Selection of an Industrial Grade 3D Vision System Using 22 Metrics for Obstacle Detection in a Warehouse Environment

Abstract

The increasing demand for online commerce has led to greater demand for autonomous vehicles in the logistics sector. In this whitepaper, we compare the performance of four different technologies which provide obstacle detection for autonomous forklifts on 22 different metrics which are important for selection of an ideal 3D sensor for obstacle avoidance. We have assembled these criteria based on learnings from our industrial customers. We show how DreamVu's PAL 3D Omnidirectional vision system with obstacle detection software wins over all the other available sensor technologies. We show the advantages and disadvantages of various sensor technologies. We also show results and testing metrics in very difficult scenarios present in a warehouse.

Introduction

The increasing demand in online commerce has led to companies desiring warehouses that operate without interruption. This has, in turn, led to an increase in the development of autonomous vehicles such as forklifts. Since the warehouses still have people working in them, safety is of the highest priority. The current way of handling logistics with manual labor and stressful environments creates bottlenecks and dangerous work situations. Between 2011 and 2017 in the U.S. alone, more than 7000 forklift-related injuries resulting in sick leave occurred annually. This is both costly for the employer and unnecessary for the employee, which is a reason to develop a safer autonomous work environment. Most of the current obstacle detection solutions use several lasers. These lasers work in two-dimensional planes that could be described as "curtains" in front of the forklift. These curtains are used to detect objects that are more than 5 centimeters above the ground. This solution has its limitations, such as not detecting an obstacle that appears after the curtain has passed but the forklift has not (e.g., at a junction). Therefore, an upgrade to a more reliable and safer obstacle detection paradigm is required. One possible upgrade is to replace the two-dimensional curtains with a three-dimensional space. Using a three-dimensional space instead of a two-dimensional curtain could provide certain benefits such as increased detection range, detection of small objects on the ground, and the ability to focus its obstacle detection in a certain direction. This paper compares four different solutions available today in the market that can be used to create a three- dimensional space in front of the forklift. This three-dimensional space is analyzed to detect obstacles using 22 very important metrics, and the most suitable technology is then determined. Aspects that affect the suitability vary from the cost of implementation and ease of installation and maintenance, to the capability in differently lit environments.

Industrial Requirements

The major industrial requirement for a robust 3D vision system is to have a detection range to be at least 3 meters, preferably 5 meters. It must have 360° detection range, the feature to detect in a 3D space that is dependent on speed and travel direction, the feature to detect the complete forklift, including the mast if possible. Obstacle tracking, i.e. "will we hit it?". (Not to react to objects moving away from the machine). Self-calibrated as to where the floor is (do not react to the floor). It must be able to detect forks on the floor, from other forklifts. The obstacle detection software must work with many different materials. It should work in many different light conditions. Request-to-Response time is expected to be under 100ms. The sensors must be able to communicate over Ethernet or CAN Open. Users should be able to upload an application to the vision system on site via a single connector on the forklift. The complete system with sensors and necessary computation units should be available. Software developed according to ISO 13849(4.6) standard.. This section will present the list of 22 important requirements for a reliable obstacle detection system. These requirements were provided by several teacher customers.

1. Range
2. Field- of-View
3. Depth Accuracy
4. Different Lighting
5. Human-sized obstacles
6. Pallet-size obstacles
7. Fork-sized obstacles
8. Reflective Surfaces
9. Non-reflective Surfaces
10. Dark surfaces
11. Obstacle tracking "Will we hit it"?
12. Allowable speed of the robot
13. Self-calibrated to the floor
14. 3D volume depends on speed and direction
15. Detect the complete volume of the forklift
16. False positives
17. Request-to-response time
18. Data bandwidth
19. Extensive APIs
20. Supported Languages for software development
21. Complete system including computational units
22. Communication

3D Vision Systems

There are many 3D sensing technologies which provide obstacle detection as a use-case, but not all of them meet the critical requirements for the warehouse robot to be safer and reliable. This includes active stereo- vision systems, passive stereo-vision systems, Infrared, Ultrasonic, LiDAR and Radar. In this paper, we compare three main technologies which meet the budget requirements and the applicability to do obstacle detection and avoidance. We consider four main technologies.

Active Stereo Vision by Intel RealSense D435
Intel RealSense D435 consists of 3 cameras that track the light projected by a single IR projector. The one IR projector and three cameras are calibrated so that slight variations in the angle of light is detected by the camera. These variations are then used to calculate the depth data of the object that reflected the light. These are mostly used indoors since sunlight interferes with the measurements. Since it detects variations in its own projections, it is an active system which means it works well in poorly lit environemnts.

Time-of-Flight by Sick Visionary-T AP

Sick Visionary-T AP implements Time-of-flight (ToF) by using phase shift technique. It calculates the distance based on the round trip time (RTT) of the wave. The RTT is the total time it takes for the wave to bounce off objects and return to the camera. A common disadvantage of RTT ToF is that multiple cameras can interfere with each other's waves, causing distortions in their measurements. This can cause a significant amount of noise and errors in the measurements, which may lead to false positives. Since the measurements are based on the reflection from an object, distinctly reflective surfaces may lead to distorted measurements.

Structured Light by TopoSens TS3
Toposens TS3 tries to mimic the ultrasonic echolocation that bats use for their vision. It measures the distance to objects with ultrasonic ToF. In order to provide 3D coordinates, it also calculates the horizontal and vertical positions of the objects. Because of the ultrasound technology, it is not as susceptible to distortions from reflective surfaces.

Omnidirectional Stereo Vision + Composite Depth technology by DreamVu PAL/ PAL Mini
DreamVu PAL is the only single sensor, omnidirectional vision system to provide 360° stereoscopic sensing with depth perception. It uses innovative binocular optics which captures two stereo panoramas but on a single CMOS sensor. It is an easy-to-use & implement system, and has no moving parts. More than just providing the 360 depth maps and 360 degree 3D point cloud, it comes with the advanced obstacle detection and avoidance software which uses semantic cues (like floor) to estimate the closest obstacle and create a laser scan (as shown below (Top) overlaid in green in the top RGB image (Bottom) Laser scan visualization in Rviz) which takes very little bandwidth making it ideal for manufacturers and operators in robotics, factory and warehouse automation, and teleoperations where safety, responsiveness/low latency/speed, efficiency, and reliability are critical.

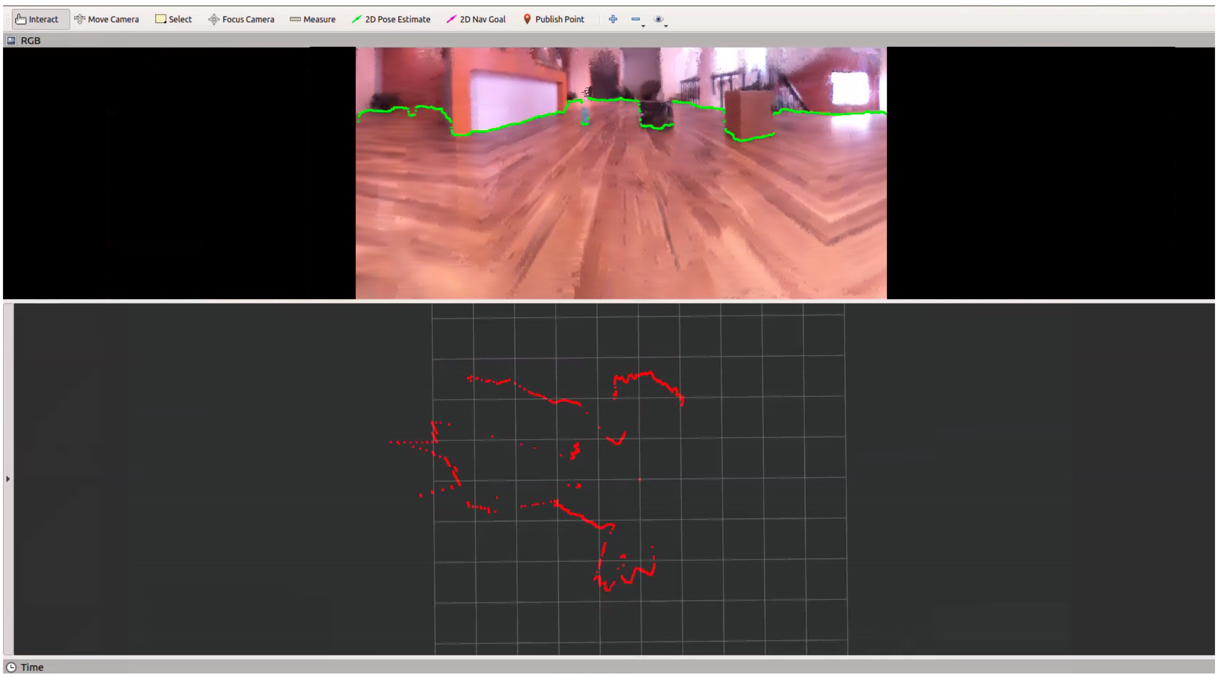

Fig 1: Top- A green laser scan marking the obstacle boundaries on the floor region, Bottom- the 2D representation of the 3D point cloud. This representation takes less memory and compute as compared to the complete 3D point cloud and is much more efficient for an industrial deployment.

