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# Sensor technologies in unmanned aerial vehicles: types and applications

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**Abstract**

Applications of unmanned aerial vehicles (UAVs) with various sensor system, have been steadily increasing. Initially, only sensors necessary for the safe flight of UAVs were employed. However, in recent years, sensor types with advanced environmental perception capabilities have been developed and integrated into UAVs. The development of sensor types and their reduced size has facilitated their integration into UAV systems and encouraged various scientific studies. UAVs equipped with sophisticated sensors find applications in a wide range of fields. These include precision agriculture applications such as monitoring crop health and determining soil moisture content, forest fire detection, natural disaster monitoring, search and rescue operations and meteorological measurements. This study provides insights into the types of sensors found in UAVs, followed by a review of relevant literature. Finally, future expectations and prospects are outlined.

## 1. Introduction

Unmanned aerial vehicles (UAVs), are defined in many sources as aerial vehicles that lack an onboard pilot and can be controlled remotely or fly autonomously, formed by the integration of various systems [1]. Whether UAV systems are operated remotely or autonomously, they are equipped with numerous sensor systems. Sensors fundamentally consist of circuits that measure a physical quantity and produce output. Without the sensing information generated by sensors, automated (autonomous) systems cannot function [2].

Advanced sensor types integrated into UAV systems have been frequently utilized in scientific research in recent years. The increasing use of UAV systems in scientific fields has brought about many developments [3]. Sensors on UAVs typically facilitate the collection of environmental data or images of the Earth's surface, but other sensors are also present on UAVs. These sensors are related to the control and security of UAVs, enhancing both the flight and mission capabilities of the UAV and enabling easier data collection. Some of the types of sensors found in UAV systems are as follows.

- Error and fault detection sensors
- Collision and obstacle detection sensors
- Safe take-off-landing sensors
- Electro-optical sensors
- Laser measurement sensors
- Positioning and angular orientation sensors
- Speed and acceleration sensors
- Altitude sensors
- Actuator/Motor control sensors
- Temperature and humidity sensors
- Meteorological measurement sensors

For instance, among angular direction determination sensors, the compass sensor determines the direction information of the UAV, ensuring a more stable flight, while electro-optical sensors collect image data of the Earth's surface. Furthermore, some sensors can monitor whether other sensors are functioning correctly (voltage, current, temperature, rotation sensors, etc.). For instance, a light sensor can enhance the accuracy of electro-optical sensors. Even in a standard UAV system today, there can be more than 10 different types of sensors [4].

The sensors mounted on UAVs can vary depending on the task to be performed. For instance, UAV systems intended for search and rescue missions may prefer optical sensors with thermal and zoom capabilities, while UAV systems intended for precision mapping may opt for high-resolution optical sensors with mechanical shutters. Many UAV systems today feature sensor configurations that can be easily changed according to the application. This allows users to have a single UAV system, thus helping to reduce application costs. Additionally, there are UAV systems designed for end users with sensors integrated internally. These UAV systems provide ease of use and compactness for end users (Figure 1).

A B

**Figure 1.** UAV models with different types of sensors. A: UAV model with replaceable electro-optical sensors, B: UAV model with integrated electro-optical sensor [5, 6].

Within the scope of this study, sensor types and application areas in UAV systems are focused on. The working structures of sensor types are explained and literature studies are examined. The roles of sensors in applications made with UAV are mentioned and examples of the work are presented. Finally, future expectations are listed.

## 2. Flight assist sensors in UAVs

Sensors are defined in the literature as devices that detect physical and chemical changes in the environment and convert these data into signals [7]. UAV systems must be equipped with a number of precautionary mechanisms in order to perform their missions successfully and safely, and for this reason, they can have many sensors with different tasks. The working processes of sensors generally take place in several steps. When a sensor first starts to work, the sensing step takes place and it starts to make physical, chemical or biological measurements. In the second step, the measured values are converted into electrical signals. In this way, the measurement results are converted into measurable structures such as voltage, current or resistance. The third stage is the transmission of this data to the central processing unit for processing. In some cases, the data is transmitted as it is, while in other cases it is subjected to a certain mathematical processing (thresholding, transformation, filtering, etc.) and then transmitted. In the final stage, the central processor processes this data and sends commands to the relevant agent and/or can be monitored as information (Figure 2).

Sensor data is transmitted to the UAV system's flight control card and/or flight auxiliary computer. The flight control card and/or flight auxiliary computer sends the data from the sensors as input to various flight algorithms and outputs are produced as a result of the calculations made. According to these outputs, the UAV system tries to perform its mission accurately and safely (Figure 3).

Sensors that help ensure flight safety and mission accuracy in UAV systems are among the most critical sensors. One of the most important of these sensors is GNSS (Global Navigation Satellite System). The GNSS sensor (by processing the signals received from GNSS satellites) provides a 3D position determination on the earth. Thanks to this sensor, the UAV system acts much more reliably during its flight. Features such as autonomous flight on a certain route, speed control, altitude control, hovering are possible thanks to the GNSS sensor. In addition, it is considered one of the most important sensors as it enables the autonomous return and safe landing of the UAV system in emergency situations such as ground station disconnection, battery problems, and various malfunctions. Today, many UAV systems are produced and offered to users with GNSS support (Figure 4).

