scalability and agility of UAV operations.

4. ATTACKS ON GPS AND WIRELESS COMMUNICATION LINKS

In addition to general security requirements, UAV swarms are highly vulnerable to targeted attacks against their navigation and communication systems. Two prominent categories of attacks are GPS spoofing/jamming and IEEE 802.11 wireless exploits, both of which can critically undermine mission reliability and swarm coordination [10,11].

4.1. GPS Spoofing and Jamming

The Global Positioning System (GPS) provides UAVs with essential information on position, velocity, and timing. While military GPS signals are encrypted and resistant to unauthorized use, civilian GPS signals are unencrypted and openly accessible, making them highly susceptible to jamming and spoofing attacks [11].

- GPS Jamming: An adversary transmits high-power interference signals in the GPS frequency band, preventing UAVs from receiving legitimate satellite signals.
- GPS Spoofing: Malicious signals are generated that mimic authentic GPS transmissions but contain false positioning data. By overpowering genuine signals, the attacker deceives the UAV into navigating incorrectly.

- Replay Attacks: Legitimate GPS signals are intercepted, delayed, and retransmitted to mislead UAV receivers.

A well-documented case occurred in 2011, when a U.S. stealth UAV (RQ-170 Sentinel) was allegedly captured by Iranian forces through GPS spoofing [10]. By broadcasting stronger counterfeit signals while jamming authentic ones, the UAV was deceived into misinterpreting its location and was forced to land in hostile territory.

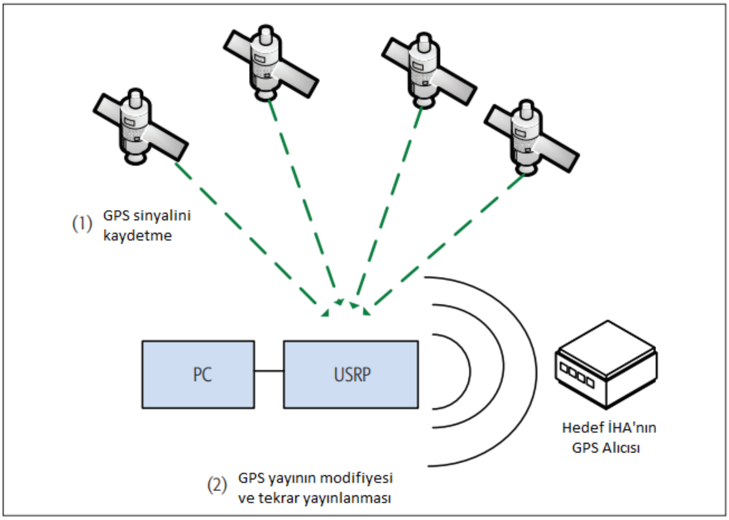

Figure 7 Depicts the process of GPS spoofing and replay attacks, showing how authentic signals can be intercepted, altered, and retransmitted to UAV receivers [11].

Spoofing Attack Workflow

A typical GPS spoofing attack involves four main stages [11]:

1. Monitoring and tracking genuine GPS signals.
2. Generating and calibrating counterfeit signals.
3. Aligning fake signals with authentic transmissions.
4. Increasing the power of the spoofed signal to overpower genuine satellite signals.

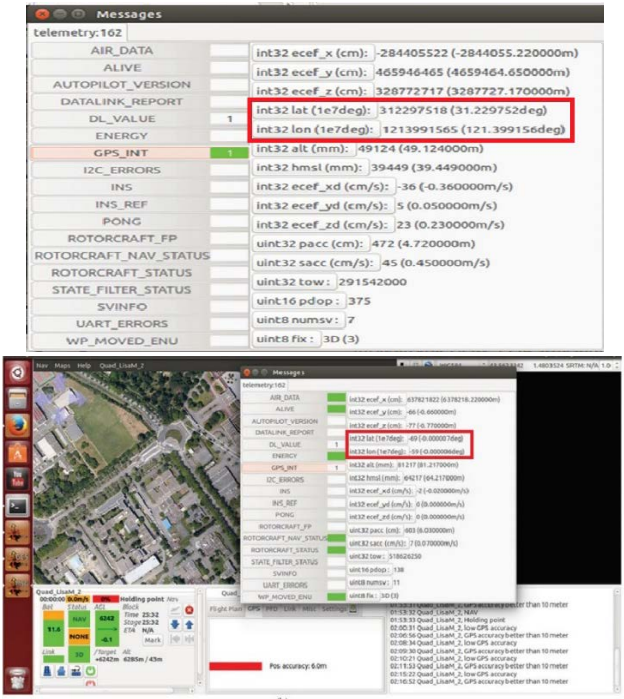

Figure 8a Illustrates genuine GPS readings of a quadcopter (longitude ~121.39, latitude ~31.23), while Figure 8b demonstrates spoofed readings that falsely report coordinates as (0, 0), confirming successful deception of the UAV receiver [11].

Countermeasures Against GPS Spoofing

Several countermeasures have been proposed:

- Anti-jamming monitoring: By continuously measuring received signal power, spoofing can be detected if abnormal power levels are observed [12]. Furthermore, a new class of jamming detectors, known as Sum-of-Squares (SoS) detectors, has been developed, which exploits the hypothesis that jamming causes correlated changes in the Carrier-to-Noise density power ratio (C/N0) values across all measured signals. These detectors, shown to significantly improve the resilience of GNSS receivers, can be implemented on low-cost real-time platforms like mass-market GPS receivers and Android devices [13].

