Toward Invisible Drones – An Ultra-HDR Optical Cloaking System

Karri Palovuori

Tampere University, Electronics, 33720 Tampere, Finland, karri.palovuori@tuni.fi

Abstract In order to reduce the visual detectability of drones, an active cloaking system was developed to match their color against the background sky. The system consists of an embedded control system connected to a smart LED tapestry and two color sensors, all capable of operating over an extreme dynamic range of 1 : 1 000 000. The cloaking system was applied to a commercial drone and the results under widely varying outdoors conditions are reported. The cloaking system successfully matches all background sky conditions, save the solar disk or halo.

1. Introduction

Depending on the situation, the visibility of airborne drones can be a vice or a virtue. On one hand, to signal their presence to people underneath and to other air traffic, bright lights are added to drones for their effortless detection during dark. This is also mandated by regulations under many jurisdictions [1, 2]. On the other hand, sometimes minimal disturbance to the environment is preferred. Such cases include non-distractive observation of wildlife or livestock and covert surveillance.

The elimination of the signal lights reduces the visibility of a drone, but the drone hull is highly contrasted against the sky under any environmental circumstances, except during the nighttime. Even white drones, which diffusely reflect the average ground color, appear visually as black (fig. 1a) in flight. During the night, any non-illuminated drone is obviously invisible by default.

To cloak a drone against the sky requires it to have the same apparent color and luminance towards the observer as the section of the sky seen surrounding it. While this fundamental principle is well known from both fiction [3] and history [4], its application to drones presents serious technological challenges: the maximum brightness of the sky is very high and its luminous intensity has a vast dynamic range. These are both difficult to match by an illumination system and to accurately measure by a sensor.

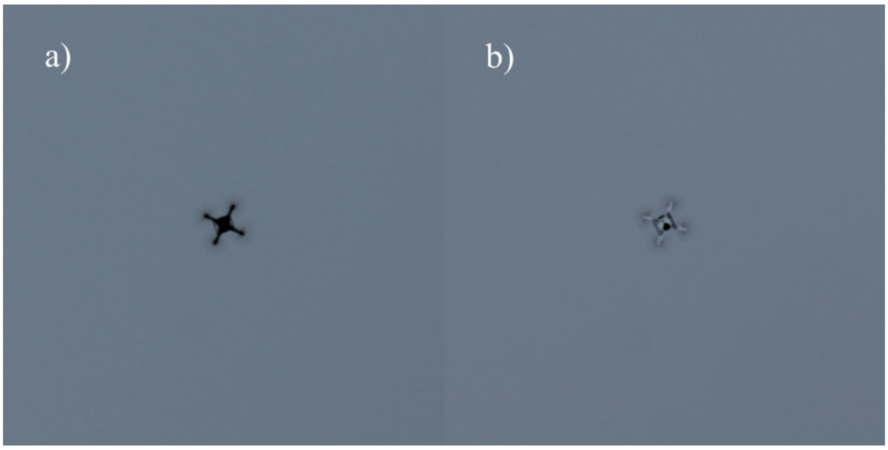

Fig. 1 a) A *white* drone against overcast sky, b) the same drone cloaked (the undercarriage and the camera remain clearly visible)

The clear sky at midday is blue and has a typical luminance of about 8000 cd/m^2 [5]. The minimum illumination condition under which any targets against the sky can be detected by the naked eye is defined as nautical twilight [6], during which the sky has a luminance of about 0.005 cd/m^2 [7]. These two limits suggest a requirement for the dynamic range of roughly 1 : 1 600 000 for both the measuring and the illumination systems. In contrast, the dynamic range of a typical 8-bit computer display is 1 : 255 and that of an entry level 10-bit HDR display 1 : 1023.

If the location or direction of the observer is not known, the drone has no information of the exact direction of the sky to match its color to. In such a case a default decision has to be made. Two obvious choices are the color of the zenith and the average color of the whole sky. Since the dynamic range of the colors the sky can simultaneously have is from near black to vivid dusk or dawn, an average is problematic and likely to yield a very incorrect result. We used the color of the zenith in all our measurements as the target color and observed the drone from underneath.

