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The utilization of gimbal systems in unmanned aerial vehicles

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Abstract

UAVs can be defined as a type of aircraft that carries payloads such as cameras, lasers, and radars, and is controlled by an onboard flight control system. UAVs are used in various application areas such as mapping, search and rescue, cargo transportation, reconnaissance, and surveillance. Considering the application areas of UAVs, it is seen that they perform many tasks involving functions such as live video recording, video transmission, object tracking, and surveillance. To fulfill the specified tasks, it requires the use of various image and video processing algorithms and video stabilization and noise reduction operations. Many control mechanisms are used in UAVs to meet these requirements. Thus, precise images can be taken and measurements can be made by minimizing distorting effects. In this article, information is first given about UAVs and their basic components. Subsequently, the importance of image stabilization techniques in camera systems is emphasized. In this context, technologies related to camera gimbal stabilization techniques used in UAVs are presented.

1. Introduction

An Unmanned Aerial Vehicle (UAV), can be defined as a type of aircraft that carries payloads such as cameras, lasers, radars, and is controlled by an onboard flight control system [1]. The unmanned aerial vehicles (UAVs), commonly used in military, civilian, and academic contexts, are employed in a wide range of tasks including mapping, search and rescue, cargo transportation, reconnaissance, surveillance, monitoring, border security, and target tracking [2,3]. In many of these applications, functions such as live video recording, video transmission, object tracking, and surveillance are required. To fulfill these functions, image or video processing algorithms are necessary. The primary requirement is to stabilize the video capture and also make it noise-free. These conditions can be met by compensating for various disturbances such as camera vibrations, vehicle motion, and wind currents. UAVs have different gimbal mechanisms to keep the camera position stable, and different control algorithms can also be used. Position control of the camera gimbal system can be controlled autonomously, independent of operator control, by using tracking software containing various control algorithms. The control algorithms commonly used in this field are Adaptive Control, PID Control, Fuzzy Logic Control. Gimbal can be defined as a mechanical device that can have two or more axes mounted perpendicular to each other [4]. Gimbals can have different mechanism movements depending on the number of axes on them. These axes are defined as yaw (roll), pitch (pitch), and roll (horizontal rotation) axes. There are different types of gimbals, including single-axis, multi-axis and redundant gimbals, depending on the number of axes they have [5]. Gimbal systems integrated into UAVs enable precise data collection by minimizing the effect of external disruptive loads on the payloads they carry (laser, camera, Inertial Measurement Units (IMUs)). The sensors and payload system used for stabilization can be mounted directly on the gimbal, or in some applications, the sensor system can be positioned on the UAV and the payload can be mounted on the gimbal [3].

The gimbal is commonly used in various industries such as aviation, medicine, defense, and remote sensing. While gimbal systems are typically utilized for camera stabilization purposes, they can also be employed to stabilize payloads such as missiles, weapons, or lasers instead of cameras. A gimbal consists of rings pivoted at right angles to each other. Single-axis or multiple-axis configurations can be used for payload stabilization with a gimbal. A two-axis gimbal can stabilize the carried payload or object along the pitch (elevation) and yaw (azimuth) axes, whereas in a three-axis gimbal system, a third stabilization axis known as the roll axis is required for payload stabilization [6]. The typical three-axis gimbal structure and its axis positioning details are illustrated in Figure 1 [7]. Hence, according to the axis configurations, gimbal systems are categorized into three main categories: single-axis, multi-axis, and redundant gimbals [5].

Figure 1. The typical three-axis gimbal structure.

This article provides fundamental information about UAVs and their components. It emphasizes the importance of the camera gimbal system for image stabilization. In this context, it presents the technologies and structural configurations of camera gimbal stabilization systems used in UAVs. Figure 2 shows the Integration of gimbal applications with different types of UAV systems.

a b

Figure 2. Integration of gimbal applications with different types of UAVs systems. (a: the integrated gimbal system for fixed-wing UAVs [8], b: the integrated gimbal system for rotary-wing UAVs [9].)

2. UAV systems

UAVs which can operate autonomously in various military and civilian missions, are equipped with various equipment. These include the Global Positioning System (GPS), camera, load transportation system (LTS), vertical take-off and landing (VTOL) system, flight control, image transfer, telemetry, and laser marking modules. Among these, the camera systems hold significant importance for enabling UAVs to track targets with minimal error. In recent years, gimbal systems have been widely used to stabilize the camera while the UAV is in motion, thereby enhancing the quality of captured images [3].

UAVs have numerous application areas including archaeology, mapping, agriculture, natural disaster management, industry, nature and ecosystem research, cinema and advertising, logistics, safety and security, mining, volcano research, indoor mapping, journalism, sports activities, and education. The type of UAV used may vary depending on the application area [10].

UAVs are evaluated in three separate categories based on their design, autonomy, size, weight, flying mechanism, and power source. These categories are fixed-wing, rotary-wing, and hybrid fixed/rotary-wing. The Figure 3 illustrates UAVs belonging to different categories commonly used [11].

a b c

Figure 3. UAVs belonging to different categories. (a: rotary wing UAVs, b: fixed wing UAVs, c: hybrid UAVs.)

