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Araştırma Makalesi / Research Article

Development of Battery-Independent Illumination Drones Integrated into Tethered UAVs for Extended Operations

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ABSTRACT: This study presents the design of an unmanned aerial vehicle (UAV) specifically developed for extended illumination in surveillance, search and rescue (SAR) operations, security enforcement, border surveillance, and other applications requiring lighting, particularly in disaster areas. Traditional battery-powered UAVs have limited operational time; therefore, a tethered drone design was implemented in this study to overcome flight duration constraints. The direct current (DC) energy required for the tethered drone is supplied by a Gold Series switch-mode power supply (SMPS) mounted on the drone. The alternating current (AC) energy needed for the SMPS is transmitted through a cable. Additionally, the light-emitting diode (LED) projector, operating on AC 220 volts, is powered by the same cable that supplies the drone, eliminating the need for an additional DC converter. This design choice reduces weight and ensures an optimized configuration. The projector is mounted on servos with dual-axis capability, allowing both horizontal and vertical movement to precisely illuminate the target area. Although studies on tethered and illumination drones exist in the literature, this work combines two distinct drone systems to create a more efficient UAV design. In the design process, considerations were made for various environmental conditions, particularly wind. Consequently, the thrust-to-weight (T/W) ratio was determined to be 1.54. For cable cross section, a 1.5% voltage drop was accounted for, yielding a required cross section of 1.16mm². However, to ensure safety and reliability, a cable with a cross section of 1.5mm² was selected. This proposed model, distinct from other studies in the literature, offers a practical design for field applications, particularly for night SAR operations in disaster zones such as earthquake sites, due to its point-focus illumination capability and extended flight duration.

Keywords: Illumination drone, Tethered drone, SAR drone, Embedded system, Electronic control

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1. INTRODUCTION

Tethered drones, also known as tethered Unmanned Aerial Vehicles (UAVs), have become prominent in nighttime surveillance, search and rescue (SAR) operations, and security applications due to their unique operational benefits. Their tethered design ensures continuous power supply and stable data transmission through a cable connected to a ground station. This feature is especially advantageous for operations requiring extended flight times and stable performance under varying conditions. A primary benefit of tethered UAVs is their ability to deliver uninterrupted power, enabling continuous operations far beyond the limits of traditional drones reliant on onboard batteries. This feature makes them ideal for surveillance tasks such as securing large-scale events or monitoring critical infrastructure. Moreover, the tether provides high-bandwidth data transmission, facilitating real-time video streaming from onboard sensors, which is essential for effective surveillance (Kishk et al., 2020). Nighttime illumination capabilities are further enhanced by integrating advanced imaging technologies. For instance, UAVs equipped with thermal infrared cameras excel at detecting heat signatures, which is vital for identifying potential threats in complete darkness (Kays et al., 2018). SAR missions also benefit from this technology, as thermal cameras can detect temperature variations, helping rescue teams locate individuals in challenging conditions (Banuls et al., 2015). In urban areas, where artificial lighting and shadows complicate surveillance, the stability of tethered UAVs ensures high-quality imagery (Semsch et al., 2009). The tether stabilizes flight by enabling the drone to hover at fixed altitudes, which is essential for precise imaging tasks, such as monitoring large areas for security breaches or conducting SAR operations (Lemaire et al., 2019; Lai et al., 2023). This stability also minimizes video jitter, improving the clarity of the collected data (Lemaire et al., 2019). Furthermore, tethered UAVs can integrate with other unmanned systems, such as ground vehicles, to create comprehensive surveillance networks adaptable to various operational needs (Bushnaq et al., 2021). Beyond surveillance, tethered UAVs have seen increasing use in environmental monitoring and disaster management. They provide real-time data for assessing forest fires or post-disaster damage, aiding emergency responders (Tao et al., 2022). The integration of artificial intelligence (AI) and machine learning further enhances these systems, enabling automated tracking and object identification—particularly valuable in dynamic environments (Cherif et al., 2023). The configuration of tethered UAVs significantly impacts their stability and maneuverability, both of which are essential for effective surveillance. Optimizing tether dynamics allows UAVs to withstand environmental challenges such as wind and turbulence while maintaining stable flight paths (Tang, 2024). Their versatility makes them suitable for deployment in urban settings where obstacles or limited visibility hinder traditional surveillance methods (Semsch et al., 2009). Tethered UAVs have also demonstrated considerable potential in SAR operations. Integrating Visible Light Communication (VLC) and advanced sensors enhances their utility in rescue missions. VLC technology allows LEDs to function as both illumination sources and data transmitters, offering low energy consumption and high-bandwidth communication crucial for real-time data sharing during SAR operations (Ibraiwish et al., 2024). Furthermore, advanced sensors, such as radar and sound localization systems, improve the UAV's ability to detect vital signs and locate victims in distress (Islam, 2021; Hoshiba et al., 2017). UAV swarms, which autonomously coordinate to cover larger areas, further enhance search efficiency and operational flexibility (Khalil et al., 2022). Compared to traditional rescue methods, UAVs offer faster deployment in disaster zones, reducing response times and costs, thus improving rescue outcomes (Hashim and Tamizi, 2018). Additionally, they can establish temporary communication networks in disaster-stricken areas, facilitating coordination and decision-making (Mayor et al., 2019). Their deployment in maritime environments highlights their adaptability across diverse terrains (Alqurashi et al., 2023). In a study conducted with the Tello drone, rapid and flexible illumination was achieved. The study involved a small battery-powered drone autonomously navigating target areas to perform brief illumination operations (Ma et al., 2024). Additionally, another study developed drones with various lighting features to attract tourists' attention on the beach (Shirbhate and Das, 2019). In research focusing on drones that perform both illumination and communication functions, both features were integrated into a battery-powered drone. This UAV provides aerial lighting for emergency situations while also enabling communication (Huang et al., 2023; Yang et al., 2019). Furthermore, the drones are equipped with LEDs of different colors, allowing for visual shows. These drones can move in coordination, creating various visual displays in the air (Huang et al., 2023). In environments with low ambient light, such as outdoor shoots, drones equipped with lighting systems have been used to illuminate subjects. This offers a portable lighting solution for moving objects (Krátký et al., 2021).

