A review on pointing, acquisition, and tracking approaches in UAV-based fso communication systems

Reham Abdelfatah · Nancy Alshaer · Tawfik Ismail

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Abstract
The challenge of tracking unmanned aerial vehicles (UAVs) is arising out of increasing their market and spread usage in many applications. Miscuing UAVs can lead to potential threats as they are considered an essential part of national security. One of the major issues in communication with UAVs is the enormous amount of data generated by UAVs that requires a high data rate link, making the free space optics (FSO) communication, with very high bandwidth, an appropriate choice. Consequently, current developments in UAVs have provided new horizons for establishing UAV-based FSO links. However, FSO is a narrow line of sight (LoS) technology that is highly affected by the misalignment between the transmitter and receiver. So, tracking mechanisms are of vital importance when considering UAV-based FSO communication systems. This paper addresses coarse to fine pointing, acquisition, and tracking (PAT) approaches and the recently developed tracking approaches to establish a reliable link for communication. Also, the various approaches are discussed and compared for precise alignment between the ground station and its associated UAV, highlighting their advantages and limitations. Current challenges and future research directions are addressed and integrated by combining different ideas.

Keywords UAV tracking · PAT techniques · FSO communications · Research challenges
1 Introduction

Unmanned aerial vehicles (UAVs) are becoming increasingly popular in various applications, which raises the possibility of security vulnerabilities. They have many applications and a strong impact, making them essential for national security. UAVs are used to advance the transportation systems in smart cities, where they are used in the assessment and investigation of accidents and damage (Outay et al. 2020). They also have been used in many applications such as aerial photography, agriculture, plant, disaster relief, disaster management (Fragkos et al. 2019), movie and television photography. The study in Kaadan (2013) claims that during the next decade UAVs market is predicted to be doubled. The demand for network UAVs increases by increasing their number. Therefore, a suitable developed and secured link is needed.

It is preferable to have a secure link between the UAV and a ground station in order to communicate with a receiver. Traditionally, radio frequency (RF) communications have been used to accomplish this operation. The growing congestion of the electromagnetic spectrum and since that optical communication blocking is less likely to happen in free space led to free-space optics (FSO) becoming an alternative to RF systems. It also provides solutions to various RF communication challenges, such as interference and crowded bandwidth, while providing a free operation license and empowering implementation. As a result of fulfilling the high data rate connectivity requirement for the massive data generated by UAVs, the FSO communication link is a strong contender in the development of a secure link between UAVs and ground stations (Quintana et al. 2019). Both techniques of RF and millimeter-wave have lower capacity and higher probability of intercept than FSO communication, where the light wave has a higher carrier frequency (Chand et al. 2010). The UAV-Based FSO systems analysis in terms of channel modeling, performance analysis, and parameter optimization was deeply investigated (Najafi et al. 2020; Dabiri et al. 2020; Khankalantary et al. 2020; Wang et al. 2021; Dabiri et al. 2018, 2019).

Despite the numerous advantages of the FSO, it is vulnerable to atmospheric turbulence, which results in the fading of the link, which is caused by random fluctuations in the refractive index of the air. The FSO links also encounter a series of practical difficulties while the optical signal propagates through the atmosphere, which can significantly degrade its quality. Attenuation due to atmospheric phenomena such as fog, rain, sleet, and snow (Mahalati and Kahn 2012), angle of arrival (AoA) fluctuations, and pointing errors are among the considerations. The pointing inaccuracy and misalignment of the FSO transceivers are caused by the internal fluctuations of the UAV caused by dynamic wind loads, mechanical vibrations, and air fluctuation, in addition to all of the previously listed behavioral and environmental conditions (Borah and Voelz 2009). It may result in inaccurate tracking of the UAV due to signal degradation or the absence of the received signal. Decisions about the operation of unmanned drones are undertaken on the ground, either before or during the flight itself. As a result, communication becomes increasingly essential and critical.

