Smart Intensity Compensation in Surgical lights to enhance Shadowlessness

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Abstract

Surgical lights with single or multiple light heads assemblies are required to provide illumination at surgical sites, but it has been observed that manual intervention is required to move the light head each time the surgeon changes their position to reduce the effect of shadows, this causes obstruction in surgical procedure as well contamination of instruments such as surgical light head, resulting into more frequent sterilization cycles. This research approach aims at designing a system capable of detecting the surgeon's head and based on the distance between the surgeon and the lighthead, sufficient rise in intensity is provided to compensate for the loss of intensity due to obstruction. It was found that the intensity compensation provided was in most cases identical to the original intensity values obtained without obstruction, and slightly lower in few extreme cases. Taking into account the hardware limits of light head assembly as well as the maximum achievable intensity limit approved, it was observed that the system with automatic intensity compensation performed better than the original system.

Keywords

Shadowless surgical light; Intensity compensation; Ultrasonic sensor; Surgical illumination system

1. Introduction

Surgical light generally consists of one or multiple light heads, it depends on the surgery being performed, illumination required for that particular type of surgery, or based on operator’s needs. However, it was found that during these operating procedures, these lights were required to be repositioned frequently or changes in the intensity settings were made with movement of the surgeons [1]. This in turn distracted the surgeon from the work being performed as well as the contamination of the light instruments were caused, which resulted in the frequent sterilization of light accessories. Particularly in case of open surgeries, frequent access of Light head is to be avoided, but frequent repositioning requirement to maintain the intensity defeats this purpose.

To solve this issue many different approaches were taken, such as tracking of the surgeon's hand using image recognition to adjust the light head position [1] and use of an array of ultrasonic sensors for automatic repositioning of the arm system [2]. But these approaches require complex mechanisms, have relatively high initial cost of implementation and do not guarantee fail-safe operation of surgical light heads.

This research work aims to compensate for the lost intensity of the light head when an obstacle occurs near it using ultrasonic sensor sensors to detect the obstacle and to provide intensity boost based on the obstacle (surgeons head in this case) distance from the light head without having to move the entire light head assembly. This makes the system more robust, less prone to errors and

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failures, cost effective, low power consuming which wasn’t the case with automated systems and more importantly an affordable solution for all.

In order to actually implement this project both ultrasonic sensors and the infrared time of flight sensors were compared, but in terms of cost, accuracy and range, ultrasonic sensors were found to be a better alternative. Since Light head operates at very high intensity and is a combination of LEDs from different wavelengths, it may interfere with the IR time of flight sensor and may result in erroneous result and this was another reason why ultrasonic sensor is selected because its operating principle is based on sound.

2. Literature Review

Fuan et al. (2019) aim to design an illumination system that will automatically track the movement of the surgeon's hand with a specific color of glove and provide the necessary illumination [1]. Choi et al. (2007) developed an auto-illumination system that autonomously tracks the surgeon's movement in X-Y-Z direction using ultrasonic sensors, and based on the surgeon's position determined, illumination is provided by moving the lighthead [2]. Walters et al. (2005) described an electronic lighting apparatus with at least one multiple position adjustable lighting pod. Each lighting pod includes at least one variable intensity light source and a proximity sensor for detecting objects interposed between the lighting pod and a work field. Each variable intensity light source is powered by a controllable pulse width modulated power supply or other suitable power supply which can be utilized to vary the intensity of the light source. In response to detection of an object interposed between a particular lighting pod and the work surface, the power to that lighting pod is increased, increasing the illumination of the work field. Alternatively, power to that lighting pod may be decreased and power to alternate lighting pods is increased, thereby minimizing shadows within the work field [8]. Michael Hollopeter et al. (2019) demonstrated the adaptive shadow control system that compensates for blockage of one lighthead of a surgical lighting system by increasing the light output from one or more other lightheads of the lighting system. The system also includes control logic for automatic enablement/disablement of adaptive shadow control by detecting whether there is blockage of a light head and whether the respective light beams of a plurality of lightheads are being aggregated to form a single aggregated co-illumination light pattern at a work area [9].