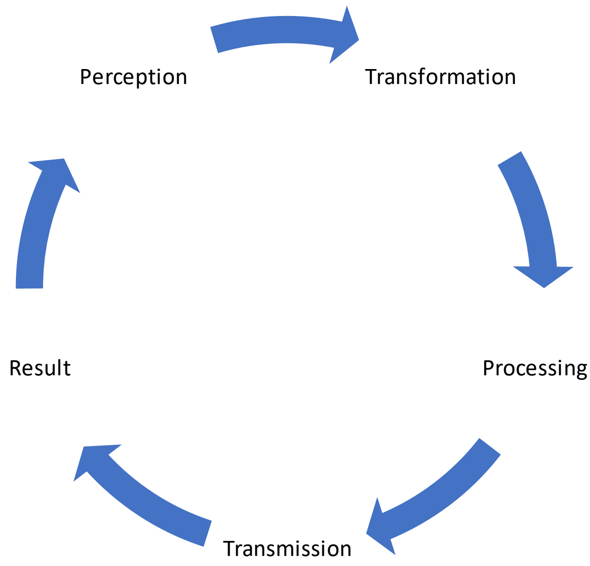



**Figure 2.** Working steps of a sensor system.

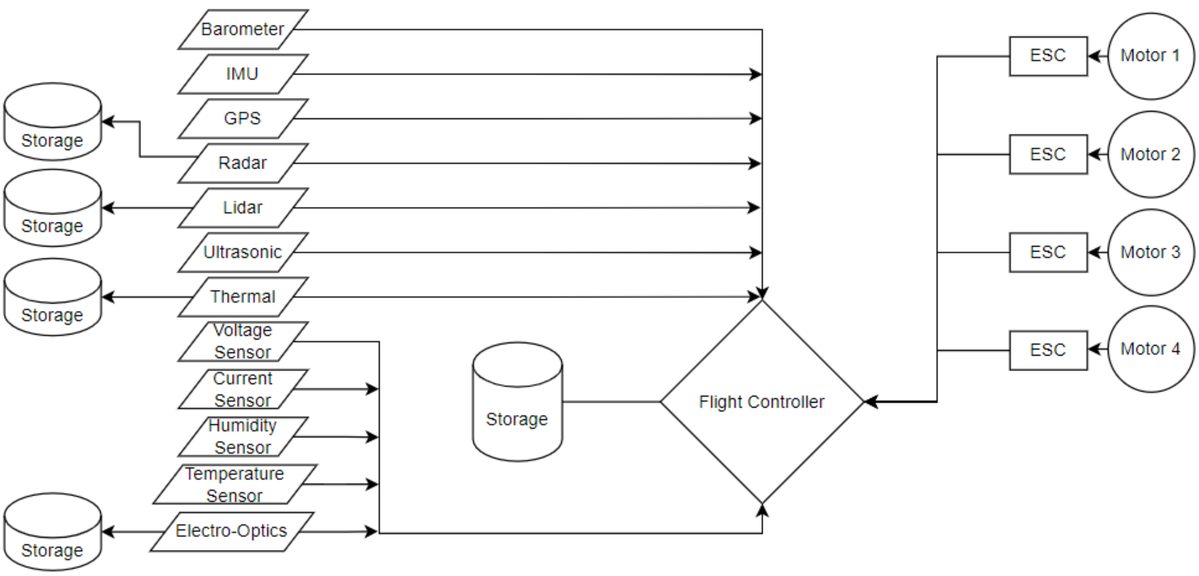



**Figure 3.** Sending sensors data to flight controller board (Some sensors may be optional).


**Figure 4.** A GNSS sensor used in UAVs [8].

In addition, multiple GNSS-supported UAV systems are also used in applications where high position accuracy is required (Figure 5).

**Figure 5.** UAV system with multiple GNSS receivers [9].

Angular heading sensors are usually integrated with acceleration sensors and are another important structure that must be present for the stable flight of the UAV (Figure 6).


**Figure 6.** An IMU sensor unit on a UAV [10]

These structures, commonly known as IMUs (Inertial Measurement Unit), can be found in more than one UAV system (Figure 7) and some models can also be included in GNSS sensors [11].


**Figure 7.** UAV flight control system (it has 3 IMUs) [12].

When flying close to the ground surface or during take-off and landing, the GNSS sensors on the UAV are not highly accurate. As the UAV ascends to a certain altitude, it can better capture GNSS signals and improve position accuracy. This is due to the fact that GNSS signals can be distorted by reflections from the ground, or that obstacles in the vicinity can negatively affect the signal quality. However, UAV systems can still move stably even when they are several meters high. A sensor called a barometer determines altitude information by continuously measuring air pressure. In this way, altitude information can be measured even if the GNSS signals are weak or degraded. In addition, stereo cameras, infrared distance sensors or ultrasonic distance sensors under the UAV systems can also determine altitude information at low altitudes (a few meters). An example of a barometric sensor in UAV systems is shown in Figure 8.