In FSO communications systems, pointing, acquisition, and tracking (PAT) techniques are critical components for satisfying LoS communication between a transmitter and a receiver. The main task of the PAT system is to point the transmitter in the direction of the receiver, where pointing is to align the transmitter in the field-of-view (FoV) of the receiver. Furthermore, acquire the incoming light signal where the acquisition of a signal is to align the receiver in the direction of the arrived beam where each terminal acquires the initial location of the other before the beginning of data transmission. Finally, maintaining
the signal acquisition and pointing by tracking the position of a remote terminal. PAT approaches achieve a successful FSO link with high efficiency, even if the transmitter and the receiver are separated over large distances. PAT systems that required mounting heavy equipment on both transmitter and receiver was discussed in details in Kaymak et al. (2018). UAVs especially the small ones require an alternative to such mechanical systems, where recently alternative asymmetrical approaches are introduced and developed to suit the payload and power limitations on the UAV terminal.

This paper focuses on UAV-based FSO communication links, discussing the equipment and methodology of each system, and comparing the various approaches. Also, it clarifies recently developed approaches that achieve the size, weight, and power (SWaP) requirements for such links to satisfy the constraints on the UAV terminal and maintain performance. Future study directions are identified, taking into account the environmental and behavioral factors that influence such connections.

The following sections of the paper are organized as follows. Section 2 presents the conventional PAT approach. Section 3 discusses the introduced asymmetric approaches used in FSO communications to attain LoS between the UAV and the ground station, and applies a classification between various approaches considering the advantage and the limitations of each system. Several challenges and future research directions are provided in Sect. 4, and the conclusions are presented in Sect. 5.

2 Conventional PAT approach

The PAT system is comprised of two modules: the first module is responsible for coarse tracking, and the second module is responsible for fine tracking. The coarse tracking module is responsible for tracking the UAV as it locates the UAV and mechanically points the ground station towards it. Additionally, it supports the fine tracking subsystem by maintaining the UAV within its FoV. A high level of pointing precision is provided by the fine tracking module within a limited and narrow FoV.

The gimbals-based PAT techniques track the moving UAV precisely regardless of the turbulence and fluctuations in the atmosphere, enabling a successful FSO communication link to be established between a ground station and a UAV. The ground-to-UAV link requires a mechanical gimbal at both the ground station and the UAV to enable active tracking and alignment of the FSO link, which adds a high load to the UAV. The PAT systems-based gimbals are suitable for large UAVs only since the payload limits their usability in small UAVs and systems with weight constraints. The gimbals are controlled by motors where the gimbal device is used to change the direction in which a mounted device such as an FSO transmitter is aligned. The large mass of gimbals due to bulky servo motors makes them unsuitable for small UAVs with a weight limit. Axial gimbals perform pan and tilt movements providing a wide angular range essential for some transceivers.

Miller et al. (2013) investigated gimbal systems suitable for limited weight and small UAVs, where smaller UAVs require design challenges for smaller gimbals with size, weight, and power constraints. Inertial Measurement Units (IMUs), fast steering mirrors (FSMs), and image-stabilization algorithms are investigated for optimal performance to align miniature gimbal for LoS communication. Gimbals also contributed to day-time surveillance for all-day detection and tracking utilizing UAV (Jedrasiak et al. 2013; Majumdar 2015) as shown in Fig. 1. Furthermore, (Stepanova and Pryanichnikov 2020) studied
the challenges of a two-axis gimbal optical communication terminal (OCT) creation to be mounted on small terminals such as mobile robots and UAVs.

In Harris et al. (2005), the authors discussed the gimbal-based approach for ground-to-UAV FSO communications. It used simulations to investigate its ability to maintain the alignment of an FSO communications link between the ground station and the UAV. Also, simulations detect the amount of divergence existing in the laser beam of the communications link due to atmospheric turbulence. The transmitter is a 633-nm helium-neon laser mounted on a gimbal using optical mounts directed to a receiver represented by a stationary duo-lateral position sensing photo-diode (PSD). The position information of the laser is acquired by a data acquisition module connected to the PSD. The data was recorded on a personal computer used to control the movement of the gimbal to point the laser beam at the PSD’s center. This internal clock of the computers was used to synchronize the data acquisition and the gimbal control software. The FSO link fading probability is analyzed using a photo-diode. The experimental results of this paper showed how effectively a mechanical gimbal could align and track an FSO link. The amount of beam divergence in such an FSO link is enough to offset any error introduced into the gimbal’s alignment and tracking algorithm. Also, a very weak probability of signal fade is predicted for the communication link. The divergence simulation showed that the geometric loss expected for a ground-to-UAV FSO link would not limit link performance. This paper also demonstrated how the gimbal-based PAT resolution and repeatability occur under different weather conditions.