Tethered UAVs integrated with advanced technologies represent a significant advancement in illumination night surveillance and SAR operations. Their ability to provide continuous power, deliver high-quality imaging, and adapt to various environments makes them indispensable tools in modern surveillance and emergency response efforts. This innovative study suggests that by adding an LED luminaire powered through the same tether, the effectiveness of these systems, particularly in areas like SAR and border security, will be enhanced. As a result, their applications will expand across a broad range of fields, from SAR to security and environmental monitoring.

2. MATERIALS AND METHODS

In this study, a tethered drone application was developed, with the necessary energy for the drone supplied using a cable. The AC power provided was used to feed an SMPS, which in turn delivered the required DC energy for the UAV. Additionally, an LED luminaire directly powered by AC was employed for illumination, eliminating the need for an extra DC converter. This approach optimized the weight of vehicle, resulting in a more user-friendly and practical design structure.

2.1 UAV Design

The most critical parameters in drone design are the weight of the UAV and the thrust force generated by the motors. In drone design, thrust (T) represents the motor's thrust force, while weight (W) denotes the total weight of the UAV. The ratio of these two values, T/W, must be greater than 1 for multicopter designs to achieve a lift-off. However, considering adverse factors such as wind resistance, maintaining this ratio above 1.5 is essential for optimal UAV performance. This ratio also directly affects the speed of maneuvers, making it generally recommended to select a T/W ratio between 1.5 and 2.0 for multicopter designs. Table 1 presents the materials used in the UAV and their corresponding weights.

Table 1. Component used in the drone, their weights, and total weight

Component	Quantity	Weight (grams)	Total Weight (grams)
Frame	1	380	380
Landing Gear	1	210	210
Brushless Motor	4	60	240
ESC (Speed Controller)	4	25	100
Autopilot	1	89	89
GPS	1	50	50

RF Transceiver	1	20	20
RF Telemetry	1	15	15
Power Module	1	15	15
Carbon Propeller	4	12	48
Cable for Tethered Power	20	16	320
LED Projector	1	142	142
100A SMPS	1	1650	1650
Servo 2 DOF Platform	1	30	30
		TOTAL	**3309 grams**

The aircraft was designed to operate at an altitude of 20 meters. For this purpose, a 2x1.5mm^2 pure copper cable was chosen. When calculating the weight, the scenario of the cable being fully extended was considered, resulting in the total weight of the 20-meter cable. The total weight of the aircraft was calculated to be 3309grams. The brand and the model of motors used are SunnySky 2814 900KV motors, paired with 10.5x5.5 carbon propellers, each providing a thrust of 1278 grams. With a total of 4 motors used, the total thrust ($Total_{Thrust}$) can be calculated using Equation 1.