In photogrammetry applications carried out using UAVs, both fixed-wing and multirotor UAVs can be employed. Multirotor UAVs possess better maneuverability, allowing for high-precision object reconstruction. On the other hand, fixed-wing UAVs have longer flight times and can capture images over larger areas. Flight with fixed-wing UAVs is generally more stable, hence gimbals may not be necessary for every application. In the case of multi-rotor UAVs, however, it is recommended to use gimbals to enhance the quality of captured images due to exposure to motor vibrations and sudden changes in altitude [12].

3. Image stabilization techniques with UAVs

Image stabilization is a technique used to correct the unstable motion vector of video sequences and achieve their stabilization [13,14]. The unstable motions of the camera and the platform to which the camera is attached affect the digital video sequences obtained by the cameras. These undesired positional fluctuations in the video sequences affect the visual quality. Errors in visual quality, in turn, hinder various applications such as motion coding, video compression, feature tracking, etc. The challenge of image stabilization systems lies in compensating for the undesired shaking of the camera while also avoiding affecting moving objects in the video sequence and intentional motion in panning conditions [15].

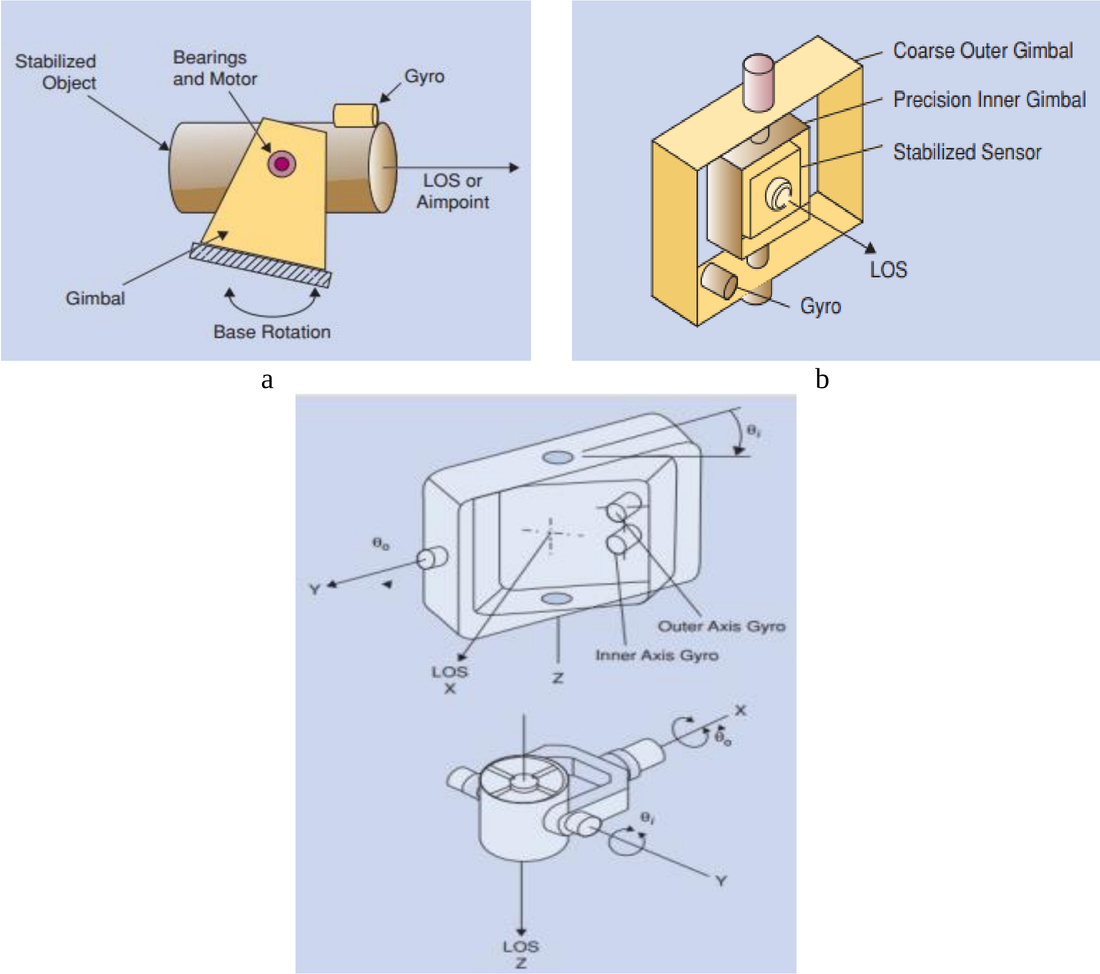
In image stabilization, three different techniques are used: electronic, optical, and digital stabilizers. In Electronic Image Stabilizer (EIS) system, sensors are used to detect camera movement and compensate for it. In Optical Image Stabilizer (OIS) system, a prism is used to dampen camera shake [16,17]. Since both techniques are hardware-based, their applications are limited to on-device online processing. Digital Image Stabilization (DIS), on the other hand, is a technique for compensating for undesired motion effects using digital imaging techniques without hardware equipment such as gyroscopic sensors and fluid prisms [18].