2. Methods

The cloaking system consists of the light emitting cloak itself, two measurement systems to measure the target color and the current cloak color, and a control system to match those. The cloaking system was developed in steps, by first building a handheld test patch to verify the feasibility before integrating it to a midsized commercial drone.

2.1. The cloak

The cloak itself i.e. the light emitting surface was constructed of a commercial unbranded adhesive LED strip consisting of 144 APA102C RGB LEDs per meter on a flexible PCB of 12.5 mm width [8]. This particular type was originally selected due to its high brightness, anticipating challenges in matching the brightness of the sky. The LEDs on the strip have a Lambertian radiation pattern, appearing of constant luminance from any forward viewing angle.

The APA102C RGB LEDs each have a red, a green and a blue LED chip and a smart controller integrated into a small surface mount package. The data is transferred synchronously with a data signal and a clock signal from unit to unit, which can be daisy chained indefinitely. Each unit regenerates both the signals to the next unit with a delay of half a clock period. The data stream contains a simple synchronization pattern and after that 32 bits of control data for each unit. Each unit strips the 32 first control bits after the synchronization for its own use and then transmits the rest unmodified.

The APA102C has two simultaneous brightness controls. First, each RGB color is defined with a 24-bit word i.e. 8 bits per component. Second, the total dimming of the LED is defined with a 5 bit word [9]. As a result, the brightness of an individual RGB LED has a dynamic range of 13 bits. With a larger number of LEDs, dithering can expand the average dynamic range greatly.

At maximum brightness each RGB LED consumes 60 mA of current resulting in total current consumption of almost 9 A per meter of strip. This is enough to generate significant ohmic losses over the power supply traces on the strip and a subsequent drop in operating voltage of the LEDs, apparent already with relatively short runs of the strip. The operating voltage changes directly affect not only the brightness of the LEDs, but also their color as the different color chips have different threshold voltages. Therefore, simple feedforward control is not enough to ensure a correct outcome from this type of light source and feedback is required. This compensates for all minor error sources (e.g. temperature, batch variation, defective chips), too.

The maximum density of the LEDs in the cloak is defined by the strip geometry. Along the strip the LEDs are placed with an interval of 6.9 mm (144 per meter) and the strip is 12.5 mm wide. The perfect visual acuity of the human eye is enough to discriminate details of ~1 arc minute [4], suggesting the individual LEDs or LED strips cannot be resolved when viewed from further than ~ 40 m. In practice, it is unlikely that the viewer would observe a cloaked target with foveal vision and perfect focus, before it is visually acquired. Thus the cloak is possibly effective from shorter distances, too.

2.2. The measurement system

In order for the cloak to match the color of the sky, the sky color needs to be measured. The dynamic range requirement of this measurement system is very large compared to common optical sensors. At the low end, cameras report colors with 8 bits of resolution per component and even dedicated color sensors only with 16 bits. The sensor of choice was the VEML6040 color sensor, which has a resolution of only 16 bits, but in addition has a configurable integration period directly affecting sensitivity, expanding the total dynamic range to 21 bits [10]. The sensor has an I^2C bus for communication.

The sensor chip itself has a Lambertian sensitivity pattern and to measure the color of the sky from a particular direction the field of view of the sensor needs to be restricted. A baffle for this purpose was designed, 3D printed with black PLA, and painted matte black. An inner optical stop of the baffle limits the field of view of the sensor to 60 degrees while an outer stop prevents direct sunlight from illuminating the inner stop at solar elevations less than 55 degrees. The latter limit was chosen to match the maximum solar elevation at the geographical location of the study.

Two identical sensor systems were constructed and mounted on the drone, one on top of it to measure the sky color and another below the fuselage on the undercarriage to measure the cloak color.

2.3. The control system

To adjust the cloak color to match the sky color, an embedded microcontroller system was built using an MBED LPC1768 module. The module is based on a 96 MHz ARM Cortex M3 microcontroller and has all the necessary infrastructure (GPIO, voltage regulation, buses etc.) required in this project. In addition, a LoRa radio link was included to provide the capability to manually control and tune the cloak parameters in flight.

