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Investigation of Visual Disappearance by Intelligent Illumination of Exterior Surfaces of Unmanned Aerial Vehicles

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Abstract

Nowadays the elimination of the visual trace is very important, especially for the low altitude unmanned ait vehicles (UAVs) to protect from their enemy targets. For UAVs, which are widely used in both civil aviation and military fields, the issues of being undetected by visual and auditory and radar are have critical importance. For this reason, visual trace destruction has been taken into consideration at this work.

For this purpose, the design of the UAV with the intelligent illumination system and disappearance technology in the desired environment has been discussed. For this purpose, a UAV with a weight of 2,5 kg, a wingspan of 1,3 m, a length of 1 m, with a brushless electric motor, mid-range, medium-height, and moderately hovering features has been produced. Lighting system equipment is placed on the fuselage, wing and tail structure of the UAV. Flight tests were carried out by installing the appropriate lighting system in order to give the UAV the ability to disappear.

In the application study on the examination of the disappearance of UAV's by intelligent illumination of the outer surfaces, the design of the Intelligent illumination system and the application of the outer surface lighting were carried out.

1. Introduction

Today's technological developments have increased the studies on UAVs and made UAVs a popular engineering application field. UAVs have performed the observation and analysis of many military and civil applications and situations in daily life quickly and safely with meteorology, aerial mine detection, digital mapping, electronic warfare, rescue, aerial photography and video graphics, traffic surveillance, small package transport, scientific research, etc. (Austin, 2010; Konar, 2019; Konar et al., 2020; Kekec et al., 2020; Yildirim Dalkiran et al., 2021; Kekeç et al, 2021).

In the process of observation and inspection of UAVs, the invisibility feature has a great contribution to the UAV in terms of camouflage. UAVs designed for special missions also have made great contributions to users thanks to visual invisibility. In order to occur the concept of visual invisibility in UAVs, there should be occurred a contrast between the surface of the UAV and the background (sky) below the contrast threshold that the naked eye can detect.

It is known that when this contrast threshold occurs, the most suitable conditions for UAV visual disappearance are provided.

Unmanned Air Vehicle (UAV) is a kind of plane in which there is no pilot or any living being to control the vehicle, but there have only suitable equipments for the function such as a camera, laser scanning machine or GNSS. The management of plane is provided by remotely or automatically controlling. Due to the military, civil (hobby and commercial) and scientific uses UAVs are becoming more and more widespread. There has clear insights in today's life that UAVs will gain a big role in our future. Among the main reasons for these interests are the wide range of uses for civil-purposes UAVs as well as, it can be included the high accuracy, time and cost savings (Konar, 2020; Traub et al. 2021; Gur et al. 2009; Avanzini et al. 2013; Chang et al. 2015; Chamaidi, 2006; Igaw, 1999; Hsu, 2015; Koçkanat, 2020; Koçkanat et al. 2015)

The first studies on giving visual disappearance feature to the UAV date back to 1943. In the Second World War, the United States Army have started the Yehudi Project (Barrett et al., 2005; Chamaidi, 2006).

Today, the loss of visual trace is of great importance, especially for small UAVs that fly at low altitudes, so that they cannot be detected by their targets.

There are some studies about sky luminance and visual disappearance feature in the literature (Barrett et al., 2005; Macheret et al., 2011; Chamaidi, 2006). However, there are very few studies on bringing this feature to the UAV.

A study examining human vision has been conducted by Wu et al. in 2009 (Bo-Wen, 2009). In this study, image recognition based on the classification of human vision has been based and human eye modelling has been emphasized. In the studied models, the Optical Transfer Function (OTF) curve has been used as the evaluation-recognition capability and the optimum recognition model most suitable for human eye physiology has been summarized. However, they stated that their studies continue to create a more suitable model because there are a number of aspects to handle such as age, brain, vision process, CCD/CMOS sensitivity, display characteristics, human night vision etc.

In another study in 2015, Hsu et al., have designed a thin dielectric meta-surface using the reflection pattern of a flat surface (Hsu, 2015). By equating the angle of reflection to the angle of incidence, it has been stated that the observer sees a flat ground instead of a dispersed surface, with a gradual meta-surface design. Extremely low wavelength dielectric resonators have been used for the meta-surface and the phase value required to achieve concealment has been calculated.

The methods which are used in the second part of the application study on the investigation of visual disappearance by intelligent illumination of exterior surfaces of unmanned aerial vehicles have been discussed. In the third part, the design of smart lighting system and the illumination of exterior lighting are given. In the last section, the results are given.

