Initial experimentation on determining the presence of a non-line-of-sight (NLOS) object through image enhancement

1. Outline

In the Shadow Cam paper[1], images are continuously collected by a camera situated on top of an autonomous wheelchair to detect the presence of a moving object around corners, to prevent collision with the object. While no deep learning processes are utilized within the Implementation, in this initial experimentation, a similar method of image enhancement and pre-processing will be implemented, feeding such images into a deep learning network.

The aim of this experimentation would be to produce a visible difference between (1) a clean and well-illuminated miniature set-up and (2) the exact set-up with additional NLOS items, merely through the enhancement on the diffusion and/or reflection of light to a designated patch of area on a flat painted surface.

2. Set-up and collection of images

The set-up of the experiment is as follows:

Figure 1: *Top view of the set-up, of height 20cm, width 25cm and length 40 cm*

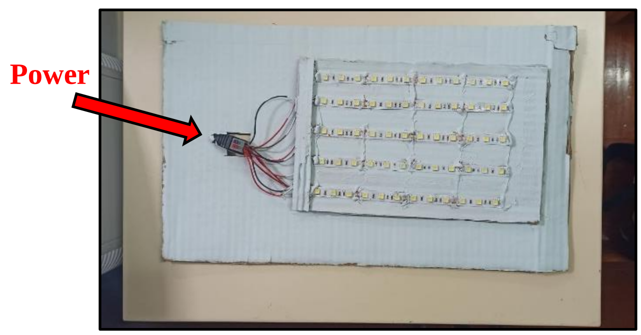


Figure 2: *Top view of the lighting set-up, consisting of 60 white LEDs connected in parallel to a 12V power supply*

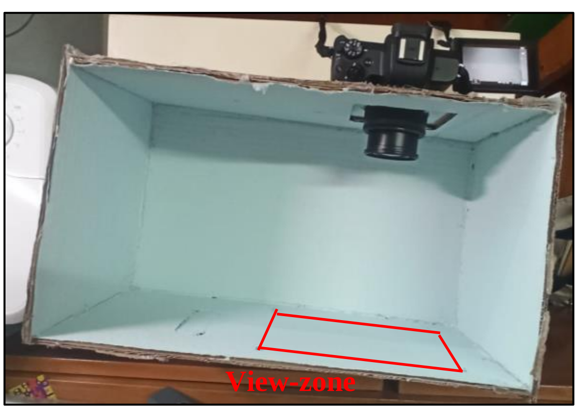


Figure 3: *Top view of the set-up, together with a Canon M50 camera inserted in the camera view-hole of 6cm in diameter*

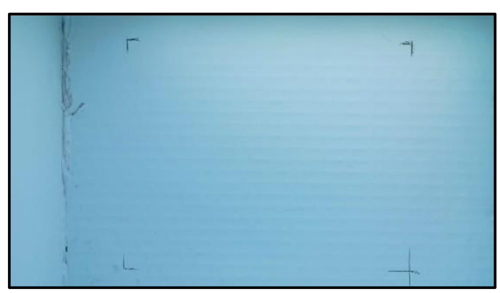
Figure 4: *The set-up together with the cover, power supply and camera inserted*

[1] https://www.researchgate.net/publication/329414647_ShadowCam_Real-Time_Detection_Of_Moving_Obstacles_Behind_A_Corner_For_Autonomous_Vehicles

To ensure the rigorosity of the experimental process, the variables related to the experiment is listed out as follows:

Controlled Variables	Independent Variables	Dependent Variable
Luminosity of illumination	Shutter speed and Aperture of camera (which affects the brightness of the image)	The intensity and visibility of the diffused pattern caused by the variation in the object, after image enhancement
Reflectance of wall surfaces	Size of object	
Area of capture in images	Reflectance of object	
	Location of image in regard to the image position	

The details of the controlled variables are as follow:

Variable	Details	Image
Luminosity of illumination	4,650 lux at the centre of designated capture area	
Reflectance of wall surface	To ensure that the reflectance or diffusion patterns are similar to that of a real-life situation, all inner surfaces of the set-up are evenly covered in wall paint (brand: Nippon)	/
Area of capture in images	To ensure the size of all images collected are of the exact dimension, crop marks are drawn at four designated corners. It covers a rectangle of length 18cm and width 15cm	

To collect images under realistic and rigorous circumstances, the object placed in the NLOS area are chosen and grouped according to 2 major aspects: size and reflectance. In conjunction, the position of the object in respect to the area of capture will also be varied.

Object	Size	Reflectance type	Position
Gloss-coated surface of 'Colgate' toothpaste packaging	Small (longest side <7cm)	Specular	A horizontal distance of 1cm from the rightmost border of the capture area
Lego miniature figure		Diffuse	
Aluminium foil-wrapped cardboard prism	Medium (longest side <13cm)	Specular	
Tennis Ball		Diffuse	
See-through acrylic sheet	Large (longest side >12cm)	Specular	
Small metal pot		Specular	
Aluminium foil-wrapped foam semi-circle		Specular	
Rubber ball		Diffuse	

Figure 5: *small objects*

Figure 6: *medium objects*

Figure 7: *large objects*

Considering that larger objects might have more influence on the diffusion and/or reflection of light, more larger objects are included in the experiment.

Side note: Most surfaces can be divided in those that give (1) specular reflection and (2) diffuse reflection[2]. Specular reflection refers to a mirror-like reflection of waves[3], such as from polished metal, while diffuse reflection refers to the reflection of light which is scattered at many angles, such as rough wood surfaces and matte white painted surfaces.[4]

[2] https://en.wikipedia.org/wiki/Reflectance#Surface_type
[3] https://en.wikipedia.org/wiki/Specular_reflection
[4] https://en.wikipedia.org/wiki/Diffuse_reflection

The capturing of images is summarized as follows:

Focal Length	Focus	Aperture	ISO	White Balance	Shutter Speed	Position	Group of object size
15mm	Manually Focused to the top-left crop mark	F3.5	100	5600K	1/200	1cm	S, M, L
					1/500		
					1/800		

To ensure the reliability of the images, they are captured in a pitch-black environment (near 0 lux) and images of each category is captured once. They will be labelled and categorized for the enhancement.