Testing Metrics and Results

1. Range

A robust 3D vision system should have a minimum detection range of 3 meters. Therefore, in our scoring, if a 3D Vision system had the obstacle detection range of 3 metres, it was given 1 point, if it had a range between 3 and 5 meters it should provide adequate response time, so it is provided 2 points. Anything greater than 5 meters is simply a bonus, so it is provided with 3 points. Intel Realsense D435 has the depth range upto 10m, Visionary T-AP has depth range up to 60m, TS3 of depth range of 5m, whereas DreamVu PAL and PAL mini system have depth range of 0m- 5m and 0m- 3m respectively.

2. Field-of-View

In order to minimize the amount of components, a robust and reliable 3D vision system needed a fairly wide Field-of-View (FoV). A low FoV would require too many components and would, therefore, provide fewer points. Therefore, in our scoring, For the horizontal axis, if a FoV is less than 60° it is given 0 points, between 60° and 90° is given 1 point, and greater than 90° is given 2 points. For the vertical axis, a FoV less than 50° is given 0 points, between 50° and 80° is given 1 point, and greater than 80° is given 2 points.

The DreamVu PAL System is 360° (as shown in Fig 2) and only uses a single sensor whereas with the other available 3D vision systems, this would require too many systems which increases the overall cost of the system in production. Hence, selecting a 3D vision system which can increase the scalability of the robot in the future is a must. After DreamVu PAL and PAL Mini systems, only TS3 has the wide FOV but it is limited to 140degree which is 2.5x lesser than PAL's FOV. Whereas IntelRealsense D435 and Sick Visionary- T AP has only 87 deg and 69 deg FOV respectively. The vertical FOV of Intel Realsense D435 and Sick Visionary- T AP is also limited to <60 degrees whereas the PAL system has the widest FOV among all - 110 degrees.

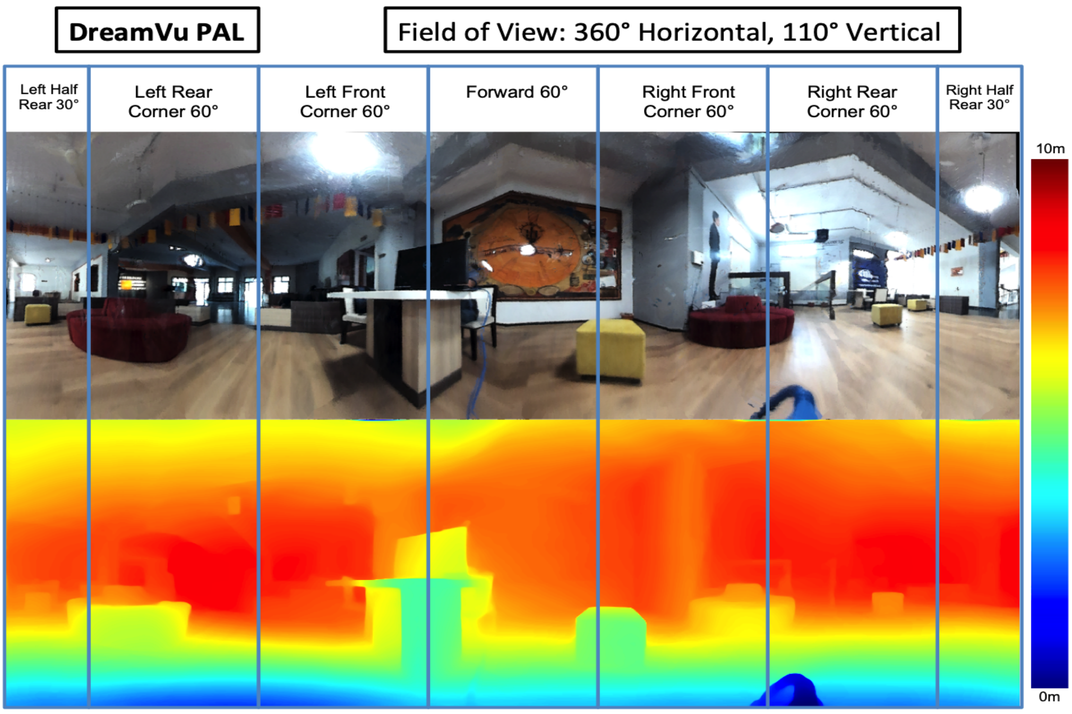

Fig 2: The Field-of-View of DreamVu PAL 3D Vision system indicating the different look-at directions around the camera.

3. Depth Accuracy

The depth accuracy is defined as the depth error rate at a given distance. It is usually expressed as a percentage of the distance. Depth accuracy is an important attribute in order to reduce false positives and increase reliability. Therefore, in our scoring, a depth error rate of less than 1% is given 3 points, 1%-2% is given 1 point, and more than 2% is given 0 points. Fig 3 shows the depth accuracy of DreamVu PAL 3D Vision system upto the range of 10 metres (at different mounting heights) whereas the depth accuracy of Toposens TS3 depth accuracy is 10% according to their datasheet.

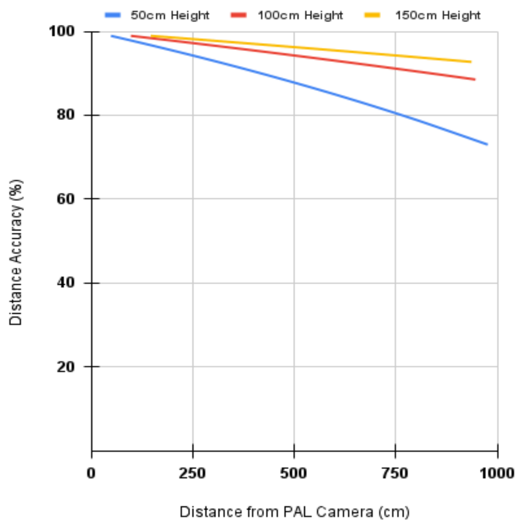

Fig 3: Percentage accuracy of depth (distance) measurements from the DreamVu PAL 3D Vision System at different mounting heights.

4. Different Lighting

Since warehouses usually have both dark and light areas, the products need to be unaffected by these differences. Therefore in our scoring, a 3D vision system received 1 point if their measurements were not affected by different lighting conditions, and 0 points if they were.

Intel real sense uses an active projection method and the infrared light of the sun interferes with the infrared of the Intel RealSense camera hence fails in the bright light condition. As a result, the software will have both false positives and false negatives. This phenomenon is shown in Figure 4 where the failure cases of Intel Realsense . There are a few hacks which are currently used to alleviate this problem, for example: tilting the camera or altering the exposure time of the camera, but these hacks are ineffective and introduce more problems than they solved. Tilting of the camera can cause objects to "blend in" to the floor. A comparison of RGBD data from the Intel Realsense in low-light as well as normal indoor illumination is shown in Figure 5.

