Mitigation of Repetitive Pattern Effect of Intel® RealSense™ Depth Cameras D400 Series

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Rev 0.3

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Abstract

Presented here are methods to mitigate the problem of depth errors with stereo vision depth cameras caused by repetitive patterns within the captured image field. The methods presented are specific to the Intel® RealSense™ Depth Cameras D400 series although the principles may apply to other cameras. These errors can result in vision systems reacting in ways that are counter to proper operation.

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1 Introduction

Intel® RealSense™ Depth Cameras D400 series calculate depth based on stereo vision however repetitive patterns in the image may result in regions of incorrect depth pixels, either a nearer or invalid depth. Presented here are methods that can be implemented to mitigate the repetitive pattern effect. False depth images may cause systems to operate unexpectedly due to detection of ghost objects that appear closer than the true object; using a combination of the given methods can greatly improve system operation.

2 The Repetitive Pattern Effect

2.1 Definition of the Repetitive Pattern Effect

Stereo depth computation depends on determining matches between left and right images. If there are repetitive structures in the scene, like fences or wire-grids, this determination can become ambiguous.

Although typically caused by physical objects, an image of a repetitive pattern such as alternating lines on a flat surface can also cause this effect if the laser projector image becomes washed out as may occur in conditions such as bright sunlight for example.

Figure 1 'V' corrugated surface, ventilation louver

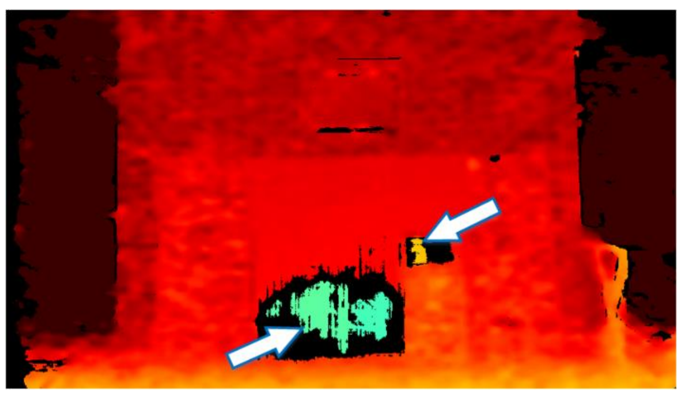

Figure 2 Error depth imaging of corrugated surface, ventilation louver

3 Methods for Mitigating the Repetitive Pattern Effect

There are several known methods that may help mitigate the repetitive pattern effect: Second Peak Threshold and Census Enable Register adjustments, enabling depth HDR mode, applying an IR pass filter, increasing projector power or use of an external projector, and use of multiple cameras.

3.1 Second Peak Threshold and Census Enable Registers

One of the tools we have for determining confidence is the advanced depth parameter, DS Second Peak Threshold. The Intel RealSense vision processor D4 determines match scores for both the best match as well as the second-best match. If the best match is of similar quality to the second-best match, this may occur due to aliasing caused by repetitive structures; the required differential between the two matches is determined by the Second Peak Threshold. By increasing the threshold value, more depth results will appear as black or zero, reducing the number of matches resulting from aliasing.

In addition to the Second Peak Threshold the Census Enable Registers can help mitigate the repetitive pattern effect. There are two registers, u-diameter and v-diameter, and their effects will differ dependent on the orientation of the repetitive pattern.

Controls for DS Second Peak Threshold and Census Enable Regs in the Intel RealSense Viewer are shown in Figure 3 and Figure 4 respectively.

Figure 3 DS Second Peak Threshold control in RS Viewer

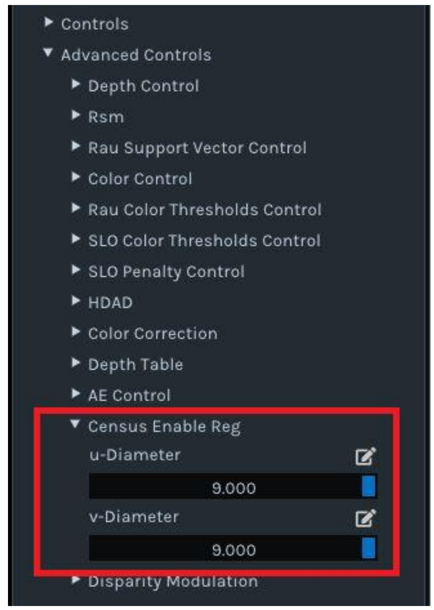

Figure 4 Census Enable Reg controls in RS Viewer

An example of setting the DS Second Peak Threshold in C++ is shown in the code snippet below,

```
// Declare RealSense pipeline
rs2::pipeline pipe;
rs2::pipeline_profile pipe_profile = pipe.start();
s2::device dev = pipe_profile.get_device();

//Advanced Mode
if (dev.is<rs400::advanced_mode>())
{
      auto advanced_mode_dev = dev.as<rs400::advanced_mode>();
      // Check if advanced-mode is enabled
      if (!advanced_mode_dev.is_enabled()) {
            // Enable advanced-mode
            advanced_mode_dev.toggle_advanced_mode(true);
      }
      const int max_val_mode = 0;
      auto depth_control = advanced_mode_dev.get_depth_control(max_val_mode);
      depth_control.deepSeaSecondPeakThreshold = (uint32_t)500;
      advanced_mode_dev.set_depth_control(depth_control);
}
```

Table 1 illustrates the effects of the DS Second Peak Threshold and Census Enable Registers on the repetitive pattern effect. These results are only demonstrative, and results will be highly dependent on each particular scene and combination of settings.