In Locke et al. (2011), an alternative PAT mechanism based on gimbals is presented. The tracking algorithm utilized by the gimbal on the UAV was evaluated in order to align the transmitter laser onboard the UAV with the receiver on the ground station during the flight. The chosen design achieved the lightest weight while also providing a fast response that is convenient for real-time tracking and a wide FoV. The integration of the gimbal with motor controllers and drivers provided a continuous tracking capability. It improved the accuracy and reliability of the precision laser pointing system desired for the UAV FSO
communication link. However, the practical implementation and the proof of concept introduced an air-to-ground communication system. A computer onboard the UAV is used to control the two-axis gimbal with the help of the global positioning system (GPS) to locate the ground receiver. The UAV autopilot’s differential global positioning system (DGPS) is used to calculate latitude, longitude, and altitude, and IMU is used to provide the roll, pitch, and yaw data. The gimbal is controlled to precisely aim the laser transmitter at the ground receiver as a coarse tracking mechanism.

The authors in Liu et al. (2021) offered a detection and tracking system that makes use of enhanced light detection and ranging (LIDAR) system on a gimbal with two degrees of freedom, as well as a tracking system that makes use of a gimbal. Two high-torque motors operate the gimbal system with distinct rotation speeds, which enables the gimbal to point in multiple directions. Additionally, this tracking system is minimal in cost, has great robustness, and is easy to set up. The gimbal is controlled by software running on a PC, which sends instructions to the gimbal to modify its pose in order to place the UAV in the center of the LIDAR FoV.

3 Asymmetric approaches

Small UAVs require an alternative to conventional PAT systems with a high payload. Asymmetric approaches introduce a lightweight mechanism at the UAV mobile terminal and transfer the load (PAT system) to only the ground terminal. The ground station is equipped with coarse and fine tracking modules, which is essential for the system to operate fast and with precise pointing and positioning.

3.1 Visual tracking approaches

The Modulating retro-reflector (MRR) systems achieve the alignment criteria while satisfying the load requirement for such small moving terminals. An MRR device is mounted on the UAV terminal to modulate and then reflect the received beam through the same optical path. The retro-reflective FSO communication system is demonstrated for the purpose of being the fastest demonstration of outdoor link type. The systems seek the lowest possible bit error rate (BER) with the highest possible data rate link.

Quintana et al. (2016) introduced a secured link between the ground station and the UAV to allow communication between them. An MRR device is mounted on the UAV offering lightweight, low power consumption, and low complexity. The PAT mechanism on the ground station enables a steady illumination of the UAV retro-reflector. In order to investigate this system, experimental field trials were carried out. A common control module manages the two subsystems of coarse and fine holographic tracking, as shown in Fig. 2. The system was tested on real environment data from the UAV to the ground station and managed to achieve BER around $2 \times 10^{-4}$ with a rate of 2 Mbps. For coarse tracking, a video tracker board is used with a charge-coupled device (CCD) camera to calculate the UAV’s coordinates using an adjustable zoom lens to find and zoom into the UAV’s region. The mechanical motion is performed by a pan and tilt unit (PTU) with an angular resolution to meet the system requirements. The coarse tracking worked cooperatively with a holographic fine tracking module based on a spatial light modulator (SLM), where a mechanical head is used to hold the fine tracking module.
The fine tracking subsystem uses a beam steering unit and a position sensor device to precisely align the UAV with the base station, which is necessary for optimal system performance. Traditionally an FSM is used for fine beam steering introducing high efficiency and quick response. This paper introduced SLM to perform this task as it can perform beam divergence, which increases the system flexibility. The SLM has been integrated into a complete tracking system, allowing for establishing a data link between a UAV and a base station. The light reflected off the MRR is collected at the ground station. It is detected by both a PIN photo-detector and a high frame rate camera, acting as a data receiver and a position sensing device.

