A Sensor for Visibility Determination under Fog Conditions

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ABSTRACT

In this paper, we describe a sensor approach utilizing commercial highway cameras for visibility determination under fog conditions. We achieved this by creating an engineered object in the field of view (FOV) of the camera that utilized two measurement approaches (contrast and light evaluation) via image processing. We employ the Koschmieder's law to estimate visibility conditions from fog measurements, and scattering profile to estimate visibility conditions from visible measurements of a modulated light. The contrast measurements are used during the daytime, and light evaluations during night. We discuss the merits and challenges of such an approach.

Keywords

Weather Sensor, Image Processing

1. INTRODUCTION

The onset of sudden fog or extremely dense fog is an issue that is critical to driver safety. Current State of the Art in real time fog detection is plagued by several false positive and false negative events due to the nature of fog formation, specifically when looking at low fog formation that would impact drivers. Both the thermodynamics and kinetics of fog formation make it difficult to evaluate over a small interrogation volume. Existing laser based sensors, such as the Vaisala PWD12, while excellent at close range measurement, are expensive, and are not able to get around the elusiveness of the type of fog that decreases driver visibility and detect with high confidence. Highway and other commercial cameras have the advantage of viewing a scene near a roadway and other areas of interest and typically have a large viewing area. We sought to take advantage of this by creating an object in the field of view of the camera and used it in conjunction with image processing for the purpose of visibility determination.

There are similar studies that utilize image processing on commercial cameras for either visibility or fog determination. The contrast of a "black" target is one established way of making visibility determinations that has been accepted and widely used since the 1920s. Hautiere et al. [1] demonstrated an onboard vehicle camera for fog detection. Similar to our approach, this group utilized a variation of contrast evaluation in the FOV based on the treatment by Koschmeider [2]. This technique provided only an estimation of visibility, and was inoperable at night. Tang et al [3] also sought to create a contrast sensor utilizing a camera. They compared a black target to the horizon. At reduced visibilities, their approach began to deviate and see decreased correlation. This is likely because they used the horizon as the contrast media to the black and was not controlled in the measurement.

In our approach, we also utilize Koschmieder's law as a basis of our contrast measurement but utilized against a tightly engineered contrast piece. We also utilized an LED light (650 nm) to monitor scattering with increased fog density.

2. SENSOR APPROACH

For the contrast portion of our initial sensor prototype, we utilized a high albedo, diffuse white surface with a near perfect black contrasting agent for visibility determination at varying fog densities. The departure from convention that makes our sensor unique is that a high albedo material (the front contrast pattern) is used in place of the sky or horizon as a proxy to ambient light or scene brightness, Figure 1.

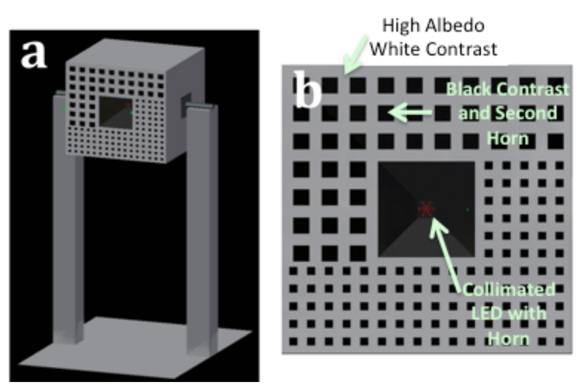

Figure 1. a) CAD of first sensor prototype and b) Sensor face and main components.

For our initial sensor prototype, a horn geometry was implemented behind the high albedo pattern, into the box, and utilized a highly absorbing, non reflective paint (black). The high albedo (white) front pattern utilized a paint and substrate that was highly diffuse and behaved as a lambertian surface. The difference in reflectivity between the dark and light portions of the contrast piece across visible wavelengths is close to 90%.

Figure 2. Prototype of sensor during a live field test in winter of 2017 along I-75 near Wildwood, FL.