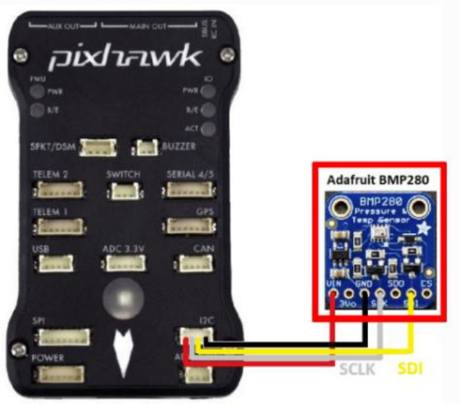


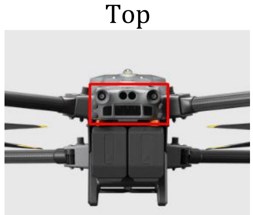

**Figure 8.** A barometric sensor in UAV systems [13].

UAV systems must be cautious against obstacles in order to fly safely. Whether pilot-controlled or autonomous flight, obstacle detection and avoidance sensors must be active. The first UAV systems developed for end-users had only ultrasonic sensors located on the bottom and working during take-off and landing. Since ultrasonic sensors detect using sound waves, they caused inaccurate measurements on surfaces where sound waves were not properly reflected (water surface, carpet or woolen surfaces, etc.) and caused accidents/crashes. In today's UAV systems, there are sensor groups that can detect 360 degrees. These sensors are usually stereo cameras, infrared distance sensors or radar/lidar units. These sensors, which can detect obstacles with very high sensitivity, warn the pilot when an obstacle is detected and, if necessary, prevent the UAV system from hitting the obstacle by applying sudden braking. Some advanced UAV models can continue their mission by avoiding the obstacle instead of braking when an obstacle is detected (Figure 9).

Front and side

Top

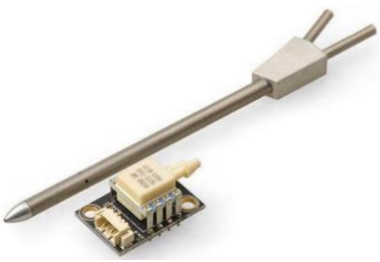
Bottom



Rear

**Figure 9.** An advanced 360-degree obstacle detection UAV model [14].

Unlike rotary-wing models, fixed-wing UAV models have to move continuously in the horizontal plane. Therefore, the forces acting on the wing surfaces are different. To avoid turbulence and stall situations, they need one more sensor, which is not required in rotary wing UAVs. The pitot sensor is used to measure the air speed and calculates the air speed by measuring the pressure difference of the air flow. The engine speed, horizontal speed and pitot sensor data are subjected to some mathematical operations on the flight controller board and the stall condition can be predicted. In this way, the unmanned aircraft can avoid stall, change course and altitude, increase or decrease speed (Figure 10).



A

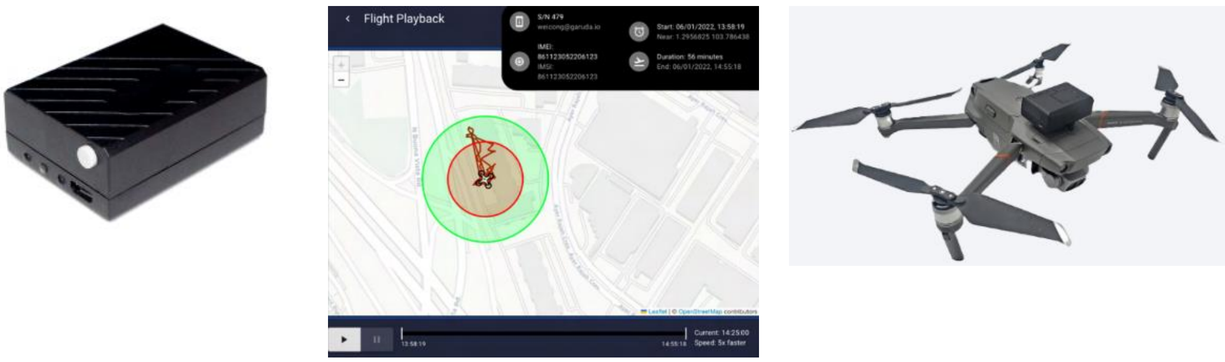
B

**Figure 10.** The pitot sensor unit (A) and a pitot-carrying fixed-wing UAV (B) [15, 16].

Although UAV systems have advanced protection and prevention systems, various malfunctions can still occur due to environmental factors. In addition, problems may occur in the hardware and software of the ground control station and the UAV connection may be lost. In addition, sensor failures, power and battery failures, signal loss and interference effects are other important problems. There are various techniques developed to address these problems. For example, sensors developed to easily locate the UAV system when it is lost or crashed for any reason are among the most widely used techniques. These sensors are usually connected to the flight control board, and when the flight control board is disabled, damaged or disconnected from power, it starts to give a loud warning. This allows users to easily locate the UAV (Figure 11).

**Figure 11.** Missing UAV locator sensor (buzzer) [17].

Advanced locator sensors contain a GPRS (General packet radio service) module and a GNSS sensor. In this way, they can continuously transmit instant location information and flight route to the user's mobile phone by using the services of telephone operators via SIM card. Many of these sensors also include their own power unit. This is so that the sensor can operate without being affected by malfunctions that may occur in the power unit of the UAV system (Figure 12).