2. Method and Procedure

In this part, visual disappearance technology, and analysis of invisibility in different conditions, theoretical infrastructure for invisibility, design of UAV and mechanism design for invisibility have been discussed.

2.1. Disappearance Technology

Today, the removal of visual trace can be achieved efficiently with the following technology-method: When cover of UAV which is luminous with electricity is brightened enough to create a level of contrast between the sky as the background and the UAV surface, which is the main surface, below the contrast level that can be perceived by the human eye, the relevant UAV will not be detected by the naked eye by the target on the ground (Igawa, 1999). In this way, invisibility will be ensured. In the figure 1, it has been presented the reduction and elimination of visual detection of a UAV with illumination at different altitudes (Hambling, 2020; Barrett, et al., 2005; Macheret et al., 2011). Visibility decreases with illumination at 5 m altitude, while at 300 m, invisibility has been fully achieved.

Figure 1. Visual detection analysis

2.2. Theoretical Background for Invisibility

Invisibility can be ensured when a contrast occurs between the surface of the UAV and the background (sky) below the contrast threshold that the naked eye can detect. This contrast threshold depends on the sky luminance and the eye's viewing angle of the UAV. Luminance refers to the intensity of light emitted in a certain direction from the unit area of the surface. Because of the intensity of light does not depend on the distance between the observer and the point whose luminance is calculated, luminance is also independent of the distance in between. Although brightness is an objective magnitude which is based on subjective evaluations by observers. Brightness largely both depends on the luminance of the surface, and also on the overall luminance distribution in the field of view, called adaptation luminance (such as the gray square on a white background appearing darker than on a black background, although they have the same luminance).

The correlation expressing the contrast threshold, sky luminance, and the eye's viewing angle of the UAV has been presented in Figure 2. (Barrett,R et al., 2005; Macheret et al., 2011). In Figure 2, the x-axis represents the sky luminance in foot-lambert units on a logarithmic scale, and the y-axis represents the contrast threshold perceived by the naked eye on a logarithmic scale. In this way, the object viewing angle of 5 different eyes has been handled in terms of arc minutes. These are 3.6, 9.68, 18.2, 55.2 and 121.0 arc minutes. In order to better understand the above shape and relations, it has been briefly summarized in Equation 1, which expresses the concept of luminance necessary for contrast and invisibility. The contrast can be found with the following formula (Equation 1):

$$C = \frac{L - L_B}{L_B} \tag{1}$$

In 1 in equation L; the luminance level of the object, L_B the luminance level of the background, and C; represents the level of contrast between the object and the background.

Luminace required to achieve contrast invisibility can be found by the following formula Equation 2. (Bo-Wen, 2009; Macheret et al., 2011; et al., 2011; Gordon, 1964; Blackwell, 1964). The lighting system on the UAV will create luminance at this level and it will be invisible to the eye.

$$L_0^* = L_B\left(1 - C_t\, e^{aH\frac{m}{m_0}}\right) \tag{2}$$

In Equation 2 (Macheret et al., 2011) a; damping coefficient, m; mass density of air in kg/m^3 at the level of the object, m_0; is the mass density of the air in kg/ m^3 at the zenith point. C_t; contrast threshold perceived by the naked eye, H; is the atmospheric altitude setting.

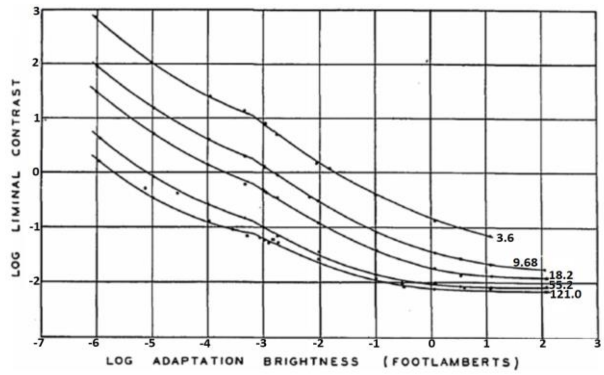

Figure 2. The amount of contrast required for invisibility in different sky luminance and the eye's different viewing angles

2.3. Analysis of Invisibility in Different Conditions

In Figure 3 (Macheret et al., 2011), the variation of the threshold light power required for invisibility at different times of the day with altitude and area has been given (for 10.30 in the morning and at sunset). When viewed with this graphic, an object must be almost the same with the sky luminance to disappear (Bo-Wen, 2009).