3. Proposed Methodology

The proposed system is an efficient and cost-effective solution to the problem of shadows occurring due to obstacles (Surgeon’s head in this case) present under the light head.

3.1. Block Diagram of System

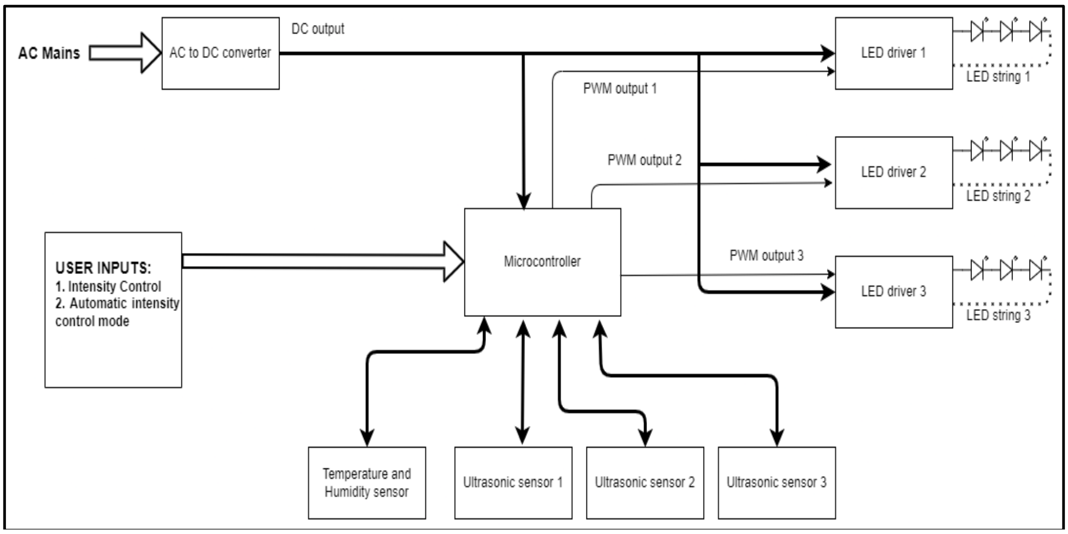

Figure 1: Block diagram of entire system

As seen from Figure 1 The DC output generated from the AC to DC converter is used to power the LED drivers as well as the microcontroller. Three Constant current LED drivers are used to drive three different strings of LEDs. The output current of these LED Drivers are controlled using the input PWM from the microcontroller, which in turn controls the output intensity of the LEDs. The manner in which these LEDs will operate are defined by the user inputs given to the microcontroller. Three Ultrasonic sensors are connected to the microcontroller which will be used to control the intensity of the LED strings, or for gesture sensing based on the user input. A temperature and humidity sensor is used to gather real time temperature data, which will be used for generating more accurate data from ultrasonic sensor reading.

Ultrasonic sensor module used is HC-SR04, it sends eight 40 kHz signals and reads the received signal, depending on the time gap between sending and receiving of the signal the obstacle distance is calculated. Details of HC-SR04 sensor is mentioned in table below:

Table 1: HC-SR04 ultrasonic sensor specifications

Working voltage	DC 5V
Working Current	15 mA
Working frequency	40 kHz
Max range	4 m
Min range	2 cm
Measuring angle	15 degree
Trigger Signal	10uS TTL pulse
Echo signal	Input TTL level signal and the range in proportion
Dimensions	45*20*15mm

Three different ultrasonic sensors are mounted on the lighthead sub-assemblies, each having a sensing angle of 15 degrees, with a range of 2-400 cm. All the lighthead readings are performed at a height of 100 cm, and the sensing range of the ultrasonic sensor is effectively limited to 80 cm. As illustrated from Figure 2. the obstacle sensing is divided into three sections, The section below 40 cm is represented as Band 1 and it has been found that this section is least prone to shadows, Band 2 lies in the range 40-60 cm and this section is moderately prone to shadows due to the obstacles occurring, Band 3 lies in the 60-80 cm range and is found to be highly prone to the shadows occurring at operating area due to the obstacles present in this section.