3. Processing and enhancement of images[5]

With reference to ShadowCam, three main steps are employed in enhancing the image:

(1) Cropping
(2) Gaussian Blur
(3) Image subtraction
(4) Multiplication of image

First of all, the images (consisting of the designated focus area) are cropped to a size of 500 x 500. Then, a gaussian blur is added to the images. Mathematically, this experimentation computes

$$output = \left| G(img_{obj}, k) - G(img_{ref}, k) \right| \cdot a$$

Where k is the Gaussian kernel size and a is the amplification parameter. In our implementation, the following combinations of variables will be tested:

Gaussian kernel size	Amplification Parameter
(5,5)	$\{n \mid n \in \mathbb{Z}^+, 5 \leq n \leq 20\}$

[5] The code for image enhancements could be obtained at https://github.com/stevolopolis/NLOS_object_detection

To test out the basic effect of applying the above steps, they are carried out on an additional set of images. The enhancement is fixed to be a kernel size of (5,5) and amplification parameter of 5:

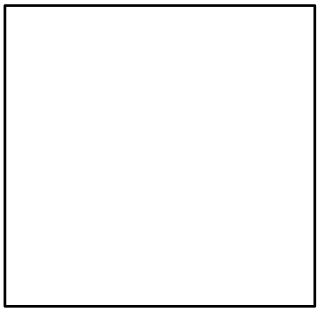


Figure 8: *pure white background without enhancement*

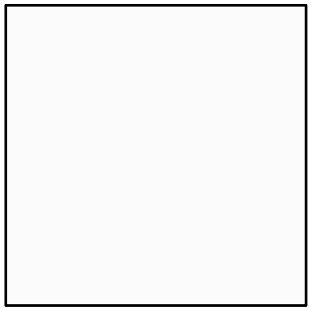


Figure 9: *pure white after enhancement (more yellowish colour)*

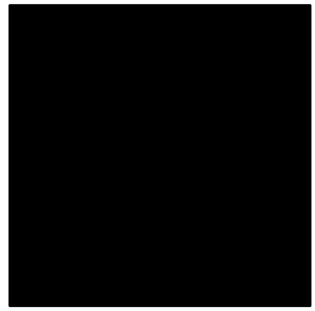


Figure 10: *pure black background without enhancement*

Figure 11: *pure black after enhancement (no visible difference)*

Figure 11: *pure white background with arbitrary black patterns*

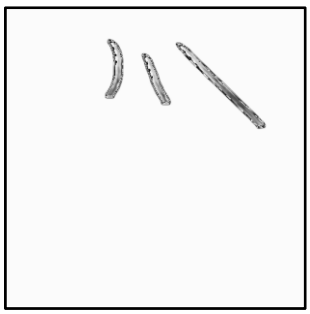


Figure 12: *pattern after (5,5) kernel and amplification parameter of 5*

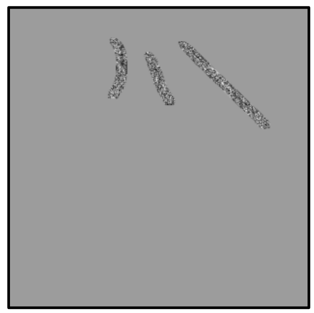


Figure 13: *pattern after (5,5) kernel and amplification parameter of 100*

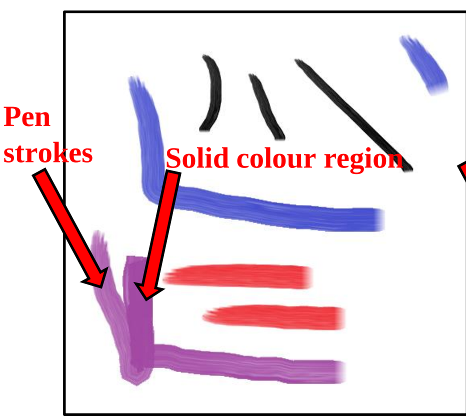


Figure 14: *pure white background with arbitrary colourful patterns*

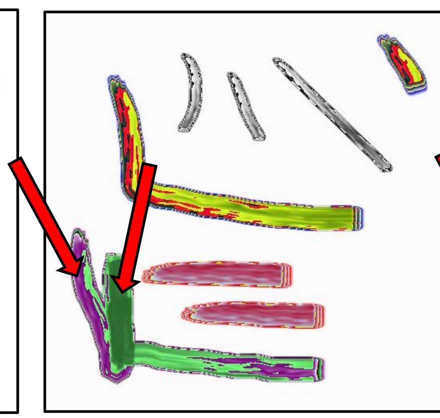


Figure 15: *pattern after (5,5) kernel and amplification parameter of 5*

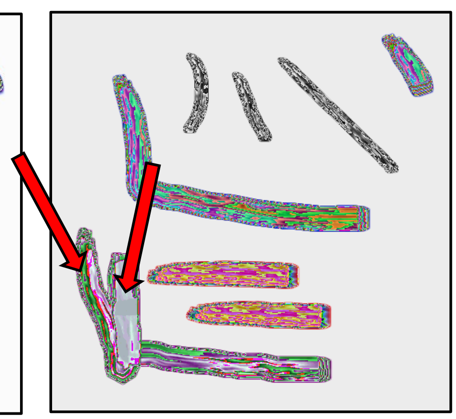


Figure 16: *pattern after (5,5) kernel and amplification parameter of 20*

As seen from the results above, while the gaussian blur function merely removes unwanted noise in the image, the size of the amplification parameter is deterministic to the level of detail of the resultant image. For instance, the difference in the depth and colour in pen strokes are amplified and represented by different colours. *The larger the amplification parameter, the more detailed the representation would be*, as shown in Fig. 16.

Moreover, an *Image subtraction* step is also present and applied to all images. Considering the original set-up as a reference, the presence of an object, despite located in NLOS, should diffuse light towards the area of viewing. In other words, there should be 'something more' comparatively. Therefore, this experimentation subtracts the *reference_img* from *object_img*. Such a step is illustrated below:

Figure 17: *reference image*

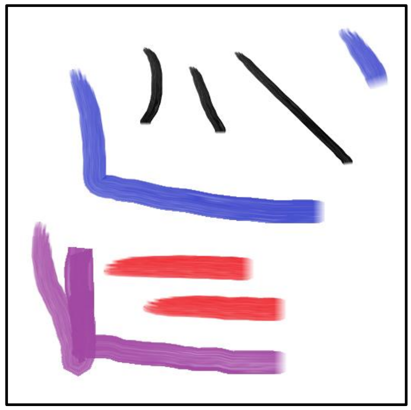


Figure 18: *object image*

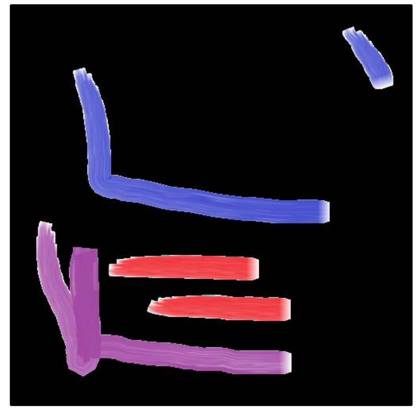


Figure 19: *result of subtraction*

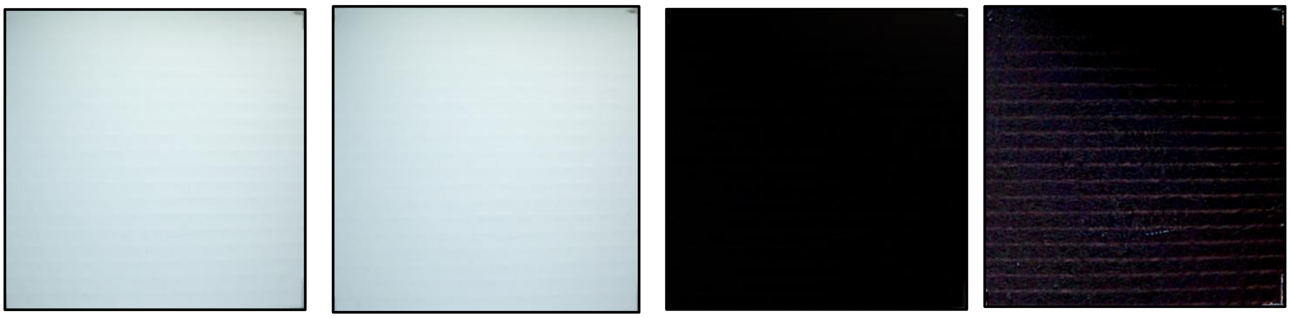
As shown above, the *image subtraction* step, when well-implemented, could effectively concentrate our focus onto the 'difference' between two images, and carry out further implementation. However, source of experimental error includes the slight variations in the light source, which affects the brightness and appearance of diffused light.