$$Total_{Thrust} = Motor_{Thrust} \times 4 \tag{1}$$

When calculating using Equation 1, the total thrust is found to be 5112 grams. Accordingly, the thrust-to-weight ratio (T/W) is calculated to be 1.54. Each motor generates 1278 grams of thrust and draws 22.27A of current. For a total of 4 motors, the total motor current (I_{TM}) is calculated to be 89.08A using Equation 2.

$$I_{TM} = I_{Motor} \times 4 \tag{2}$$

For avionic components excluding the motor, the total current consumption (I_{TCO}) was measured to be approximately 0.45 A for other components such as the autopilot, telemetry, GPS, transceiver, and 2 DOF servo. Consequently, the overall current consumption (I_{TC}) was calculated as 89.53 A using Equation 3.

$$I_{TC} = I_{TM} + I_{TCO} \tag{3}$$

For DC conversion, a Gold 80 Series AC/DC converter was selected. Low-quality SMPS units may not provide the advertised power ratings under increased current demands, particularly with inductive loads such as motors, making them unsuitable for such applications. However, an 80 Plus Gold-rated SMPS meets these requirements and will not pose any issues when used in this type of aircraft (Joung et al., 2012). The specifications of the SMPS used in the UAV are presented in Table 2 below.

Table 2. The specifications of the SMPS used for the drone

Supply Voltage	Output Current	Output Voltage	Total Power
220V/AC	100A	12V/DC	1200W

The LED projector employed in this study is a 100W unit featuring a total of 128 LEDs and is designed to operate on an input voltage of 220V. Its compact dimensions of 173mm x 101mm were carefully selected to ensure unobstructed movement within the drone’s chassis. The on/off operations of the projector are controlled via a relay system, enabling the user to activate the device as needed. The auxiliary (AUX) outputs from the autopilot system have been utilized for this control mechanism. These output pins are specifically configured for On/Off operation and are assigned to a dedicated button on the transmitter. Figure 1 illustrates the relay circuit along with the transistor connection schematic, which is utilized for controlling the projector at 220V.

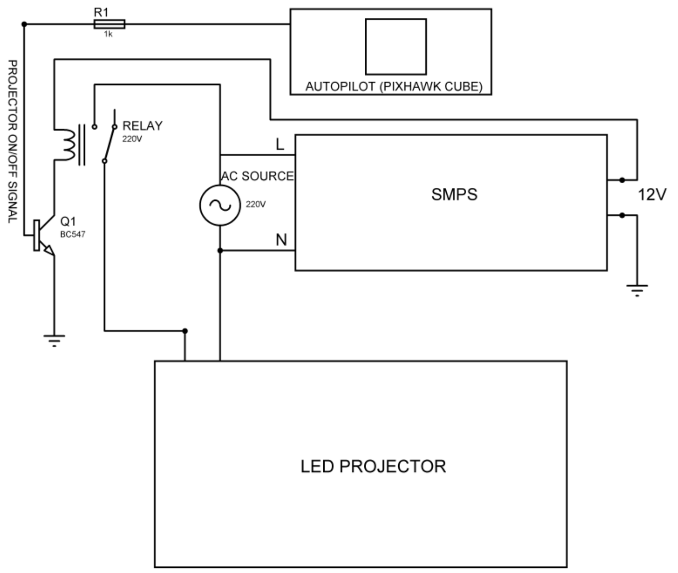


Figure 1. The schematic diagram used for controlling the projector's on/off function

A single NPN type BC547 BJT transistor was used to control the projector's on/off function via an On/Off signal. This transistor drives a relay which is activated to power the 220V projector when required.

Figure 2. Servo 2 DOF platform

For the pan-tilt control of the LED projector, a single 2 DOF servo platform, as shown in Figure 2, is utilized to achieve its orientation. Two of the AUX outputs from the autopilot are configured as servo drivers, and the servos were mounted accordingly.

2.2 Optimal Cable Cross-Section Selection

One of the most critical parameters for ensuring system safety and long-term operation in the design is cable cross-section selection. When choosing the cable, factors such as total power (T_{Power}), number of phases (Phase), cable length (L), desired voltage drop (e%), operating voltage (U), and the conductivity coefficient (K) of the conductor are of paramount importance for determining the cross-sectional area of the conductor. The parameter values used in the system are provided in Table 3.