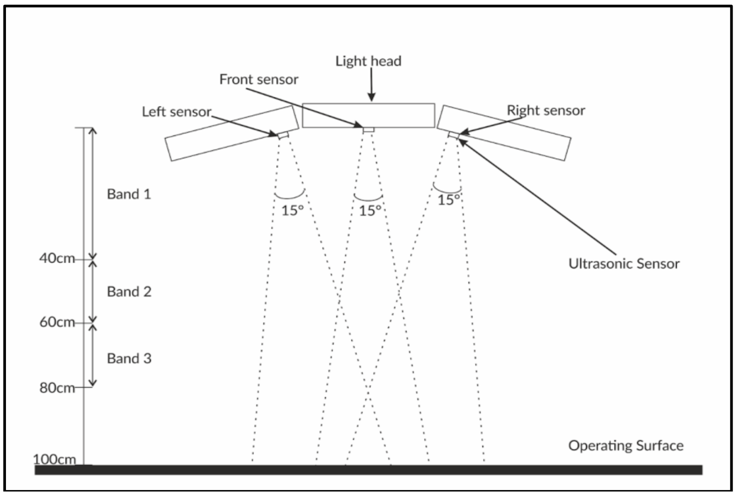

Figure 2: Ultrasonic sensor assembly

Table 2: PWM count vs INTENSITY (in LUX)

Sr. No	PWM COUNT	INTENSITY (in LUX)
1	25	1352
2	50	8971
3	75	18220
4	100	29670
5	125	40960
6	150	51020
7	175	60240
8	200	69040
9	225	74900
10	255	78190

Table 2. Represents the relation between PWM count and the output intensity obtained when no obstacle is present under the light head. This PWM count is used to control the output current of the LED driver and thus the output intensity of the light head is adjusted.