A B C

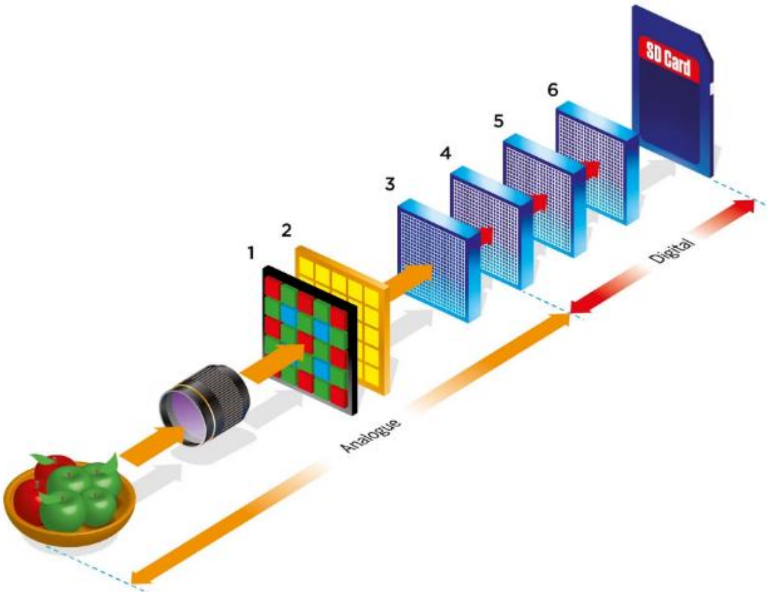
**Figure 12.** An advanced lost UAV locator sensor (A: Sensor, B: Instant location tracking on mobile application, C: Integrated on UAV) [18].

## 3. Electro-optical sensors in UAVs

Electro-optical sensors are sensors that collect and store environmental data. Electro-optical sensors, in other words camera systems, measure the reflected values of a light source off objects. To do this, the reflected light must first be collected and projected onto an image sensor. The image sensor converts the optical energy into electrical signals. These signals are converted into digital images by a processing unit. During this conversion, the contrast, colors and brightness of the image are adjusted. In the final stage, the data converted into the desired image format is stored in a recording unit (Figure 13) [19-21].

Initially, the cameras on civilian UAV systems were small-sized devices known as action cameras without any stabilization unit. Stabilization and image correction processes were performed at the end of the operation and caused excessive workload. With the development of stabilization systems, camera systems started to collect clearer images [22].

Thanks to the motors and angle sensors on these stabilization systems, they can keep the camera systems in balance without being affected by the sudden movements and maneuvers of the UAV. Today, stabilization units called gimbals can stabilize even larger camera systems (Figure 14).




*1. Light reflected from the object is reduced to the image sensor by the lens.*
*2. The image sensor has a mosaic filter for color conversion.*
*3. Electrical signals generated by the sensor are converted into digital signals.*
*4-5. Various color correction and adjustment operations are performed.*
*6. The image processor performs digital coding and saves the data in the desired format in the storage unit.*
**Figure 13.** Digital camera working principle [21].

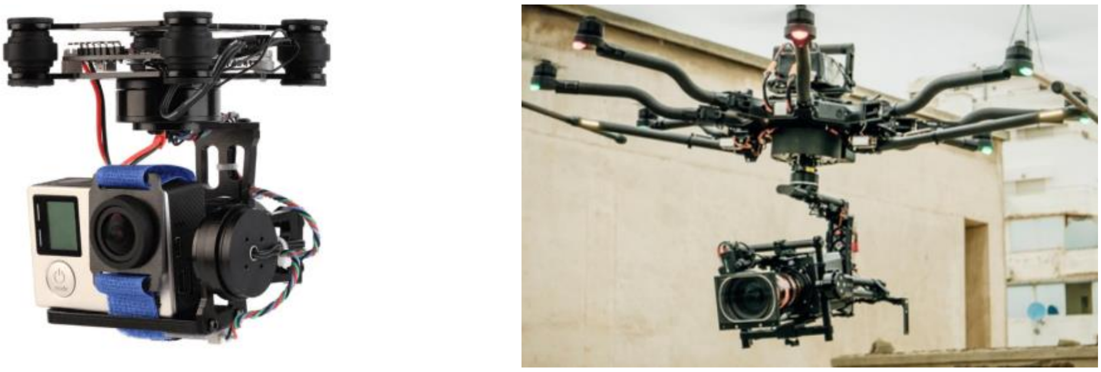


**Figure 14.** Different size gimbal types [23, 24].

High-resolution visible light cameras are among the most common camera types found in UAV systems. Many manufacturers integrate the gimbal and visible light camera into the UAV system and offer them to users. However, visible light cameras are often insufficient for scientific research [25, 26]. Visible light cameras can only record reflections in a certain electromagnetic spectrum (Figure 15).

There are many parameters available to change the detection sensitivity of visible light cameras. By changing these parameters, changes can be made to the data produced by the light passing through the lens. As an example, adjusting the time it takes for the light to fall on the sensor.

Some of these parameters are as follows:

- Resolution: Defined as the number of horizontal and vertical pixels and refers to the amount of detail contained in the image.
- Aperture: The aperture setting that determines how much light the lens receives.
- Shutter speed: Specifies the duration of light falling on the sensor to create an image frame.
- ISO sensitivity: Expressed as sensitivity to light.
- White balance setting
- Focus adjustment
- Stabilization level
- Focal length
- Sensor type
- Sensor size