To alleviate the effect of such error, the reference image and object image is taken alternately within a short time period, Gaussian Blur is applied to both images before subtraction, and the white balance is fixed as well.

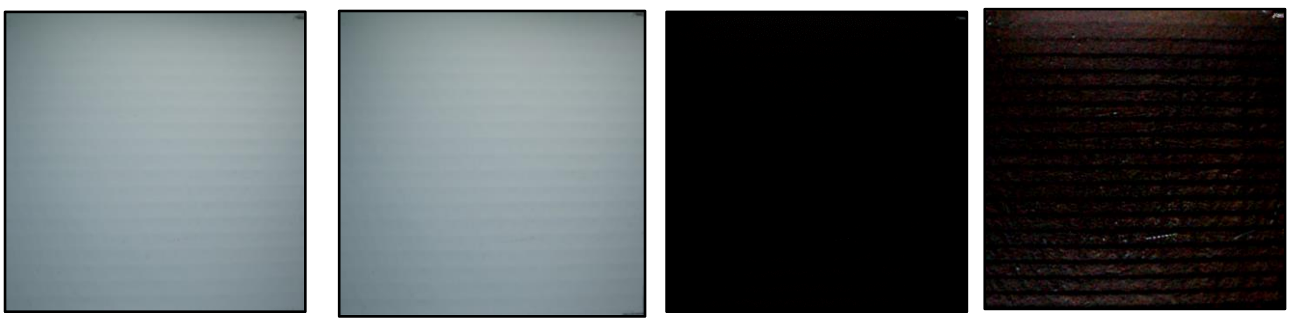
4. Results and sources of error

The following part exhibits multiple sets of images which consists of 4 parts each: The reference image, the object image, the difference image and the amplified image. Normally, the amplification parameter (a.p.) will be set at 5. However, under circumstances where the amplification effect is barely visible, it would be set at 20 or above.

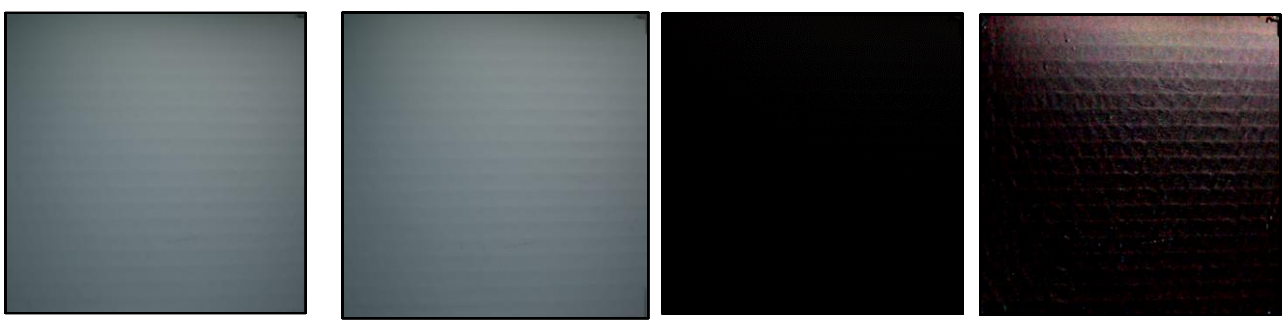
4.1 Small objects – Lego



Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/200 seconds, with a.p of 20

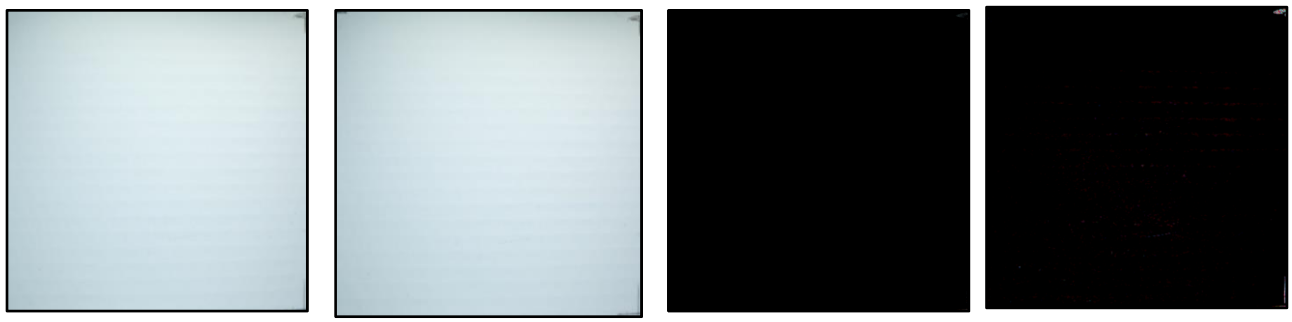


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/500 seconds, with a.p of 20

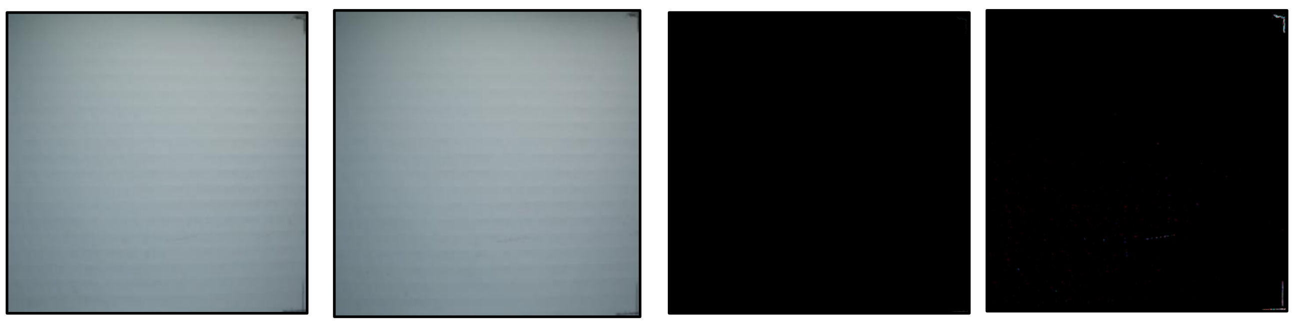


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/800 seconds, with a.p of 20