3.2. Software Flowchart

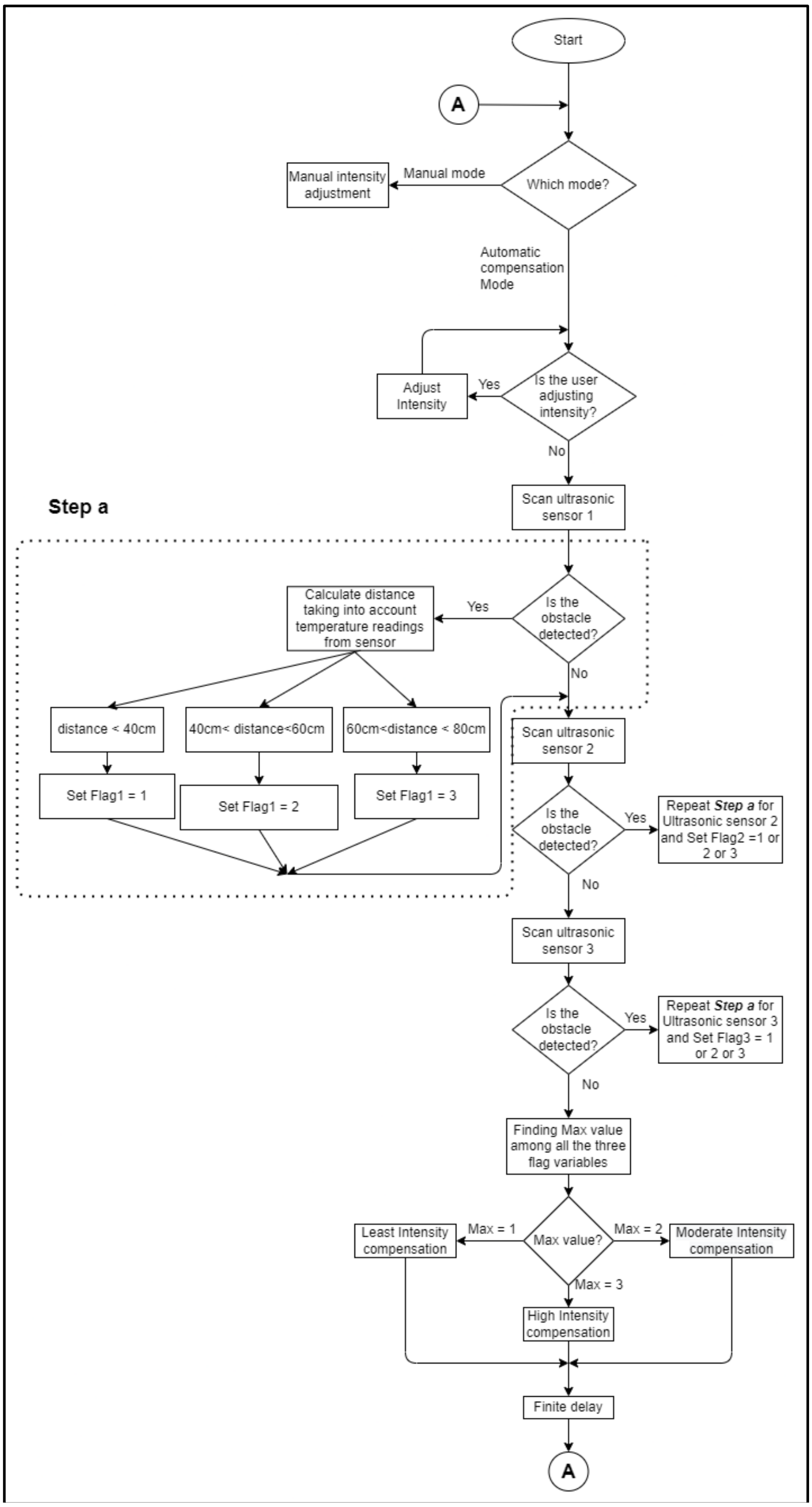

Figure 3: Software flowchart of the system

Software Approach for Intensity Compensation

When in Manual mode, surgical lighthead operates normally and requires human intervention for adjusting the intensity, manually positioning the Lighthead for reducing the shadows and to put it in or out of standby mode. In Automatic compensation mode, along with manual control Surgical lighthead performs automatic intensity compensation to reduce the effect of shadows occurring due to obstacles, for ease of surgery.

When manual adjustment is not detected, Ultrasonic sensor 1 is scanned to check if the obstacle is present and as seen in Fig 3. the following cases occur:

Case 1: Obstacle is detected

Temperature and humidity of the surrounding area was measured using a DHT11 sensor to accurately calculate the speed of sound, Since the temperature and humidity of the operating room may vary slightly in various cases. Speed of sound is calculated as follows:

Speed of sound(in M/S) = 331.4 + (0.606 * temperature) + (0.0124 * humidity)

Speed of sound(in cm/ms) = (331.4 + (0.606 * temperature) + (0.0124 * humidity)) / 10000

In Operation theatre, temperature is maintained at 21°C ± 3°C and humidity between 20 to 60% [10]

Once Speed of sound is calculated based on temperature and humidity readings, the time interval is measured between trigger and echo pulses and distance is calculated using the formula:

Distance (in cm) = (duration / 2) * Speed of sound (in cm/ms)

Here duration is divided by 2 since the sound wave covers the same distance twice (i.e going towards and returning from the obstacle)

Based on the distance obtained, three different ranges of bands are defined i.e Band1 for distance below 40 cm, Band2 for distance in between 40 and 60 cm and Band3 for distance in between 60 and 80 cm as seen in Fig 2.

- Flag1 is set to 1, 2 or 3 based on the distances lying in different bands.
- Now Ultrasonic sensor 2 is scanned.

Case 2: Obstacle is not detected

If no obstacle is detected then sequential scanning of another ultrasonic sensor is initiated.

Similar process is repeated for Ultrasonic sensors 2,3 as well and the Flag2 and Flag3 data obtained from them are stored as seen in Fig 3. After all the sensors are scanned in a cycle, the Flag variables are compared to find the maximum among them. Once max value is identified, three cases originate as follows:

Case 1: When Max = 1

In this mode the obstacle detected is at a distance less than 40 cm from the lighthead.

All the measurements illustrated in Figure 4. And Figure 5. are performed at a fixed intensity of light head adjusted at around 60k ± 2% lux and at a distance of 1 meter from the operating table.