Table 3. Cable cross-section calculation parameters used in the system

T_{Power} (Watt)	Phase	L (meter)	e (%)	U(Volt)	K ($\frac{S.m}{mm^2}$)
1175W	1	20	1.5	220	56

The total power (P_T) is determined by aggregating the power consumption of the entire UAV with that of the LED projector, referred to as P_L. This calculation is expressed in Equation 4, yielding a total power consumption of 1175 W.

$$P_T = I_{TM} \times 12 + P_L \tag{4}$$

Using Equation 5, (Özkaya and Tüfekçi, 2011) it was calculated that the cable cross-sectional area (S) should be 1.16mm² for a 1.5% voltage drop.

$$S = \frac{200 \times L \times N}{K \times U^2 \times e} \tag{5}$$

With a 25% safety margin, the closest higher cable cross-sectional area to this value is 1.5mm², ensuring that the voltage drop remains within a maximum of 1.5% for these system parameters.

2.3 Experimental Setup

In the study, a Pixhawk autopilot was used to ensure stable and autonomous flight of the UAV. This autopilot was selected due to its open-source software, which allows for configuration through external AUX and MAIN ports to accommodate various options. Additional AUX pins were utilized for controlling the projector's power functions as well as the pan-tilt adjustments. Figure 3 illustrates the system's connection diagram.

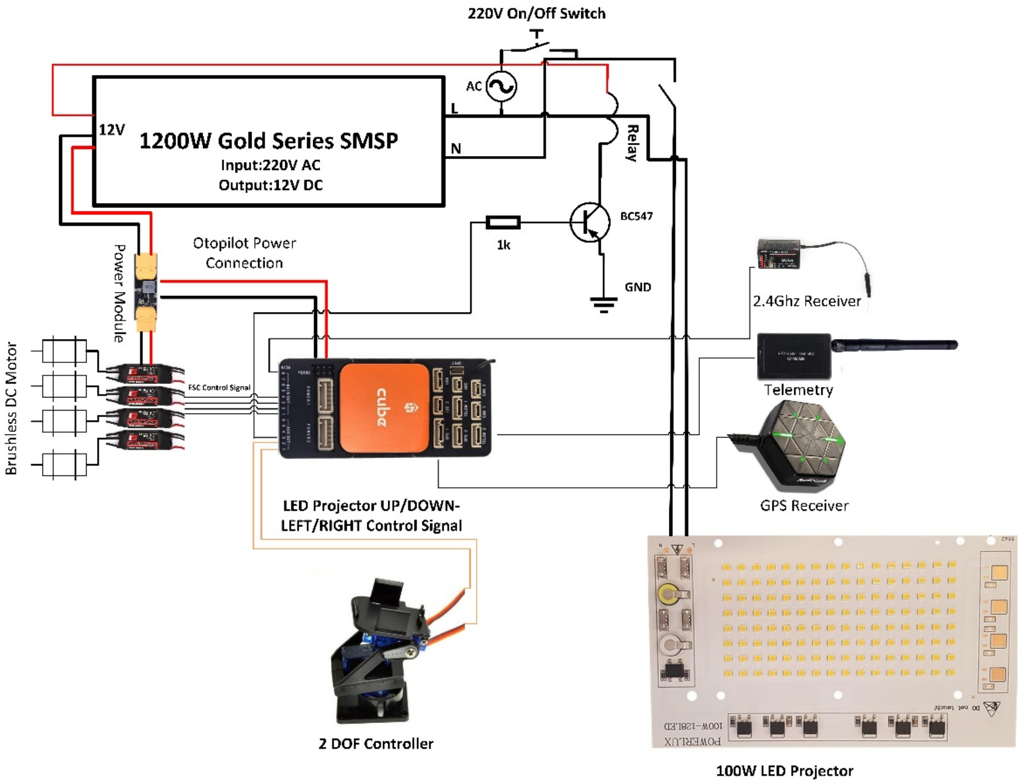
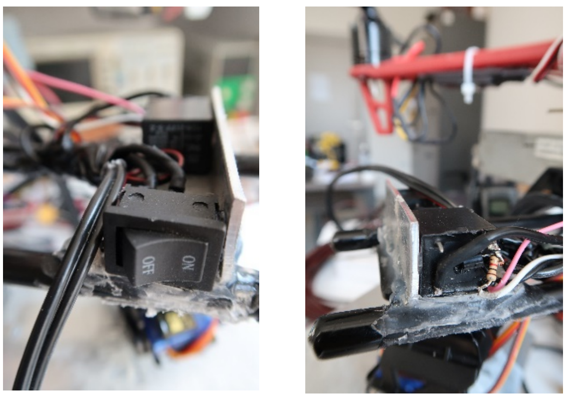