- Shutter type
- Color space
- Data recording format

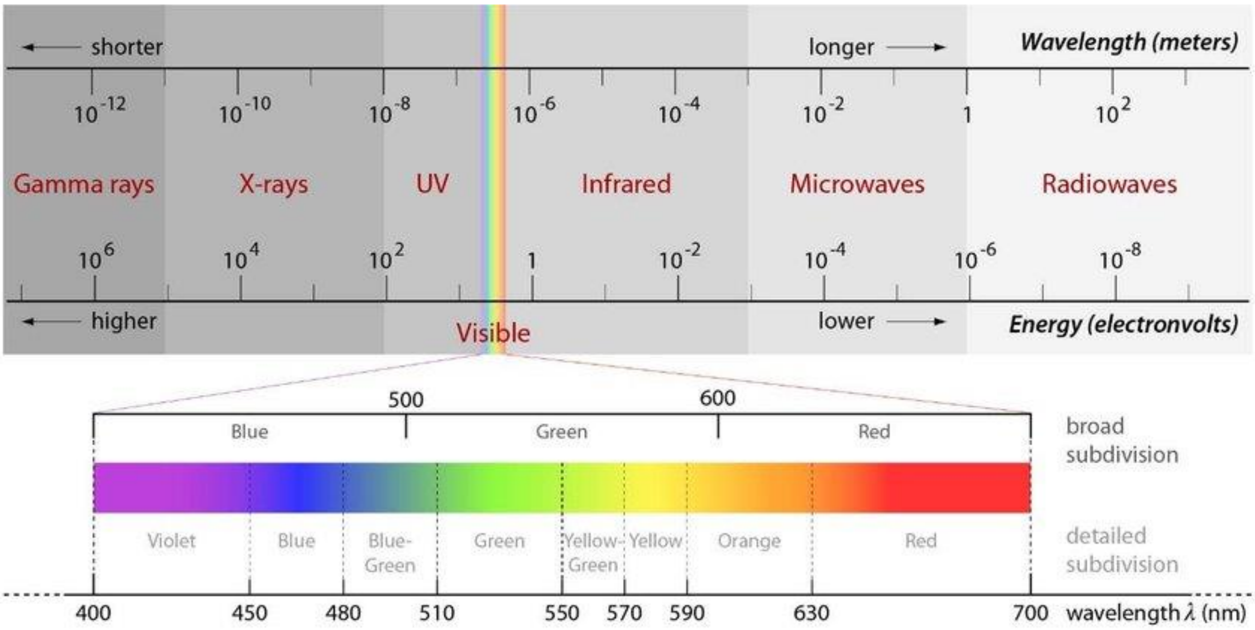



**Figure 15.** Regions of the electromagnetic spectrum [27].

All these settings may vary depending on the application. For example, in mapping operations, blurred images may occur because the photo will be taken in motion. To avoid this, it is necessary to use a camera with a mechanical shutter. In this way, sharpness is maintained. Or having a camera with high ISO sensitivity on a UAV performing a search and rescue mission makes it possible to obtain successful results in low light conditions.

Multispectral and hyperspectral camera types can detect in a much wider range. These cameras, which can detect and record reflection values invisible to the human eye, have achieved successful results in many applications [4, 28, 29]. Images taken with multispectral and hyperspectral cameras, which can collect data in a wide spectrum range, are processed with various photogrammetric evaluation software to obtain valuable data. Studies such as weed detection, plant water stress detection, soil moisture and water analysis, camouflage detection, monitoring of endangered species, natural disaster analysis, and classification can be carried out [30, 31, 32].

Multispectral cameras detect in the near infrared spectrum along with visible light. Multispectral cameras, which generally operate at wavelengths between 400 and 1200nm (nanometers), can be integrated into UAV systems or can be retrofitted onto the UAV (Figure 16).

**Figure 16.** UAV on-board (A) and post-integrated (B) multispectral cameras [33, 34].

Hyperspectral cameras (Figure 17), another optical sensor used in UAV systems, can collect data in a very wide spectrum.

With these cameras, the spectral signature of an object can be analyzed. Capable of detecting between 200 and 30000 nm wavelengths, these camera types are mostly used in military applications, but their use in scientific studies is increasing day by day. In the field of agriculture and forestry, it is used in studies such as plant health, disease diagnosis, weed detection and tree species detection. In the field of environmental monitoring, applications such as water quality monitoring, pollution detection, natural disaster analysis can be performed. In the fields of geology and mining, mineral exploration, soil analysis, geological mapping studies can be carried out. In the military field, camouflage detection, foreign element monitoring and intelligence gathering tasks can be carried out. Hyperspectral cameras provide flexibility in applications compared to other camera types since spectral bands can be used according to the application. This often increases their cost. Hyperspectral cameras are still being developed and are becoming more compact and accessible with technological advances. Although there are various difficulties in their integration into UAV systems, they are frequently preferred due to their advantages and sensitivity.


**Figure 17.** A hyperspectral camera unit that can be used in UAV systems [35].

Thermal cameras are cameras that detect and image objects based on their temperature. Thermal cameras can record and visualize infrared radiation emitted depending on the temperature of objects. Thermal cameras can detect the temperature difference and create images in poor light conditions. Therefore, they are widely used in search and rescue missions, fire detection and night operations. In the field of military and defense, there are applications such as reconnaissance and surveillance, target detection and target tracking. In addition, applications such as fault detection, inventory counting, plant and soil analysis can also be performed with thermal cameras [36]. Thermal cameras, like other camera types, can be integrated into UAV systems, or they can be integrated later (Figure 18).

**Figure 18.** Thermal cameras on the UAV (A) and subsequently integrated (B) [37, 38].

Lidar (Light Detection and Ranging or Laser Imaging Detection and Ranging), an active sensing electro-optical sensor, is used to create a 3D map of an object or an environment. Lidar emits laser beams and detects them by measuring the reflected laser beams [39, 40, 41]. Precise distance information is obtained by using the path of the laser beam in the air gap and the reflection time. In this way, the position of objects, their distance to the sensor and height information can be determined. In addition to the laser data, the current angles of the sensor and GNSS position information can be used to obtain highly accurate 3D data. First of all, the laser source in the Lidar sensor rotates on a rotating structure at a certain angular velocity, generating laser pulses and launching them into the air gap. The receiver captures the reflected laser beams and communicates with the timer unit. The processor part records this data (Figure 19).