Table 1 Effects of DS Second Peak and Census Enable Registers Parameters

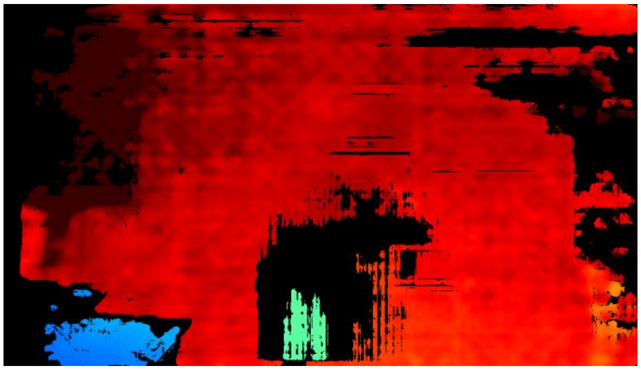

Figure 5 Error region; Second Peak = 325, Census Reg U-diameter = 1

Figure 6 Error region replaced by no depth pixels; Second Peak = 650, Census Reg U-diameter = 1

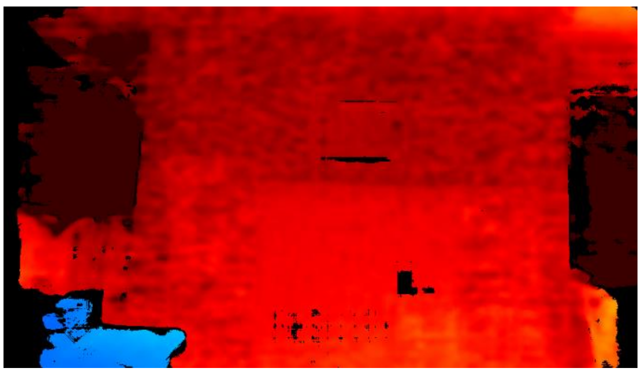

Figure 7 Error region eliminated; Second Peak = 325, Census Reg U-diameter = 2

3.2 Depth HDR mode

High dynamic range (HDR) imaging is a technique that enables an imaging system to image scenes that contain a combination of very dark and very bright regions. This is accomplished by using different gain, exposure, binning, more bits etc. in consecutive frames and then merging them to one frame. Once the HDR mode is enabled, the camera can see more details thereby eliminating some aliasing.

In many use cases, the repetitive pattern objects are usually associated with high contrast light condition, such as window blinds or reflective industrial pipes.

HDR function expands the depth performance by using the technique that produces and combines images of different exposure and gain settings.

The D400 global shutter camera, D435, D435i and D455 supports the HDR function from firmware version 5.12.9. Intel RealSense SDK2 provides APIs to enable and configure the HDR and integrate this capability for the application.

The API is currently available for the C/C++, python, and ROS wrappers.

An example of enabling HDR in C/C++ is shown in the code snippet below,

```
// Query the list of connected devices
context ctx;
auto devices = ctx.query_devices();
size_t device_count = devices.size();

if (device_count) {

      // Get the first connected device
      auto dev = devices[0];
      // Get the depth sensor
      auto depth_sensor = dev.query_sensors().front();

      // First – turn OFF auto exposure for depth sensor
      depth_sensor.set_option(RS2_OPTION_ENABLE_AUTO_EXPOSURE, 0);

      // Second – define number of sequence and exp and gain value per sequence
      // Use one exp/gain pair per SEQUENCE_ID
      depth_sensor.set_option(RS2_OPTION_SEQUENCE_SIZE, 2);
      depth_sensor.set_option(RS2_OPTION_SEQUENCE_ID, 1);
      depth_sensor.set_option(RS2_OPTION_EXPOSURE, 3200); // setting exposure to 3200
      depth_sensor.set_option(RS2_OPTION_GAIN, 16);       // setting gain to 16x
      depth_sensor.set_option(RS2_OPTION_SEQUENCE_ID, 2);
      depth_sensor.set_option(RS2_OPTION_EXPOSURE, 800);  // setting exposure to 1600
      depth_sensor.set_option(RS2_OPTION_GAIN, 16);       // setting gain to 16x

      // Third - turning ON the HDR
      depth_sensor.set_option(RS2_OPTION_HDR_ENABLED, 1);
}
```

In addition, the Intel RealSense Viewer exposes the HDR controls and allows the user to easily evaluate and preview the effect of the HDR in real time while continuously streaming. These controls are located in the 'controls' sub-menu of the 'stereo module' menu as shown in Figure 8.