For the light evaluation portion of our sensor, we utilized a modulated 650 nm collimated LED. We tested smaller versions of the prototype in an environmental chamber in the lab. These smaller sensor mock ups were the validation pieces used to validate the physics that lead up to the full sensor prototype shown in Figure 2. We describe the validation procedure below.

Using the treatment by Koschmeider, we can describe the following relation between the visual contrast $C_v(x)$ at a distance x with the extinction coefficient b_{ext} as,

$$C_v(x,b) = C_v(0)e^{-bx}; \tag{1}$$

Assuming b to be zero under no fog conditions, $C_v(0)$ will be the measured contrast at the camera under these conditions. We use a laser – photodetector setup to estimate the true extinction coefficient using the following relationship,

$$P(b) = P(0)e^{-bd}; \tag{2}$$

where P(0) is the power received at the photodetector under no fog conditions. From equations 1 and 2, we obtain

$$\ln C_v(x;b) = [\ln C_v(0) – (x/d)\ln P(0)] + (x/d)\ln[P(b)] \tag{3}$$

This implies that the log-log plot of the contrast versus the power detected at the photodetector should be linear with a slope of x/d.

It was also necessary for us to create a table that related visibility back to our sensor scheme. We adopted a version of the International Visibility Code [4, 5] that ties visibility to contrast under differing fog conditions, Table 1. This is done by relating our known laser values under different fog conditions to the contrast calculated from the evaluated camera image.

Table 1. Sensor Adaptation of the IVC

International Visibility Code			Scattering Coefficient σ (km^{-1})	
Code	Weather Condition	Meteorological Range (m)	0.05 contrast	0.02 contrast
0	Dense Fog	<50	>59.9	>78.2
1	Thick Fog	50-200	59.9 - 15	78.2-19.6
2	Moderate Fog	200-500	15-5.99	19.6-7.82
3	Light Fog	500-1000	5.99-3	7.82-3.91
4	Thin Fog	1000-2000	3-1.5	3.91-1.96
5	Haze	2000-4000	1.5-0.749	1.96-0.954
6	Light Haze	4000-10000	0.749 - 0.3	0.954-0.391
7	Clear	10000-20000	0.3-0.15	0.391-0.196
8	Very Clear	20000-50000	0.15 - 0.06	0.196-0.078
9	Exceptionally Clear	>50000	<0.06	<0.078

3. SENSOR PERFORMANCE

3.1 Test set up

We created an environmental chamber for controlled fog density in our lab with the ability to directly control the amount of ambient light in the chamber. A typical test set up is shown in Figure 3. The contrast portion of the sensor, or LED, is typically set up at the back of the chamber. The desired ambient light conditions (direct visible light, diffuse visible light, or near infrared - NIR light) could be created depending on the intended outdoor conditions. A 635 nm laser is used to monitor the fog density in the box. A custom fog machine was utilized that outputs a persistent fog with a median particle size of 1 μm.

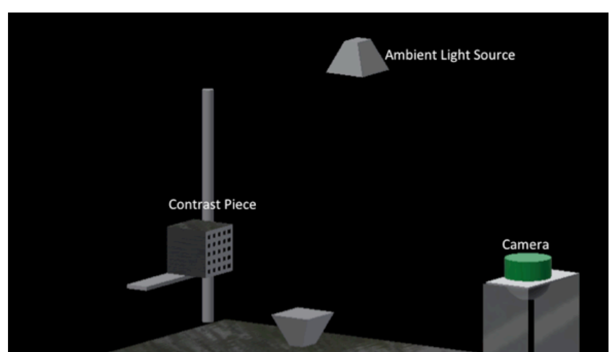

Figure 3. Placement of components within environmental chamber. Not shown are laser, photodetector and fog input.

Two different cameras were utilized during our experiments. A Bosch surveillance camera similar to those used on major interstates in Florida, and a Thorlabs 1.4 Megapixel Color Scientific CCD Camera. The scientific camera was utilized to help us understand and confirm the baseline physics of our approach. We also used it to better understand the compensation mechanisms, as well as camera response function, utilized in high-end surveillance cameras such as the Bosch, and their impact on utilizing visible cameras as measurement platform.