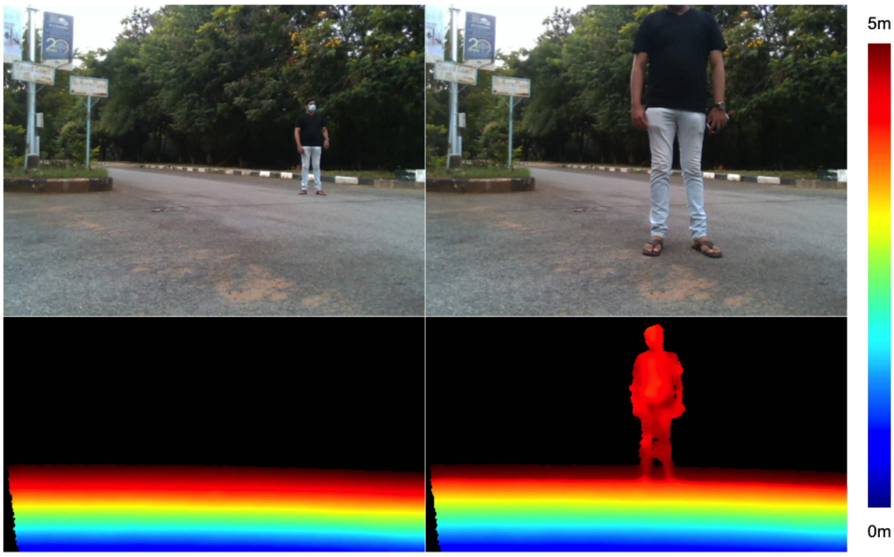

Fig 4: Even in a moderately illuminated bright environment (~1KLux), Intel Realsense does not capture the scene depth accurately

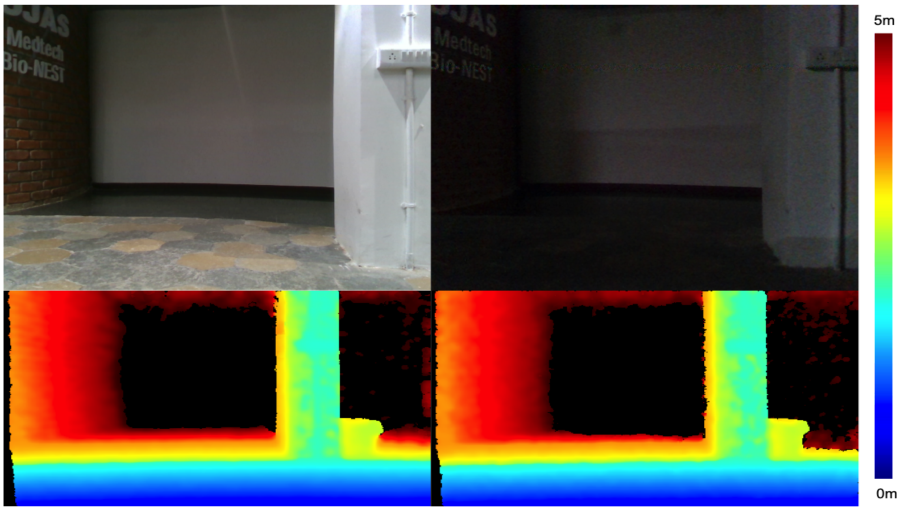

Fig 5: Left: Intel Realsense RGBD in an Indoor (150Lux) environment. Right: Intel Realsense RGBD in an Indoor (20Lux) environment

Similarly, Visionary-T, the camera is supposed to handle light up to 50 kilolux (klx). Since the Sun provides between 30-100klx. Whereas DreamVu PAL system can handle upto 100 Klux with its adaptive illumination support. In Figure 6, the 360 RGB panorama and the depth map from the DreamVu PAL Camera is shown in an indoor low-light environment (approximately 20 Lux). The depth map shows accurate 3D reconstruction owing to DreamVu's proprietary adaptive illumination. The same scene is shown in typical indoor lighting in Figure 7, here slightly more details are visible in previously underexposed areas such as the chair on the right. Since the DreamVu PAL system is composed of a single sensor and does not rely on active projection, it can also scale to bright outdoor conditions as shown in Figure 8, as well as dimly light outdoor scenes in the night as shown in Figure 9.

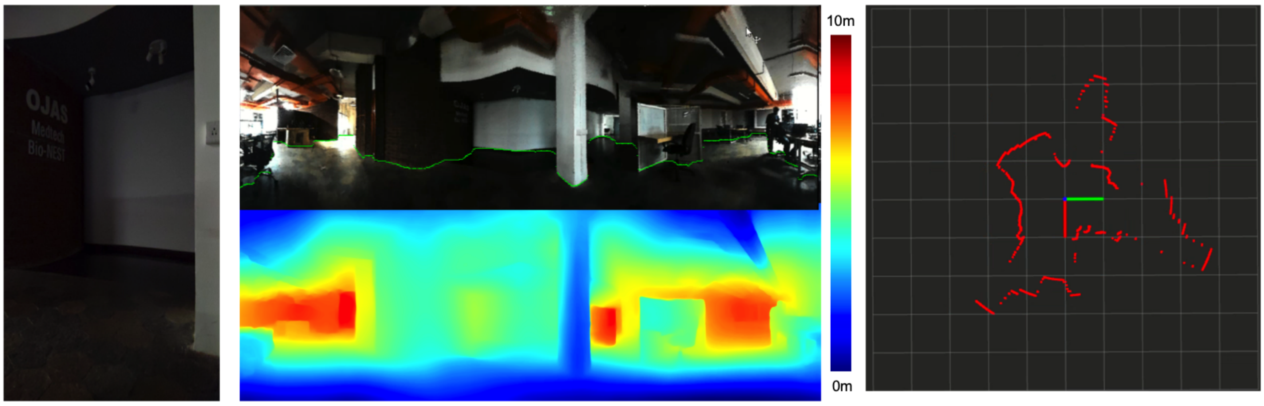

Fig 6: Left: Image from an RGB Camera in an Indoor low-light (~20Lux) environment. Center: RGBD 360 Panorama from the PAL camera, overlaid with a green laser-scan representing the obstacles around the camera. Right: The laserscan overlaid on an RViz grid.

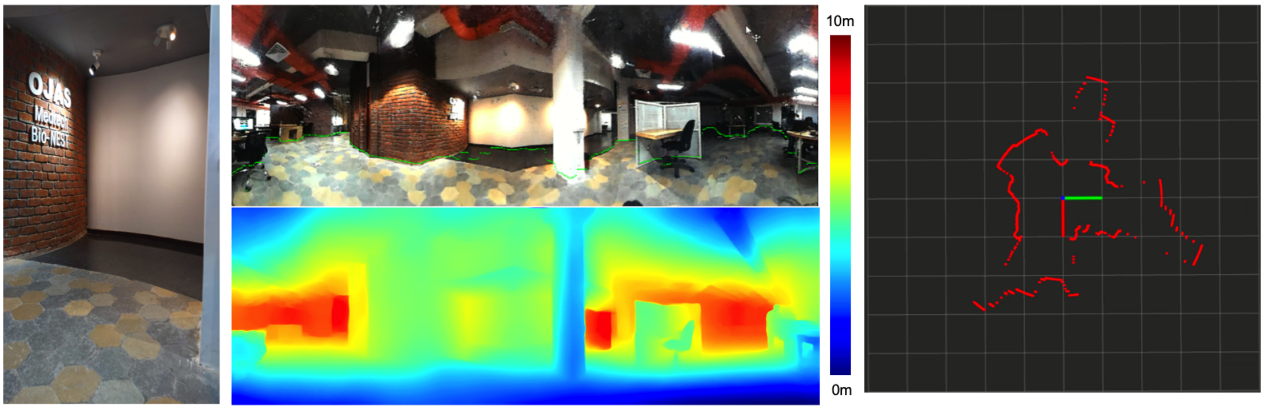

Fig 7: Left: Image from an RGB Camera in a normal indoor (~150Lux) environment. Center: RGBD 360 Panorama from the PAL camera, overlaid with a green laser-scan representing the obstacles around the camera. Right: The laserscan overlaid on an RViz grid.