Among optical image stabilization techniques, gimbal technology is a hardware device primarily utilized to prevent shaking during video recordings. A gimbal stabilizes the camera using a rotating mechanism. These devices are designed for handheld use as well as for products such as UAVs [19].

4. Gimbal systems

A gimbal is defined as a mechanical device consisting of two or more axes mounted at right angles to each other [4]. The gimbal system provides the stabilization feature of the platform by minimizing external disturbances, allowing for more precise data collection with measurement devices such as lasers, cameras, and Inertial Measurement Units (IMUs) that are attached to the UAV [3]. One of the primary considerations in designing a gimbal system is determining the number and configurations of gimbal axes required to achieve the desired Line of Sight (LOS) control and field of regard (FOR) [20]. According to the axis configurations, gimbal systems are categorized into three main categories: single-axis, multi-axis, and redundant gimbals [5]. Figure 4 illustrates typical single-axis, multi-axis and redundant gimbal configurations [5].

The gimbal on which the gyro is mounted consists of a shaft and bearing elements that provide rotational motion along a single axis, and a platform containing damping devices to prevent the addition of rotational disturbances from the base. In practice, most applications require motion control in two axes perpendicular to the LOS. This holds true for most beam steering and weapon systems, as well as many imaging systems. However, in cases where image orientation is significant, or when rotational motion around the LOS induces unwanted motion at the outer edges of the field of view, the system needs to be equipped with a third control axis. Both two-axis and three-axis gimbal systems require gyros mounted perpendicular to the LOS for stabilization. When gyros cannot be mounted perpendicular to the LOS on the inner gimbal, or when LOS control is required along all three axes, three perpendicular gyros are necessary to stabilize the LOS and obtain sufficient information [5]. Figure 5 illustrate the configuration of the multi axes gimbal system [20].



a b

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Figure 4. Illustration of typical single-axis, multi-axis and redundant gimbal configurations (a: single axes gimbal, b: redundant gimbal, c: multi-axes gimbal).

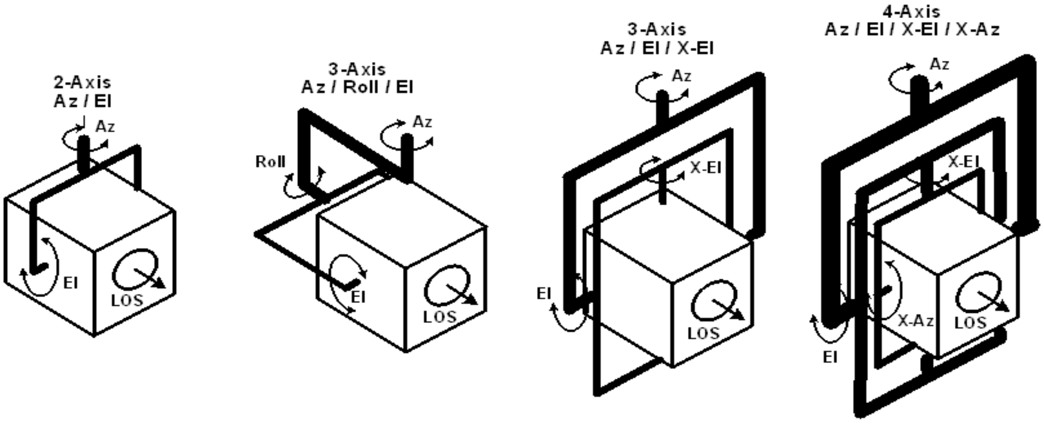


Figure 5. Typical 2-axis, 3-axis, and 4-axis gimbal configurations.

Redundant gimbal systems operate with two different gimbals interconnected in a configuration where the inner gimbal is stabilized by mass. The outer coarse gimbal is moved in a closed loop to track the inner gimbal. This structure ensures stable control of precise movements and is commonly used in optical systems, spacecraft, and precision devices [5].

Roa et al. [21] designed a single-axis gimbal mechanism to be used in the calibration of the gyroscope sensor in the IMU used in Micro Air Vehicles (MAV). They completed the design work of the single-axis gimbal mechanism using SOLIDWORKS computer-aided design (CAD) software. The gimbal mechanism consists of a servo-controlled DC motor, digital square encoder and microcontroller as electronic hardware. The mechanical structure of the gimbal includes the gimbal mechanism, the platform holding the IMU sensor, a slip ring, and a spur gear mechanism. For the calibration of the gyroscope, the IMU was rotated around a certain axis at several constant speeds and the obtained speed values were transferred to the microcontroller with a digital square encoder. The simulation studies of their designs were completed in the Simulink environment. CAD model of the gimbal they designed shown in Figure 6.