Initially, a basic software PID controller was created to control the color matching, but was soon found to be unsatisfactory. The integrating I term is necessary to compensate for unknown changes in the LED cloak caused by e.g. temperature or operating voltage. However, due to the vast dynamic range of the system, I term values high enough to yield a reasonable response time resulted in oscillation under low light levels near the obvious system discontinuity of zero i.e. darkness. This was remedied by using the PID controller to control the logarithm of the individual color brightness levels instead of the level values themselves. Thus the adjustments *relative* to the brightness level were performed with a constant response time and the darkness did not present a discontinuity.

The color of the cloak was set with three simultaneous methods. To maintain the best possible color resolution, the 5 bit overall brightness of each single RGB LED was set to the lowest value still sufficient and the 8 bit R, G and B values scaled accordingly. The error between the required and the resulting LED colors was accumulated over the array of LEDs, always carried over to the next LED, performing automatic dithering over the cloak. This was obvious under the darkest circumstances causing most of the LEDs to remain completely black.

The LoRa radio link was realized with an RFM95 868 MHz module. From the ground station, requests were transmitted to the cloak system and status responses were returned back with a rate of 50 Hz. The requests contained commands to turn the cloak on or off and to control the color either purely autonomously or with manual adjustment factors for R, G and B. The responses reported the measured colors, the calculated LED brightness and the radio link quality. The brightness information was of interest to verify the margin from the brightest sky color to the cloak maximum output.

The power for the cloaking system was obtained from switching regulators and batteries built into the control system. In drone use, it would be preferential to divert this power from the drone itself.

3. Results

The cloaking system was first applied to a small handheld test patch and then to a commercial drone. Both systems were tested under various natural lighting conditions including the brightest clear and overcast skies. It was found that the cloak constructed with 100% LED strip coverage was indeed bright enough to match the sky, already with ~25 % of its maximum brightness. Somewhat unexpectedly, the brightest clear and overcast skies were of almost the same brightness. Since the minimum light output of the cloak is zero, the cloak thus has the capability to match all sky colors, except the solar disk and halo.

The dynamic range of the cloak depends on its size, as the minimum nonzero light output of the entire cloak is the minimum output of a single LED and the maximum is the maximum output of the entire array. Therefore larger cloaks have larger dynamic ranges. The minimum size cloak consists of a single LED and has a dynamic range of 1 : 8191.

3.1. The test patch

A 10 cm x 12.5 cm test patch of the cloak was built onto a piece of clear acrylic plate (fig. 2a). A white patch was placed next to the cloak as a reference. The control system and the sky measuring sensor were placed behind (on top of) the cloak and the cloak measuring sensor was held manually in a position to measure the cloak color. This positioning is relatively non-critical as if the sensor observes only partly the cloak and partly the sky, the control system will still force these to match i.e. the end result remains the same. The cloak LED array consisted of 144 LEDs and thus covered a dynamic range of 1 : 1 179 648. To power the LEDs, two switching regulators with 5 A output were connected in parallel and driven from their internal 18650 Li-ion batteries.

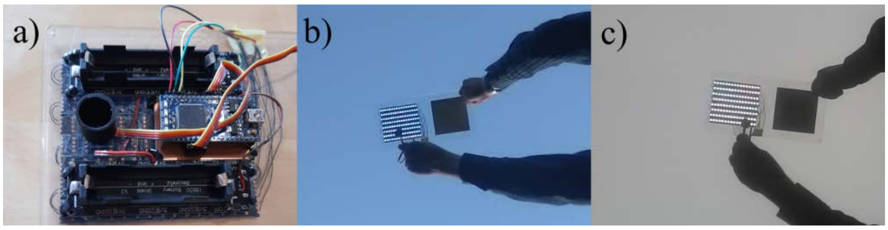

Fig. 2. a) The test patch, b) cloaking against blue sky, c) cloaking against overcast sky

In fig. 2b and fig. 2c the individual LEDs are clearly visible, but the overall brightness and color of the cloak matches the background. This was verified by swapping the two sensors and having the same result. The white reference patch appears as black revealing the huge contrast between the sky and the diffuse ground reflection.