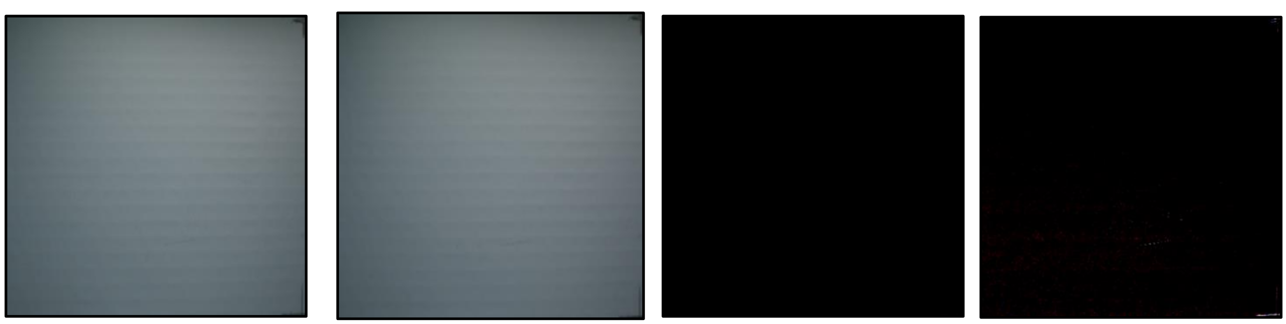
4.2 Small Objects – ‘Colgate’ Toothpaste packaging



Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/200 seconds, with a.p of 20

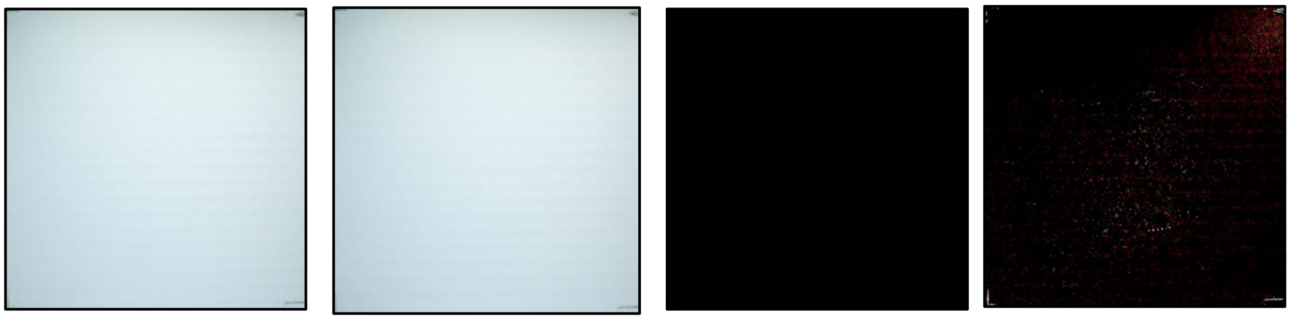


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/500 seconds, with a.p of 20

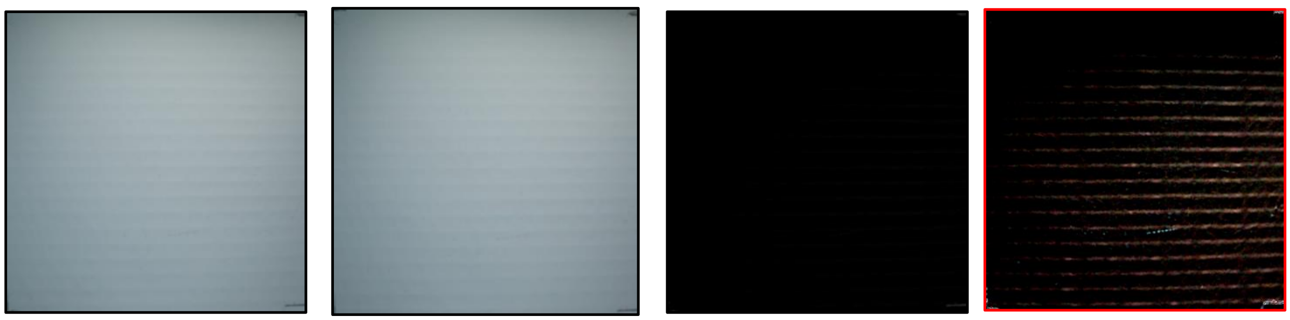


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/800 seconds, with a.p of 20

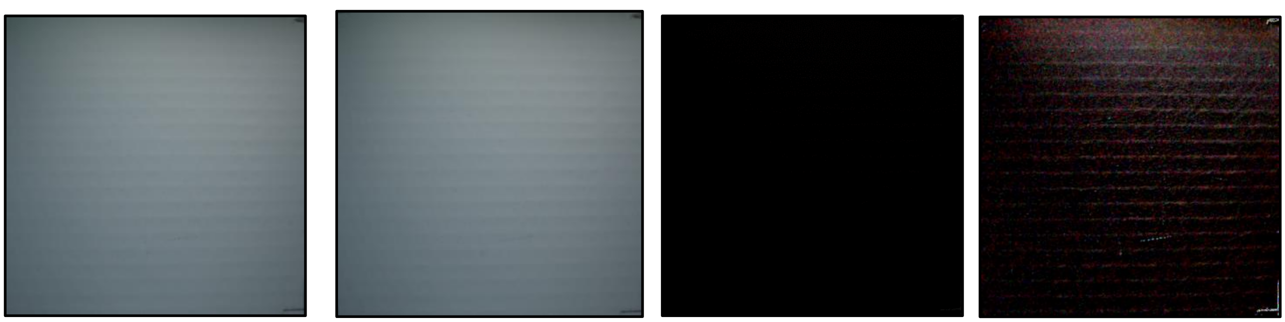
4.3 Medium Objects – Aluminium Foil Wrap



Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/200 seconds, with a.p of 50

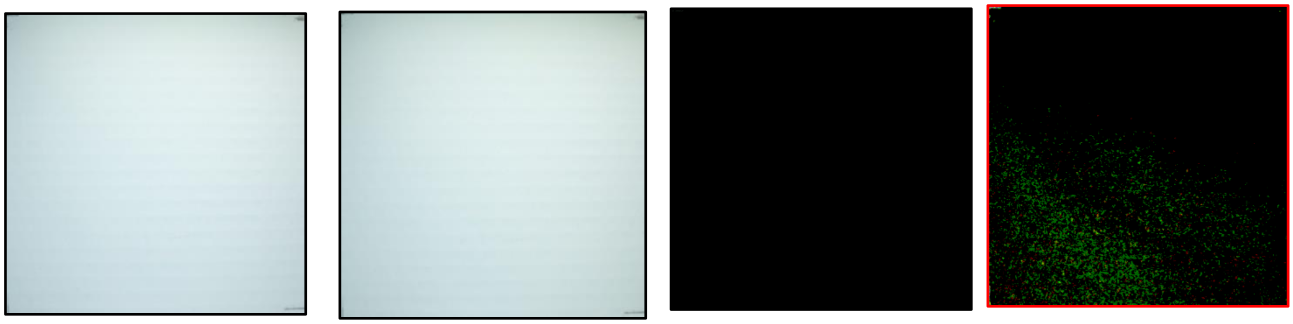


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/500 seconds, with a.p of 20