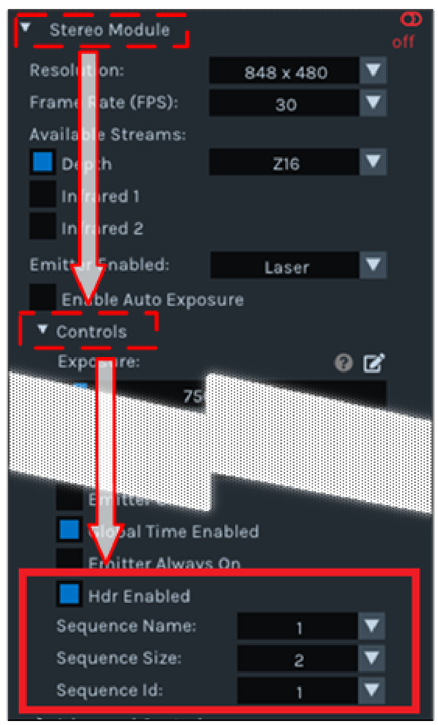

Figure 8 HDR controls located in the controls sub-menu of the stereo module menu in RS Viewer

When the depth HDR is enabled, the in-coming IR stream will consist of two alternating IR images captured using two pre-configured exposure and gain settings. With the preview, the IR stream display will alternate (flicker) between the two settings. The settings are modifiable on the fly to accommodate different scene and light conditions. The two IR images are merged to create a single image with proper exposure throughout the image and thus enabling improved depth computation.

Table 2 contains depth images without and with HDR enabled in Figure 9 and Figure 10, respectively. Correspondingly, Figure 11 shows the IR image with autoexposure and HDR disabled while Figure 12 shows the alternate frame exposures (seq 1, seq2) that are merged in the HDR process.

Without HDR some areas of the image in Figure 11 are overexposed while some are underexposed. With HDR, the high exposure image provides details in the previously underexposed regions while the low exposure image provides details in previously overexposed regions. Merging the images allows sufficient details in all areas for accurate depth computation for all pixels.

Table 2 Reduction of Repetitive Pattern Effects using HDR

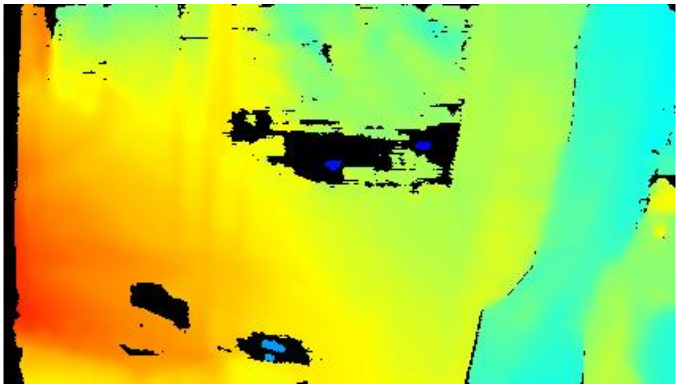

Figure 9 HDR disabled; false depth points

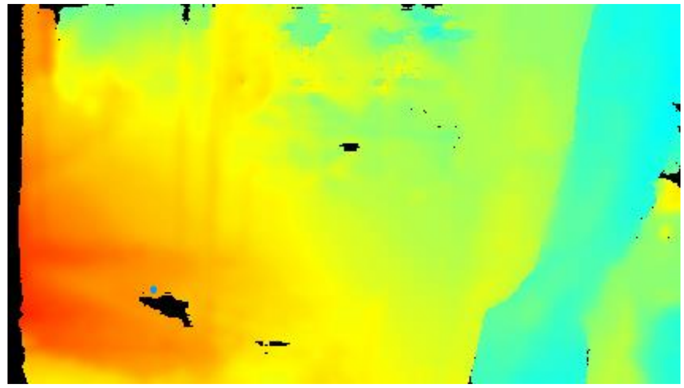

Figure 10 HDR enabled; elimination of false depth

Figure 11 HDR disabled; IR image, auto exposure

Figure 12 HDR enabled; IR images, seq1 / seq2

3.3 Application of an IR Pass Filter

An IR pass filter can increase the relative strength of the textured IR projector pattern relative to the ambient lighting. A common cause for the repetitive pattern effect is when bright sun light washes out the IR projector pattern coming from the camera. The repetitive pattern effect can be significantly mitigated by adding a high-pass filter that passes IR light from the projector but attenuates some portion of visible light increasing the relative intensity of the projector pattern.

Below is a comparison of IR images ‘before’ and ‘after’ IR filter application. The target in this example is a camping thermal mat containing vertical repetitive pattern.

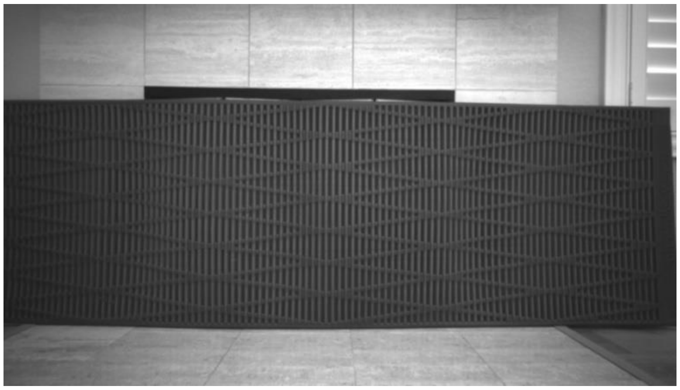

Figure 13 IR image without IR pass filter

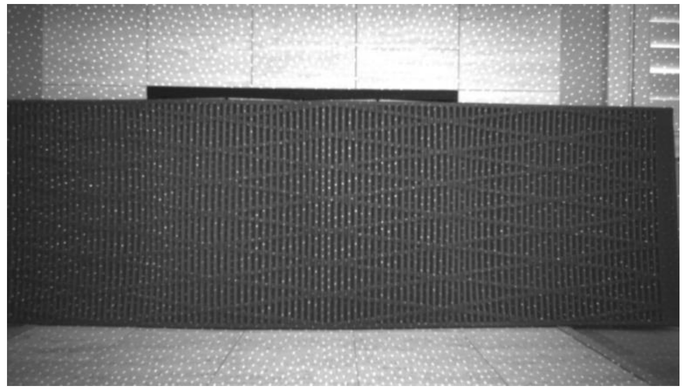

Figure 14 IR image with IR pass filter (NIR-75N)