3.2. The drone

For the drone to serve as the carrier for the cloak, we chose a very popular commercial model, the DJI Phantom 4. This drone is of medium size (350 mm diagonal, 1.4 kg) and it is very easy to fly due to its high level of autonomy and advanced collision avoidance features. From previous experience we knew the drone to be capable of lifting at least 1 kg of extra payload. The drone has integrated signaling LEDs at the ends of its motor booms, and these cannot be completely disabled through the user interface. Simply covering the LEDs was unsuccessful as they are very bright and the white plastic hull of the drone is slightly translucent, scattering enough light to make the drone highly visible under low light conditions. So these LEDs had to be removed altogether, which required a complete disassembly of the drone.

The control system and the sky measuring sensor were mounted on top of the drone and the cloak measuring sensor was mounted on the drone landing gear. First flight tests revealed a significant decrease in the GPS visibility for the drone, which was traced back to the close proximity of the GPS receiver antenna of the drone to the control system electronics and power bank of the cloak. The problem was solved by lifting the control system on top of a lightweight supporting platform (fig. 3). The greater number of LEDs required the power system to be upgraded to 4 parallel 5 A switching regulators powered from a single LiPo Battery. The power could not be obtained from the drone itself, as the drone self-diagnostics interpreted it as a power system malfunction.

Fig. 3. The drone equipped with the cloaking system.

The underside fuselage of the drone was covered with the LED strip to the best of our ability. The surface in question is not flat, but curved in all directions, making the task very challenging. While the strip is flexible, it does not stretch, and it bends easily only in the lengthwise direction. Underside the fuselage, the drone has a gimballed camera and a fixed landing gear, neither of which could be cloaked due to their complex geometry. One end of the removable battery extends slightly outside the fuselage and presents the same problem. Additionally, the drone has several types of downward facing sensors which were left uncovered. The cloak of the drone consisted of 287 LEDs resulting in a dynamic range of 1 : 2 351 104.

The drone was flown under different lighting conditions to verify the cloaking function (fig. 4). Both the color and the brightness adapted as expected and the cloaked parts of the drone disappeared visually after reaching the distance where individual LEDs could not be discerned any longer. The undercarriage, the camera and the battery end remained visible nonetheless. With a bright background, the propeller disks were slightly visible as dark halos as well. During the darkest test conditions, the dithering function of the cloak became apparent, as most of the LEDs were completely black. While this is evident from the camera shot (fig. 4c), it was exceedingly difficult to see by the naked eye due to the depth of darkness. The few LEDs that are still emitting light are all at their lowest brightness setting. The ratio of actual brightness between fig. 4a and fig. 4c is close to 500 000 : 1.

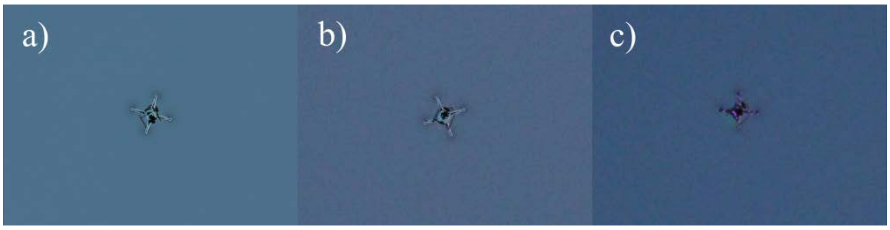

Fig. 4. The cloaked drone under extremely different lighting conditions. a) Bright sky, b) civil twilight, c) nautical twilight

3.3. The cloaking factor

The visual acquisition of a drone is a multifaceted process including e.g. visual, temporal, environmental and psychological aspects, and it is therefore quantifiable only through user studies. One of the technical aspects of the cloaking system is the reduction of the visual cross-section it provides to the drone. We measured this from the photographs of the cloaked vs uncloaked drone against different background sky conditions. The sky around the drone in these photographs was verified to be homogenous and thus provided a credible estimate of the drone background (which being occluded by the drone was not observable). The relative cross-section was calculated with MATLAB as the difference of pixel colors between the cropped drone image and a similar size background sample (around the drone) relative to the background size and brightness.

$$\sigma_{DRONE} = \frac{\left|\sum pixels_{DRONE} - \sum pixels_{BG}\right|}{\sum pixels_{BG}}$$

This definition is insensitive towards changes in drone distance and camera parameters, as long as the camera transfer function is linear. Using the difference of the sums instead of the sum of the differences as the nominator allows for the dithering to succeed and also makes the definition insensitive towards camera focus.

