STANDARD OPERATING PROCEDURES

Drone Camera Calibration

I. General

Commercially available drones attached with cameras can be used to replace tripod-mounted cameras as a significant improvement to the photographic measurement protocol developed for the street lighting audit. It is worthwhile to establish standard procedures so that such technique can be implemented on a regular basis. Due to the differences inherited in various camera performances and settings, the camera needs to be calibrated first before field measurement to ensure accuracy. This standard operating procedure is developed to provide instructions on how to calibrate the Zenmuse X5S™ camera mounted on the DJI Inspire™ 2 drone for the application of field measurement of illumination levels at intersections. The same procedure has previously been conducted to calibrate the Canon EOS Rebel T3® camera and the measurement error range was proven to be less than ± 4%.

II. Methodology Overview

To calibrate the Zenmus X5S™ camera, a set of monochromatic images with different levels of scene illumination will be taken, and pixel information will be extracted through image analysis to convert into scene luminance. Then a luminance meter and illuminance meter will be used to measure the scene illumination level to serve as a standard, and the measured results of the Zenmus X5S ™ camera will be calibrated against the standard.

III. Required Equipment

The following equipment will be required as a minimum to conduct this calibration procedure:

- The DJI Inspire™ 2 drone attached with Zenmuse X5S™ camera
- Fully charged Intelligent Flight Batteries for the drone

- A 4GB SD card for storing captured scene images
- An Extech-HD450® illuminance meter
- A Gossen Starlight2® luminance meter
- An extra 9V battery for illuminance meter
- A dimmable lamp

IV. Drone Camera Calibration Procedures

A. Identification of Scenes with Different Illumination Levels

Step 1: Find a room without any natural lighting, define a rectangular area on a flat surface using tape. This is to ensure that the pixel information will always be analyzed within the exact same area so that for the subsequent image analysis, the illumination level changes of the provided lighting source are the only variable that will influence the measured results.

Step 2: Once the scene area to be measured is determined, a dimmable lamp is placed in front of the area at a distance. This lamp will serve as the only lighting source for the camera calibration process.

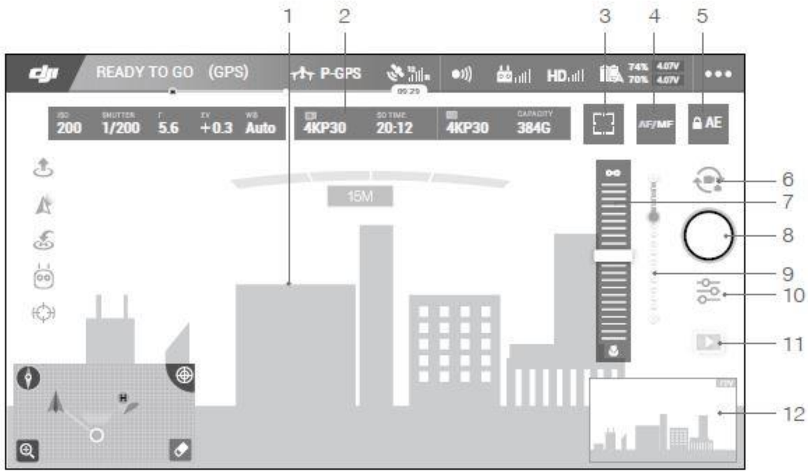
Step 3: Adjust the output levels of the dimmable lamp from the brightest to the darkest until completely turned off to obtain different scene illumination levels. It is up to users' choice of the number of illumination levels to be tested. Figure 1 shows an example of one selected scene under different illumination levels.

Figure 1. Scenes with Different Illumination Levels

Step 4: For each illumination level, use the luminance meter to measure the luminance values of the defined rectangular scene. Record the measured values for the subsequent calibration. Additionally, an illuminance meter will also be used to monitor incident light output from the dimmable lamp. This helps to confirm that the data collection is done under constant luminance and any variation in the measured pixel intensities of different target images is only influenced by the camera’s exposure settings or source luminance instead of voltage fluctuations.