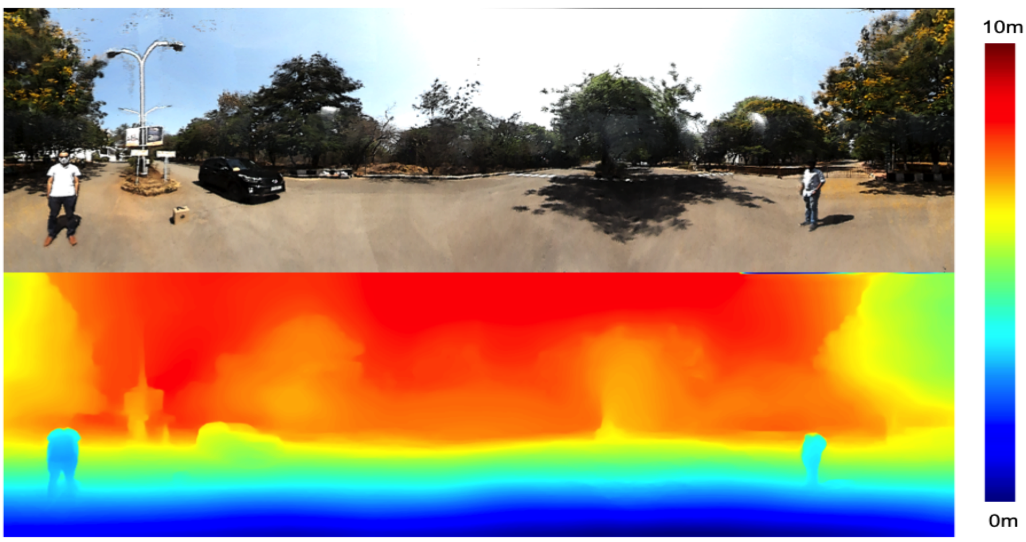

Fig 8: PAL RGBD Panorama in a bright outdoor (~10KLux) environment

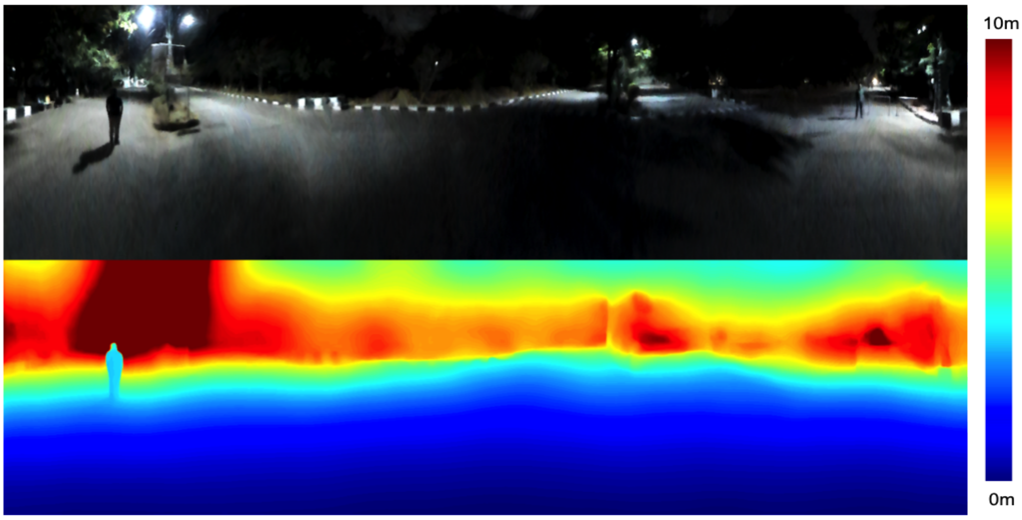

Fig 9: PAL RGBD Panorama in a night outdoor (~20Lux) environment

5. Human-Sized obstacles

The 3D Vision system should be able to detect the human-sized object from the range of 3m- 10m. If the system is reliable in depth measurements, it was given 2 points, if the reliability in measurement is dependent upon the clothing of the human, then 1 point and if the system does not provide this capability, it was given 0 point.It is seen that for the narrow FOV 3D systems, the detection range greatly depends on the clothing of the person.

DreamVu's proprietary person detection system is able to detect persons within the large context of the 360 scene and can detect persons in a variety of positions and at distances up to 10 meters from the camera. Figure 10 provides an illustrative comparison of DreamVu's PAL person detection system with Intel Realsense RGBD. On the left side, the RGB panorama and the corresponding depth map is shown with a person at 1.5m, 3m and 5m from the camera. The 3D silhouette of the person is clearly represented in the depth map. On the right is a similar demonstration from the Intel Realsense where the person is completely missed at the 5m distance.

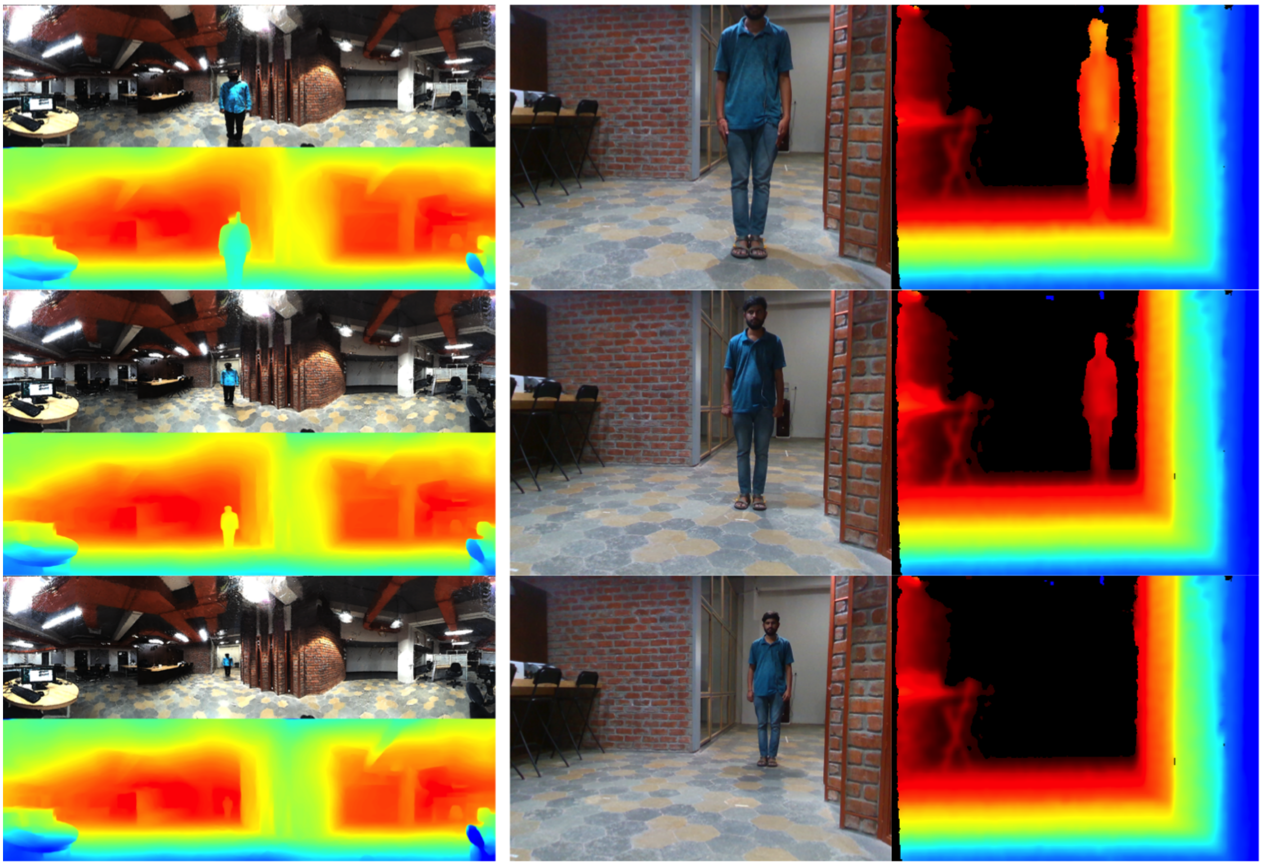

Fig 10: PAL RGBD Panoramas (left) capture human sized objects at much larger depths than corresponding Intel Realsense RGBD images (right). The PAL camera is able to accurately identify the 3D shape of a human being at different distances from the camera.

6. Pallet- Sized obstacles

The 3D Vision system should be able to detect the pallet-sized object from the range of 3m- 10m. If the system is reliable in depth measurements, it was given 2 points, if the reliability in measurement is dependent upon the clothing of the pallet, then 1 point and if the system does not provide this capability, it was given 0 point.

Figure 11 shows a pallet-sized obstacle at 5m detected in DreamVu PAL's 360 RGBD panorama. Owing to the large field of view, the pallet can be detected both in the upright and low-lying orientation and the more difficult scenario of low-lying pallet is shown in the figure. As a comparison, Figure 12 shows a similar scenario from Intel Realsense where the pallet detection in the depth map is limited and even missing beyond a range of 4 to 5 meters.