Lidar sensors offer precise solutions for mapping and obstacle detection in many fields and are frequently used in unmanned vehicle technologies, military applications and robotics. UAVs are used for mapping and modeling, forest and nature monitoring, agricultural applications, infrastructure monitoring and construction, transportation and road safety, and disaster analysis.

Hydrographic Lidars (Figure 20) are sensors used for mapping the water surface and underwater structures. With these sensors integrated on UAVs, maritime applications, water management, coastal protection, underwater mapping, wreck analysis and underwater archaeology studies are carried out [43].

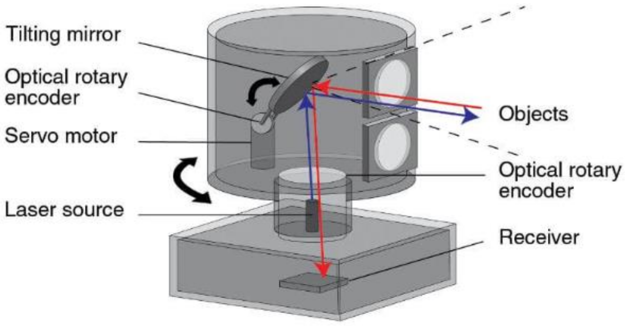



**Figure 19.** Lidar sensor structure [42].

**Figure 20.** A Lidar model used in hydrographic studies [44].

Cameras used in traditional photogrammetric studies are sometimes insufficient to create 3D models. Oblique camera systems, on the other hand, are used to obtain 3D models and better results are obtained. Thanks to oblique images that can be recorded from different angles (especially in building images), objects on the earth can be viewed from many angles. Building facades, surfaces not visible in the orthophoto, or terrain structure analysis are often used in oblique cameras [45]. The figure below shows an oblique camera (Figure 21).

**Figure 21.** Oblique camera [46].

Radar Radar (Radio Detection and Ranging) sensors are among the active sensors like Lidar sensors. While Lidar sensors detect using the reflection of laser beams, radar sensors detect using the reflection of electromagnetic waves (radio waves). Radar sensors integrated on UAVs are frequently preferred for obstacle detection and obstacle avoidance. Some radar types can also be used for distance measurement and measuring the speed of an object. Today, there are also meteorological radar systems developed for weather monitoring and precipitation prediction.

UAV systems used for spraying operations in agricultural areas generally carry out operations at low altitude. In low-altitude flights, the signals of global positioning systems can reflect from the ground, reducing position accuracy. For this reason, Radar sensors are used to maintain the distance between the ground (or plant) and the UAV. In this way, the UAV can safely carry out its mission even if the height of the plants or topographical features in the area of operation change (Figure 22).

While pulse radar systems are generally preferred for distance measurement, continuous wave (CW) radar systems are preferred for object (obstacle) detection [48]. In addition, "Doppler" radar systems are used in meteorological measurements and speed detection applications [49], but due to the large size of meteorological radars, they are not suitable for integration into UAV systems.

**Figure 22.** An agricultural UAV with a radar sensor [47].

## 4. Other sensors

UAV systems have many sensor systems specific to their missions. UAVs used in mining sites or for monitoring various pipelines may have sensors capable of measuring gas. Sensors that measure the density or presence of gases such as methane, carbon monoxide, nitrogen monoxide, nitrogen dioxide, sulfur dioxide, ammonia, hydrogen, hydrochloric acid, phosphine, chlorine, ethylene oxide (Figure 23) are some of them [50].

A

B

**Figure 23.** Gas detection sensors. A: Multiple gas detection sensors. B: Methane gas detection sensor [51, 52].

Wind speed measurement sensors, which are among the meteorological sensors, can also be integrated on UAVs. In this way, wind measurements can be made at different altitudes or in hard-to-reach areas (Figure 24).

**Figure 24.** Wind meter sensor that can be integrated into UAV systems [53].

## 5. Literature studies and case studies

Photogrammetric techniques are quite common in studies with visible light cameras. Especially for the preservation and documentation of historical buildings, these techniques are frequently utilized [54].

[55] In their study, Alptekin & Yakar collected 107 images from a height of 30 meters with the visible light camera built in the UAV. The internal camera used in this study, which was carried out to digitize cultural heritage, has a resolution of 21 MP and 4608 x 3456 pixels. Since the images obtained with the visible light camera also contain coordinate and altitude information, they were able to obtain a 3D model with photogrammetric evaluation software. In this way, all facades of the building were clearly reproduced.

[56] Yakar & Mırdan conducted studies for 3D modeling and recording of areas with historical features. In their study, they utilized an integrated visible light camera on the UAV and processed the images obtained in Agisoft Photoscan Pro and Pix4D photogrammetric evaluation software.

[57, 58] Similarly, Karataş et al. used a visible light camera integrated on a UAV for 3D modeling of historical ruins and detecting deformations in the ruins (Figure 25).

Exfoliation (a) Joint Discharge (b)

**Figure 25.** Deformations in historical structures [57].

Jiao et al. [59] analyzed aerial photographs taken with a visible light camera with the help of deep learning-based models and focused on forest fire detection (Figure 26).