As seen in Figure 4. Case-a the intensity drops down to around 46.5k when obstacle is present in band 1 i.e distance less than 40 cm from lighthead. An intensity boost of around 15k lux is provided to compensate for the reduced intensity as seen in Figure 5. case-a

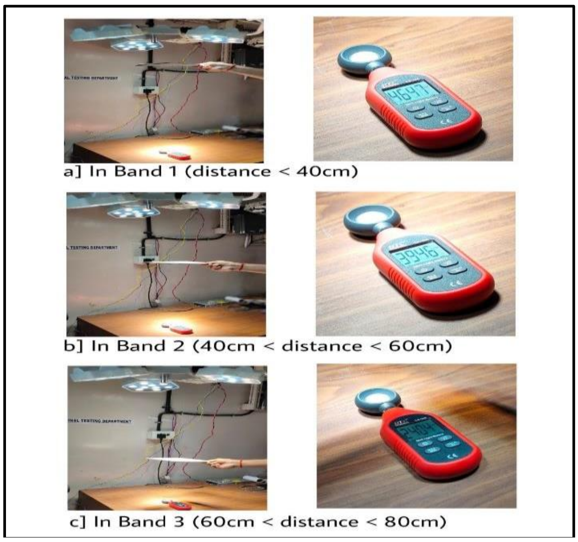

Figure 4: Measurement taken in absence of Ultrasonic sensor

Case 2: When Max = 2

In this mode the obstacle detected is at a distance between 40 cm to 60 cm from the lighthead.

As seen in Figure 4. case-b the intensity drops down to around 39.5k when obstacle is present in band 2 i.e in between 40 cm and 60 cm from lighthead. An intensity boost of around 20k lux is provided to compensate for the reduced intensity as seen in Figure 5. case-b

Case 3: When Max = 3

In this mode the obstacle detected is at a distance between 60 cm to 80 cm from the lighthead.

As seen in Figure 4. case-c the intensity drops down to around 24k when an obstacle is present in band 3 i.e in between 60 cm and 80 cm from the lighthead. An intensity boost of around 35k lux is provided to compensate for the reduced intensity as seen in Figure 5. case-c

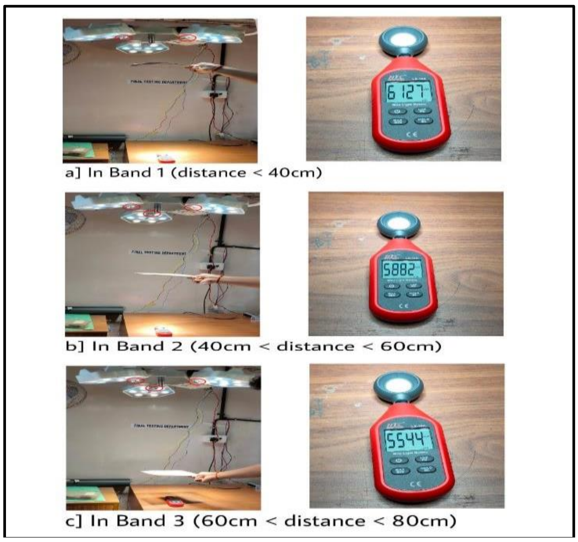

Figure 5: Measurement taken in presence of Ultrasonic sensor

Calculations

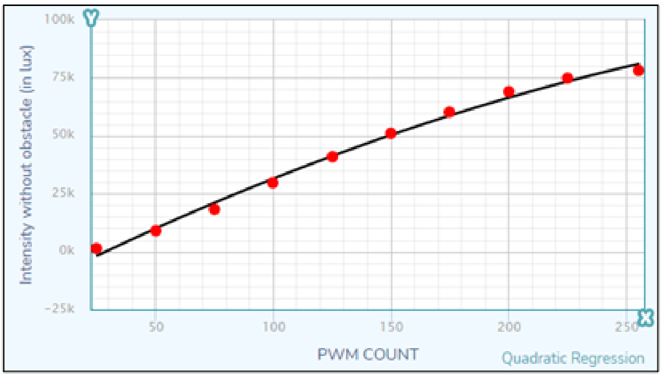

Figure 6: Plot of PWM count vs Intensity when no obstacle is present

For applying the intensity boost based on the obstacle position, the change in pwm count necessary was needed to be determined.