B. Zenmuse X5S™ Camera Settings for Image Shooting

DJI provides the DJI GO™ 4 app to control the drone and the attached camera through a mobile device connected to the drone’s remote controller. After the mobile device has been successfully connected to the remote controller, the touch screen of the mobile device can be used to record videos, capture photos, and set professional photography configurations. Figure 2 shows the user interface of the DJI GO™ 4 app. To activate still image capturing and video recording functions, users need to first insert a supported Micro SD card into the drone (DJI Inspire™ 2). Once the image capturing function is activated, the drone camera settings should be set based on the recommended values provide below.



1. Live HD Video
2. Current Camera Settings
3. Spot Metering/Focus Switch
4. AF/MF Switch
5. AE Lock
6. Shutter/Record Switch
7. MF Adjustment (in MF mode)
8. Shutter/Record
9. Gimbal Slider
10. Photography Configurations and Parameter Settings
11. Playback
12. FPV (Tablets)

Figure 2. User Interface of the DJI GO™ 4 App

- **Shutter/Record Switch:** Tap the shutter/record switch ([6] in Figure 2) and select shutter. To take a picture tap the shutter/record button ([8] in Figure 2).

- **Shooting Mode:** The default mode of the drone camera is set to be Single Shooting Mode and this mode will also be used for camera calibration. If the shooting mode has been changed, it can be reset by tapping the photo configurations menu ([10] in Figure 2), then choosing sub menus in the following order: Settings → Video/Photo Setting → Photo.

- **Exposure Mode:** The exposure mode must be set to Manual. This can be done by tapping the photo configurations menu ([10] in Figure 2) and then choosing sub menus in the following order: -> M. This will allow aperture, shutter speed, and ISO to be set manually based on field conditions.

- **Shutter Speed:** This will vary based on the user-selected ISO sensitivity. Each ISO sensitivity has a different calibration curve and a fixed exposure time that must be used. The possible shutter speed values for images range from 8s to 1/8000s.

- **Aperture:** This can very between the recommended f-stops for the selected ISO. The maximum aperture is F1.7 and the minimum is F16.
- **ISO:** This can be set at 3200, 6400,12800, or 25,600 depending on users' data collection needs. The possible ISO values for images range from 100 to 25,600.
- **Photo Style:** This should be set to Standard.
- **Photo Color:** Photo color should be set to Black and White.
- **White Balance:** This should always be set to automatic white balance (AWB).
- **Image Format:** The images should be taken in (.DNG) format. DNG format is a generic, and highly compatible format developed by Adobe. It offers the advantage of smaller file sizes without loss of data and a universal format that is independent of manufacturer or camera-specific software.
- Any other settings meant to enhance the images taken by the camera should be turned off. Some of these include 'Exposure compensation / AEB settings', 'Lighting optimizer', etc.
- The camera must be set to Spot Metering instead of Spot Focusing.

C. Image Shooting Process

Step 1: Power on the DJI Inspire™ 2 drone and unlock the Travel Mode to switch the drone into Landing Mode by pressing the drone power button a minimum of five times. Mount the Zenmuse Camera to the drone gimbal, as shown in Figure 3.

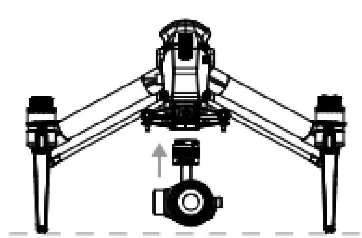


Figure 3. Zenmuse X5S™ Mounted to the Drone

Step 2: Place the drone at a table in front of the defined rectangular scene area, tilt the gimbal by scrolling the left dial of the remote controller to adjust the camera's field of view so that the defined scene area is centered in the camera view.

Step 3: For each scene with different illumination levels, change the ISO values to 3200, 6400, 12800, or 25,600 respectively depending on users' data collection needs. For each ISO sensitivity, select different levels of aperture ranging from F1.7 to F16.

Step 4: For each combination of ISO, aperture, and shutter speed, tap the shutter/record button ([8] in Figure 2) to take a photo. For each captured image, record the camera's current settings including the shutter speed, aperture, and ISO values.

D. Pixel Information Extraction

To extract pixel intensity information from the captured images, an image analysis software ImageJ® is used and a script is developed accordingly to automatically extract the minimum, average, and maximum pixel intensity from the defined scene area in each image.