2.4. Design of the UAV

At this part, first of all, the data of the UAV, which is planned to be produced, and the technical drawings of the UAV have been handled (Coban et al., 2018). In addition, the inertia matrix terms have been determined along with the positions of the luminance strip panels. The inertia matrices of the fuselage, wing and tail, which have luminance strip panels, have been found, and the parametric variation of the inertia matrix has been determined by the Parallel Axis Theorem (Oktay et al., 2016, Coban et al., 2018). Finally, a few basic assumptions used for the power assembly and have been passed in the manufacturing phase. The planned UAV will weigh 2.5, have a NACA 2415 profile with a width of 1.3 m, a length of 1 m, an electric motor, mid-range, mid-altitude flying, and moderately hovering. The presentation of the UAV is given in Figure 4.

2.5. Mechanism Design for Invisibility

Smart lighting system which is designed by detecting the sky luminance and the light dependent sensor will be given as an input to the control card. An external ground station control input will be added to the smart lighting system control card for any malfunction in the light dependent sensor. These two inputs will be processed on the smart lighting system control card and information will be sent to the luminance strip panel. Thus, the UAV, which will have the same luminance level with the sky, will be provided invisible.

The first control of the mechanism will be done on the ground. At the stage of ground controls, the sensitivity test of the mechanism to be measured with a lux-meter will be carried out. Then, the device tests will be carried out during the flight, and the UAV will be provided invisible (Figure 5).

The control chart of the mechanism to be used for invisibility is given in Figure 6. According to this scheme, an Arduino-based main control card will be used in the project works.

Arduino-based main control board will be programmed depending on 4 basic inputs: light dependent sensor input information, ground station lighting input, ground station selection control and ground station lighting active/passive control. The light dependent sensor input information will be obtained with the light dependent sensor, which offers a linear output between 0 and 2.3 volts at its output, depending on the sky luminance.

Thus, the sky luminance will be measured. The ground station luminance information will form the input where the amount of luminance can be adjusted manually by the ground station. The sky luminance information sent by the ground station will be received via the receiver on the aircraft. Another function of this input is that it allows the aircraft to be manually controlled against any malfunction that may occur in the light dependent sensor. With the ground station selection control input of the main control card, it will be possible to select whether the light dependent sensor or ground control input will be used to adjust the luminance. The last input information of the main control card (ground station lighting active/passive control) will be used to activate the lighting system. In terms of flight safety, the active and passive lighting system will be made by the ground station. Again, the control card will automatically deactivate the lighting system in case of disconnection from the ground station.

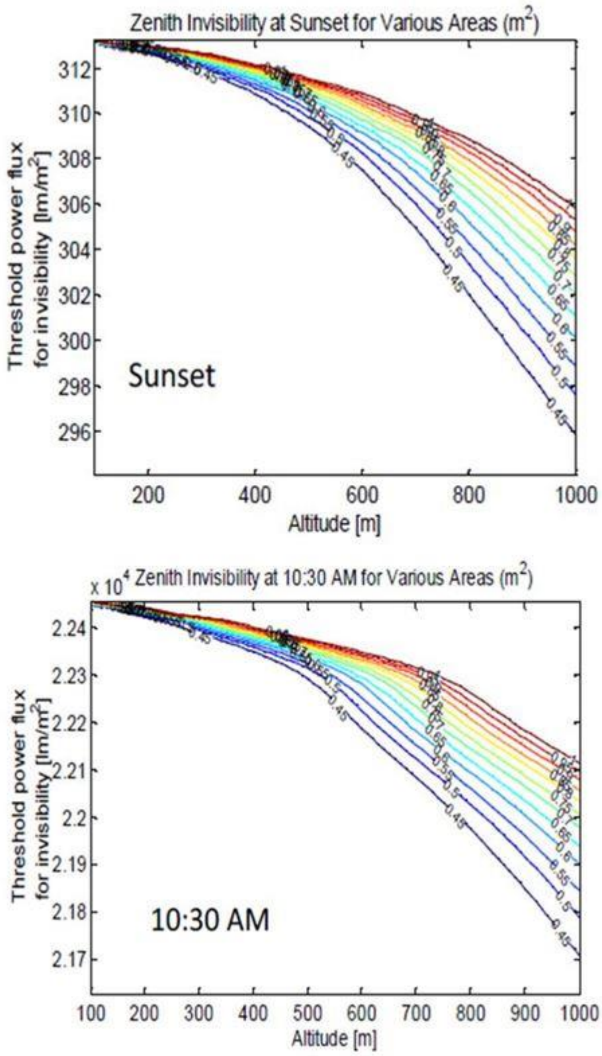

Figure 3. The variation of the threshold light power required for invisibility at different times of the day with altitude and area