Figure 3. Tethered lighting drone system architecture

As shown in the Figure 3, the system includes essential avionics components required for a drone. The autopilot is connected to a GPS ground station for communication and to facilitate configuration loading, along with a telemetry module and a nine-channel 2.4 GHz receiver. The receiver operates in PPM mode using the RC-IN pin on the autopilot, freeing up the AUX pins for pan-tilt and on-off configurations. Additionally, a power module is included for power monitoring and to supply the autopilot. The motor control system comprises four ESCs and four brushless DC motors. The 2 DOF servos are connected to MAIN pins 5 and 6, and configurations are managed through the ArduPilot software. AUX pin 5 is configured as a relay on/off to control the LED projector's operation. Two gray adjustable inputs on the transmitter are assigned to channels 5 and 6 for pan-tilt control, with logical connections made via ArduPilot and telemetry. Figure 4 shows the UAV's projector on/off switch and main power switch.



(a) (b)

Figure 4. (a) On/Off switch and (b) relay transistor control circuit assembly

The switch depicted in the diagram controls the power to the system, allowing it to be turned on or off. In case of an emergency, the entire system can be powered down using this switch. The circuit shown in Figure 3 illustrates the relay transistor resistor connection required for the activation and deactivation of the lighting. This circuit has been mounted underneath the relay. The white wire is connected to AUX pin number 5, which has been configured for relay on/off control by the autopilot. The pink wire is connected to the 12V output of the SMPS, providing power to the relay coil. The black wire is connected to the common GND of the system's DC side.

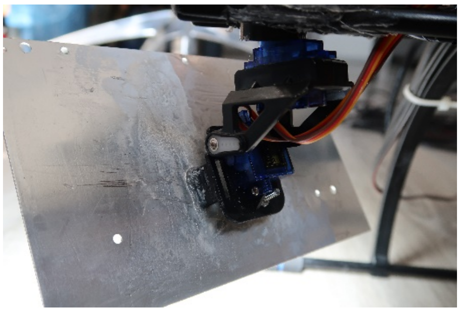
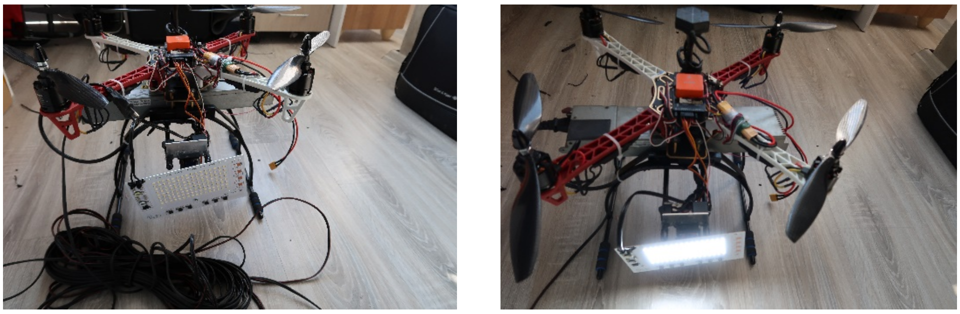


Figure 5. Pan-Tilt mechanism and projector assembly

Figure 5 illustrates the pan-tilt mechanism, which includes two servos and servo mounts. The LED projector is mounted onto the mechanism to enable directional adjustments. The servos are connected and powered through yellow, red, and brown wires. These connections are made to the MAIN outputs on the autopilot, specifically pins 5 and 6, ensuring both control and power supply for the servos.



(a) (b)

Figure 6. (a) System configuration with mounted AC cables (b) Operational system with active projector

Figure 6(a) shows the system with mounted cables, SMPS, and LED projector, including a 20-meter cable connected to a 220V outlet connector. Additionally, an XT60 connector has been installed on the 12V output of the SMPS to facilitate easy connection and disconnection of the power module. Figure 6(b) depicts the system energized with the projector turned on.