Step 1: Convert all the captured images into the lossless TIFF format and put them along with the developed script in the same folder.

Step 2: Open the ImageJ® software, and the initial interface is demonstrated in Figure 4.

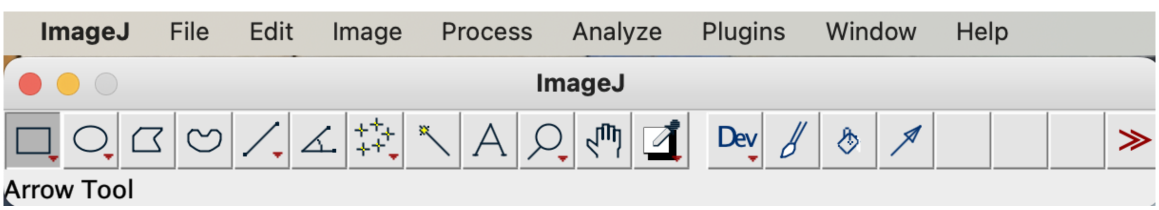


Figure 4. User Interface of ImageJ®

Click 'Plugins -> Macros -> Edit' to open the script in a separate window. Then click 'Plugins -> Macros -> Record' to open the Recorder window. Keep these two windows open during the entire image analysis process.

Step 3: Open the first image in ImageJ® by clicking 'File -> Open' and selecte the image. In the toolbar, select the 'Polygon selection' function as shown in Figure 5.

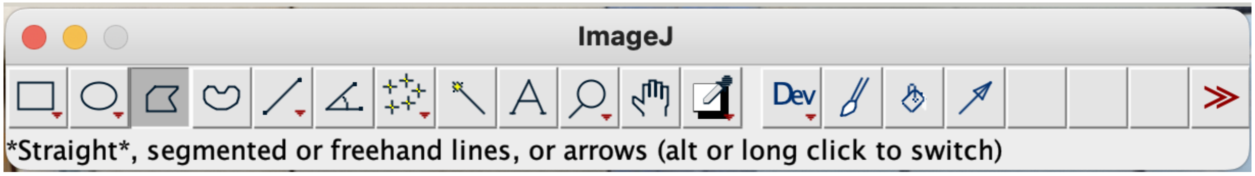


Figure 5. Select 'Polygon' Function in the Toolbar

On the selected image, draw a polygon with the same shape of the defined scene area, similar to the one highlighted in yellow in Figure 6.

Figure 6. Draw A Polygon in the Selected Image

Step 4: After the polygon is drawn, switch to the Recorder window, find the according coordinates of each drawn polygon's corner in the brackets of the 'makePolygon' function, as underscored in Figure 7.

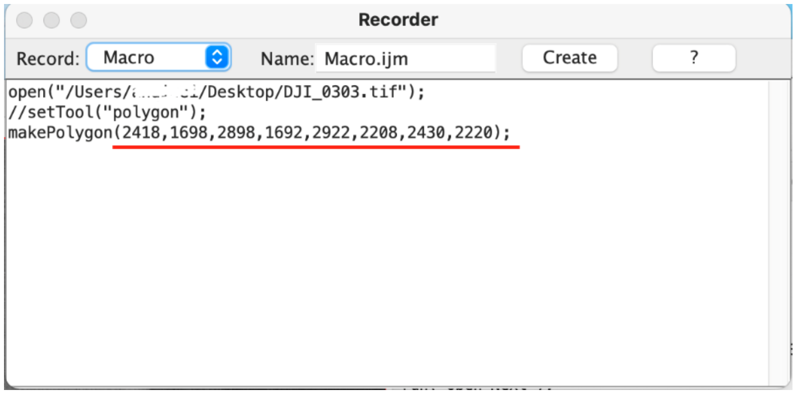


Figure 7. Coordinates of Each Polygon's Corner in the Recorder Window

Copy all the coordinates and paste them into the developed script to replace the values of the 'makePolygon' function (underscored in Figure 8). Additionally, change the number in the 'for loop' condition (marked in Figure 8) based on the number of actual images that users intend to analyze.

```
//The next script repeats the process for all the shots

//makePolygon(1937,1426,1764,1473,2207,1520,2287,1451);
//run("Measure");
        for (i=1;i<=6;i++){
                //run("In [+]");
                //run("In [+]");
                //run("In [+]");
                makePolygon(2418,1698,2898,1692,2922,2208,2430,2220);
                run("Measure");
                run("Open Next");
        }
```

