

Human-Centered Drone LED Illumination System: A Proof-of-Concept Prototype

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Recent years have seen a rapid increase in drone usage in both commercial and personal use, due to recent changes in guidelines by the Federal Aviation Administration (FAA). In those guidelines, however, there seems to be very few requirements in terms of illumination requirements, apart from the need to use a visible strobing anti-collision light for nighttime operations. Hence in this study, we reviewed existing LED illumination systems in off-the-shelf drones to determine what type of configurations they have and how is the LED illumination system generally used. We also introduced a customizable LED illumination system and tested it in a human in the loop study. Our preliminary findings have revealed that the colors that are preferred by the participants did not match the most used colors in existing LED illumination systems in most off-the-shelf drones. We also observed a possible relationship between the color preferred and the weather conditions.

INTRODUCTION

Throughout their existence drones were mainly used in the military for aerial reconnaissance and bombardment (Blom, 2010). Commercial use for drones however came much later and officially started when the FAA issued its first drone permit in 2006. Commercial drone usage did not become mainstream until the mid-2010s, mostly due to the low number of permits issued by the FAA. Starting in 2016, FAA relaxed its regulations, allowing more companies to use commercial drones. The number of drones has skyrocketed since then and it continues to grow. According to the most recent number from the FAA, more than 1.7 million drones are registered across the US up from 300 thousand when drone registration first began in late 2015 (FAA, 2016; 2020). Among the 1.7 million drones registered, many of them are for personal use, but a significant number, 520,541 are commercial.

The principal regulations for commercial drones are in the 14 CFR Part 107, Small Unmanned Aircraft Systems. Part 107 covers three main topics; operating rules for drones, regulations on how to be certified as a drone pilot, and lastly waiver information on operating in otherwise prohibited settings. The operating rules cover topics such as the ideal state of the drone operator, prohibited airspace for drone operation, and safe drone operating procedures. However, in terms of the specificity of these regulations, they tend to be on the broader side. For example, Part 107.39 states that drone operation is prohibited over people unless they are directly participating in the operation of the drone. However, there is no information on the minimum required distance between the drone operator and the drone or other people that are part of the drone operation.

Comparing the regulations and safety precautions of other manned vehicles such as cars which are also primarily used by non-professionals, we can observe ample amounts of visual cues that indicate their status and intention (e.g. where the vehicle is headed, whether the car is decelerating or stopping). The absence of these indicator lights is illegal and punishable by a fine. Even in other vehicles such as planes and boats, it is a requirement to have an indicator light of some sort to tell where the vehicle is headed. However, as of right now, these

indicator lights are largely missing from drones. The only requirement in terms of lighting during drone operations is having anti-collision lights for operations after sunset. These lights must be visible for three statute miles, have a strobing pattern, and be either white or red. There are not any requirements on signaling the drone's intended or current direction. The lack of such lighting systems is understandable as previously the drone applications were almost all in open spaces and far from humans (Veroustraete, 2015; Restas, 2015). However, with the unprecedented advancement in ubiquitous drone technology, it is only a matter of time when close-quarter human-drone interaction scenarios are (e.g., drone delivery, drone-based traffic control, drone-based surveillance) commonplace (Brunner et al., 2019; Cohn et al., 2017). This presents a significant security problem for drone operators, people who will interact with drones, and people who are in the general vicinity of the drone. The lack of human-centered drone lighting systems represents a gap that must be filled before truly ubiquitous Human Drone Interaction (HDI) can become a reality. Therefore, in the current study we aim to initiate the effort in filling this gap. Firstly, we will present a review of present illumination systems of the most used drones in the US. Subsequently, we will introduce a human-centered LED illumination system prototype and assess its feasibility with a human in the loop study.

OVERVIEW OF OFF THE SHELF DRONES

While selecting which civilian small drones to investigate, we looked at the market share of companies in the US. According to an industry report for 2019, DJI Inc. dominates drones' sales in the US, with a 76.8 % market share in the US (Schroth, 2020). Its nearest competitor, Intel has a much smaller share with 3.7%. Thus, we included more than one DJI model in our analysis to cover their product lineup. We also included primary competitors of DJI that make similar drones, so drones from companies such as Autel, Parrot and Yuneec were included in the investigation. We also factored in drones that are geared towards the introductory level. Companies like Holy Stone and Ruko make relatively cheap camera drones (their most advanced offerings are around ~\$300 compared to \$1600 of DJI Mavic 2). Apart from being inclusive in terms of market representation, we wanted to include drones with different

designs, as the drone market is currently populated by quadcopters with foldable wings. Hence, we included hexacopter drones such as the DJI Matrice and Yuneec Typhoon H3 and the DJI Phantom 3, which is a quadcopter with skids.