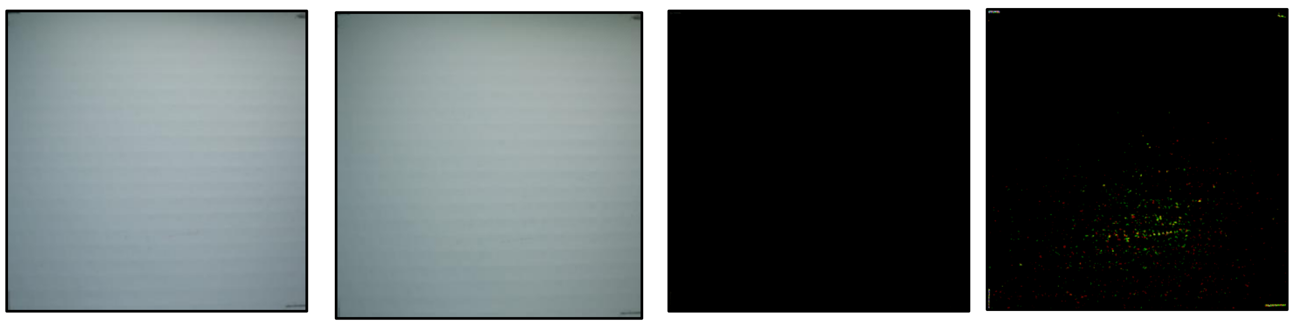


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/800 seconds, with a.p of 30

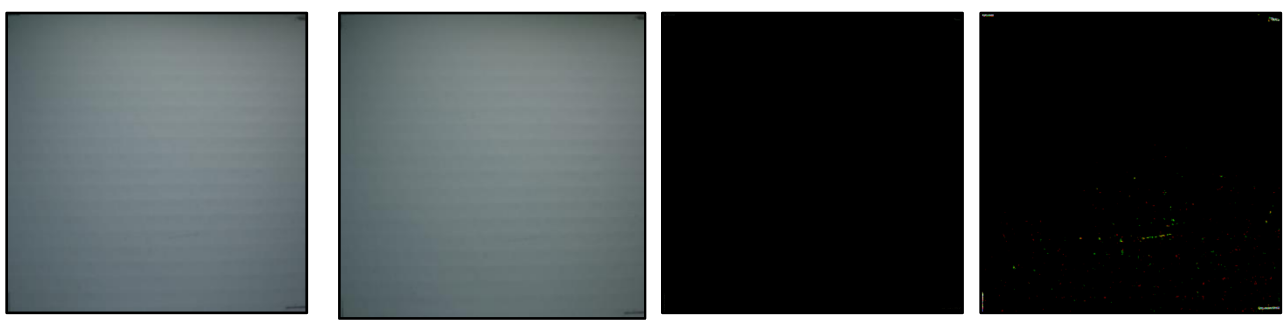
4.4 Medium Objects - Tennis Ball



Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/200 seconds, with a.p of 100

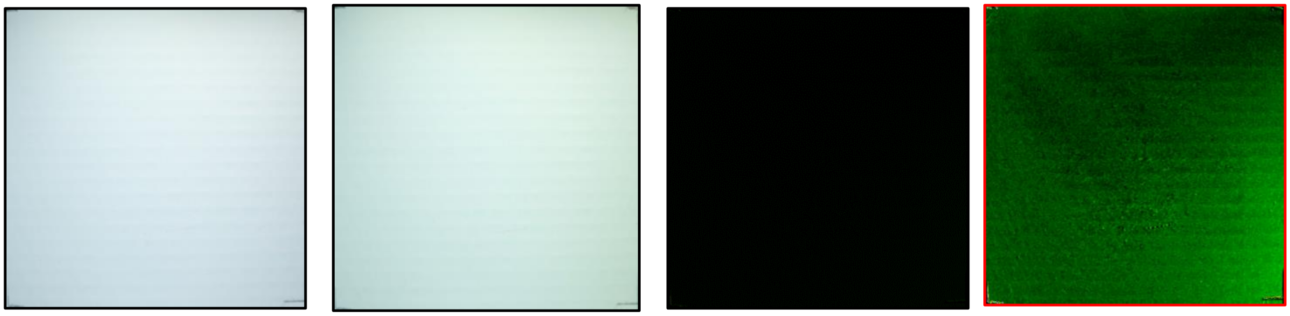


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/500 seconds, with a.p of 100

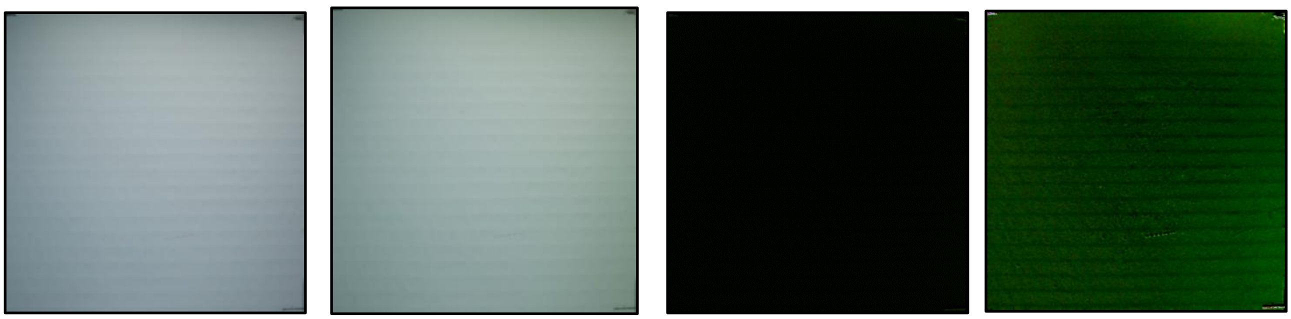


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/800 seconds, with a.p of 100