Figure 8. Replace the Underscored Numbers with Copied Coordinates in the Script

Step 5: Ensure the current window is the script edit window, run the script by clicking 'Macros -> Run Macro'. The analysis results will be displayed in a separate window named as Results. Users can export the extracted pixel results into csv files and save the files to a local folder.

It should be noted that because the position of the drone camera hasn't been changed during the image shooting process, the defined scene area will always be in the same location within the camera's field of view, thus the same polygon can be applied to every captured image for pixel extraction. However, if the position of the camera has been changed, then users will need to draw new polygons manually for images with a different field of view, and repeat the above process.

E. Dark Current Estimation

Step 1: After the image shooting process, keep all the equipment at the same place, turn off the lamp completely.

Step 2: For each ISO sensitivity selected in the image shooting process, take another set of images with different aperture settings.

Step 3: Conduct the pixel information extraction process on the captured images, and record the mean pixel intensity of each image. Obtain the dark current for each ISO value by calculating the median of the images' mean pixel intensity.

F. Camera Calibration Process

To calibrate the camera, a relationship between the measured pixel intensity and actual scene luminance should be established. Previous studies have found that the relationship between pixel intensity and scene luminance can be simplified into a linear equation, as shown in Equation 1. The term 'RHS' can be defined as the interaction of scene luminance and camera's exposure parameters, which equals to the product of shutter speed (t) and ISO sensitivity (S) and scene luminance (L_s), divided by the square of the aperture number (f_s^2). K is a constant that will be calibrated for the drone camera.

$$N_d = \left(\frac{tS}{{f_s}^2} L_s\right) K \ldots = (RHS)K$$

Equation 1. Relationship between Pixel Intensity and Scene Luminance

Step 1: For each analyzed image, subtract the estimated dark current from the measured mean pixel intensity to obtain the adjusted pixel intensity. Then input the adjusted pixel intensity into Equation 1 to calculate RHS.

Step 2: Plot the extracted mean pixel intensity against the calculated RHS based on the collected data for each ISO sensitivity. Figure 9 shows an example of the plot made during a previous study. The plot is based on data collected at scene luminance of 54.4, 2.94, 1.28, 1.2, 0.26, and 0.24 cd/m^2 with the Starlight2®.