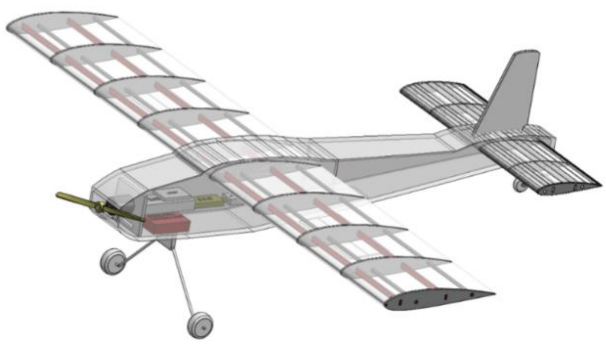

Figure 4. Demonstration of UAV

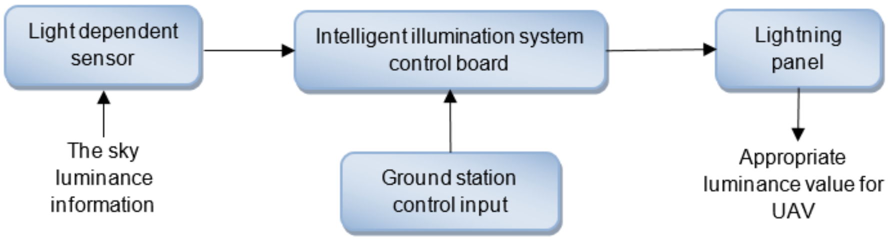

Figure 5. The mechanism used for the invisibility

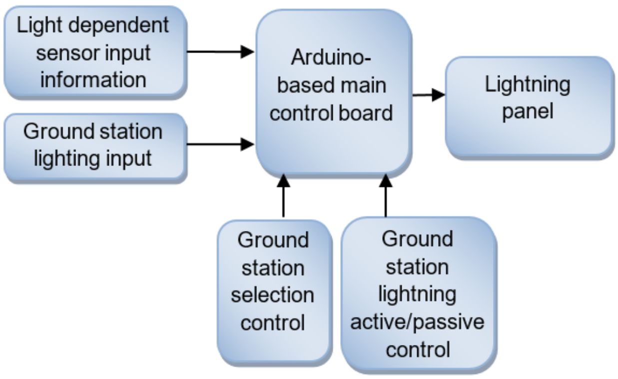

Figure 6. The working scheme of the mechanism used for invisibility

3. The Practice Phase

3.1. Circuit Diagram and Working Principle

The circuit diagram created for the smart lighting system is given in Figure 7. 555 integrated circuit is used as an astable multivibrator in this study. The capacitor C2 in the circuit is connected to the trigger (pin number 7) of the integrated circuit and is charged through the LDR in the circuit. This charge time varies depending on the RC time constant, where the "R" resistor is the LDR internal resistance. This resistance change causes the charging time of the capacitor C2 to change and as a result, the output frequency to change. Since the change of the output frequency will also change the time that the BD664 transistor connected to the output remains on per unit time, the power transferred per unit time on the load will change. Since the internal resistance of the LDR changes depending on the light change on it, it will show low internal resistance in cases where it receives a high amount of light, accordingly the output frequency will increase and the power transferred to the load will be high. On the contrary, when it receives low amount of light, it will show high internal resistance, accordingly the output frequency will decrease and the power transferred to the load will be low. In summary, the led lighting, this is used as a load in the circuit, will shine brightly under high light and dim under low light.

In Figure 8 the frequency value of the circuit in low light and in Figure 9 the frequency values of the circuit in high light are presented. In addition, before the printed circuit stage of the circuit, the circuit diagram has been tested on the board.