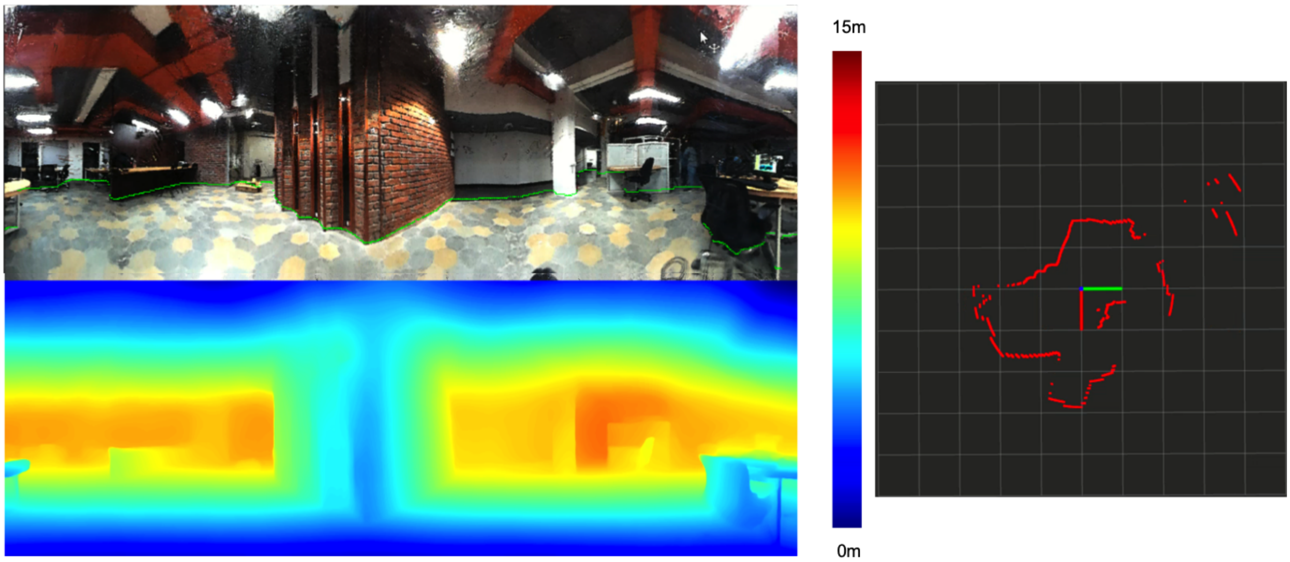

Fig 11: PAL RGBD Panoramas can detect Palette sized obstacles at several distances from the camera. On the left is the PAL RGBD panorama with the overlaid laserscan on the panorama in green. On the right is the laserscan overlaid on an Rviz grid.

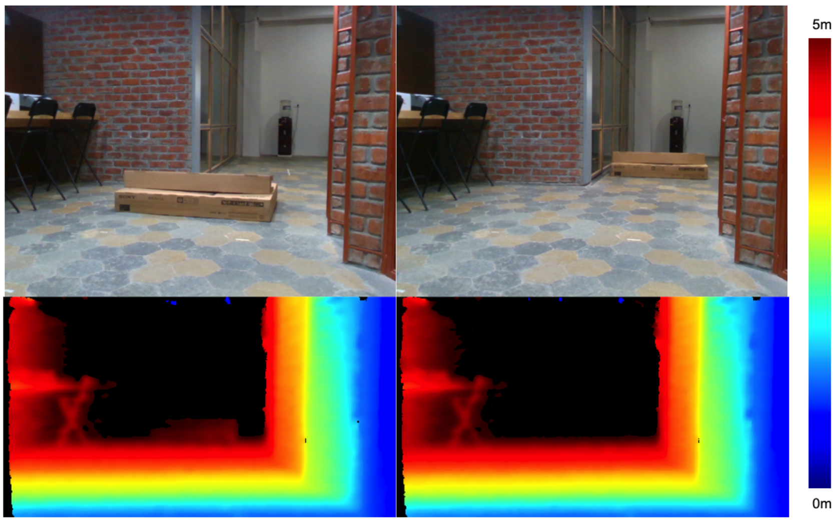

Fig 12: Intel Realsense in comparison has a limited depth estimation capability for Palette sized obstacle.

7. Fork-sized obstacles

The 3D Vision system should be able to detect the fork-sized object on the floor from the range of 3m- 10m. If the system is able to detect it more than 8 out of 10 frames, it was given 2 points, if it only detects half the times, then 1 point and if the system does not provide this capability, it was given 0 point.

Figure 13 shows the detection capability of the PAL camera on low-lying fork sized obstacles. Even though the obstacle is small and on the floor, the depth estimated from the PAL panorama shows the presence of an obstacle. Furthermore, a 2D laser scan of the obstacle is also shown on the right. Low-lying obstacles like the fork sized object shown in the scene are completely missed by the Intel Realsense as illustrated in Figure 14.

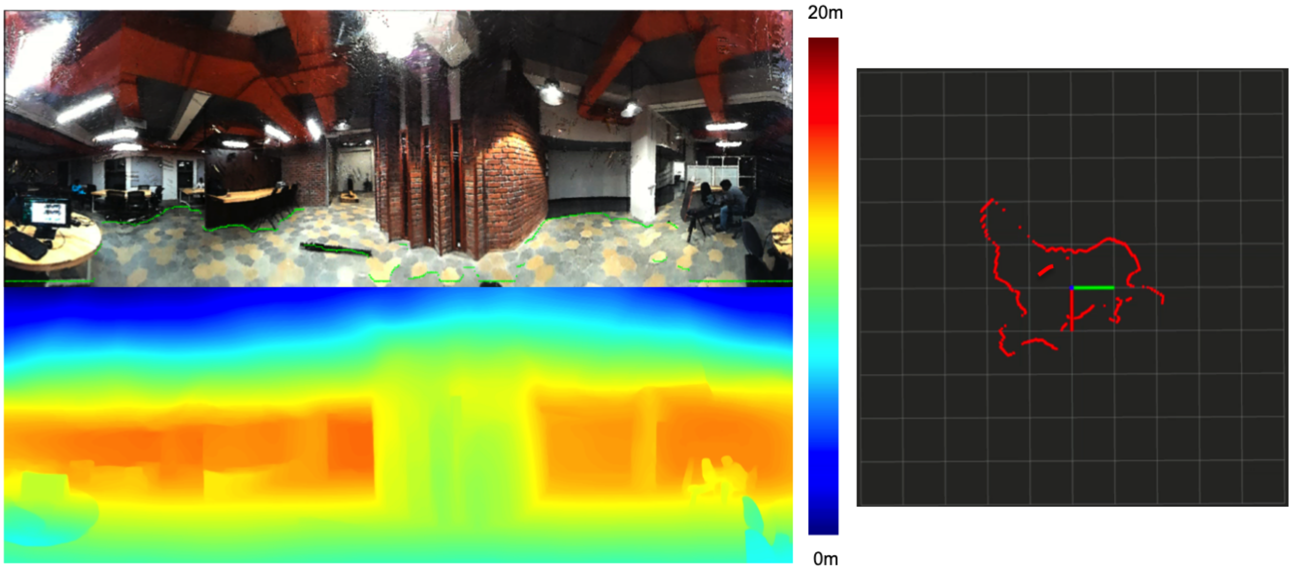

Fig 13: PAL RGBD Panoramas can detect low-lying fork sized obstacles. On the left is the RGB image overlaid with the obstacle detection laserscan in green. On the right is the laserscan overlaid on an RViz grid.