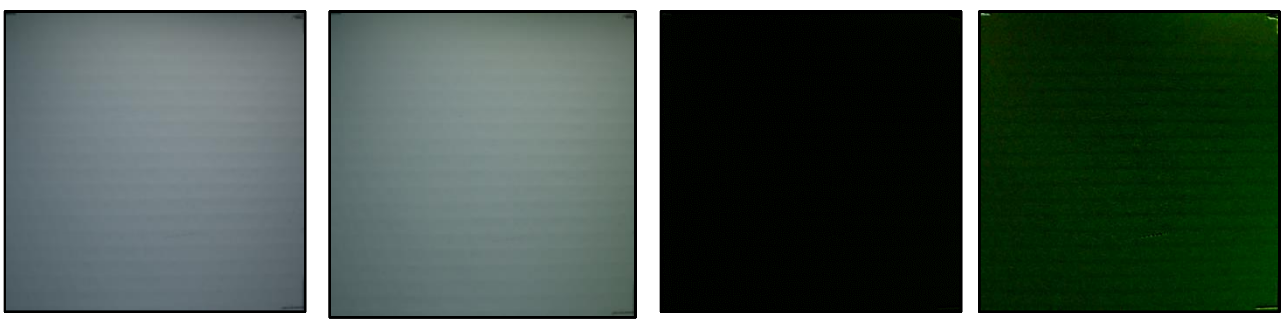
4.5 Large Objects – Acrylic Board



Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/200 seconds, with a.p of 20

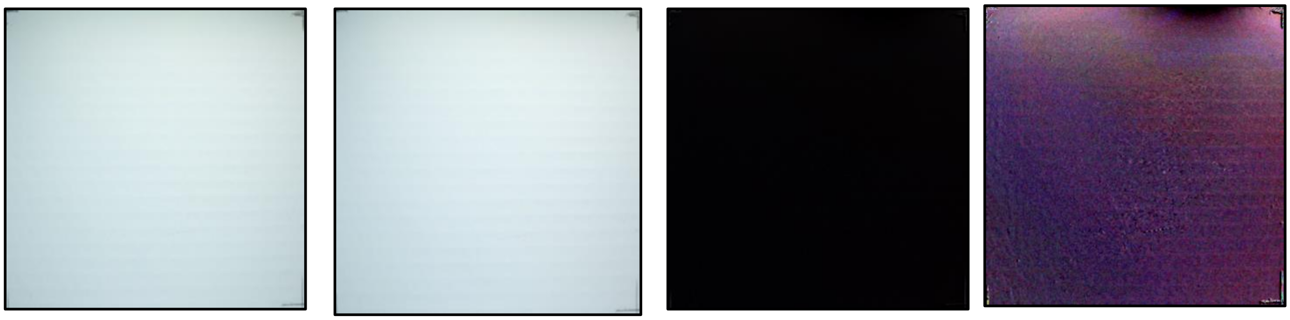


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/500 seconds, with a.p of 10

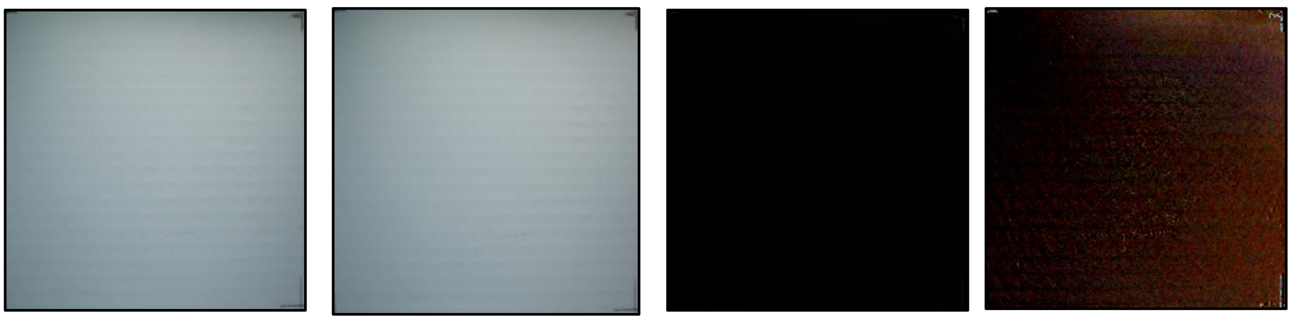


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/800 seconds, with a.p of 10

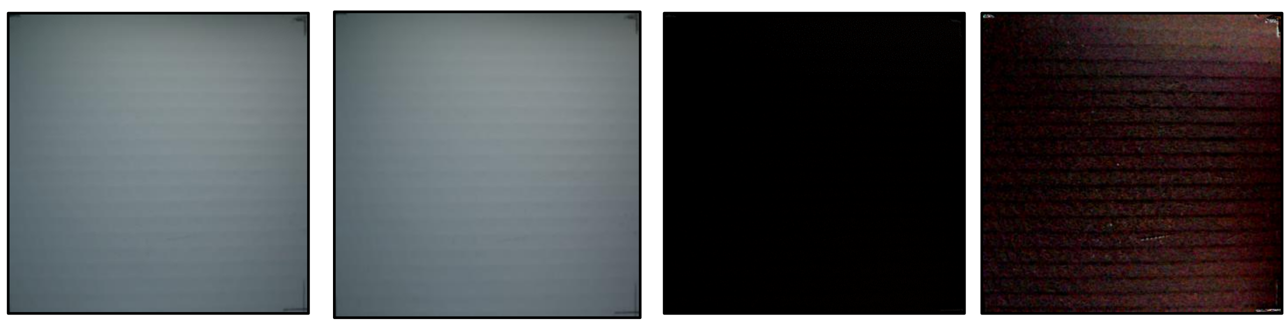
4.6 Large Objects – Aluminium Foil-wrapped hemisphere



Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/200 seconds, with a.p of 20

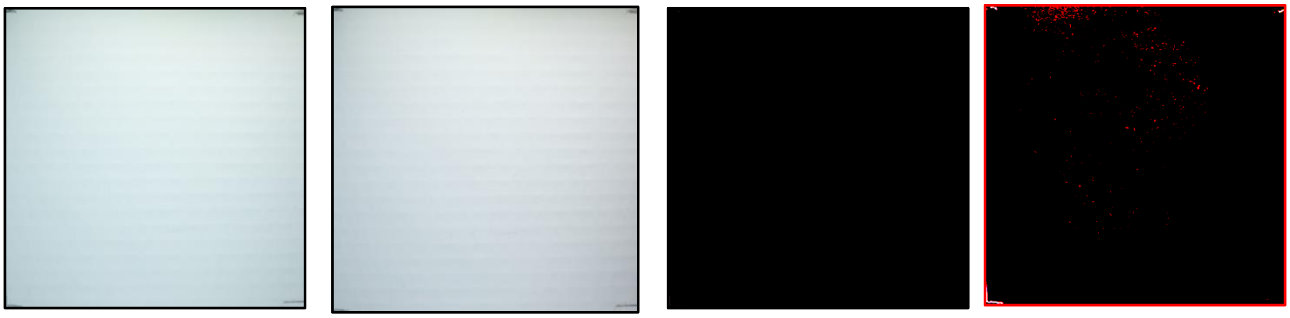


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/500 seconds, with a.p of 20