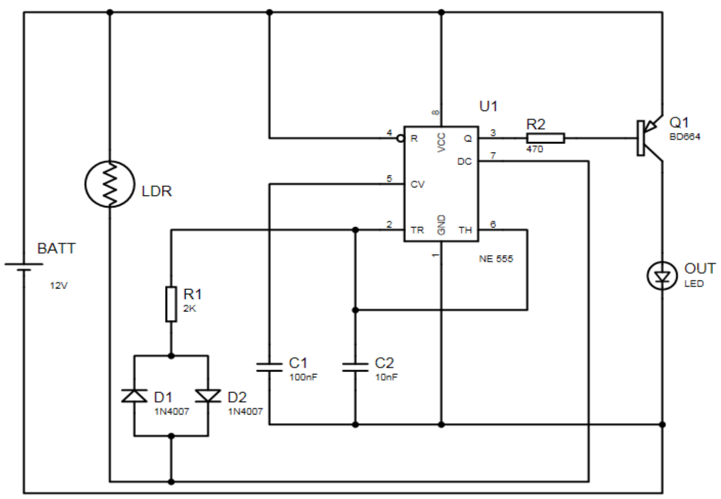

Figure 7. Circuit diagram

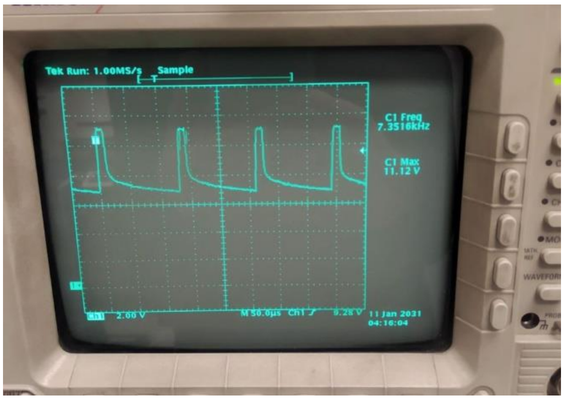

Figure 8. Frequency value of the circuit in low light conditions

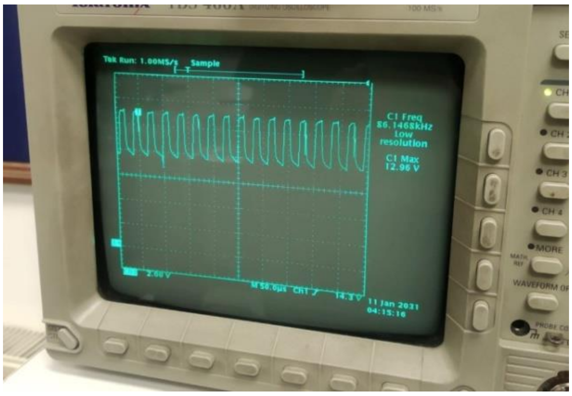

Figure 9. Frequency value of the circuit at high light conditions

3.2. Pre-flight Tests

It is of great importance to conduct ground tests before the flight. The most important of these is weight weighing. After weight weighing, the weight of the UAV must be covered by the propulsion system. If there is no enough propulsion system or the weight of the UAV is more than the calculated before, it will cause to the UAV not be able to fly. Therefore, the relationship between the Weight propulsion systems needs to be adjusted correctly. In Figure 10, the measurement of the gravitational force obtained from the propulsion system of the UAV is given.

The installation of the smart lighting system on the UAV is given in Figure 11 and Figure 12. As can be seen in the figure, the operating test at maximum brightness has been carried out in the UAV workshop environment. It has been checked whether the test time is sufficient for a 20-minute flight. The maximum brightness test has been carried out by using the manual input of the smart lighting system, that is, by giving it from the remote control. In this process, the change between the maximum and minimum levels has been observed by increasing and decreasing the brightness level from the dimmer channel of the controller. During this change, the smart lighting system circuit has worked well. After manual control, sensor control, which is smart lighting control, has been passed. It has been checked whether the smart lighting system works or not, taking into consideration of the sensor and the sky luminance. The representation of the sensor used is given in Figure 13. In Figure 14, the display of the brightness measurement of the UAV is given.

The brightness test of the smart lighting system installed on the UAV has been performed indoors, and the brightness level has been measured with luxmeter. In this measurement, it has been observed that luminance was obtained at the daylight level. After these tests, the flight test has been started.