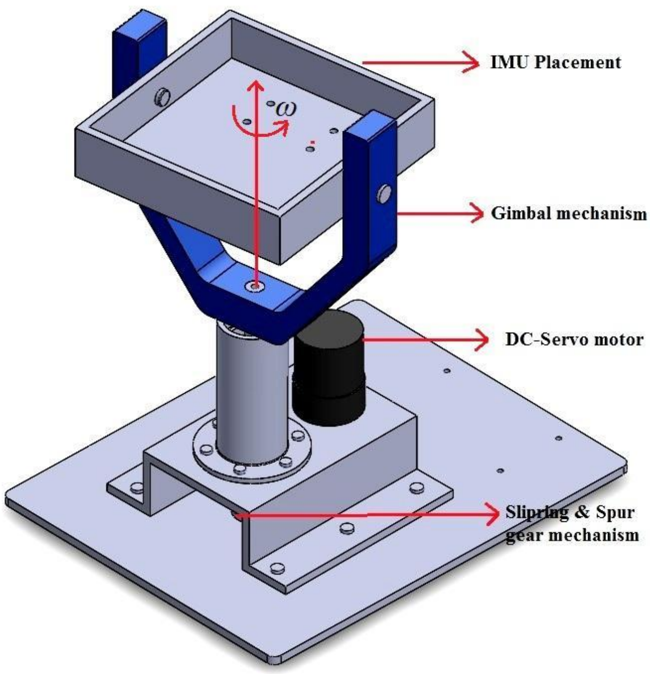


Figure 6. CAD model of the one axes gimbal mechanism.

Sangveraphunsiri and Malithong [22] designed a 2-axis gimbal to be used in aircraft for target tracking and camera image stabilization. The control structure of the gimbal they designed for image stabilization includes both mechanical and electronic control. Low-level control is associated with the gimbal's internal axis and is achieved through robust reverse dynamics control and sliding mode control. The upper-level control structure is positioned externally and serves as a control device that maintains the line of sight in cases where the camera gimbal is subjected to external movements (such as base movement). Figure 7 shows the CAD model of the two-axis gimbal mechanism.

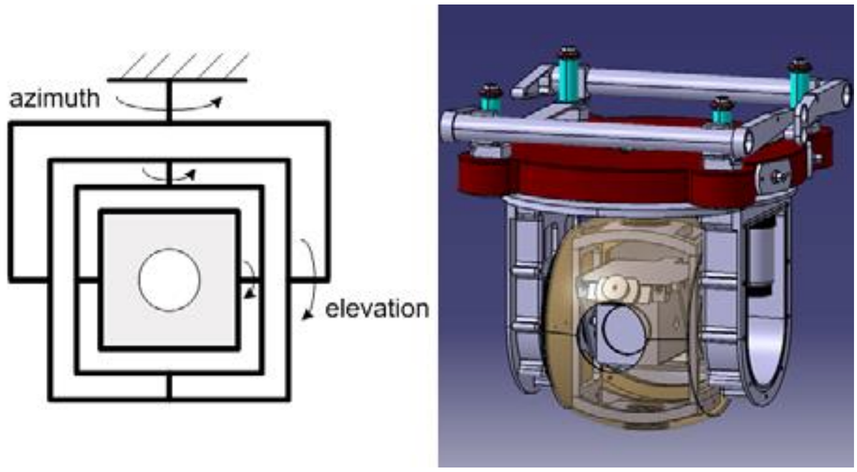


Figure 7. CAD model of the two axes gimbal mechanism.

Kamaruzzaman et al. [23] designed a three-axis gimbal in their study. They realized their designs using SOLIDWORKS CAD software and chose PLA, which is widely used in 3D printer production, as the material. They completed the static analysis studies and determined the maximum strength values of their designs. The force value specified in Figures 8-b and 8-c was calculated by adding the weight values of the stepper motor, o-ring and base parts to be placed at the connection points. Although the total force was equal to 6.87 N, the results showed that the design had sufficient strength. CAD model of the gimbal they designed shown in Figure 8-a.

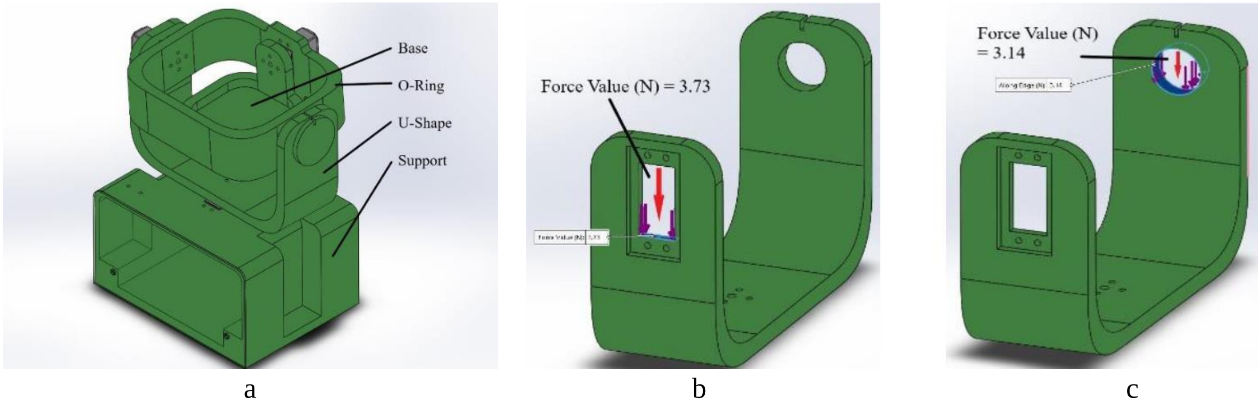


Figure 8. CAD model of the three axes gimbal mechanism. (a: assembly model, b: left point, c: right point).