Figure 15 shows the depth image of the scene above without the IR pass filter and illustrates the repetitive pattern effect by the false depth areas circled. Figure 16 shows the depth image with the addition of the IR pass filter and the removal of the false depth areas.

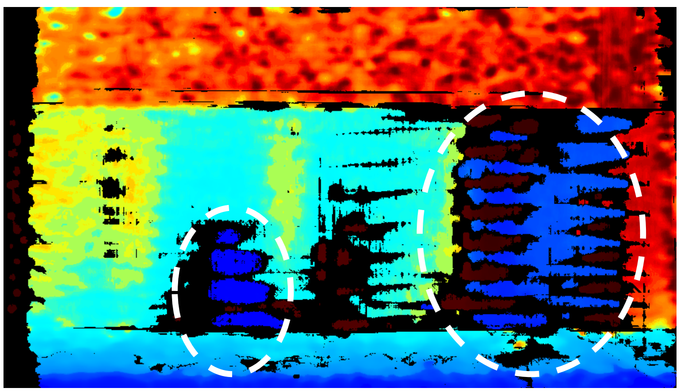

Figure 15 Depth image without IR pass filter

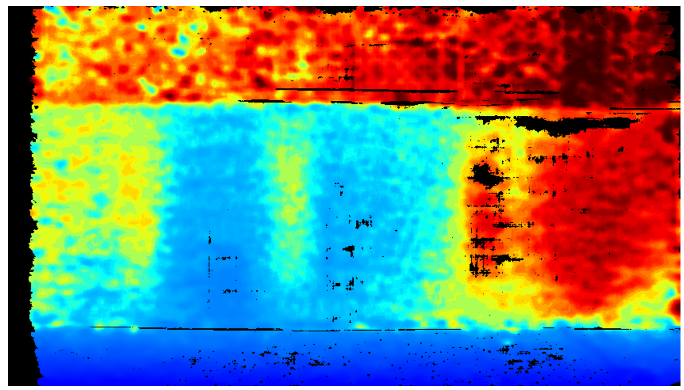

Figure 16 Depth image with IR pass filter (NIR-75N)

Figure 17 shows the 3D point cloud illustrating the false depth image while Figure 18 shows the absence of the false depth with the application of an IR pass filter.

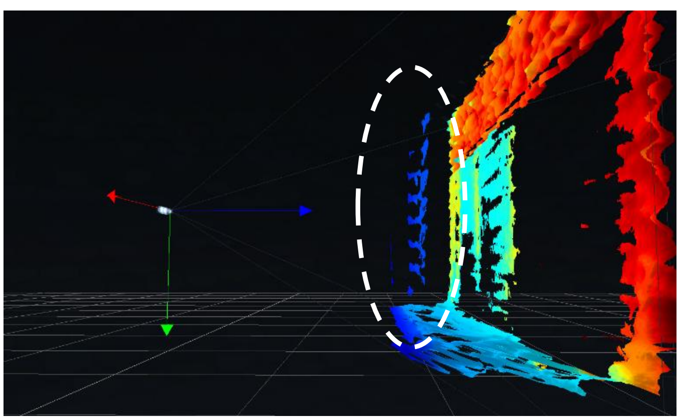

Figure 17 3D Point Cloud without IR pass filter; error depth highlighted

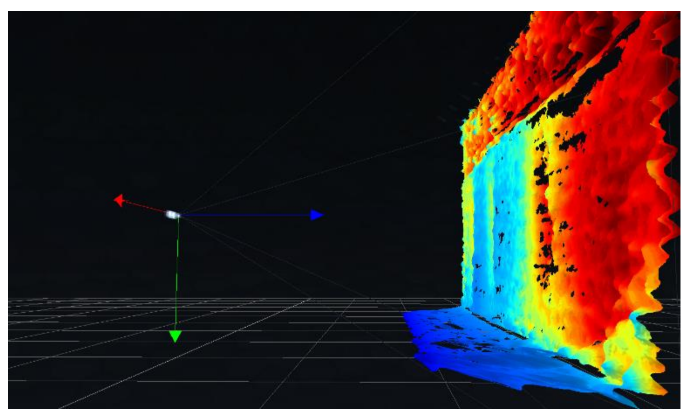

Figure 18 3D Point Cloud with IR pass filter (NIR75-N); no error depth present

A recommended IR pass filter is the **CLAREX® Near-Infrared (NIR) Filters -*NIR-75N;*** additional information can be found at the Astra Products product page, [https://astraproducts.com/info-acrylic-nir-filters.asp.](https://astraproducts.com/info-acrylic-nir-filters.asp)

Figure 19 below shows the transmission graph for the recommended IR pass filter courtesy of Astra Products.