Figure 10. Propulsion test of the UAV

Figure 11. Display of UAV’s lighting

Figure 12. Illuminated UAV display

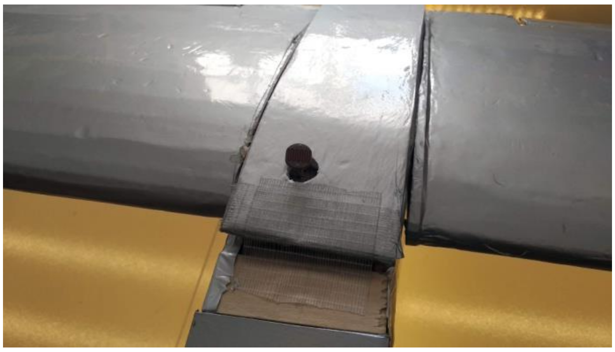

Figure 13. The representation of the external surface sensor on UAV

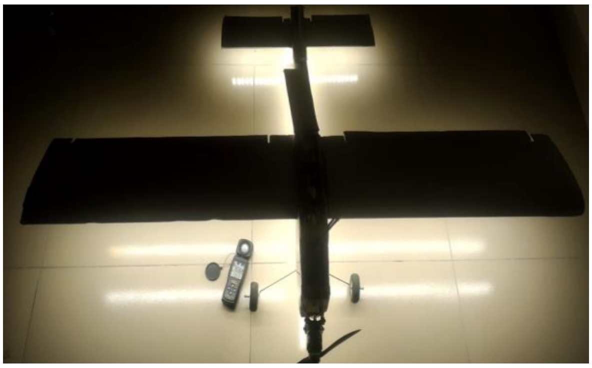

Figure 14. Display of the brightness measurement of the UAV

3.3. Flight phase

After the tests such as weight, accuracy test and balance, which was made in the atelier environment, UAV has started the flight phase. The flight phase consists of two phases. From the first stage, flights have been made without smart lighting system and the necessity of trim and balance settings have been checked. After these settings, a stable UAV is set.

The second flight stages are the flights with the smart lighting system. At this stage, first of all, stability has been taken into consideration, and after a stable UAV has been formed, the smart lighting system has been put into use in order to get visual disappearance feature.

A view from the first flight tests of the UAV is given in Figure 15. Take-off and flight views of the UAV are given in Figure 16 and Figure 17.

Figure 15. The view of the UAV in flight tests

Figure 16. Take-off view of the UAV

Figure 17. Aerial view of the UAV

3.4. The Disappearance of the UAV

With the completion of all ground and flight tests, the smart lighting system has been put into use. This stage, which has been carried out on the Talas Municipality Model Airplane Runway, has been tested in clear weather conditions. First of all, this test has been carried out in a short time, and it has been tried to avoid accident crashes of the UAV. Accidents have been experienced in the long-term trial. In the light of the findings related to the study, it has been observed that the visual disappearance changes depending on its location relative to the ground. It is obvious that visual disappearance obtained from different perspectives will be different. As a result of the study, it has been concluded that the UAV visually disappeared at an altitude of 300 meters in the view given in Figure 18.

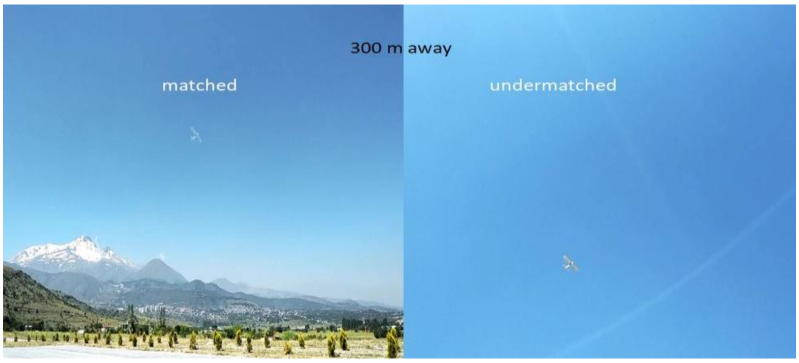

Figure 18. Comparison of UAV disappearance in mid-air

4. Results

In this study, UAV which has an electric brushless motor, 2,5 kg weight, 1.3 meter wingspan, 1 meter longitudinal length has been produced. The design and production stages of the UAV are explained. UAV electronic components used after production have been introduced. With the completion of the UAV, flight tests have been made.

In the study, the sky luminance has been detected by the light dependent sensor and given as an input to the designed smart lighting system control card. Also, a second ground station control input has been added for control at the ground station. These two inputs have been processed on the smart lighting system control card and the LED lighting level has been adjusted. The first control of the apparatus has been made on the ground in a dark environment, using a luxmeter. Then, the setup set up during the flight has been tested.

After successful flight tests, the designed smart lighting system has been installed on the UAV. Flights have been carried out with the smart lighting system. Visual disappearance has been observed with the activation of the smart lighting system in flights.

Ethical approval

Not applicable.

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