5. Literature studies

There are numerous studies in the literature focusing on the use of gimbal systems in UAVs to obtain more precise imagery. For example, Altan and Hacıoğlu [3] have conducted research on real-time precise target tracking using an integrated gimbal system in UAVs. In their work, they have utilized the Model Predictive Control algorithm based on the Hammerstein model for precise imaging. They have supported the accuracy of the developed control system through both real-time flight tests and comparison with the PID control algorithm they used as a reference algorithm. In their study, they have employed a hexacopter as the type of UAV. They have mounted the IMU sensor on the Pitch axis of the gimbal system they used. During real-time flight tests, impact loads were applied to the UAV as external disturbances, and the results were analyzed. The simulation and experimental results demonstrate that the proposed MPC algorithm with the Hammerstein model in this paper can ensure precise target tracking by the UAV while maintaining stability, even in the presence of external disturbances. A typical gimbal mounted on the UAV has joints and a mechanical structure as shown in Figure 9.

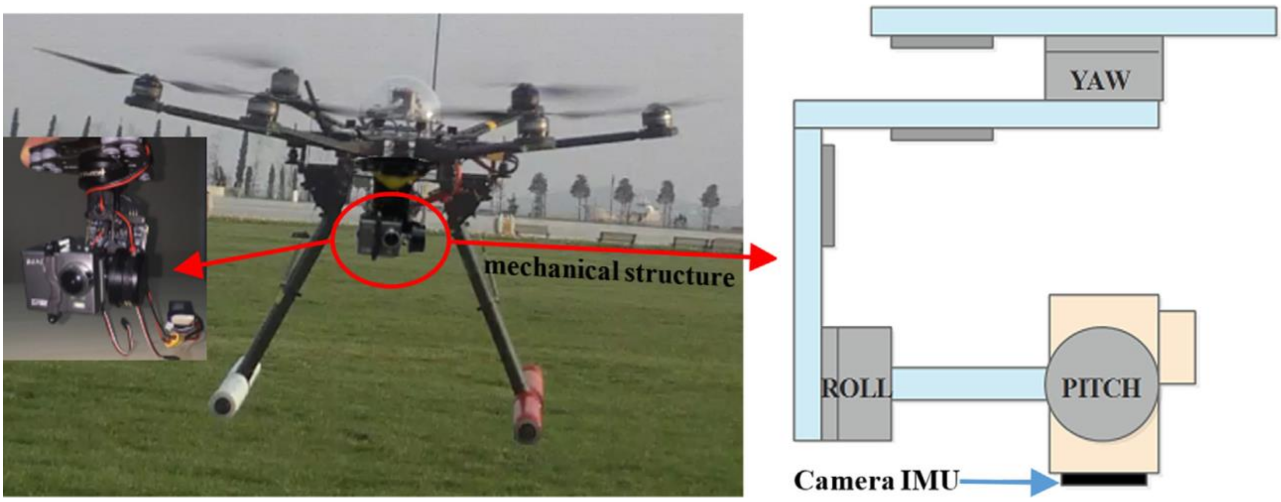


Figure 9. Three-axis gimbal system and mechanical structure mounted on UAV.

Lin and Yang [24] conducted a study on the configuration of aerial photography by integrating UAV autopilot system with camera gimbal control. The autopilot system featured in their study enables the UAV to follow specific flight routes or move towards a target. The proposed configuration, as outlined in the article, allows for more precise and effective control of aerial photography by synchronizing camera gimbal control with the UAV's autopilot system. Thus, they aim to enhance efficiency in applications such as documentation and monitoring of remote areas. In the experimental flight tests, the Paparazzi automatic pilot-equipped Ce-73 vehicle, depicted in Figure 10a, was utilized. Camera stabilization was achieved using the 3-axis gimbal shown in Figure 10b and Figures 10c. The control method employed for camera gimbal control is characterized as a combination of auto-stabilize mode and PWM (Pulse Width Modulation) control mode. Utilizing data from the IMU and GPS, the microcontroller unit (MCU) can calculate the aircraft's altitude and relative position between the aircraft and the target. Finally, the MCU adjusts the desired gimbal attitude angle corresponding to the PWM duty cycle value.

a b c

Figure 10. Flight experiment details (a: Ce-73 with Paparazzi, b: camera gimbal and its mounting, c: Gopro Hero 3 with its mounting).

Ding et al. [25] conducted a study on the detection and quantification of cracks occurring in concrete structures. In this study, they employed a UAV and transformer-based method. Their study consists of three stages: determination of full-field scale, crack segmentation, and experimental validation. Specifically, they utilized a Zenmuse H20T gimbal camera equipped with a laser rangefinder, mounted on an enterprise-grade UAV, DJI MATRICE 300 RTK, to facilitate easy control of rotation angle. Zenmuse H20T is a UAV camera and sensor system belonging to DJI's Zenmuse series, incorporating a three-axis gimbal system. Figure 11 depicts the camera gimbal system and the imagery associated with the UAV.