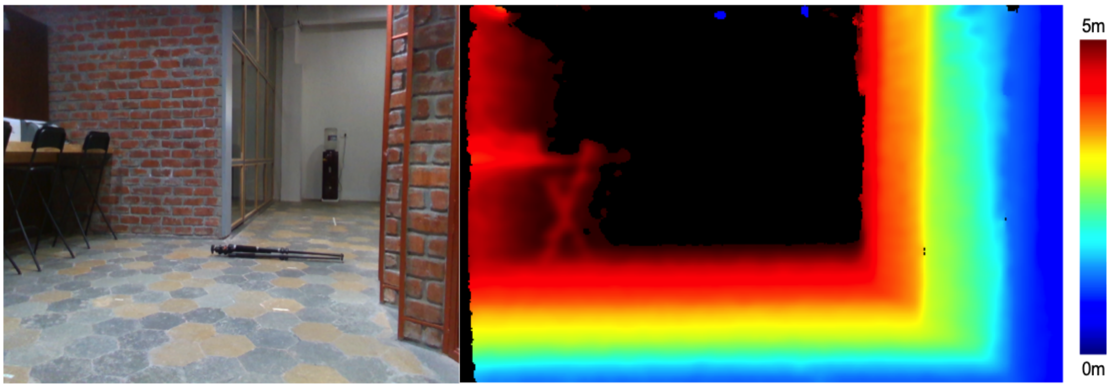

Fig 14: Obstacles that are fork-sized and low-lying fork are often completely missed by Intel Realsense.

In a narrow FOV active 3D Vision system, the forklift fork does not get detected all the time. There was no significant difference in the detection range between the gray and black forks. It is clear that the dark colors caused the detection issues because it typically absorbs the infrared light.

8. Reflective Surfaces

In most warehouse environments, there are usually a significant number of reflective surfaces such as bare metal. Consequently, it was important that these reflective surfaces are handled correctly. Therefore 1 point was given if reflective surfaces did not distort the measurements. A 3D Vision system received 0 points if they could not handle reflective surfaces. Different colors and materials had a substantial effect on the detection range.

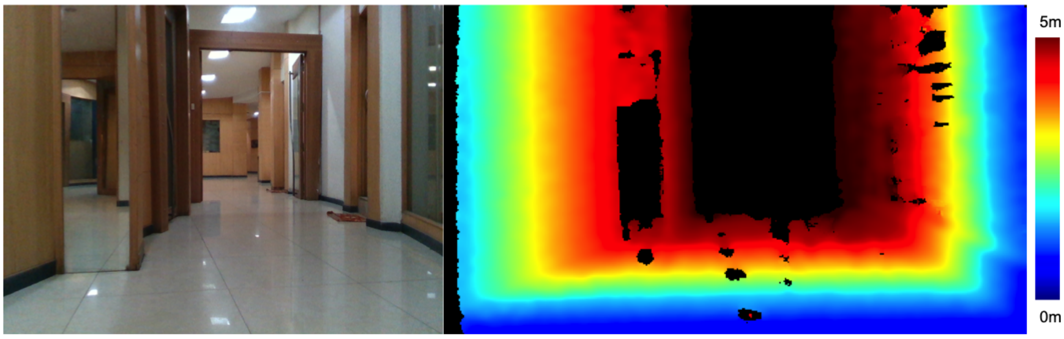

Fig 15 : Active Cameras like Intel Realsense have trouble estimating the depth of reflective and glossy surfaces

If the 3D Vision system uses phase-shifting infrared Time-of-flight (ToF), reflective surfaces will have measurement errors. With intel real sense the objects are interpreted as closer than they actually are, when measured on the reflective surfaces. This is true for obstacles both at short and long distances and at lower exposure times as well. As a result of this issue from these two 3D vision systems, the forklift would have to slow down and stop sooner than needed. Furthermore, the presence of reflective and glossy portions in the scene results in holes in the depth map as shown in Figure 15.

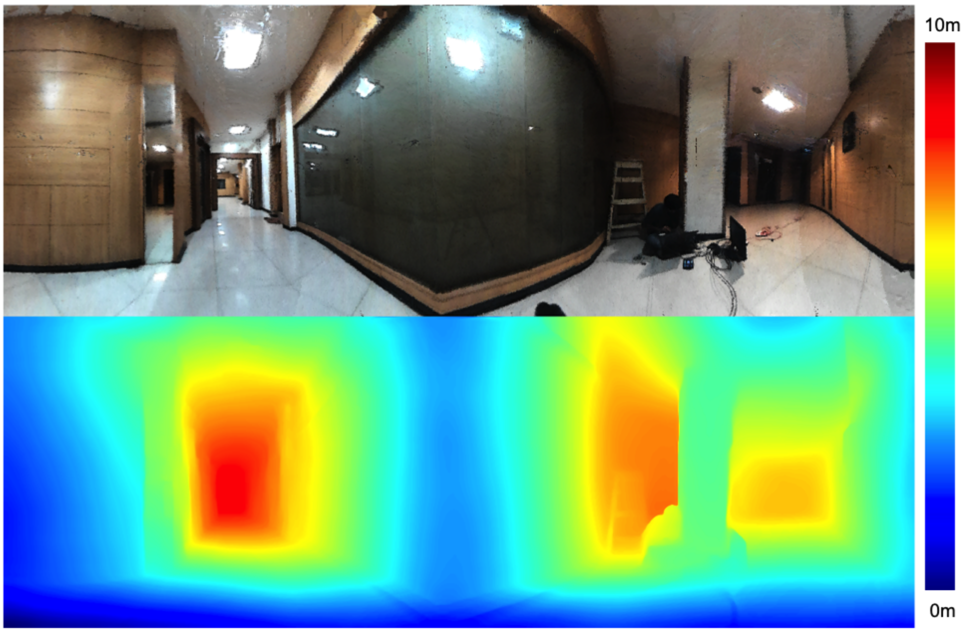

Fig 16 : PAL RGBD Panorama depicting accurate scene depth even in the presence of glossy floors and reflective mirrors.

On the other hand, the PAL RGBD panorama is much better suited for the presence of glossy and reflective surfaces in the scene. As shown in Figure 16, the DreamVu PAL 3D Vision system can not only detect reflective surfaces at their correct depth (the mirror on the left of the scene does not show farther than its actual location), but also remains unaffected by glossy reflections on the floor.

9. Non-reflective Surfaces

With the same motivation as for reflective surfaces, it was important to be able to handle non-reflective surfaces. A 3D vision system was given 1 point if non-reflective surfaces did not distort measurements, and 0 points if it did.