3. RESULTS AND DISCUSSION

It has been observed that the 80 Plus Gold Series SMPS continues to operate at high performance levels under full power. The circuit designed for the system's power on/off function has been seen to perform its switching operations reliably. In the configuration, when the button on the remote control is activated, the relay triggers, powering the projector with 220V.

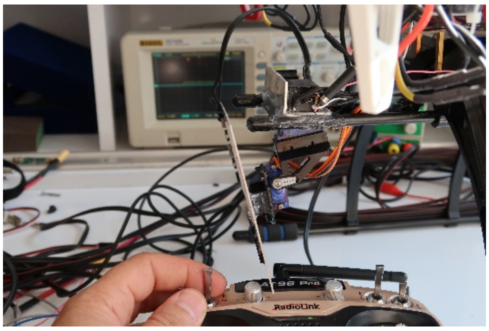


Figure 7. Measurement configuration for trigger signal generated by the on/off switch on the remote control

Figure 7 shows the experimental setup used to measure the trigger signal generated at the AUX 5 pin of the autopilot when switching occurs. For the measurement, one channel of the oscilloscope is connected to the resistor at the base of the transistor. During this process, the on/off operation is performed via the remote control, and the trigger signal is measured using the oscilloscope.

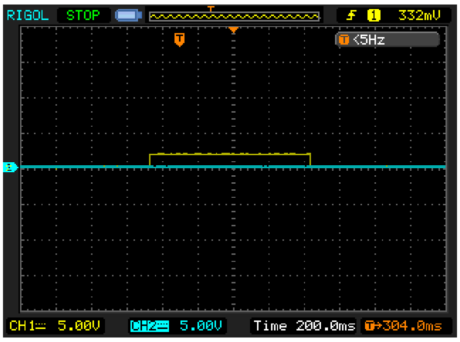


Figure 8. Trigger signal display on the oscilloscope screen

In Figure 8, the oscilloscope screenshot of the trigger signal is shown. As seen on the oscilloscope screen, when the on/off signal is sent from the remote control, a logic 1 signal appears on AUX pin 5, and it returns to 0 when turned off. The peak value of the logic 1 signal is measured at 3.3V. Thus, this signal triggers the transistor to drive the relay, which safely controls the 220V supply to the projector.

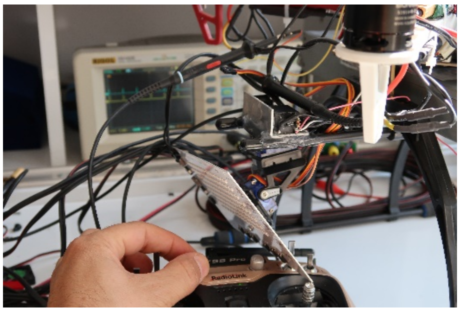


Figure 9. The test setup for measuring the channels while adjusting the pan-tilt controls on the transmitter

The test setup for measuring PWM signals from the MAIN 5-6 channels, connected to the outputs, as observed through the oscilloscope, is shown in Figure 9.

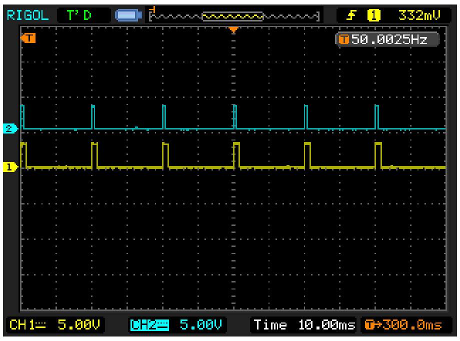


Figure 10. When adjusting pan-tilt controls on the controller, the PWM signal waveforms of the channels on the oscilloscope screen

In Figure 10, it is observed that the PWM signals are successfully generated while controlling the channels from the remote. Additionally, when the signal transmission from the remote is stopped, the last position PWM values continue to be output, resulting in the projector remaining fixed in its last position. Tests have shown that the designed system operates without issues, and the drone is capable of flying smoothly. The calculated T/W ratio of 1.54 clearly demonstrates that the aircraft remains stable even in windy conditions. Furthermore, the pan-tilt mechanism was tested for extended periods. The projector's on-off operations were carried out smoothly, and the system was observed to perform its tasks without problems. Although the projector was noted to heat up during prolonged ground tests, it was observed to cool down due to the airflow generated by the two front propellers during flight. Therefore, no additional cooling unit was installed to avoid increasing the aircraft's weight, as it would not overheat during operation.