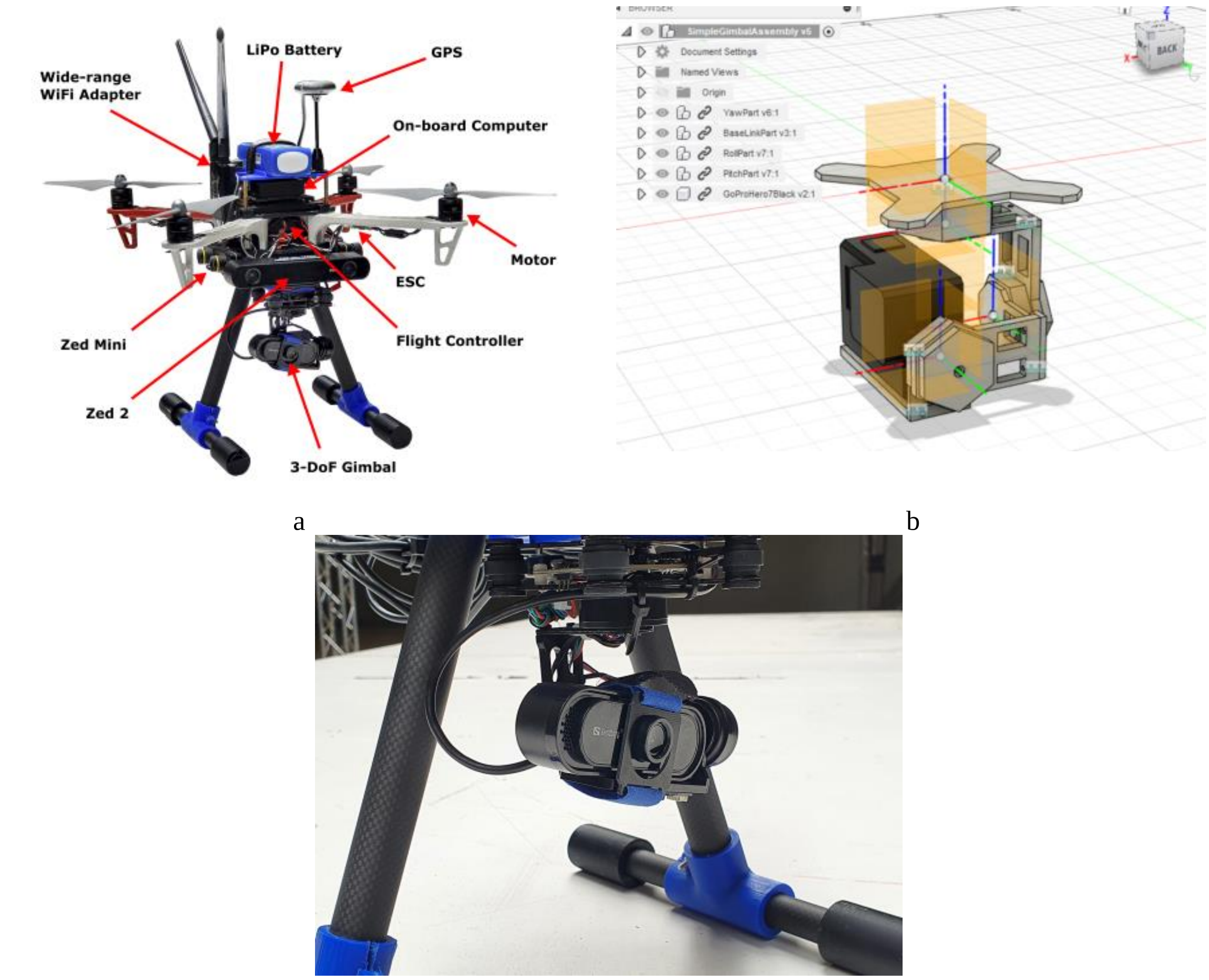
Figure 11. Components of UAV system.

Tan et al. [26] propose an "global-local" adaptive inspection method for building surfaces by integrating Building Information Modeling (BIM), UAV, and edge computing technology. Through the integration of a UAV-mounted camera gimbal system, crack data can be collected and analyzed in real-time. The study utilizes the DJI M300 RTK model UAV for adaptive inspection of building surfaces, along with the multifunctional H20T camera from the same company. The H20T camera is equipped with a 3-axis gimbal system. Figure 12 depicts the UAV and camera gimbal system used during the study. With the "global-local" adaptive inspection system used in this study, they aim to reduce the time required for crack detection and analysis in buildings compared to traditional methods. Additionally, they aim to increase data accuracy through the integration of the multifunctional camera system mounted on the UAV and the captured images.

a b

Figure 12. Research objects and equipment. (a: M300 RTK UAV, b: H20T camera.)

Hansen and Figueiredo [27] investigated the advantages of active tracking approaches using a three-degree-of-freedom (DoF) gimbal system mounted on UAVs. In their study, they aimed to enable stereo vision and active object tracking of vessels using the UAV, camera, and gimbal system. Within this scope, they designed a control drone equipped with an active tracking system. Simulation tests on the functionality of the tracking method were conducted in the Gazebo simulation environment. Initially, tracking of a spherical object was performed in the simulation. Subsequently, tracking of the 6D poses of planar fiducial markers was achieved, and their performances were measured. They aim to complement their work with real-world tests in future studies. Visuals of the designed control drone are depicted in Figure 13.