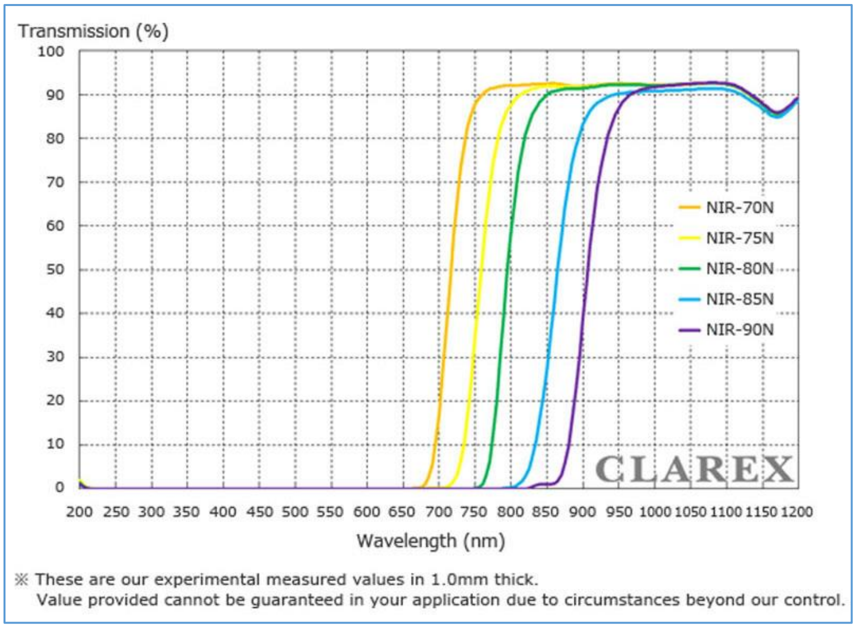

Figure 19 IR filter transmission graph (courtesy of Astra Products)

Recommended dimensions for the IR pass filter is shown in Figure 20; two filters for each camera are required, one for each IR sensor.

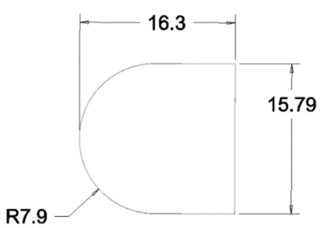

Figure 20 Recommended IR filter dimensions for D400 cameras

Illustrations showing suggested application of double sided adhesives to the IR pass filter and locations to apply filters to the D435/D435i camera sensors are shown in Figure 21.and Figure 22.

Figure 21 Pre-cut double-sided adhesives attached to the IR pass filter

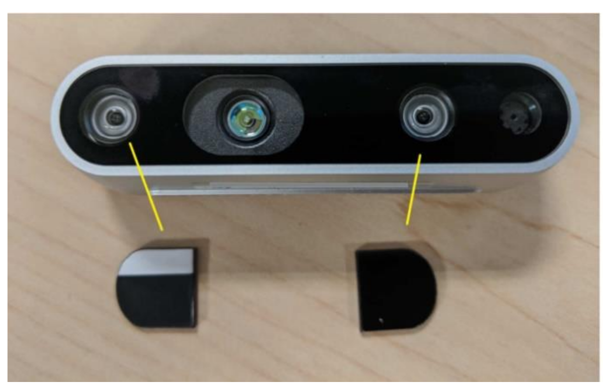

Figure 22 IR pass filters ready to be attached to D435/D435i

3.4 Increasing Projector Power or Use of an External Projector

Increasing projector power or using an external projector can improve the visibility of the projected pattern seen by the camera such that the captured images have sufficient distinct features to perform the correct depth computations.

Table 3 Effects of Projector Power

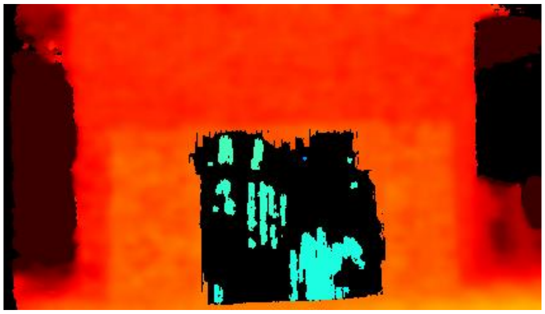

Figure 23 Projector off (0 mW, distance to error region is 2.3 m)

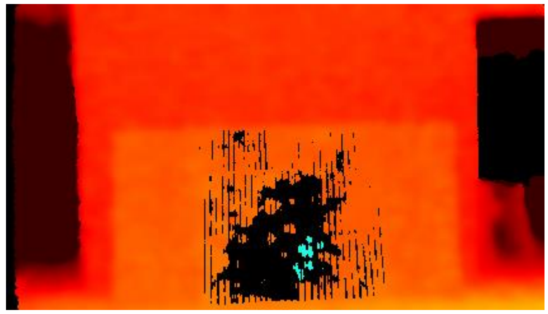

Figure 24 Projector default value (150 mW)