According to (Quintana et al. 2021), the authors developed an MRR system that included a pixelated electro-absorption modulator (EAM) which provided an error rate (BER) of $7.6 \times 10^{-4}$ and a data throughput of 500 Mbps over a range of 560 m. This design and implementation claim to be the fastest in the world, and it has been tested experimentally. An entire FoV is provided by the ground station tracking modules, which direct the interrogator beam towards the UAV position equipped with an MRR, where it modulates and returns a fraction of the beam recorded back towards the ground station for detection of the receiver. The PTU, as a part of the coarse tracking module, offers high flexibility, which is controlled by a video tracker board and works in cooperation with the fine tracking module to reach a precise alignment between the terminals and overcome the UAV’s expected vibrations and the disturbance caused by the atmospheric turbulence. The coarse tracker points the fine tracker towards the MRR to start the acquisition stage to locate the MRR on the UAV, where the SLM in the acquisition stage increases the beam divergence to cover the FoV rapidly.

Recently, experimental analysis for the effect of the physical channel on the retro reflected FSO link between UAV and terrestrial terminal is reported in Trinh et al. (2021), with insights for the receiver AoA fluctuations. The misalignment introduced from mounting an MRR on a hovering UAV is considered instead of only considering the forward link.
misalignment. An experiment of optical beam propagation between a ground station and a UAV is reported to visualize the AoA fluctuations at the ground station. Coarse and fine tracking is performed using a hybrid PAT mechanism by employing an FSM alongside a gimbal on the ground station. FSM is responsible for the fine tracking, and by mounting it on a gimbal, a wide field of regard is provided to the hybrid PAT mechanism. The field of regard is the covered area by a movable sensor.

In Carrasco-Casado et al. (2011a, 2011b), a UAV-to-ground PAT mechanism for FSO communications system is proposed. The main component of the PAT mechanism on a UAV is the micro-electromechanical systems (MEMS) retro-reflector mirror, which is used to attain the least size, weight, and payload power. The ground station for this FSO communications system is made up of a gimbal and an FSM. On the ground station, coarse and fine pointing is accomplished with the use of a gimbal and an FSM. A beacon-based PAT technique is designed to have the laser in the ground station. The MRR device is used as a beacon reference, which significantly benefits the system. In addition, the beacon system onboard the UAV will not be suitable due to the added weight. The ground station emits an interrogating laser directed to the UAV. The interrogating laser is modulated and reflected towards the ground station with encoded information by the retro-reflector mirror mounted on the UAV shown in Fig. 3. The MRR device mounted on the UAV is responsible for modulating and reflecting the laser beam as it acts as a retro-reflector and an optical modulator. It has the ability to reflect light from a remote interrogating laser source without the need for additional aiming needs on board, and it can control the strength of the reflected light on the way back.

The position of the UAV is determined using a GPS system, and then it is transmitted to the ground station in order to perform coarse tracking. The gimbal uses this position to track the UAV’s trajectory and transmits an infrared beacon laser to illuminate the

Fig. 3 MRR mounted on UAV reflecting back the interrogating laser (Carrasco-Casado et al. 2011b)
UAV. This task assures the UAV’s continuous illumination and compensates for the GPS errors, where the beacon laser forms a spot of size five meters. A zoom lens is used to optimize the signal-to-noise ratio received by the IR camera. The UAV’s retro-reflector mirror reflects the beacon laser to the ground. The IR camera captures it and controls the gimbal’s movement by controlling signals from the IR camera and the GPS. The retro-reflector mirror reflects the beacon on the UAV. The IR camera on the ground captures it, where both of IR camera and GPS provide a combination of control signals to control the gimbal’s movement. The FSM is used to correct the misalignment of the interrogating laser in the fine pointing stage. Also, this paper introduced an experiment trying to use a Liquid-Crystal device instead of FSM for fine pointing, as it controls the laser beam angle accurately in two dimensions. A novel liquid crystal device was developed specifically for this system, and it is the only component that is non-off-the-shelf in the market (Carrasco-Casado et al. 2011b).