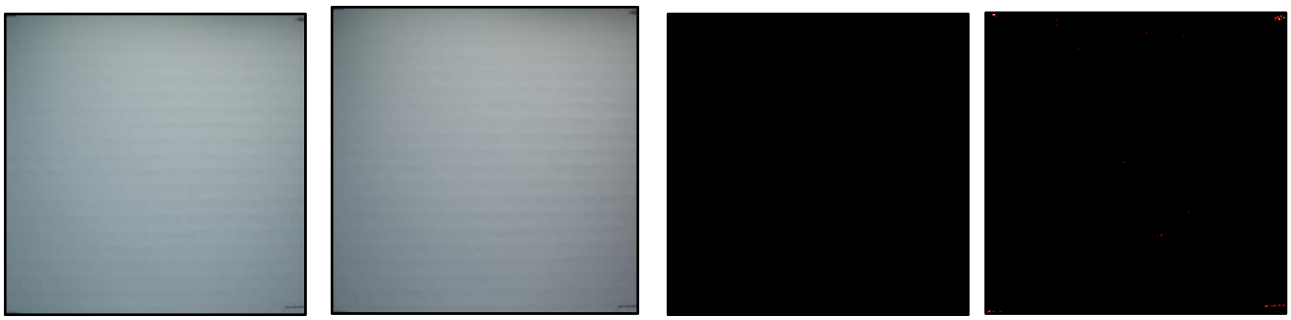


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/800 seconds, with a.p of 20

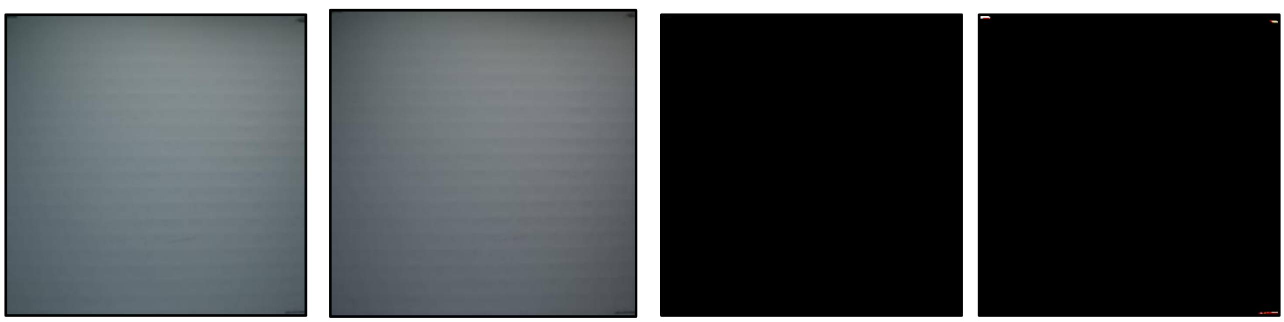
4.7 Large Objects – Rubber ball



Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/200 seconds, with a.p of 1000

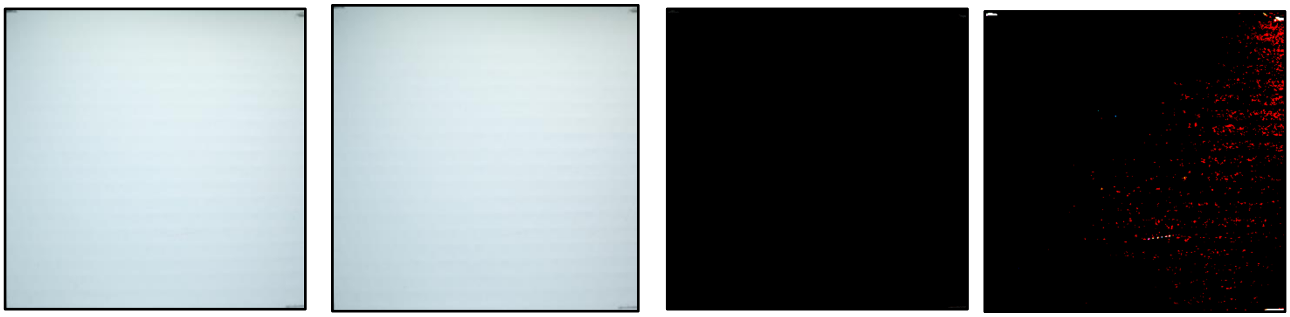


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/500 seconds, with a.p of 1000

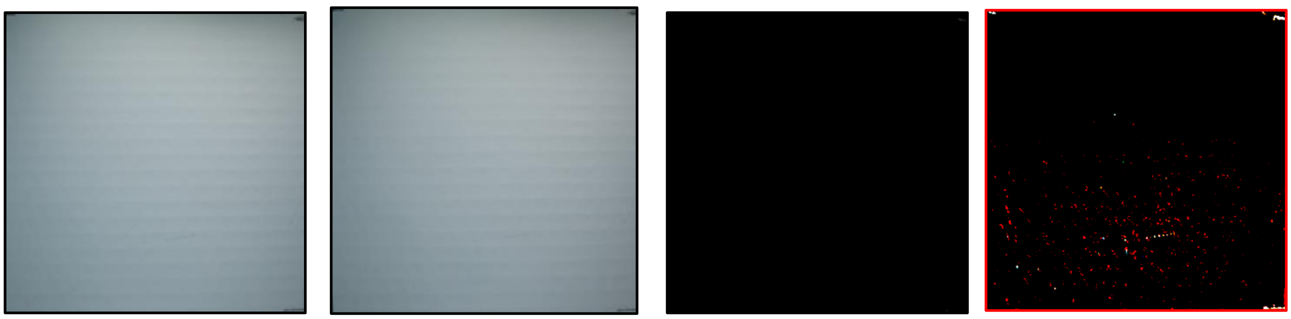


Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/800 seconds, with a.p of 1000

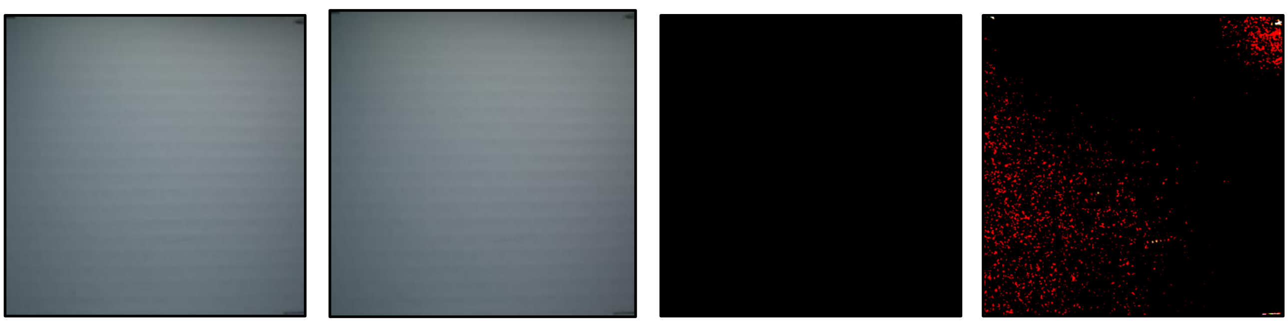
4.8 Large Objects – Metal Pot



Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/200 seconds, with a.p of 1000