**Figure 26.** Automatic fire detection on images taken with visible light camera [59].

Ok & Ozdarici-Ok [32] collected images from an agricultural area using a visible light camera. They combined the collected images with Pix4D photogrammetric evaluation software and applied image processing techniques in MATLAB computer software to calculate the number of trees. Similarly, Donmez et al. [26], Villi [25] and Wang et al. [60] conducted tree counting studies with the images they collected on agricultural areas (Figure 27).

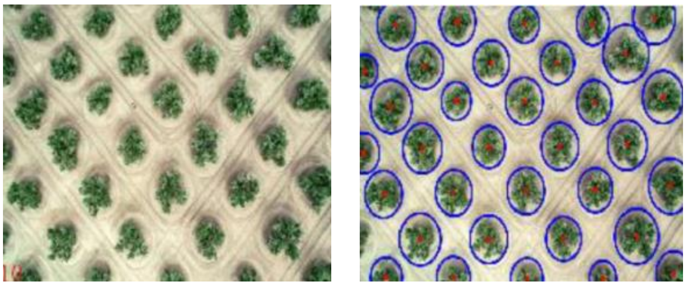


**Figure 27.** Tree detection and counting with visible light camera [60].

Kınalı & Çalışkan [61] obtained data that can be used in forest road projects by using aerial photographs taken with a visible light camera.

Tükenmez [62], on the other hand, focused on map production that can be used as a base for road projects. In his study, he mentioned that the images taken with the visible light camera integrated into the UAV can be used in many road projects.

UAV images are frequently used in movies, commercials, TV series, artistic and sporting events, celebrations, openings, anniversaries and ceremonies all over the world. In this context, high-resolution visible light cameras can be used both internally and by being added to the UAV as needed. Tutuş [63] focused on effective shooting techniques in his study and explained the scene plans for the studies to be carried out in these areas.

In real estate valuation applications and real estate sector, UAV photographs have become very popular in recent years. Promotions and presentations made with high quality aerial photographs and videos collected with visible light cameras are very effective [64].

Zhou et al. [65] collected images using a thermal camera. Using these images, they performed erosion detection and detected the presence of leakage with a 94.9% success rate.

Silvagni et al. [66] utilized a UAV system with thermal camera in avalanche rescue operations. They developed a UAV system with a thermal camera that can perform search and rescue activities regardless of day and night.

Quebrajo et al. [67] imaged the agricultural area with sugar beet plants with a thermal camera. They stated that they can develop an irrigation method by analyzing the images taken.

Working on roof insulation monitoring and inspection, Zhang et al. [68] developed an approach that automatically detects thermal anomalies in roofs using images taken by a thermal camera mounted on a UAV.

Liao & Lu [69] studied a UAV system with a thermal camera for fault detection in solar farms (Figure 28).

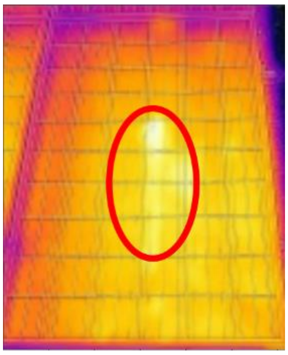


**Figure 28.** Solar panel failure detected using thermal camera [69].

Asad et al. [70] performed gas leak detection using a thermal camera in a similar way (Figure 29).

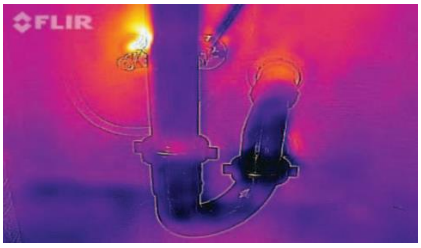



**Figure 29.** Gas leak detection using a thermal camera [70].

Donmez et al. [26] created NDVI (Normalized Difference Vegetation Index) map using a multispectral camera system and analyzed the general health status of plants. Many index maps can be created with multispectral sensors. NDVI index is one of the most well-known and widely used index types [31, 71].

Tang et al. [72] utilized multispectral cameras to measure water stress of grapevine plants and develop irrigation methods accordingly.

Song & Park [73] conducted studies to identify and protect aquatic plants that improve the quality of dam and river waters. In their study, they created index maps to detect these plants using multispectral camera. They tested which index would be the best index for detection and concluded that NDVI and GNDVI indices have the best performance.

3D maps made using oblique cameras can be more realistic and innovative than traditionally obtained 3D maps [45]. In this context Yang et al. [74] compared the 3D images obtained using oblique camera system with the 3D images obtained by conventional method. They concluded that the coordinate accuracy was 8.7% better and stated that oblique cameras can be more efficient in 3D building modeling processes.

Similarly, Zhou et al. [75] reported that the use of oblique cameras is successful in urban 3D modeling studies. They revealed that the side surfaces of buildings can also be created effectively and will give better results compared to traditional methods.

Toschi et al. [76] integrated oblique camera and Lidar sensor data in their study. For 3D mapping, they stated that the simultaneous data collection of both sensors will increase the accuracy of the resulting images and reduce the time cost.

Hu et al. [77] used Lidar sensors to determine tree height in forest surveys. They stated that the success rates are also high in forest areas that are not very dense.

Cao et al. [78] similarly used Lidar and UAV for forest inventory and sustainable forest management in planted forests. They stated that they accurately obtained the structural characteristics of forest trees.

Li et al. [79] analyzed glaciers by using Lidar and aerial imagery together. They tried to observe the changes in glaciers by comparing the data obtained at different times.