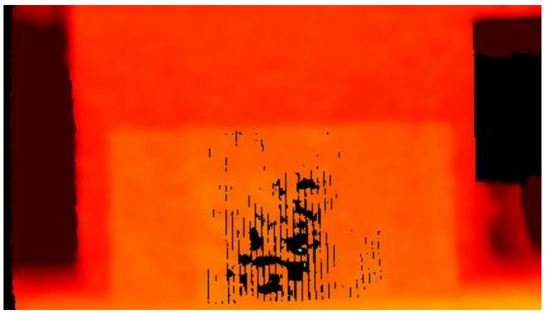

Figure 25 Projector maximum (360 mW)

3.5 Use of Multiple Cameras

Merging depth maps from multiple cameras with different view perspectives can be used to reduce false depth points caused by the repetitive pattern effect. Specific false depth points transmitted by a camera is dependent on the specific perspective of the camera to the object(s), in this case the repetitive pattern Using two cameras that have slightly different perspectives to a scene, will, if there are false depth pixels, typically result in each having different false depth pixels relative to the scene while true depth points will be common to both. By merging the depth maps and rejecting non-equal depth pixels results in a point cloud with the false depth points removed.

Figure 26 below shows a pair of depth images from two side-by-side cameras with slightly different view angles that demonstrate how each has false depth points but at different locations. In the merging

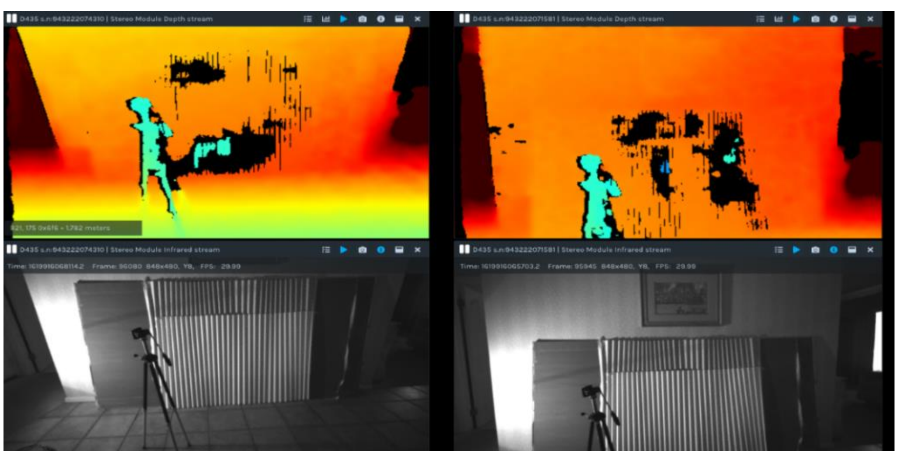

Figure 26 Multiple camera perspectives showing differing depth images

process, non-equal depth pixels would be rejected as invalid pixels while true depth pixels common in both images, such as the tripod in the foreground as well as all of the wall would be included in the point cloud.

This method requires custom software design and implementation as well as a host hardware of higher processing power to detect, remove and merge multiple depth maps. Merging of depth maps is beyond the scope of this document.

Besides mitigating the repetitive pattern effect, some benefits of using multiple cameras include, increasing overall depth field of view and adding projector patterns from a different emitter. To achieve the benefit of additional projector patterns it is necessary for the emitter must be on during image capture by the objective camera; this may be accomplished either by having the laser always on or by synchronizing the secondary projector. More power is wasted by having the laser always on but synchronization requires additional sync cabling. Improved depth performance is achieved with the added image detail that will be used in the depth algorithm.

There are many possibilities for configuring multiple cameras and here we present three possible two-camera configurations. For each configuration the principle remains the same but of course the actual process may vary. As an example, for the first case presented with cameras with opposing Y-Axis', one of the images is required to be inverted to align with the other image.

3.5.1 Parallel X-Axis with Opposing Y-Axis Configuration

In this configuration two cameras are parallel, but one is rotated 180 degrees about the Z-axis, that is parallel X-axis with opposing Y-axis orientation. This results in the images inverted to each other, a slight horizontal offset of the reference IR imager, and a slight vertical (Y-axis) offset. **Error! Reference source not found.** is a diagram showing the camera faces for this configuration.