Further robust PAT system is designed, analyzed, and developed in Ortiz et al. (2003), for UAV-to-ground FSO communication link, mitigating the effect of atmospheric fades and dealing with UAV flight and vibration uncertainties. The UAV uses a high-definition video camera (HDTV) to take scientific images of geological interest, such as volcanic regions, then transmits the images to the ground station through the optical communication channel. The UAV follows a particular path around the ground station receiver to attain the LoS requirement of optical communication. An OCT is used to initiate the optical communications to achieve a robust PAT system. The terminal uses both the GPS updates collected by the UAV’s GPS and the ground station location to point the gimbal. The ground station illuminates the UAV with a beacon signal to transfer the data (Ortiz et al. 2003). The PAT system acquires and tracks the beacon laser from the ground and accurately points the down-link laser to the receiver. A wide field-of-view (WFoV) camera and a narrow field-of-view (NFoV) camera are used with a gimbal in the coarse acquisition and tracking stage. The GPS information initially points the gimbal towards the ground receiver. On the other hand, the fine tracking stage’s primary function is to track the ground beacon to compute the error vector between the pointed direction and the received beacon direction and to command the steering mirror to correct the error, compensating for the UAV’s microvibrations. The hybrid mechanism developed in Xiu et al. (2020) uses a two-axis gimbal and two single-axis FSMs, where the FSMs achieve image motion compensation and the gimbals complete the pointing control. Ground imaging and flight tests are made to verify this method and ensure an accurate LoS between terminals.

Additionally, the research in Ryu et al. (2018) discussed two acquisition and tracking control strategies which were verified using computer simulations and experiments. In the first strategy, the ground station is driven by PTU to attain LoS between the ground station and the UAV. Due to the short distance between the UAV and the ground station, the changing rate of the directional angle is fast, which requires a tracking system and a fine control system, which is presented in the second strategy. This strategy involves finely controlling the optical module mounted on the UAV in order to align it with the optical module on the ground station. The proposed system requires a sensor to measure the intensity of the received laser light and an actuator to control the laser module direction. The actuator is a gimbal equipped with a PTU or an FSM, with the PTU being used on the ground station’s side due to its extensive operating range. The FSM is employed in UAVs due to its compact size and lightweight. Additionally, (Talmor et al. 2016) investigated the gimbal and FSM integration for the lowest possible weight applicable for a link between HAPs and a ground terminal, where the lightweight and high-performance requirements are fulfilled with trading multiple gimbals configurations.
The impact of pointing errors on such MRR FSO communication systems in the presence of moderate to strong turbulence conditions was investigated in El Saghir and El Mashade (2021). Monte Carlo simulations are obtained to verify the derived average system BER, outage probability, and ergodic capacity results for the performance of the system. The authors of El Saghir et al. (2020) presented a comprehensive analysis of the MRR FSO communication, which was modeled using the generalized Málaga distribution to model the FSO link.

In Stepanova et al. (2018), a pointing and tracking approach for an OCT is developed and implemented with selected hardware. A video sensor is mounted at the OCT to receive the orientation beacon. An image processing algorithm is responsible for detecting the center of the received beacon, and then it generates the signal for the control system. The field programming gate array (FPGA) implementation for the algorithm enhanced the pointing and tracking accuracy by reducing the control system latency. Also, (Stepanova et al. 2019) is concerned with the precise pointing and tracking through integrating image processing algorithm with an advanced RISC machine (ARM)-FPGA implementation. It investigated the PAT system from a mass, cost, and size point of view.

### 3.2 Beam tracking approach

An alternative approach for mechanical PAT systems is the beam tracking approach which offers a reliable link between the UAV and the ground terminal. The previously discussed mechanical or piezoelectric equipment is inappropriate in the case of small UAVs. Beam tracking introduces a suitable mechanism for systems with limited payloads as UAVs, where photodetectors are mounted at the receiver terminal, replacing the PAT unit. Practically the PAT system requiring higher weight is placed instead at the ground terminal (Safi et al. 2019, 2021; Bashir and Alouini 2020). Atmospheric air fluctuations and the internal hovering fluctuations of UAVs, position, and orientation fluctuations are unneglectable. All are random fluctuations that cause beam misalignment and AoA fluctuations. It requires enlargement at the FoV of the receiver maintaining low implementation complexity. Beam tracking is preferred for transceivers that require a wide FoV at the receiver terminal, where enlarging the FoV compensates for the effect of the fluctuations.