- Multi-antenna approaches: Spoofing becomes difficult when signals are observed across spatially distributed antennas [14].
- Cryptographic authentication: The most robust solution involves embedding authentication codes within GPS signals, though this requires significant hardware/software modifications and higher costs [15].

4.2. IEEE 802.11 Wireless Attacks

The IEEE 802.11 standard, widely used in Wi-Fi communication, is commonly employed for UAV-to-controller or UAV-to-smartphone links. However, the management frames that establish these connections are often unprotected, leaving UAVs vulnerable to exploits [16].

One of the most critical vulnerabilities is deauthentication attacks, where adversaries send forged management frames to disconnect UAVs from legitimate controllers. Once disconnected, attackers can initiate further exploits to hijack UAV control [11].

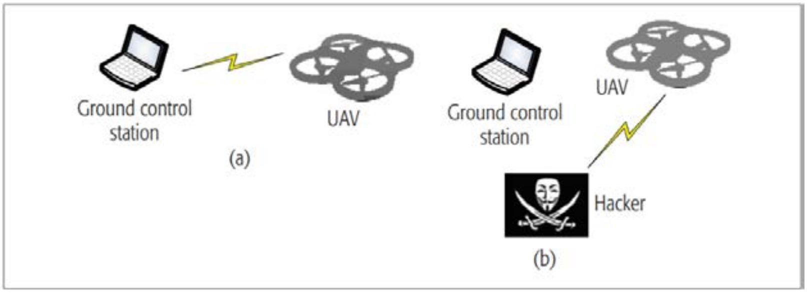

Figure 10 demonstrates the impact of a deauthentication attack: (a) before the attack, and (b) after the UAV has been disconnected from its legitimate operator [11].

Practical Wi-Fi Exploits

Tools such as Aircrack-ng allow attackers to capture Wi-Fi packets, deauthenticate UAVs, and subsequently gain unauthorized access [16]. A notable example of such exploitation is the SkyNET project, which demonstrates a mobile attack drone designed to scour urban areas and compromise wireless networks. This drone leverages existing attack frameworks and tools like Aircrack-ng for WEP cracking with packet injection, and attacks WPA/WPA2 networks by deauthenticating associated clients to capture 4-way handshakes, often offloading the computationally intensive cracking process to cloud-based GPU clusters [17]. The attack sequence typically follows these steps:

1. Monitoring mode activation: Tools like *Airmon-ng* switch the wireless card to monitor mode.
2. Packet capture: *Airodump-ng* intercepts data frames, isolating packets from the targeted UAV.
3. Deauthentication injection: Forged packets are transmitted to forcibly disconnect the UAV.
4. Hijacking control: Once disconnected, the attacker uses cracked credentials to assume full control of the UAV.

Countermeasures Against Wi-Fi Exploits

Defensive strategies include:

- Encryption protocols: Employing WPA2 (IEEE 802.11i) with long, complex keys significantly increases resilience to brute-force and dictionary attacks [11].
- SSID concealment: Disabling SSID broadcasts reduces visibility to attackers.
- MAC filtering: Restricting access to predefined MAC addresses limits unauthorized connections.

- Key management practices: Using strong, 20+ character keys combining upper/lowercase letters, numbers, and symbols enhances protection.

5. CONCLUSION

The communication architecture of UAV swarms is fundamentally dependent on wireless channels, which, while enabling mobility and flexibility, also expose the swarm to a variety of cyber and physical threats. Unlike traditional communication systems, UAV swarms must operate in highly dynamic environments where adversaries can launch attacks from both aerial and ground-based platforms.

One of the most critical risks is the loss or disruption of control and data links, which can lead to reduced mission effectiveness, partial or complete mission failure, or, in the worst case, the permanent loss of UAV assets. For this reason, the design of secure and resilient control and data links is indispensable. These links must be resistant to jamming, spoofing, and unauthorized intrusion while maintaining real-time, reliable communication for both command-and-control (C2) and payload data transfer.

The future of UAV swarm security lies in the integration of advanced defense mechanisms tailored to the unique characteristics of swarm operations. These include:

- Adaptive anti-jamming techniques, capable of dynamically detecting and mitigating interference.
- Robust encryption and authentication protocols, ensuring confidentiality and integrity of swarm communication.
- Distributed security frameworks, reducing single points of failure by leveraging decentralized control.

- AI-driven intrusion detection systems, enabling real-time anomaly detection and rapid response to cyber threats.
- Blockchain-based identity management, offering tamper-resistant authentication across heterogeneous UAV fleets.
- Quantum-resistant cryptographic schemes, preparing UAV networks for the next generation of computational threats.

Ultimately, the development of comprehensive communication security frameworks for UAV swarms will be a decisive factor in their successful deployment for both military and civilian missions. By ensuring availability, integrity, confidentiality, and resilience, secure communication will not only safeguard UAV operations against evolving cyber-physical threats but also unlock the full potential of swarm intelligence in future airspace operations.

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