Figure 1. Drones that are Included in the Review. From the Top Left Autel Evo II, Parrot Anafi, Ruko F11 Pro 4K, DJI Phantom 3, DJI Matrice 200, DJI Mavic 2 Pro, Yuneec Typhoon H, Intel Falcon 8+

The LED lights that are equipped are mainly used for two purposes, indicating which direction the drone is facing, and conveying system information (ready to fly, connection error, calibration etc.) to the user. The colors that are used in drones are not universal and change from manufacturer to manufacturer. However, the placement of LEDs seems to be consistent in some types of drones, especially the foldable quadcopter design. In DJI's Mavic Pro 2, Autel's Evo II, and the budget Ruko F11 all have their LED lights located at the side of the motors, facing outwards. Among the foldable drones that are reviewed, only Parrot Anafi had LED lights in a different location which was on the bottom. As the design becomes more complex, such as in commercial-grade drones, light placement becomes more varied. For the Yuneec Typhoon H for example, the LEDs are placed underneath the motors and at the end of the main body facing backward, and for Intel's Falcon 8+ it is placed on the sides of the main body of the drone. When it comes to the colors that are used, the most common ones were red, blue, green, and yellow with white and purple also being used in some drones. DJI drones seem to have the same lighting scheme with the front 2 lights being solid red and back two lights indicating the status of the drone while flying, with a green blinking lighting indicating the drone is ready to fly and in GPS mode. The backlights start to blink red when the low battery warning is triggered. Red is mostly used in drones to either indicate low battery or critical system failure. The Parrot Anafi has a different set of colors, with the main color being blue. Different shades of blue are utilized for different statuses. In Anafi's case, a steady dark blue light indicates the drone is ready to fly. The Autel Evo II has a similar lighting setup as its main competitor Mavic Pro 2, however, the most significant difference of the Evo II is that the body has a bright orange color akin to a traffic cone. The Yuneec Typhoon H3 has the most variety in terms of LED colors, with red, purple, green, blue, white, yellow, and orange used in at least one instance. During the flight, the front two LEDs are lit white, the left one blue and the right one green. The back LED changes

colors and patterns according to the flight mode that is selected and the system condition.

Although the current LED systems of common off-the-shelf drones do a good job indicating the drone's current condition and the orientation of the drone, they lack a few key elements. Firstly, none of the current LED lightings that are listed in our review are customizable in terms of lighting color, pattern, and lighting intensity. LED color that is not suitable to the weather conditions that are existing limits the visibility of the drone, which can cause safety hazards for both the operator and the surrounding environment. Also, it may affect the usage of colorblind drone operators, as they might interpret either the system condition or the direction that the drone is facing incorrectly due to existing colors. The existing weather conditions also affect the visibility of the drone in the sky. On sunny days for example, it will be hard to keep a drone that is surveying taller structures in the line of sight as sun glare would be an issue. Having a clear line of sight is necessary for a safe operation and it is mandated by the FAA. Hence there is a need for an LED lighting solution for drones that is customizable enough to make drones conspicuous in the sky and accommodates all operators and people that will be around the drone.

HARDWARE PROTOTYPING DESCRIPTION

There were three key modules for the proposed prototyping: lighting module, power module, and integrated communication module. The system diagram is shown in Figure 2.