3.2 Verification of Sensor Behavior

We performed a series of experiments aimed at verifying that our engineered contrast approach obeyed Koschmieder's Law; that the contrast of an object decreases exponentially with extinction coefficient. We increased the fog density incrementally in our environmental fog chamber while measuring the contrast at each density. We placed a contrast pattern in the fog chamber (Figure 3), and recorded a video of the pattern under each fog density with the research grade camera. The frames from the video were used to measure the contrast at each fog density. The ground truth information for fog density was retrieved through retrieval of the extinction coefficient by means of a laser-photodetector setup.

In this experiment, we used 10 fog densities. To test the effect of ambient light on contrast measurements, we varied the ambient light intensity for each fog density in the fog chamber, and made contrast measurements for each ambient light intensity. This test was to make sure that we were successfully compensating for the camera response function in the pixel values. Successful compensation should be manifested by independence of the contrast measurements on the ambient light intensity. The ambient light intensities were measured using a Lux sensor connected to an Arduino. This measures the perceived light brightness to a human eye. For each fog density, we recorded the power of a laser beam measured at the photodetector.

To measure contrast, we computed the contrast every frame in each video and split the contrast measurements according to the different light intensity levels in the video. An average contrast and light intensity were computed for each light intensity, as well as for each fog density. As shown in Figure 4, the contrast measurement is almost invariant to the ambient light. We averaged contrast values over all ambient light levels in our verification of Koschmieder's law.

Ideally, the apparent contrast of an object should only depend on the extinction coefficient of the medium (fog or forming fog), and not on the ambient light intensity. However, due to various post processing and optical adjustments performed in commercial cameras, this is not the case in general. Figure 5 shows the change in contrast measured from our commercial camera with change in ambient light conditions. The x axis in Figure 5 corresponds to recorded ambient light using a lux meter, and the y axis corresponds to the measured contrast in the pattern. The figure on the right shows the contrast measurements after adjusting for the Camera Response Function (CRF) of the camera. As can be seen, accounting for CRF does not produce any appreciable improvement in the measured contrast. This indicated that adjustments to exposure and software adjustments play a dominant role in changing contrast with changes in ambient light.

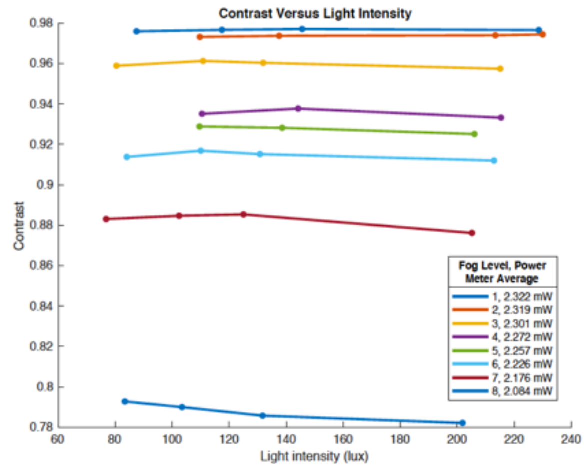

Figure 4. Change in contrast of engineered piece as a function of ambient light intensity

Therefore, for this preliminary proof of concept experiment, we used a research grade camera and shut off all the post processing. As expected, the contrast was then invariant to ambient light intensity. Figure 4 shows the contrast measurements with changing ambient light under various fog levels, and Figure 6 shows the average (over all light intensities) contrast for each fog level.

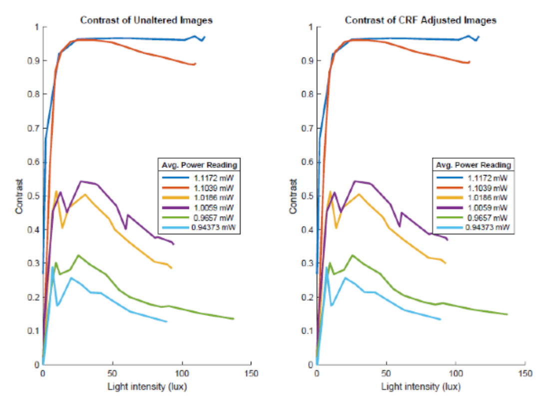

Figure 5. Contrast of unaltered commercial camera data (left) versus CRF adjusted data (right).