As illustrated in Figure 6. PWM vs intensity plot was obtained based on the points from Table 2.

From the points plotted it was identified that a curve with a quadratic equation would fit this plot. Thus, a second order polynomial quadratic equation that would fit the curve is found as follows:

$$y = a + bx - cx^2$$

Where

a = -14240.24, b = 512.4376, c = - 0.543691

x = PWM count, y = Intensity (in lux)

$$y = -14240.24 + 512.4376x - 0.543691x^2 \qquad \text{Equation 1}$$

When obstacle is detected, PWM count at that instant is taken into account and based on it intensity value is obtained using above Equation 1, After intensity is obtained amount of boost required is added to it, Now this New boosted intensity is again converter into PWM count using Equation 1, which is then used to control the LED brightness by adjusting the output current of LED drivers as illustrated in Fig 1.

4. Results

This section presents the results for the Intensity compensation due to an obstacle present under the light head and from gesture control of light head.

4.1. Intensity compensation under presence of obstacle

Figure 8. Illustrates two different cases when an obstacle is present in Band 1, i.e a) when intensity compensation is not applied and b) when intensity compensation is applied. As evident from case a of Figure 8. Both the plots have similar behavior after pwm count of 100, only the magnitude of intensity is reduced due to presence of an obstacle. In case b where intensity compensation is applied, it is observed that both plots exhibit different behavior before pwm count of 100, but after that they assume a similar behavior.

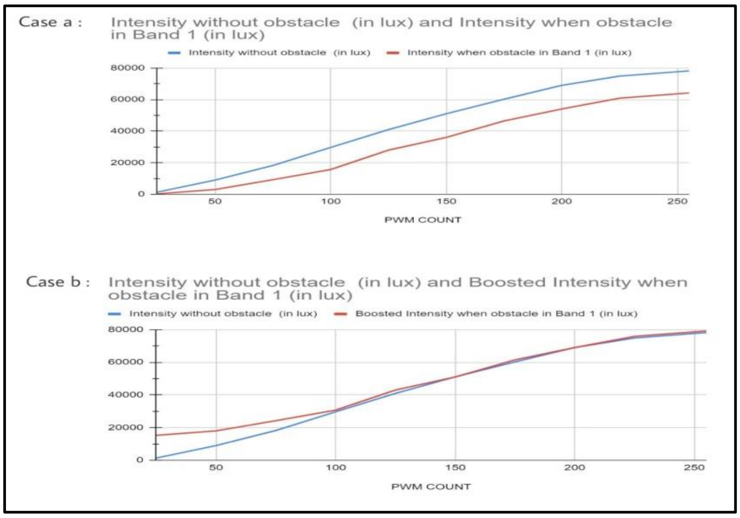

Figure 8: Plot of lighthead behavior when obstacle is absent vs when obstacle in Band 1

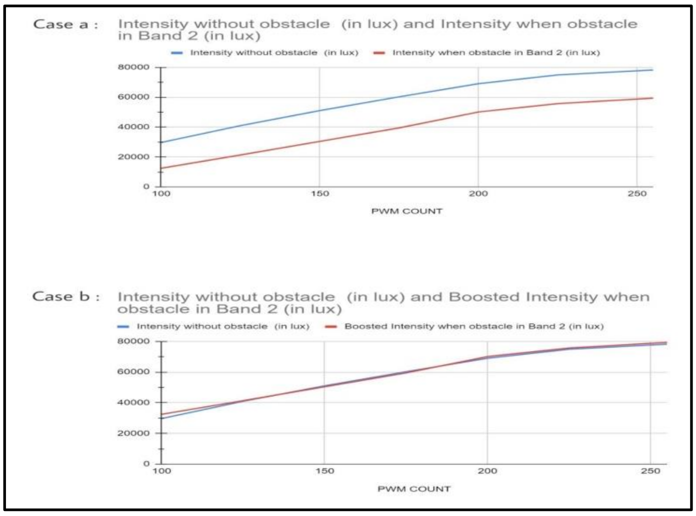

Figure 9: Plot of lighthead behavior when obstacle is absent vs when obstacle in Band 2

When obstacle is present in band 2, the plot of intensity without obstacle exhibits behavior very similar to plot of intensity when obstacle is present as seen in case a of Figure 9, only the magnitude remains different, thus by applying intensity compensation the plot of intensity with obstacle assumes a similar behavior to the curve when obstacle was not present as in Figure 9 case b.