Curcio et al. [80] utilized Lidar sensors to investigate salt marsh areas in their study. They stated that UAV-LiDAR technology is a suitable solution for coastal survey applications that require high spatial and temporal resolution.

Bandini et al. [81] utilized visible light camera, Lidar and Radar sensors for water surface analysis. They stated that the calculation and regular monitoring of water height is very important for flood forecasting and climate change monitoring.

Abushakra et al. [82] developed an ultra-wideband UAV Radar system in their study. They tested their radar system at an altitude of 100 meters and reported that they were able to detect soil moisture and vegetation with high success rate.

Honkavaara et al. [83] used UAV systems carrying hyperspectral cameras to estimate surface moisture in a mining area where peat coal is produced. They obtained meaningful data by classifying the acquired images with machine learning methods.

Similarly, Jackisch et al. [84] collected data from a coal mining area with a hyperspectral camera. They tried to detect Fe(II)-ferrous and Fe(III)-ferric compounds (Figure 30).

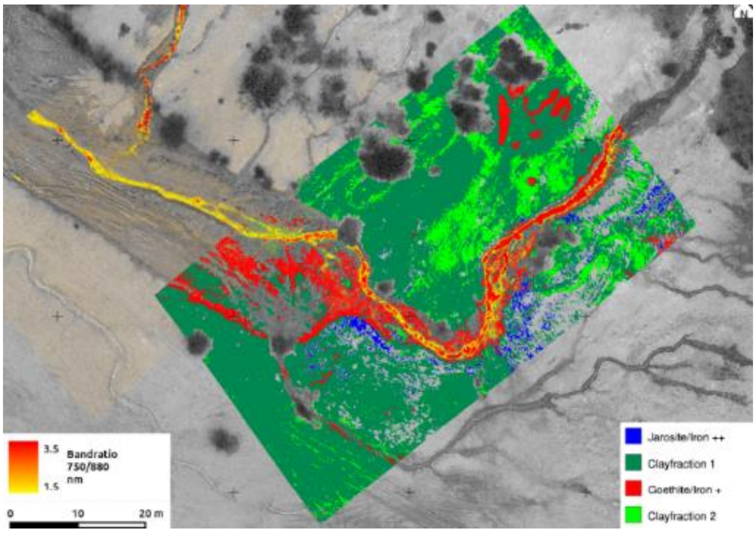
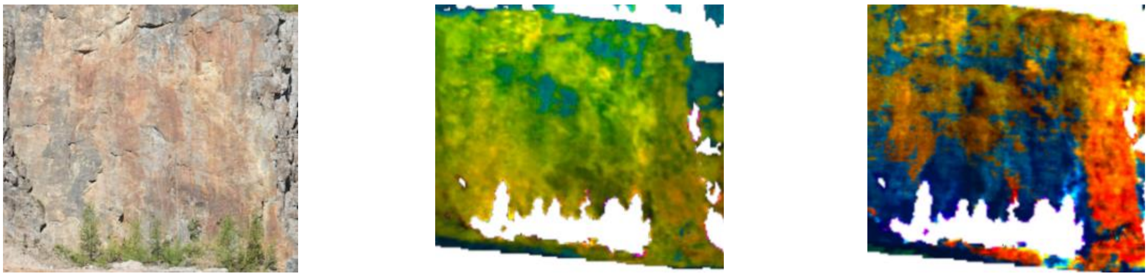



**Figure 30.** Classified result image obtained with hyperspectral mapping and ground-based data [84].

In their study on lithology mapping and analysis, Kirsch et al. [85] acquired images with a hyperspectral camera in a sulfide-rich quarry. They classified the images and detected magnesium hydroxide and iron hydroxide (Figure 31).



A B C

**Figure 31.** Classified hyperspectral images (A: Original image, B: Magnesium hydroxide image, C: Iron hydroxide image) [85].

Mahmood et al. [86] utilized ultrasonic sensor and visible light camera to protect an orchard from birds. With the visible light camera integrated on the UAV, it is aimed to detect the type of birds and to adjust the ultrasonic sound frequency appropriately to miss that type of bird. In this way, they stated that orchards can be protected autonomously.

## 6. Discussion and conclusion

Although UAV systems were first developed for military purposes, they have also become widespread in scientific and industrial fields. Today, they are used in many fields and sectors for different purposes and provide many conveniences to researchers. Thanks to the flight assist sensors on them, they can fly precisely and safely. With the help of environmental data collection sensors, they can make fast and precise measurements about the earth in a short time.

UAV systems can be equipped with a large number of sensitive sensors thanks to the development of sensor technologies day by day. The large data obtained can be transformed into meaningful data with various photogrammetric evaluation software and artificial intelligence techniques, providing convenience to users. UAV systems equipped with sensors are used in many areas from the analysis of historical artifacts to natural disaster monitoring, from search and rescue to agricultural activities, from energy applications to mining operations.

Within the scope of this study, the types of internal and external sensors found in UAV systems are explained and examples of flight assist and data collector sensors are given. Explanations about optical sensors are made and examples from the literature are listed. This study is expected to be a guide for future studies.

In the future, there is no doubt that UAV and sensor groups will carry out fully autonomous activities, automatic analysis and artificial intelligence applications will increase, and swarm UAV systems will conduct operations together.

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**Author contributions**

**Osman Villi:** Writing, Conceptualization, Methodology.
**Murat Yakar:** Writing-Original draft preparation, Reviewing and Editing.

**Conflicts of interest**

The authors declare no conflicts of interest.

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