The cloaking factor was defined as the ratio of the relative cross-sections of the uncloaked and cloaked drone images.

$$F = \frac{\sigma_{UNCLOAKED}}{\sigma_{CLOAKED}}$$

Thus a cloaking factor *F* of 1 signifies no cloaking at all and a cloaking factor of 2 that the remaining relative cross-section is one half of the uncloaked drone. Since the absolute visual cross-section is inversely related to the square of the viewing distance, the acquisition distance *d* decreases as the cloaking factor increases.

$$d_{CLOAKED} = \frac{d_{UNCLOAKED}}{\sqrt{F}}$$

Table 1. Measured cloak effectiveness (including non-cloaked parts)

Lighting condition	Typ. sky luminance (cd / m^2)	Cloaking factor	Relative minimum acquisition distance
Daylight	10 000	3.1	0.57
Civil twilight	1	3.2	0.6
Nautical twilight	0.005	1.6	0.8

Table 1 summarizes the results of the cloaking experiments. It can be seen that the cloak reduces the visual cross-section significantly. From the photographs in fig. 4 the heavy impact of the uncloaked camera and undercarriage to these results are clear, but no effort was made to exclude these from the measurements or results.

4. Conclusions

A cloaking system for drones that matches their color to the background sky was constructed and tested. A commercial LED strip was used to build the cloak and proved to be sufficient for all lighting conditions already at 25% of its maximum output. Considering the huge dynamic range necessary for this application, that margin was quite narrow. Nevertheless, at these same conditions, the LED density could be slightly reduced without diminishing performance.

The cloaking system reduces the visibility of the drone down to a fraction, even while large parts of the drone were uncloaked. This allows the drone to operate at a closer distance undetected, which was the original goal.

The commercial drone we used was not an optimal object for cloaking due to the built-in lights, the non-planar underside and the external payload. To fully cloak a drone with this approach, a suitable drone should be designed with the cloakability in mind from the start. Extrapolating from the successfully cloaked parts of our test drone, such a drone would be completely invisible for observers at a suitable distance.

References

[1] Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft. http://data.europa.eu/eli/reg_impl/2019/947/oj (28.12.2020)
[2] Federal Regulations (US) Title 14: Aeronautics and Space PART 107 — SMALL UNMANNED AIRCRAFT SYSTEMS. https://www.ecfr.gov/cgi-bin/text-idx?node=pt14.2.107 (28.12.2020)
[3] Robley, Les Paul (1987) "Predator: Special Visual Effects". Cinefantastique 18(1):34.
[4] Bush, Vannevar; Conant, James; et al. (1946). "Camouflage of Sea-Search Aircraft". Visibility Studies and Some Applications in the Field of Camouflage. Office of Scientific Research and Development, National Defence Research Committee. pp. 225–240.
[5] Lighting Design and Simulation Knowledgebase. Lighting Design Glossary. Luminance. https://www.schorsch.com/en/kbase/glossary/luminance.html (28.12.2020)
[6] Bowditch, N. 2002. The American Practical Navigator. p. 227.
[7] American Meteorological Society. Glossry of Meteorology. Nautical Twilight. https://glossary.ametsoc.org/wiki/Nautical_twilight (28.12.2020)
[8] Addressable LED strip. https://www.aliexpress.com/item/32806765132.html (29.12.2020)
[9] APA102C Datasheet. http://cdn.sparkfun.com/datasheets/Components/LED/APA102C.pdf (29.12.2020)
[10] VEML6040 Datasheet. https://www.vishay.com/docs/84276/veml6040.pdf (29.12.2020)