A review of the literature reveals that various studies on lighting drones present distinct advantages and disadvantages. In Table 4, the proposed tethered lighting drone from this study is compared with other lighting drone designs found in the literature.

Table 4. A Summary of illumination works

Reference	Wide-area Illumination	Suitability for Disaster Zones	Long Operation Time	Flexibility	Continuous Operation	Adjustable Lighting Direction	Operation at High Altitudes
Huang et al.	×	√	×	√	×	×	√
Ma et al.	×	×	×	√	×	×	√
Shr. and Das	×	×	×	√	×	×	√
Krátký et al.	×	×	×	√	×	×	√
Yang et al	×	√	×	√	×	×	√
This paper	√	√	√	×	√	√	×

Since illuminating large areas requires a powerful LED or lighting fixture, the LED projector used in this study is larger than those in comparable works, allowing for significantly broader area coverage. Considering the requirements for disaster zones, the need for long-term illumination of extensive areas becomes evident. The use of small, battery-powered drones in other studies limits their applicability for SAR operations in disaster areas. When examining other designs, it is evident that the proposed drone is powered by a cable from the ground. This configuration enables the drone to remain airborne for extended periods, ensuring continuous illumination of the designated area. The designed drone has limited mobility due to its tethered configuration; however, it can operate freely within the range of the cable length. If required, the cable length can be increased with a modified design to expand the operational range. Since the drone in this study is powered through a tethered system, it provides uninterrupted illumination compared to other battery-powered drones. In contrast, battery-powered drones need to land for battery replacement once depleted, preventing continuous illumination. The proposed tethered drone is equipped with a servo-controlled LED projector system, enabling precise illumination of the desired area. In comparison, other drones need to maintain a specific angle to achieve targeted lighting, which can negatively impact their flight duration. Drones that operate independently of cables can ascend to higher altitudes; however, as altitude increases, illumination intensity decreases, necessitating operation at an optimal height. Exceeding a certain altitude creates disadvantages for effective lighting, making the 20-meter cable length sufficient for the optimal height in this tethered design. From this perspective, the height limitation is not a significant disadvantage for the lighting drone.

When considering potential applications, such as in disaster zones, area surveillance, or border security operations, the advantages of the tethered lighting drone demonstrate that it is more suitable than wireless designs for these use cases.

4. CONCLUSION

In the conducted study, the wired illumination drone was successfully operated, completing its application. The system's T/W ratio of 1.54 ensured that it continued to perform effectively even in adverse weather conditions, as demonstrated by the tests. Additionally, the drone's power supply through the cable enabled it to operate for extended periods. Despite the total DC power requirement of 1075W, the design included a high-performance SMPS and a 1200W operating mode (at 220V) with a 20% tolerance, allowing for long hours of operation without overheating. The cable cross-section, calculated for a 1.5% voltage drop, was found to be 1.16 mm², but considering the tolerance factor, a 1.5 mm² cross-section was chosen. This choice ensures high system performance and prevents overheating issues.

Moreover, system configurations were made for the on-off functionality of the LED projector via the controller. The integration of the pan-tilt mechanism for focusing the projector on the desired area in flight was completed, enabling successful point illumination control through the remote. The projector was mounted underneath the front propellers to facilitate cooling, thereby maintaining high performance and operational stability without increasing the T/W ratio. Unlike previous studies, this work combined the powerful features of tethered drones with the capabilities of illumination drones, resulting in an innovative aerial vehicle. This design provides a flexible and innovative solution for long-term illumination in nighttime disaster response, SAR operations, border security, and specialized area lighting.

In future studies, a reflective-type LED projector with higher luminous power can be utilized to illuminate larger areas, particularly during disaster scenarios, ensuring broader coverage.

5. ACKNOWLEDGEMENTS

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6. CONFLICT OF INTEREST

Author approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper

7. AUTHOR CONTRIBUTION

Tarık ÜNLER has the full responsibility of the paper about determining the concept of the research, data collection, data analysis and interpretation of the results, preparation of the manuscript and critical analysis of the intellectual content with the final approval.

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