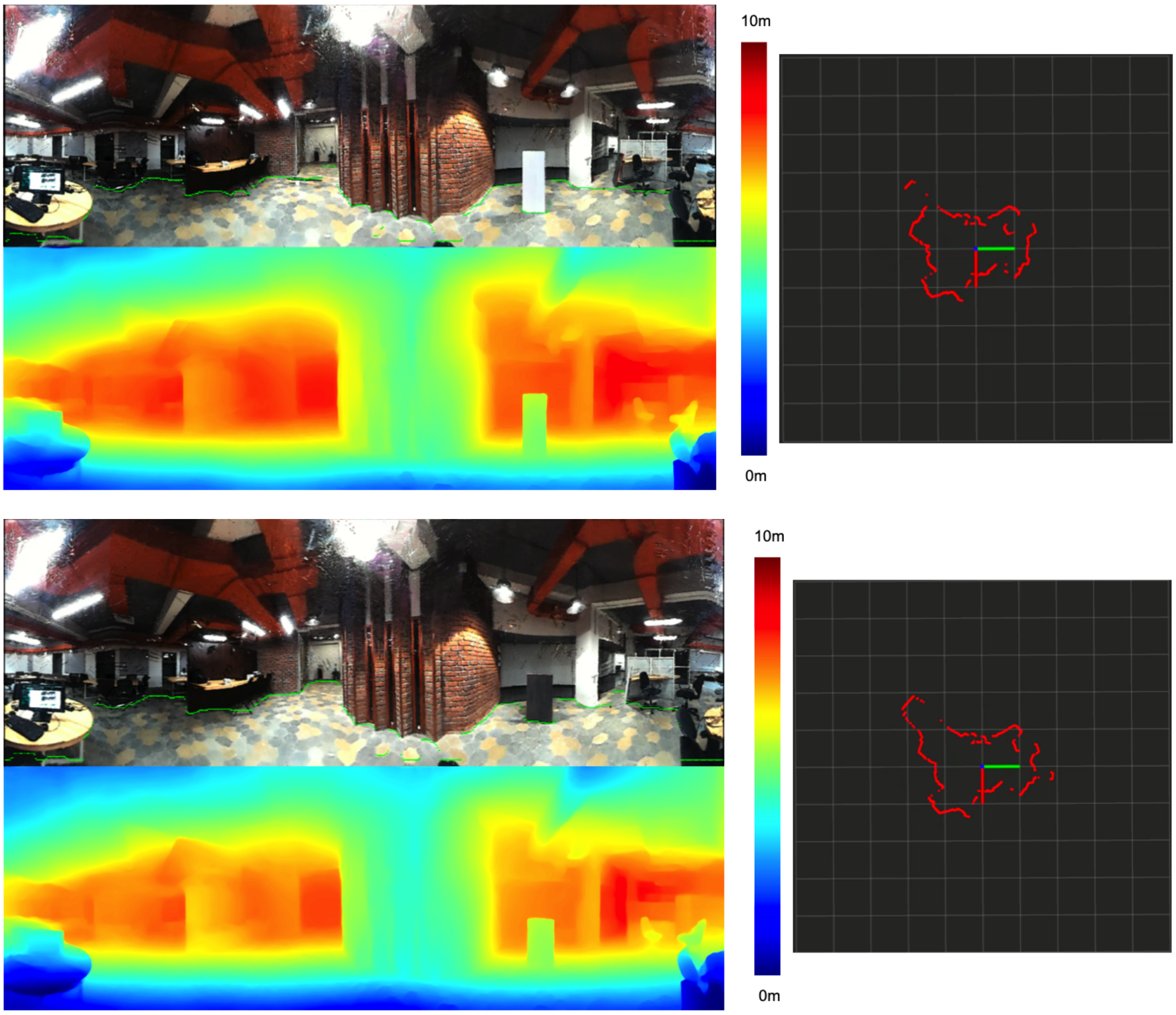

Fig 17 : PAL RGBD Panoramas accurately detect non-reflective surfaces - both dark and bright. In each image, the left side represents the RGBD panorama with the overlaid laserscan in green on the RGB image. On the right is the corresponding laserscan overlaid on an Rviz grid.

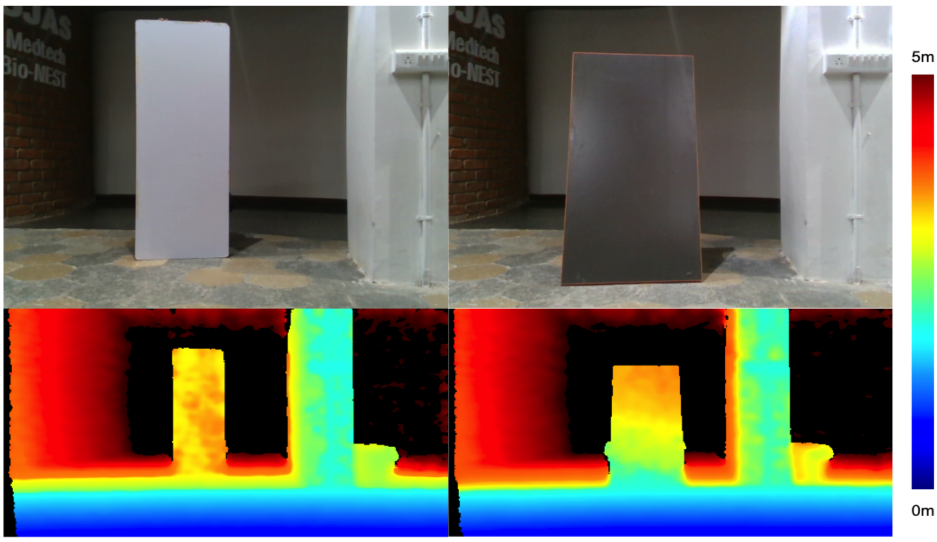

Fig 18: Performance of Intel Realsense on non-reflective surfaces - both dark and bright.

The performance of Intel Realsense on matte and partially glossy surfaces is shown in Figure 17. In Figure 18, the same obstacles are imaged in the PAL RGBD 360 panorama. The PAL camera is able to identify both obstacles with equal fidelity.

10. Dark Surfaces

It is important to be able to handle dark surfaces. A 3D vision system was given 1 point if dark surfaces did not distort measurements, and 0 points if it did.

Dark surfaces such as matte-black surfaces absorb the infrared light, and they are practically invisible to the Intel Realsense camera. For these objects, if only a vision-based approach is followed to detect the obstacles, then the 3D vision system will fail terribly. There are a few image processing methods which can be used to solve this issue, for example considering zero valued pixels in an image as an obstacle, but in this case, there is no possible way to determine the distance of said object. As a result, obstacle detection is not possible for matte black objects using Intel real sense of ToF systems. An example is shown in Figure 19 where a matte black chair is not detected appropriately by the Intel Realsense camera.

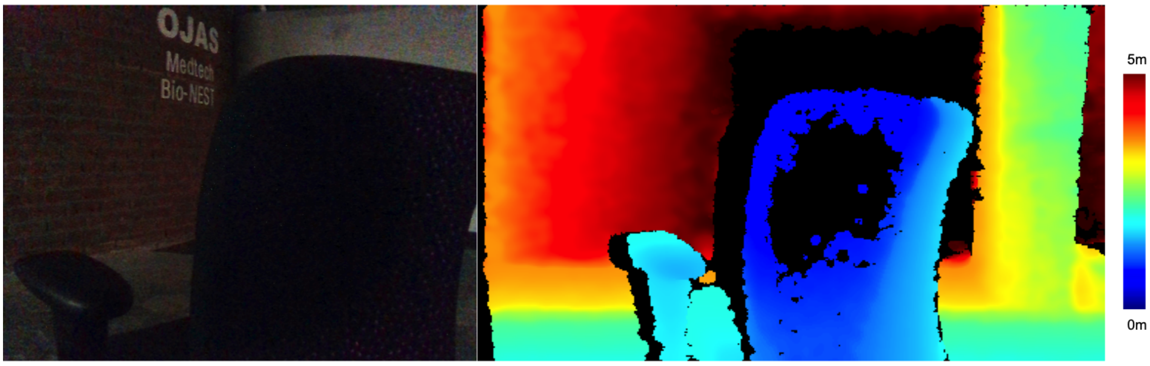

Fig 19: Performance of Intel Realsense Active on dark surfaces. The surface of the object is ambiguous in the depth image.

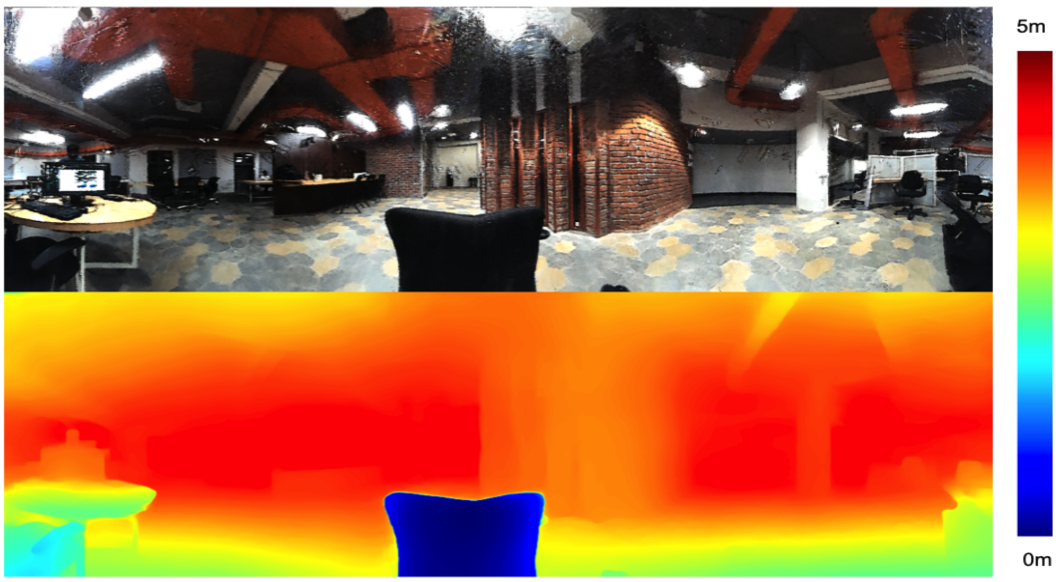

Fig 20: PAL RGBD Panoramas can accurately detect dark surfaces.

On the other hand, the DreamVu PAL system uses a different approach, and it can accurately detect dark surfaces owing to the large contextual information in the 360 Panorama as shown in Figure 20.