For instance, utilizing an array of detectors for the purpose of beam tracking and symbol detection is investigated depending on photon-counting detectors. Introducing a mobile terminal of balloons or UAVs as a transmitter terminal as shown in Fig. 4 (Bashir and Alouini 2020). The mathematical analysis of the photodetector array in Bashir and Alouini (2020) is introduced by the author in Bashir (2019).

In Safi et al. (2021), photodetectors consisting of a 4-quadrant array are used at the receiver terminal, and the tracking performance of the system is evaluated using mathematical analysis while the system is exposed to random fluctuations. Although the increased size quadrants helped the system’s performance, the background noise limited the system’s improvement. In such situations, system performance is evaluated using tracking error and bit error rate, which is usually less than $10^{-9}$, corroborating Monte Carlo simulations. The research study (Safi et al. 2019) is concerned with the trade-off between system performance and complexity. Also, the proposed methodology improved the bandwidth efficiency by eliminating the pilot symbols in estimating the channel coefficients. Under various degrees of UAV fluctuations, quad-detector size is optimized for minimum tracking error. Taking into consideration, the fast performance of beam tracking to accommodate the gigabit transmission in FSO systems (Safi et al. 2019, 2021).
In Kiasaleh (2018), the authors describe non-negligible aiming errors caused by platform fluctuations, beam tilt, and background noise that influence the FSO link deploying photodetector arrays detection. By combining the output of photodetectors for detection and analysis, the BER is addressed for performance evaluation. The communication techniques with machine learning algorithms have been utilized recently through deploying the UAV for intelligent communication (Song and Ko 2020). The research study in Zhao et al. (2018) integrates GPS and IMU sensors alongside the beamforming signal to track the UAV precisely, as shown in (Figure 3, Zhao et al. (2018)). The novel machine learning method of Gaussian process regression (GPR) is utilized for channel estimation for optimal beamforming (Song and Ko 2020).

Furthermore, in high mobility scenarios as in UAVs, beam control adjusts the degradation in beam tracking (Chung et al. 2020; Mai and Kim 2018). In Chung et al. (2020), the simulation results introduce the effectiveness of beam control alongside beam tracking in cases of high mobility. The work done in Mai and Kim (2018) adopted two beam control approaches from power consumption and link availability point of view regarding airborne FSO communication systems. The first approach optimized beam divergence for link availability with fixed transmitter power, while the second adjusted beam divergence for minimizing the transmitter power. In Mai and Kim (2019), instead of utilizing fixed beam sizes, the adaptive beam control technique is introduced to mitigate the fluctuations of the AoA and the pointing error.

The PAT mechanism should suit the weight limit of the designed vehicle, the system budget, the weather condition, and other conditions. Table 1 shows a classification of the PAT mechanisms regarding their advantages and limitations.
Table 1  Tracking mechanisms classification regarding advantages and limitations

| Methodology                                                                 | Advantage                                                                 | Limitation                                                                 |
|----------------------------------------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Conventional approach (Miller et al. 2013; Jedrasiak et al. 2013; Majumdar 2015; Stepanova and Pryanichnikov 2020; Harris et al. 2005; Locke et al. 2011; Liu et al. 2021). | The gimbals perform coarse tracking by maintaining the LoS between terminals. | Not suitable for small UAVs with a weight limit.                          |
| Visual tracking approaches (Quintana et al. 2016, 2021; Trinh et al. 2021; Carrasco-Casado et al. 201, a, b; Ortiz et al. 2003; Xiu et al. 2020; Ryu et al. 2018; Talmor et al. 2016; Stepanova et al. 2018, 2019). | Mounting MRR device on the UAV-terminal, the FSM is responsible for fine tracking and adopting image processing algorithms. | Higher cost and complexity compared to gimbal-based systems, FSMs have a limited angular range of motion. |
| Beam Tracking approach (Safi et al. 2019, 2021; Bashir and Alouini 2020; Kiasaleh 2018; Song and Ko 2020; Zhao et al. 2018). | Array of PDs at the UAV-receiver terminal | Suitable for small UAVs as the system payload is transferred to the ground station (The lowest in the aspect of weight) and wider FoV | differentiation between the required received signal and the noise at the receiver terminal and optimizing the size of PD array. |
4 challenges and future research directions