Using the average laser power and the average contrast measurement for each fog density, we were able to fit a regression line to the log(contrast) versus log(power level) curve. From Equation 3, we know that the slope of the log-log curve is equal to the ratio of the two distances: the distance from the contrast pattern to the camera and the distance from the laser collimator to the photodetector. The slope of the regression line in Figure 7 was 1.892 while the actual ratio (x/d) was 1.860, with an error of 1.6% in the slope. This is in very good agreement with theory and we feel confident that our contrast approach is appropriate to determining fog density.

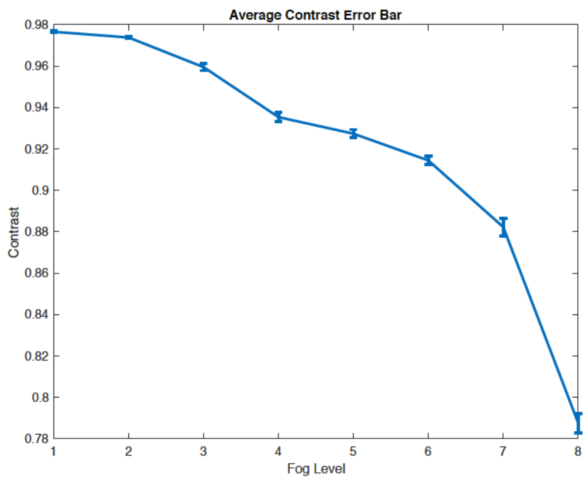

Figure 6. Average contrast measurement with standard deviation of the pattern, with increasing fog intensity

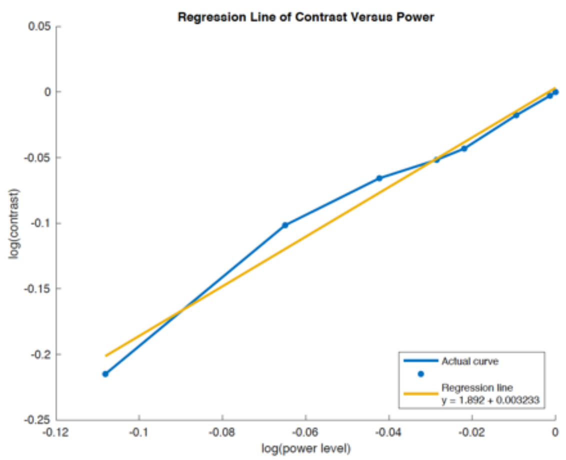

Figure 7. Regression line of the log-log curve of contrast and power level.

3.3 Live Test of Prototype Sensor

We ran a "live test" of our sensor prototype on I-75 near Wildwood, Florida. We placed 2 sensor boxes in the FOV of the cameras located at 167ft and 261ft from the camera post. These distances were chosen to have one sensor box in the depth of field of focus for the camera (167ft) and another just outside of the depth of field for focus (261ft) while maintaining a single scene for the test. Our test protocol was that the camera at that location is panned to a determined preset (with the focus conditions mentioned above) and is set there for 5 minutes while we acquire data. We were not able to utilize the cameras full time since they were in active use by the Orlando Regional Transportation and Management Center (ORTMC).

We utilized the following in evaluating our sensor:

1. When ambient light is available, we measure the contrast of the pattern on our sensor. The visibility is then estimated using Koschmieder's law.

2. During nighttime, we measure the scattering profile of our modulated light source, and estimate the visibility from this scattering profile. The camera records in the visible and NIR mode (gray scale) during nighttime. Here we present some of our preliminary findings from that test.

3.3.1 Visibility Estimation During Day

Figure 8 shows snapshots from 3 videos, one each under a) no-fog, b) low/medium fog and c) dense fog condition. We measured the contrast of the pattern on the sensor from each video. Table 1 summarizes the contrast measurements. Table 2 clearly indicate that at least as a first step, the contrast measurements provide a simple means for classifying the visibility into these 3 categories.