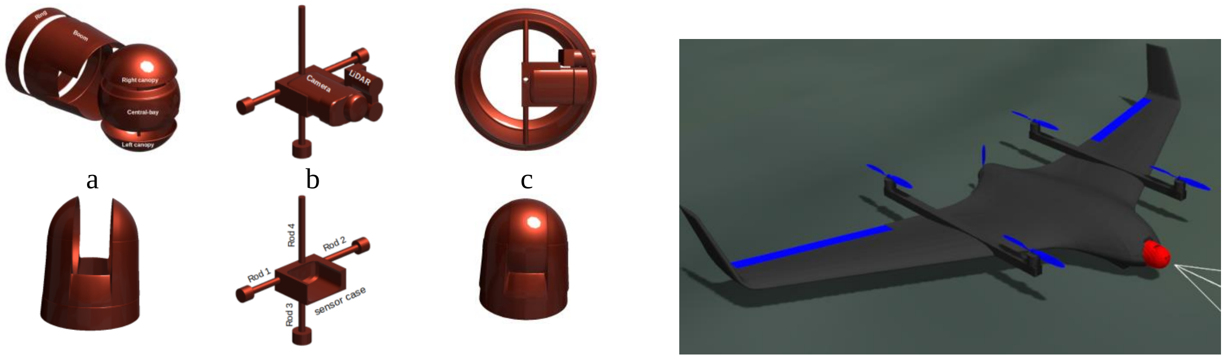
a b

c

Figure 13. Proposed active inspection drone system. (a: UAV design, b: Gimbal CAD model with individual part frame, c: HakRC Storm32 v1.3 mounted on the inspection UAV.)

For the purpose of meeting the requirements of tasks such as ground target tracking, crime scene monitoring, and traffic management in urban areas, small-scale UAVs are required to have robust autonomous navigation systems. To address this need, Shen et al. [28] designed a 2-axis gimbal integrated into a small-scale UAV. In their design of the 2-axis gimbal, they mathematically modeled the system and then utilized simulation software to test the performance of the system. The simulation results indicated that the platform could effectively perform obstacle avoidance and target tracking tasks, and that any steering of the gimbal system did not adversely affect the UAV aerodynamics. Figure 14 displays visual representations of the designed platform system and the integrated UAV within the scope of their study.

Goodrich et al. [29] conducted a study on target detection, positioning, and surveillance using a fixed-wing mini UAV and gimbal camera system. In their study, they equipped a fixed-wing mini UAV with a structure and control system for a gimbal camera system they designed themselves. The type of gimbal they designed has 2 axes and is of the 'direct-drive gimbal' type. In this type of gimbal assembly, azimuth control is achieved by directly connecting a servo motor to the gimbal fixture, while another servo motor serves as a pivot for elevation control. They presented the creation of flight paths and a human-UAV interaction plan in their work. Thus, the UAV is primarily manually flown and then autonomously tracks targets. The Operator is allowed to control and intervene in flight during autonomous operation. Visuals of the gimbal system they designed for the fixed-wing UAV they used in their study are presented in Figure 15.



a b c
d e f g

Figure 14. Platform components and their configuration (a: Components of the platform, b: sensors configuration in the platform, c: inner gimbal, d: outer gimbal, e: sensor case and connection rods, f: assembled platform, g: platform nose-mount on fixed-wing VTOL UAV).

a b

Figure 15. Proposed small IHA system (a: direct-drive gimbal mounted on a 48" flying-wing mini-UAV, b: direct-drive gimbal).

Rajesh and Ananda [30] conducted a study on the control of a 2-axis gimbal system used for controlling the camera mounted on UAVs for various applications. They designed a PID controller to control the camera position. In their study, they compared the traditional PID with coefficients tuned using the PSO method. They tested their control algorithms developed on Simulink and compared the results. The PSO-based PID controller for camera stabilization yielded better results.

Kurbanov and Litvinov [28] designed a gimbal system capable of integrating the Parrot Sequoia multispectral camera onto the DJI Phantom 4 Pro UAV with the aim of enhancing productivity in agriculture. Their developed gimbal design is compatible with all sensors mounted on the gimbal and exhibits damping properties in response to vibration forces. The design requirements for their developed gimbal include balancing the UAV and maintaining functionality, having collapsible brackets for simple mounting of a multispectral camera, and facilitating sensor mounting through technological holes. Details of the gimbal they developed in accordance with the technical requirements are provided in Figure 16. Bracket 1 contains the necessary mounting holes for sensor installation. Slots for mounting the number 3 rubber dampers are provided on bracket 1. Locks number 4 are used for mounting bracket 2 onto bracket 1. Dampers number 3 are secured in the slots of bracket 2 with the cover number 5 of the camera body 6. Grooves are added to the design for the mounting of parts number 6 and number 5 [31].