The recent advance in FSO communication systems allows it to be more applicable to ground-to-UAV communication. The rapid development of UAVs and their size reduction requires new PAT designs with the minimum size and complexity possible. The PAT system mounted on the UAV must have a proper weight that suits the UAV’s weight limitations, whereas small PATs have not been fully developed as they are challenged by the mobility requirements, such as small weight and size. The UAV’s high mobility and speed may be challenging for FSO technology, requiring an agile PAT mechanism to maintain the optical link between the ground station and the moving UAV and keep up with the UAV’s speed. Also, the recent growing interest in using UAVs in emergency management and disaster response in urban environments with a thick presence of buildings is challenging, as such scenarios present a challenge for signal acquisition and tracking.

Additional research interest is the predictive PAT mechanism. In the predictive PAT mechanism, the laser beam is pointed towards the moving direction of the UAV or the tracked object generally. The advantage of the predictive PAT mechanism is eliminating the time needed to get the vehicle’s location using its GPS. Having prior knowledge about the UAV’s trajectory may decrease the handover time of a ground-to UAV or UAV-to-ground. However, it has a high cost, which is a disadvantage to this mechanism as it requires at least two transceivers on a moving vehicle connected to two consecutive ground stations. Also, as being demonstrated in the previous section, the communication systems based on MRR suit the UAVs. Depending on that, the MRR electronics should be improved to increase the link’s data rate between the ground station and the UAV. Also, increasing the MRR FoV will increase the data link robustness against severe weather conditions. Furthermore, the integrated millimeter-Wave and FSO communication systems can be seen as a potential for accurate tracking between UAV and ground stations under various weather conditions and channel variations. This integration enables the UAVs to operate with high mobility and data transmission capabilities.

Using machine learning, the visual tracking of UAVs is a promising alternative to the traditional coarse tracking mechanisms in terms of accuracy and speed. The research done in Chen and Yu (2020) conducted an indoor experiment using a visual tracking system based on target imaging for gimbals steering. They developed a PAT system utilizing a special beacon and a camera for vehicle-to-infrastructure communication. The target has been a shape beacon of a vehicle instead of the conventional received beacon signal. A machine learning approach of training a simple network on positive and negative images for vehicles is utilized, where classifiers are trained and then used to detect the target on a bounding box. Inspecting the aforementioned visual tracking system on a UAV terminal, the authors of Isaac-Medina et al. (2021) introduced a benchmark performance for the available UAV datasets and the developed detectors and trackers. The work focused on tracking the UAV in noisy adverse backgrounds taking into consideration the fast movement of the UAV and its introduced fluctuations. A powerful detector could be trained on a UAV dataset and integrated with the latest enhanced trackers such as deep SORT (Wojke et al. 2017) for establishing a shape beacon at the OWC terminals. The previously mentioned research was concerned with UAVs’ visual tracking irrespective of the communication system. So, applying visual tracking using machine learning in UAV-based FSO communication systems is recommended for future work. It is expected that such integration will help enhance the FSO system’s performance metrics.
This work reveals a shortage in the research concerned with the evaluation of the FSO system performance metrics when using the tracking system (coarse/fine tracking). The authors in Alshaer et al. (2021) apply integrated sensor fusion with GPS and Extended Kalman filter (EKF) correction to determine the variances in UAV orientation and position through the generation of 10,000 records data set from three sensors. The obtained variances are used to evaluate the performance of the proposed quantum key distribution (QKD)-FSO system. This is achieved by deriving closed-form expressions for the probability of error, outage probability, and secret key rate under attack. The applied channel model considers critical FSO channel parameters such as attenuation, turbulence, pointing error, and AoA.

5 Conclusion

This paper presented various tracking approaches required to align UAVs with a ground station utilizing FSO communication links in order to achieve LoS communication. Different approaches are classified according to their advantages and limitations. Also, their availability under certain conditions is represented, especially as weight reduction and low power consumption are key requirements in the next generation of UAVs. The technical details of the systems and devices onboard the UAV are introduced in order to expand the limitations of each system. The challenge of transmitting information between a ground station and UAVs is increasing by utilizing UAVs in more applications. Various current research challenges were reviewed, and some recent research directions were introduced.

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Declarations

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