(a)

(b)

(c)

Figure 8. Snapshots from videos under (a) no-fog, (b) medium-fog, and (c) dense fog conditions.

Note that the contrast even under no fog conditions is rather low (≈ 0:4). There could be two reasons for such a low contrast, 1) the camera does not have sufficient resolution to clearly resolve the pattern, or 2) the recording method we used to record these videos causes loss of resolution. We are currently investigating which of these is the actual cause for low contrast under no fog conditions. We are also currently working on estimating the actual visibility (in meters) from the contrast measurements.

Table 2. Image luminance and contrast measurements from the images above. Ib is the background luminance, I is the black target luminance, and C is the contrast.

Frame	I_b	I	C
Nonfoggy	143.5748	89.3829	0.3774
Foggy	178.0281	156.6073	0.1203
Super-foggy	156.8281	154.7122	0.0135

3.3.2 Visibility Estimation During Night

The pattern on the sensor (being passive) is not visible during night. We are currently estimating visibility at night using the scattering profile of a modulated light source (preliminary results presented in this paper).

Under no fog conditions, the angle of incidence at the camera of light rays emanating from the light source will be very close to the direct line of sight. Under foggy conditions however, the scattering from the fog particles increases the range of the angle of incidence of these rays. We define the scattering profile to be function I(θ), where I is the irradiance of the modulated light incident on the camera at a 2-dimensional angle θ. Our objective is to classify the visibility conditions using I(θ).

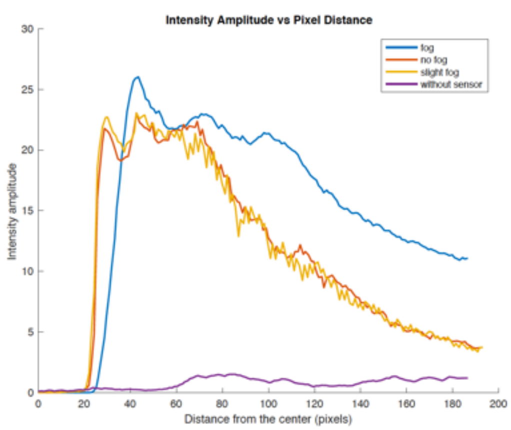

Figure 9. The scattering profiles extracted from videos taken at night under various visibility conditions.

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Figure 9 shows the scattering profiles extracted from videos under different visibility conditions. For clarity of presentation, we restricted θ to a straight line. Note that in this case, the angle θ will be proportional to number of pixels from the center. We can make the following observations about the scattering profiles:

1. As Figure 9 shows, the scattering profile is much broader under foggy conditions when compared to no fog conditions. This shows that the scattering profiles can be used for classification between fog and no-fog conditions.

2. The scattering profile is almost flat (in fact, a random curve) when the camera is not focused on the sensor. This indicates that the demodulation algorithm successfully removes background illumination.

3. The sensitivity of the scattering profile is not sufficient to distinguish between no fog and light fog conditions. We are currently working on improving the demodulation algorithm to improve this sensitivity. Our end goal will be to use the scattering profile to estimate scattering coefficient, and hence the visibility.

4. The scattering profiles are close to zero near the center because the pixels in the direction of the line of sight are saturated and hence all modulation information is lost. This cannot be avoided since the Bosch camera will adjust its aperture to compensate for the low ambient light conditions, thus saturating these pixels. This automatic adjustment also introduces inaccuracies in the demodulation algorithm.

4. CONCLUSION

We have demonstrated a viable sensor approach for visibility determination due to fog using an image processing approach for an engineered sensor piece, utilizing commercial road-side cameras. Both contrast and light evaluation are approaches that can be utilized. Challenges associated with this approach are compensation mechanisms in commercial cameras that make it challenging to determine true sensor conditions from a baseline. Future approaches will look at variants of our sensor approach that avoid triggering these conditions.

5. ACKNOWLEDGMENTS

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