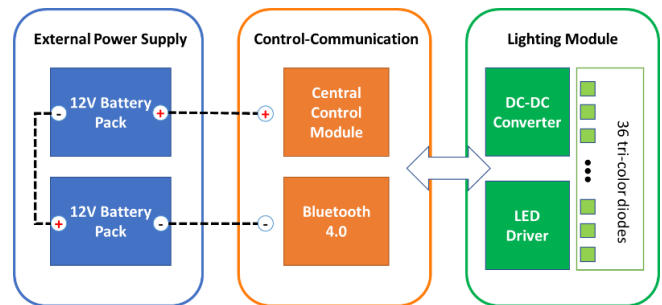


Figure 2. System Diagram for the LED Illumination System

The maximum thrust of the 4-axis propellers is 3200g, and the current load of the prototype is approximate 770g and it is evenly distributed (i.e. no negative impact on the drone flight stability). A platform made of carbon fiber is used to mount every external hardware to the drone body (Figure 3). Two separate 12V battery packs are serially connected to provide energy for the lighting and integrated control-communication modules. Each battery pack consists of 10 rechargeable AA NiMH cells, features a high-capacity rating of 2000mAh. The control module utilizes Bluetooth 4.0 as the protocol of wireless communication. Based on the design guidance, the outdoor maximum effective communication distance is 50 meters. Also, the lighting module can exert a max luminous flux of 1600 lumen with the rated power of 20W and 16 million color options.



Figure 3. The Carbon Fiber Frame and the Battery Packs

HUMAN IN THE LOOP EXPERIMENT

To assess the feasibility of the prototype and to test the effects of lighting and different lighting colors, we interviewed participants from an ongoing study we are conducting (#IRB202002748) in which the participants performed a drone intention and status perception task. This task involved estimating the distance of the LED drone described in the previous section as the drone hovered at different points and was lit up with red, white, and blue colors (Figure 4).

At the end of the task, the participants were asked to state which color they preferred the most. Among the color options, the participants preferred blue and white with no participants choosing the red color. The breakdown between blue and white

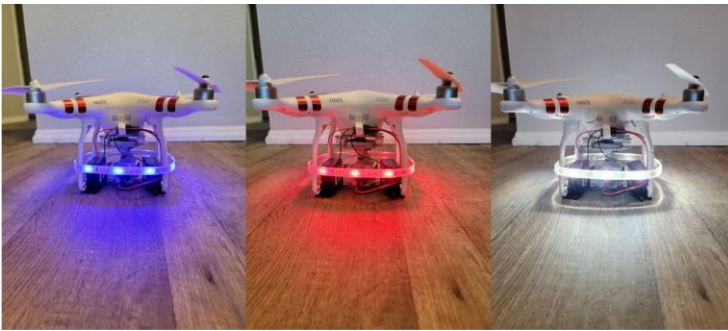


Figure 4. The Prototype LED Drone with colors of Blue, Red and White.

was not even, with 6 participants preferring blue and 3 white. At the end of the whole experiment, the participants were interviewed and asked why they chose the color they did. The responses were quite varied, and interestingly some participants gave the same reasoning for different colors. In the three instances, the participants chose the white color, two of them (P3 and P6) chose white because the white color stood out the most. The fourth participant (P4) chose white because he had no real preference when it comes to the color choice. Among the 6 remaining participants that preferred blue, 1 participant cited comfort as her preferred reason as she mentioned the white color although visible was too discomforting for her eyes. She mentioned blue was the ideal balance between visibility and comfort. Another participant said that she chose blue due to her association with the color with law enforcement. She mentioned she saw red and white lights frequently during her daily life but rarely blue other than the context of law enforcement. This made her more “aware” of blue than the

other colors. This behavior, although not the same, was observed in three other participants as well with their sentiment being blue standing out more from the other colors in the environment. Finally, one participant mentioned blue lighting was aesthetically more pleasing than the rest. This overall choice of white and blue was surprising for us, as red lighting is quite common in current commercial and personal drones. This color choice would mean that DJI’s LED color choices do not match with actual observer sentiment as DJI uses red, yellow and, green. However, there is another important factor that needs to be discussed in this context, weather.

Sunlight, or more accurately sunlight related glare has detrimental effects in many environments (Osterhaus, 2005; Pierson et al., 2018) especially in transportation. According to a Department of Transportation report, across a ten-year period 130 aviation accidents were directly caused by glare (Nakagarawa et al., 2003). Among these accidents 111 of them were in clear conditions. Another study found out the time of the day and the direction of traffic had an effect in the number of crashes, with eastbound traffic in the morning and westbound traffic in the evening being higher (Mitra, 2014). Noting these, we recorded the weather conditions of each session to see if there is a correlation between the color choice and weather conditions. Across 6 experiment sessions (in some of them there were two participants in the same session) 3 of them were under partially cloudy conditions, 2 of them under clear and one under overcast conditions. We did observe a possible correlation between weather condition and preferred color, with white being preferred exclusively by participants that undertook the experiment and 5 out of 6 participants who chose blue were under partially cloudy or overcast conditions. Only one participant (P5) preferred blue in clear conditions.