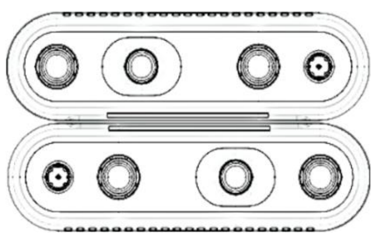

Figure 27 Opposing Y-axis orientation, parallel X-axis

Figure 28 shows the depth and IR image for each camera in this configuration

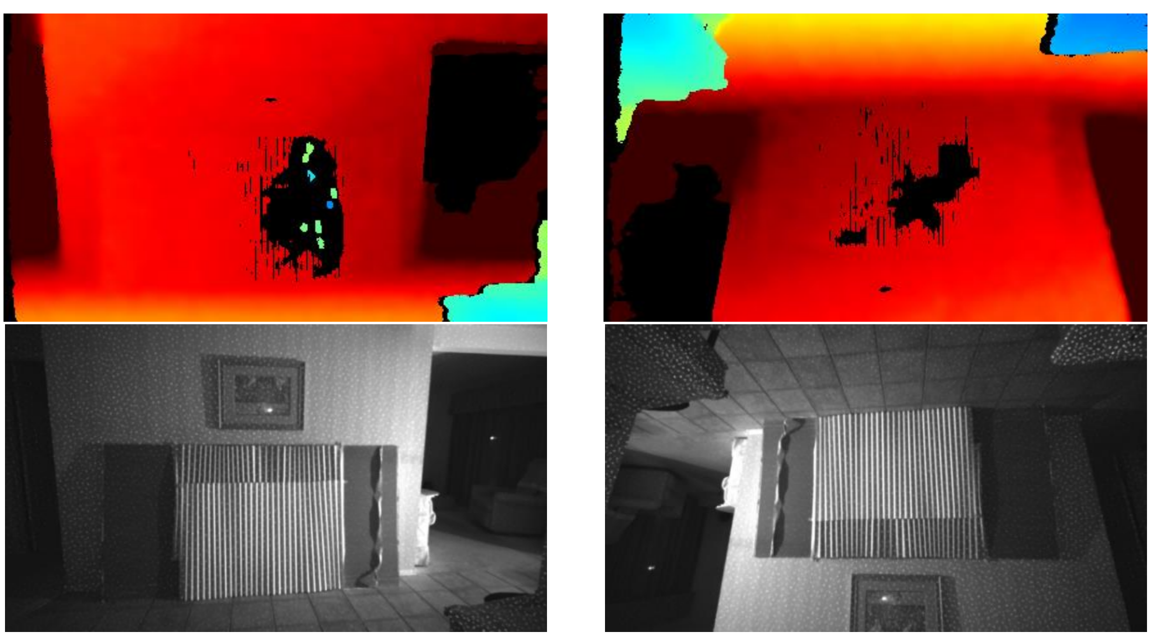

Figure 28 Depth and IR images for opposing Y-axis orientation, parallel X-axis configuration

Prior to processing the two images for depth corrections, one image needs to be inverted for proper orientation as shown in Figure 29.

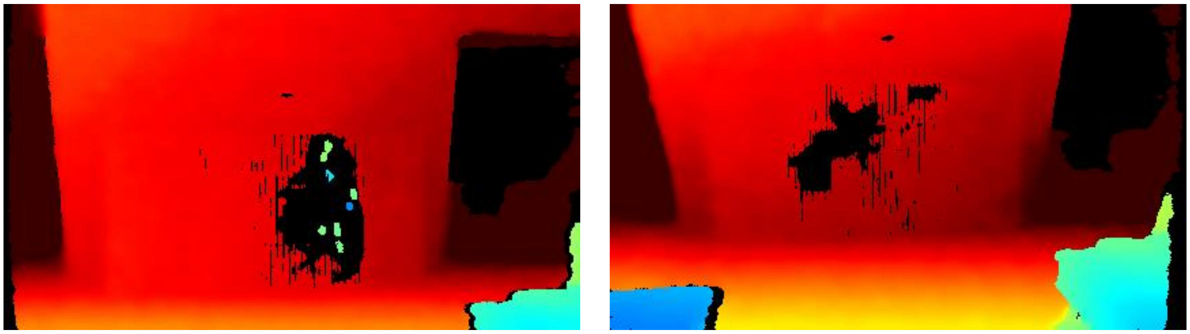

Figure 29 Depth image inverted for aligned orientation

These images clearly show false depth pixels in one image are not repeated in the other. Merging these two images and rejecting non-equal depth pixels will result in increased invalid pixels or holes however it will eliminate the false depth pixels.

3.5.2 Parallel with Inward Angled Configuration

In this configuration two cameras are parallel, but they are rotated slightly inward, ~15 degrees. Figure 30**Error! Reference source not found.** is a diagram showing the view of the cameras from the side for this configuration.

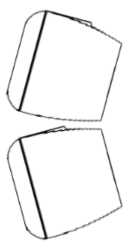

Figure 30 Parallel with inward angled configuration

Figure 31 shows the depth and IR image for each camera in this configuration; the difference in the depth images again is obvious. In this case it is easy to observe the expanded field of view (FOV).