When obstacle is present in Band 3 highest compensation is to be provided, but if the original intensity without obstacle is less than the amount of intensity compensation provided (i.e 35k lux for band 3) when obstacle is in the Band 3 than the intensity with compensation will have higher magnitude than the original intensity present without obstacle. As a result the plotted curve is from 175 pwm count onwards, because this is the range where original intensity is approached and below this count the intensity obtained will be higher than it was originally.

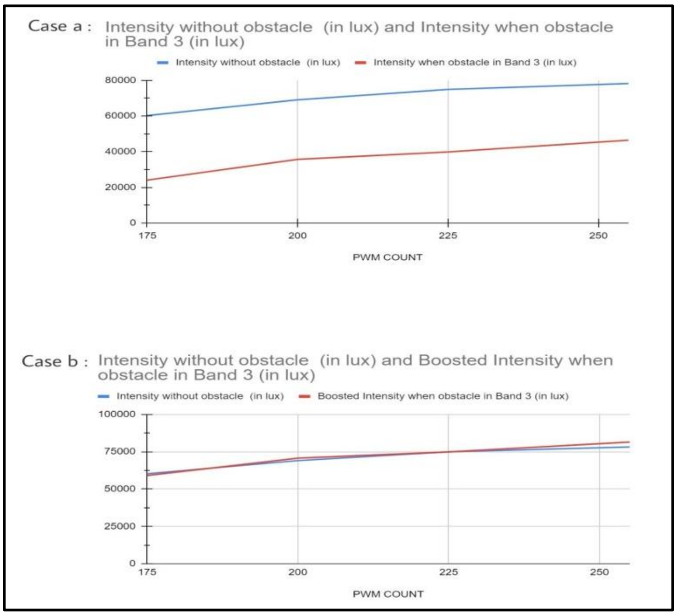

Figure 10: Plot of lighthead behavior when obstacle is absent vs when obstacle in Band 3

5. Discussion

During the measurements it has been observed that when an obstacle is close to the light head the intensity drop is lowest and as the distance between the lighthead and obstacle increases the intensity drop increases. From the results it has been deduced that when intensity is above 30k lux, the compensated intensity curve (when the obstacle is present) exhibits behavior similar to that of original intensity without obstacle. Below 30k lux this behavior is not similar but as per opinion of various surgeons, it was found that most of the surgeries are operated at an intensity equal to or greater than 40k lux hence this approach is practically feasible. Since it is very tough to implement a closed loop system based on light sensor feedback in the operating environment, this open loop system is implemented with least possible errors in the general operating intensity range.

One noticeable point is that if intensity is towards the max side and the obstacle appears then this system may not be able to increase the intensity any further due to hardware limitations as the original intensity is already at max and anything beyond would not be possible with that existing hardware, it is also due to the fact that max allowable intensity for surgical procedure is below 160k lux to prevent surgeons eyes from permanent damage due to excessive intensity.

Future scope of this system can be using multiple light heads with intensity compensation feature to overcome the problem of hardware limitations as well as intensity limitation, since one of the light heads can be at top of surgeon and the other can be placed sideways and thus even at a lower intensity, shadowless-ness can be achieved.

6. Acknowledgements

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

This research was completely self-funded and few resources used such as the LUX Meter and the surgical light external enclosure were borrowed from Prism Surgicare Pvt Ltd. Prism Surgicare had no role in collection, management, interpretation and analysis of data. It had no role in preparation, review or approval of the manuscript and the decision to submit the manuscript for publication.

Compliance with Ethical Standards

This manuscript is the authors' original work and has not been published nor has it been submitted simultaneously elsewhere.

All authors have checked the manuscript and have agreed to the submission.

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