DISCUSSION AND FUTURE DIRECTIONS

In this paper we tried to highlight the importance of introducing customizable LED illumination devices in drone to increase the perceptibility of the drones. As previously mentioned, the LED lighting systems that currently exist in off the shelf drones are largely non customizable. Although the sample size was relatively small for the human in the loop study, there seems to be some effect of weather conditions on color preference. In the future, we will seek to verify this interaction effect with a larger sample size and a more complex experiment design.

As we focused on determining which colors would be the most suitable to increase the perceptibility of the drone, we did not focus on the communication aspect of LED lighting. This has been a topic of interest of two previous studies, Szafir et al. (Szafir et al., 2015) and Doran et al. (Doran et al., 2020). Szafir et al used different configurations of lighting patterns to increase the movement legibility of drones. In future studies, we plan to introduce lighting patterns in a similar way as Szafir et al with three points of improvement; we will conduct the experiment outside as they conducted the experiment inside, we will increase both the height and the horizontal distance of the drone and we will experiment with different colors and different

patterns. Doran et al. suggested combining both LED lights and air marshalling techniques to facilitate safe communication for human drone collaboration. Their design highlights the importance of increasing the situational awareness of the human collaborator and the convenience of not wearing any bulky equipment. However, the appropriateness of the colors and patterns that are used both in terms of visibility and in terms of legibility are critical elements that need to be investigated.

Table 2. Participant Responses to the Human in the Loop Experiment

Participant	Color Choice	Weather	Reason for Choice
P1	Blue	PC	Association with police
P2	Blue	OVC	Aesthetic pleasure
P3	White	CL	Caught the eye most in the sun
P4	White	CL	No real preference
P5	Blue	PC	
P6	White	CL	Stands out from surrounding colors
P7	Blue	CL	Stands out from surrounding colors
P8	Blue	PC	Most comfortable to the eye
P9	Blue	PC	Stands out from surrounding colors

PC: Partially Cloudy OVC: Overcast CL: Clear Sky

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Table 1. Common off The Shelf Drones with their LED Illumination Systems

Drone	Year	Domain	Body and Dimensions	Colors	LED Usage
DJI Mavic 2 Pro	2018	Personal/Commercial	Foldable Quadcopter 322×242×84 mm (Unfolded)	Red, yellow, green	Next to the propellers facing outwards. Front 2 solid red during flight. Back two status light. Green blinking ready to fly/GPS mode Red blink low battery.
DJI Phantom 3	2015	Personal/Commercial	Quadcopter 350 mm (Diagonally)	Red, yellow, green	Underneath the wings at the end Same colors patterns with Mavic Pro 2
Autel Evo 2	2020	Personal/Commercial	Foldable Quadcopter 397 mm (Diagonally)	Red, yellow, green	Same placement as Mavic Pro 2 Color and pattern usage very similar to the DJI drones
Yuneec Typhoon H	2016	Commercial	Foldable Hexacopter 711x711x294 mm (Unfolded)	Red, purple, green, blue, white, yellow	Underneath the propeller motors like DJI Phantom 3 and LED status indicator light behind the drone's body Two white and two red LEDs indicate front and back, blue indicates left and green indicates right
DJI Matrice 200	2017	Commercial	Foldable Hexacopter 887×880×378 mm (Unfolded)	Red, yellow, green	Same as DJI Mavic Pro 2
Ruko F11 Pro	2020	Personal	Foldable Quadcopter 175x104x80 mm	White, Blue, Pink, Red	Same placement as DJI Mavic Pro 2 Front 2 solid white and back two solid blue ready to fly. All light flashing red low battery or controller not connected
Parrot Anafi	2018	Personal/Commercial	Foldable Quadcopter 175 x 63 x 239 mm	Shades of Blue, Red	Bottom of the drone Steady dark blue ready to fly Alternating read and blue low battery
Intel Falcon 8+	2017	Commercial	Octacopter 768 x 817 x 160 mm	Red, Green	Located on the sides of the central unit Constant green and red light indicating right and left