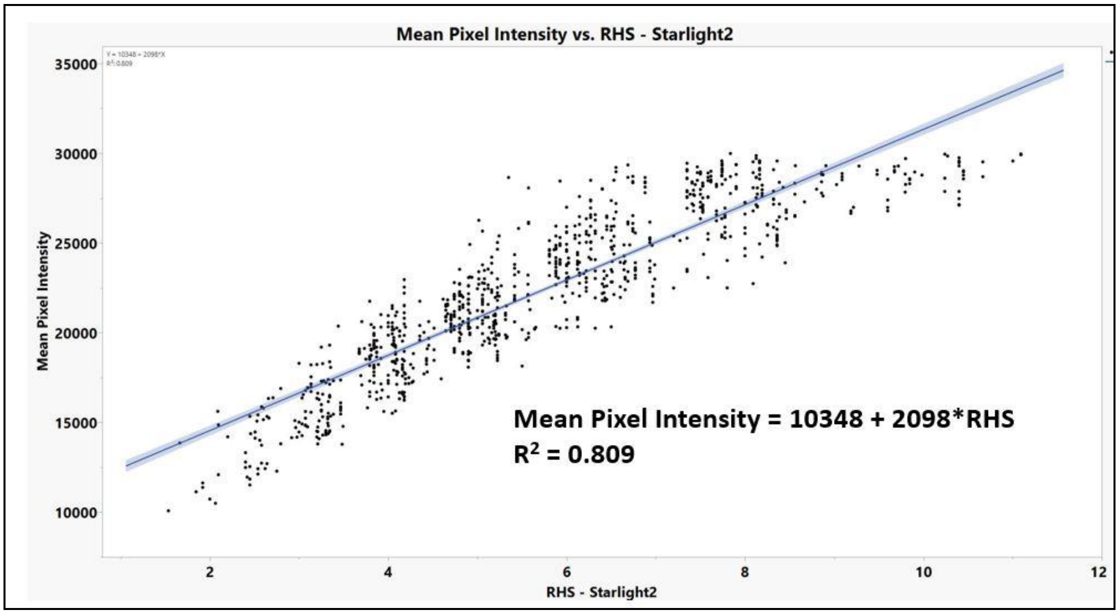


Figure 9. Example of Mean Pixel Intensity vs. RHS Plot

Step 3: Because the initial fitting of the data doesn't quite suggest a linear relationship between the mean pixel intensity and RHS in the selected linear response range, the original RHS values are transformed by natural log fitting.

Step 4: Plot the extracted mean pixel intensity against the natural log transformed RHS, as shown in Figure 10. Conduct linear regression on the processed data to obtain the value constant K of Equation 1, and the mathematical relationship between mean pixel intensity and scene luminance is established.

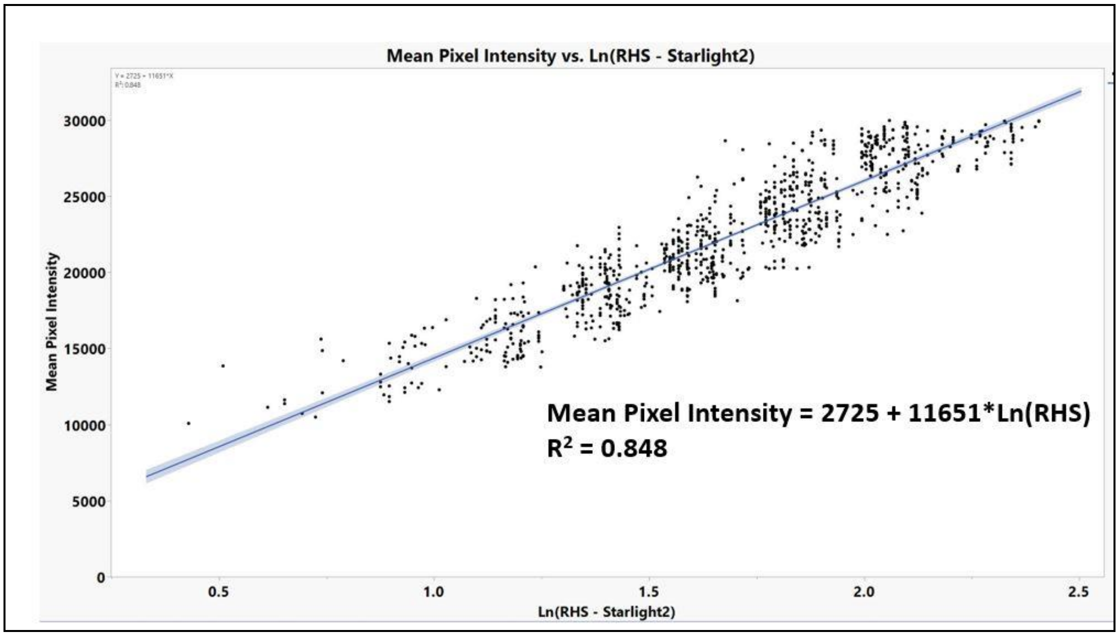


Figure 10. Example of Mean Pixel Intensity vs. Log Transformed RHS Plot

For subsequent scene illumination level measurement, simply use the calibrated camera to capture images of the interested scene, and analyze the captured images to extract the mean pixel intensity, then use the calibrated equation to convert the pixel information into the measured scene luminance.