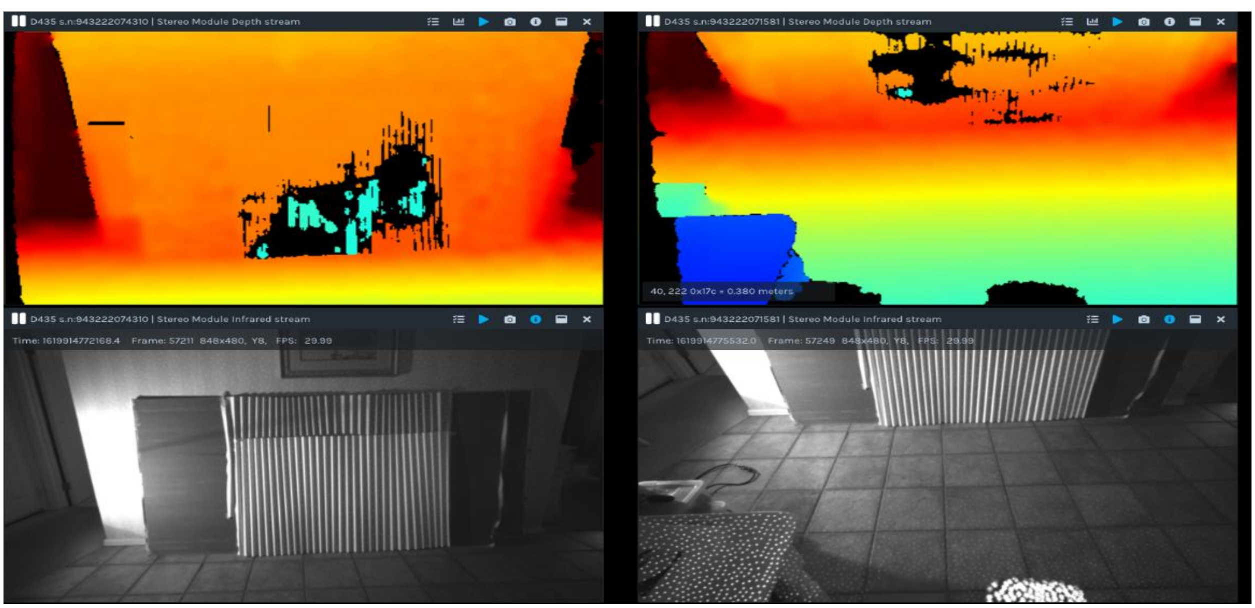

Figure 31 Depth and IR images for the parallel with inward angled configuration

3.5.3 Parallel with Outward Angled Configuration

In this configuration two cameras are parallel, but they are rotated slightly outward, ~15 degrees. Figure 32 is a diagram showing the view of the cameras from the side for this configuration.

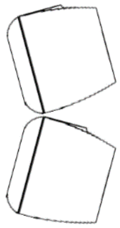

Figure 32 Parallel with Outward Angled Configuration

Figure 33 shows the depth and IR image for each camera in this configuration. Depth differences are similar to the parallel with inward angled configuration. Even though intuitively one might expect FOV to differ from the prior configuration, it is fairly similar.

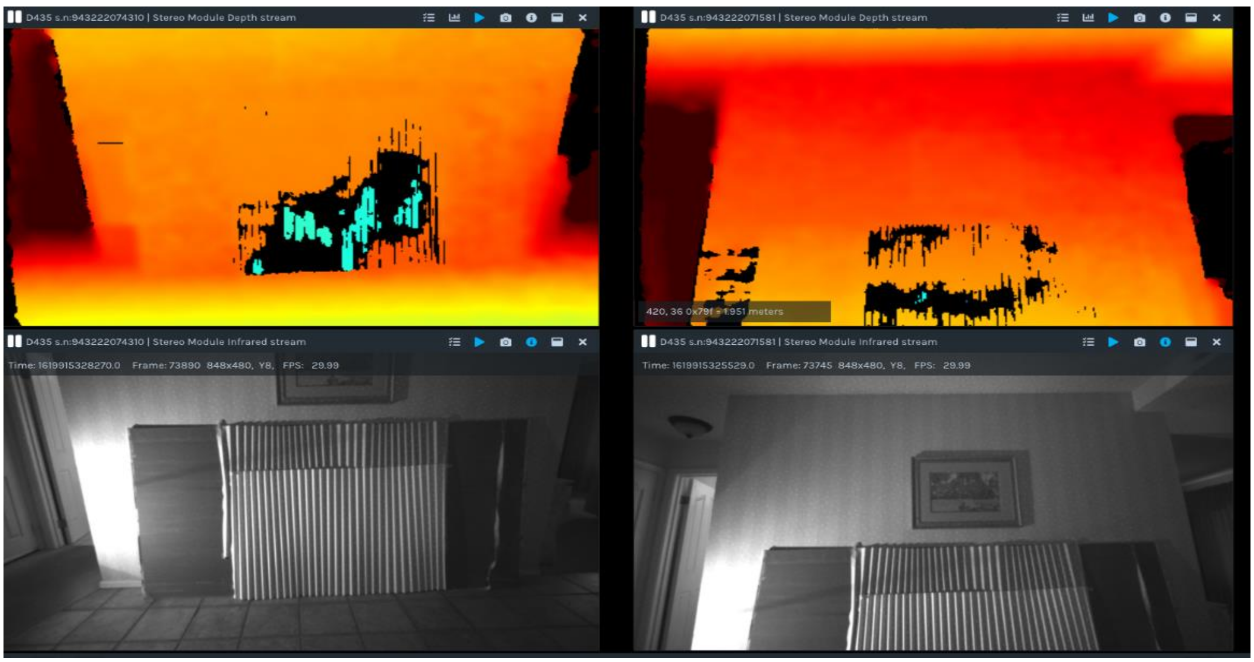

Figure 33 Depth and IR images for the parallel with outward angled configuration

4 Conclusion

The repetitive pattern effect is the result of how the stereo images are processed by the stereo depth algorithm. This impacts not only Intel RealSense depth cameras D400 stereo series, but all stereo depth cameras. However, by applying different mitigation techniques it is possible to dramatically reduce or eliminate the repetitive pattern effect.

For optimal performance, it is likely that a combination of these techniques may be required and optimized for each specific condition. Using these techniques, it is possible to achieve a high-quality depth field without the ghost depth images caused by the repetitive pattern effect.

5 References

Astra Products Inc. (n.d.). *CLAREX® Near-Infrared (NIR) Filters*. Retrieved June 16, 2021, from Astra Products: https://astraproducts.com/info-acrylic-nir-filters.asp