They conducted real-time field tests of the developed gimbal system. During the flight, the status of the UAV was monitored with the DJ GO 4 application, and no inconsistency was detected among the sensors. It was noted that the UAV, which is equipped with the developed gimbal, benefits from the advantage of reduced inertia and mass, thanks to the power supply of the gimbal system coming from the UAV, and has better maneuverability than similar systems. The mounting of the gimbal with the camera and UAV is illustrated in Figure 17a and 17b, while an image from the flight test is presented in Figure 17c [31].

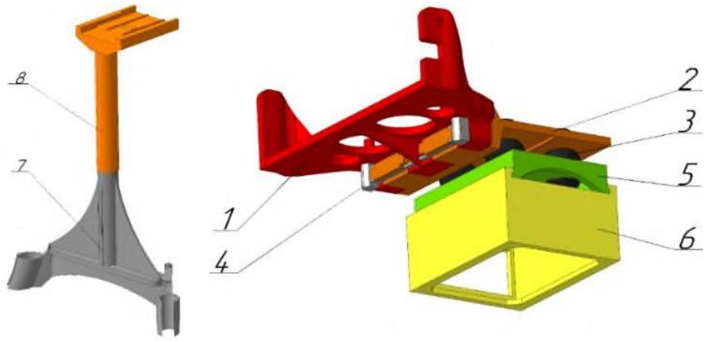


Figure 16. Gimbal for Parrot Sequoia multispectral camera for UAV DJI Phantom 4 Pro.

Figure 17. Mounting of the designed gimbal to the UAV (a: mounting of gimbal brackets to the UAV, b: mounting of multispectral camera to the brackets on the UAV, c: flight test).

Misopolino et al. [32] developed a Vertical Take-off and Landing Autonomous Unmanned Aerial Vehicle (VTOL UAV) system for the simultaneous acquisition of high-resolution vertical images at Visible Near-Infrared (VNIR) and Thermal Infrared (TIR) wavelengths, aiming at the advancement of precision agriculture techniques. In their study, a commercial unmanned hexacopter UAV platform was optimized to enhance reliability, ease of operation, and automation. To obtain vertical images during flight, a gimbal (Maytech MTGBM3F5D-B brushless 3-axis gimbal) was mounted between the landing skids of the UAV. In order to improve the obtained image quality, the gimbal was specifically designed and mounted with dampers. The system, detailed in Figure 18, was tested in a kiwifruit field located in northern Greece. During the testing phase, images acquired by the system were stitched and subjected to geo-correction. Consequently, it was noted that the quality of the images obtained at 70 and 100 meters above ground level was satisfactory, revealing significant details within the field.

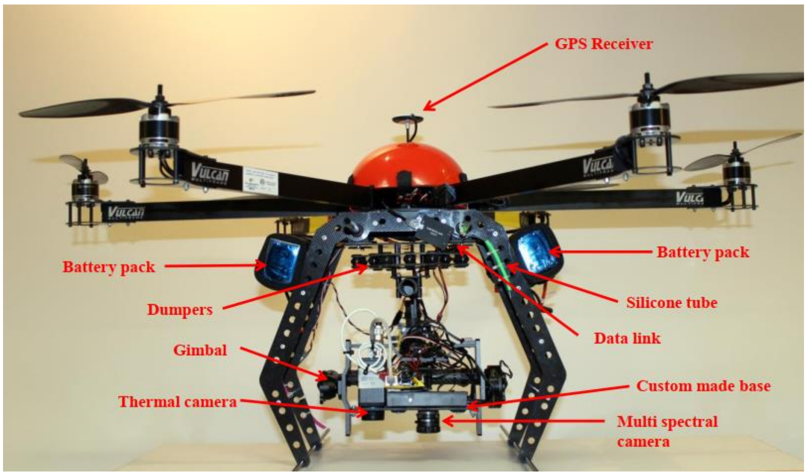


Figure 18. Hexacopter UAV platform with attached thermal and multispectral camera sensors.

6. Results and discussion

In this study, the definition of UAVs is initially provided. Subsequently, the types of UAVs and their application areas are explained. The study then discusses the image stabilization techniques used in UAVs. The gimbal system is defined as an image stabilization technique, and its working principle and structural configurations are elaborated in detail. Finally, literature studies on the use of gimbals in UAVs are presented.

Studies indicate that gimbal systems used as an image stabilization technique in UAVs enhance the quality of images obtained by UAVs. The improvement in image quality, or data quality, leads to increased accuracy in the results obtained through data processing. In the literature reviewed, there are studies using commercially available camera gimbal systems as well as studies in which researchers design and produce their own gimbal systems. It is observed that researchers also work on various methods, such as the development of gimbal mechanics, electronics, or control algorithms, to increase the image sensitivity obtained from the camera in studies where they design their own gimbal systems.

Considering the currency of the studies and the quality of the results obtained, it can be inferred that improving mechanical, electronic, or control algorithms in gimbal design can enhance image stabilization. As a result, it can be seen that testing the effectiveness of designed gimbal systems in simulation environments under various external disturbances, followed by validation of the results through real-world testing, would contribute to the literature.

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Author contributions

Özge VİLLİ: Conceptualization, literature review, writing-original draft preparation.
Hakan YAVUZ: Data curation, writing-reviewing and editing.

Conflicts of interest

The authors declare no conflicts of interest.

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