Procedure Checklist of Drone Camera Calibration

Procedure Checklist of Drone Camera Calibration		
General Information	Project Number:	Comments
	Date:	
	Time:	
	Recorder:	
Required Equipment		**Check**
Drone Camera Calibration Equipment	DJI INSPIRE™ 2 Drone attached with Zenmuse X5S™ camera	
	A set of fully charged Intelligent Flight Batteries	
	A 4GB SD card for storing captured scene images	
	An Extech-HD450® illuminance meter	
	A Gossen Starlight2® luminance meter	
	An extra 9V battery for illuminance meter	
	A dimmable lamp	
	A mobile device with DJI GO™ 4 app installed	
Drone Camera Calibration		**Check**
Identification of Scenes with Different Illumination Levels	Find a room without any natural lighting, define a rectangular area on a flat surface using tape	
	Place a dimmable lamp in front of the defined area at a distance	
	Adjust the output levels of the dimmable lamp from the brightest to the darkest until completely turned off to obtain different scene illumination levels based on project needs	
	Use the luminance meter to measure the luminance values of the defined rectangular scene for each illumination level and record the measured values	
Adjust Zenmuse X5S™ Camera Settings for Image Shooting	Connect the mobile device with DJI GO 4 app installed to the drone remote controller	
	Tap the shutter/record switch button in the DJI GO 4 app and select shutter, then tap the shutter/record button again to take a picture	
	Use the default 'Single Shooting Mode' of the drone camera	
	Set the exposure mode to be Manual	
	Set photo style to be Standard	
	Set photo color to be Black and White	

	Set white balance to be automatic white balance (AWB)	
	The images should be taken in (.DNG) format	
	Any other settings meant to enhance the images taken by the camera should be turned off	
	Set the camera to be Spot Metering	
Image shooting	Power on the DJI Inspire™ 2 drone and unlock the Travel Mode to switch the drone into Landing Mode by pressing the drone power button a minimum of five times	
	Mount the Zenmuse X5S™ Camera to the drone gimbal	
	Place the drone at a table in front of the defined rectangular scene area, tilt the gimbal by scrolling the left dial of the remote controller to adjust the camera's field of view so that the defined scene area is centered in the camera view	
	For each scene with different illumination levels, change the ISO values to 3200, 6400, 12800, or 25,600 respectively depending on users' data collection needs. For each ISO sensitivity, select different levels of aperture ranging from F1.7 to F16	
	For each combination of ISO, aperture, and shutter speed, tap the shutter/record button to take a photo	
	For each captured image, record the camera's current settings including the shutter speed, aperture, and ISO values	
Extract pixel information	Convert all the captured images into the lossless TIFF format and put them along with the developed script in the same folder	
	Open the ImageJ® software and Click 'Plugins -> Macros -> Edit' to open the script in a separate window, then click 'Plugins -> Macros -> Record' to open the Recorder window. Keep these two windows open during the entire image analysis process	
	Open the first image in ImageJ® by clicking 'File -> Open' and select the image	
	In the toolbar, select the 'Polygon selection' function, and draw a polygon with the same shape of the defined scene area on the selected image	
	Switch to the Recorder window, find the according coordinates of each drawn polygon's corner in the brackets of the 'makePolygon' function	

	Copy all the coordinates and paste them into the developed script to replace the values of the ‘makePolygon’ function and change the number in the ‘for loop’ condition based on the number of actual images that users intend to analyze	
	Ensure the current window is the script edit window, run the script by clicking ‘Macros -> Run Macro’	
	Export the extracted pixel results from in a separate window named as Results into csv files and save the files to a local folder	
Estimate Dark Current	After the image shooting process, keep all the equipment at the same place, turn off the lamp completely	
	For each ISO sensitivity selected in the image shooting process, take another set of images with different aperture settings	
	Conduct the pixel information extraction process on the captured images, and record the mean pixel intensity of each image	
	Obtain the dark current for each ISO value by calculating the median of the images’ mean pixel intensity	
Camera Calibration Process	For each analyzed image, subtract the estimated dark current from the measured mean pixel intensity to obtain the adjusted pixel intensity	
	Use the adjusted pixel intensity to calculate RHS and transform the RHS values by natural log fitting	
	Plot the extracted mean pixel intensity against the natural log transformed RHS based on the collected data for each ISO sensitivity	
	Conduct linear regression on the processed data to identify the mathematical relationship between mean pixel intensity and scene luminance	
Operator Signature		