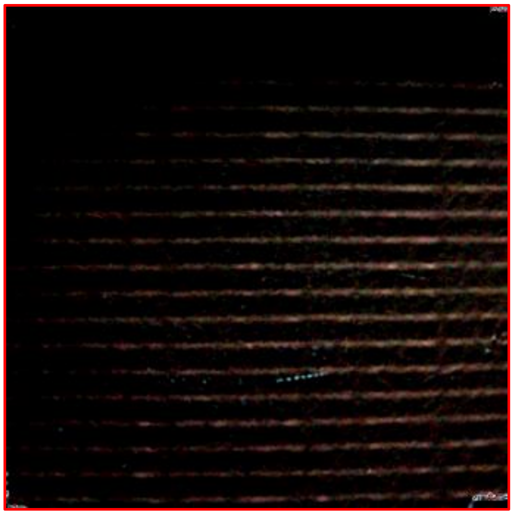
Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/500 seconds, with a.p of 1000



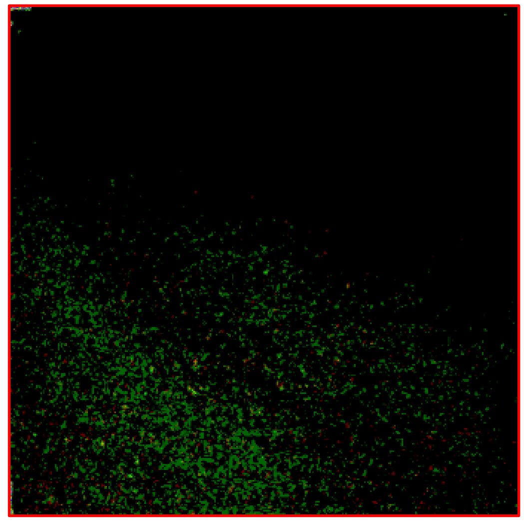
Reference Image, Object Image, difference image and amplified image of Shutter Speed 1/800 seconds, with a.p of 1000

Interesting Cases:

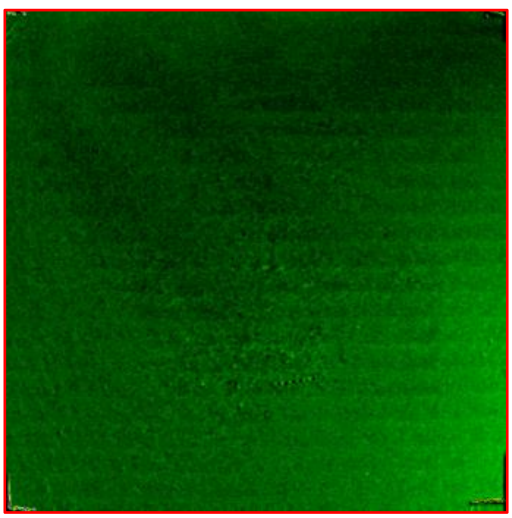
Medium Objects (Aluminium Foil Wrap)
SS 1/500



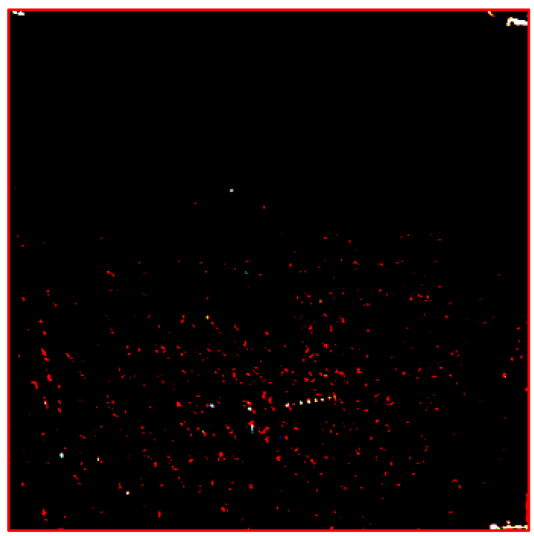
Medium Objects (Tennis Ball)
SS 1/200



Large Objects (Acrylic Board)
SS 1/200



Large Objects (Metal Pot)
SS 1/500



Sources of experimental error

As shown above, even if two images are taken consecutively (within 5 seconds) and no variables are altered, some fundamental differences exist and is clearly visible when applying an amplification parameter of 100.

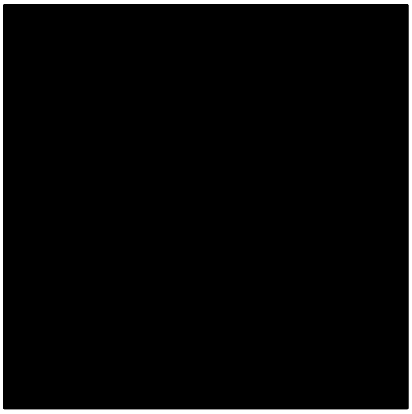


Figure 20: *resultant difference image between two consecutively taken reference images*

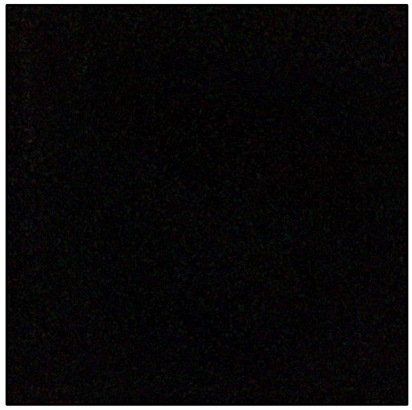


Figure 21: *pattern after amplification parameter of 20*

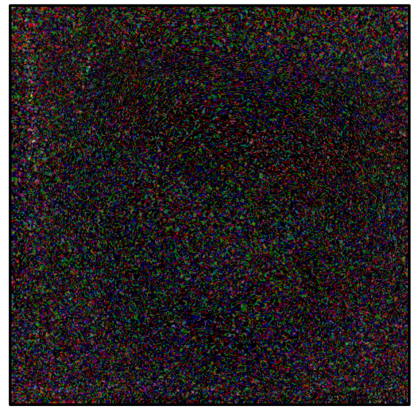


Figure 21: *pattern after amplification parameter of 100*

Therefore, the amplification parameter must not be too large (such as 20) in order to minimize the effect of such problems.

5. Conclusion

In the experiment, several observations can be made:

1. Objects placed in NLOS areas does indeed affect the shadow and/or diffusion of light in the area of focus
2. Small objects have little or no interference in the area of focus, while the larger the object, the more significant it is
3. Objects with spectrum reflection (such as acrylic boards and metal items) have a greater influence on the amplified pattern
4. The size of the amplification parameter depends on the reflectance and size of the material, where objects such as the large rubber ball requires an a.p. of 1000 in order to produce a visible amplified pattern
5. The colour of the amplified pattern does not necessarily represent the colour of the object, while such correlation could be further investigated (especially for the case of the acrylic board and tennis ball)
6. A more complex image enhancement algorithm (such as the one utilized in ShadowCam) should be used to produce a more reliable and usable output