11. Obstacle tracking "Will we hit it"?

This is one of the most critical requirements for selecting an obstacle avoidance solution. If the 3D Vision system able to detect an obstacle which it is going to hit in the current planned path from at least 2m- 3m, then we give it 2 points, if it is only able to detect the obstacle from the distance of 1m, then we give it 1 point and if it does not provide the ability to detect then we give it 0 points.

Fig 21 The PAL 3D Vision System with a depth-scan indicating all types of obstacles (small to large) detected at varying distances from PAL.

In the Intel RealSense camera, obstacle tracking is dependent on the type of object in the path more than anything else. For objects that did not have issues with distance measurements in the first place, such as humans and EUR-pallets, the results were positive, whereas, dark objects were not detected at all. Since the distance measurements for reflective surfaces were incorrect, the system is not reliable for tracking if it will actually hit it or not. Moreover, the region for the reflective surface intersected with the boundary-region and caused false positives to occur regularly as shown earlier as well.

In the case of the DreamVu PAL 3D Vision system, a broad range of obstacles at different distances from the camera can be detected accurately as shown in Figure 21. Given the large vertical field of view of the PAL, it can not only detect the low-lying obstacles as those present on the floor but also floating obstacles that may be at the same height or even higher than the PAL camera. Figure 21 demonstrates a typical use case with a robot navigating in an indoor environment laden with obstacles. The PAL camera can accurately detect small obstacles such as wires as well as large walls and stairs from the range of 3m- 5m. An overlaid 2D laserscan is shown in the figure in green that indicates the closest detected obstacle in every direction around the camera.

12. Allowable speed of the robot

The refresh rate of the 3D vision system and sensing of the depth map controls the maximum speed which a robot can safely operate on. In our scoring, if a 3D Vision system has a frame rate of 20 Hz, then it is given 1 point, if the frame rate is 30 Hz, then 2 points, and if the frame rate is more than 30 Hz, then it is given 3 points. The DreamVu obstacle detection and avoidance software provides the laserscan indicating the closest obstacle at a competitive frame-rate of 20Hz on a Jetson NX board. This allows the robot to move at a translational speed of of upto 5m/s. Toposens TS3 also has the frame rate of 20 Hz, whereas Intel Realsense has 30 Hz and Sick Visionary- T AP has the frame rate of 50 Hz.

13. Self-calibrated to the floor

The product had to be compatible in detecting the floor regions. In Intel real sense cameras, narrow FOV because of which the floor estimation is unreliable and causes depth measurement errors. It causes small objects to "blend in" with the floor. This meant that in order to filter out the floor, there was also the risk to filter out smaller objects

The DreamVu PAL has an unparalleled horizontal and vertical field of view and DreamVu's proprietary software enables accurate estimation of the floor regions around the camera. This enables the software system to differentiate between the floor and an obstacle lying on top of the floor and thereby minimize false positives. Figure 22 shows the floor estimation provided by the PAL camera in two contrasting scenarios. It is important to note that the floor detection is robust to different types of illumination conditions and is not affected adversely by glossy and reflective floors.

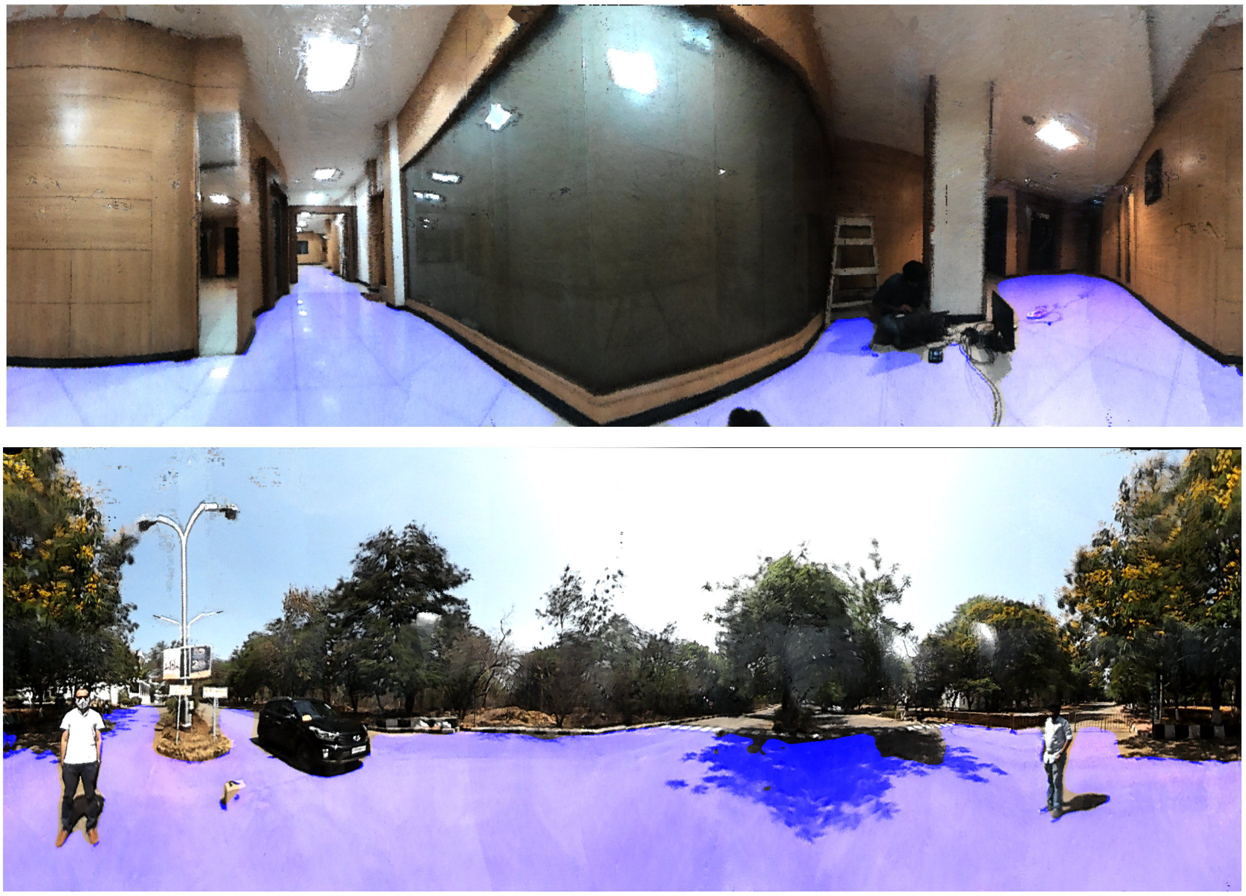

Fig 22 The PAL 3D Vision System accurately identifies the floor region around the camera for efficient obstacle detection and avoidance. The floor region around the camera is shown in the images above with a blue-tint overlay. The floor estimation is robust to changes in illumination and works on different types of floors including those with glossy and reflective floor surfaces.

14. 3D volume depends on speed and direction

Once the obstacle is detected, the navigation can be performed much better if the speed and direction of the incoming forklift or any other dynamic obstacle For ez: a person comes in the planned path. In our scoring, if a 3D vision system provides the information on the speed and direction of the incoming obstacles, then it is given 1 point otherwise 0 point. Except DreamVu's PAL 3D vision system this information is not available from the other 3D vision systems.

15. Detect the complete volume of the forklift

In our scopring if a 3D vision system can detect the complete volume of the forklift, it is given 1 point, otherwise it is given 0 point.

16. False positives

An Ideal 3D Vision system should have no false positives because of unusual objects/surfaces. The defects in the obstacle detection can appear because of many reasons, especially because of the interoperability with the reflective surfaces and dark surfaces as explained in the earlier sections. Therefore, in our scopring if a 3D vision system has a false positive rate >10% it is given 0 points, otherwise it is given 1 point.

17. Request-to-response time

All the 3D vision systems process the obstacle information which causes a latency/ request-to-response time. This becomes very crucial in the applications where safety is utmost important. In our scoring if a 3D vision system has a latency of <100 ms it is given 2 points, if the latency is < 150ms, then it is given 1 point, otherwise it is given 0 point.

18. Data bandwidth

Handling very high frame rates of 3D data with the low compute hardware is a challenge. Intel RealSense D435 captures 3D Point Cloud at 30 Hz which becomes a challenge to process for obstacle detection and avoidance on embedded hardware. Also, 3D point clouds require too much processing power, which causes a significant delay in the images. This means that the request-to-response time becomes too long. Alternatively, if the depth images are used for the obstacle detection software, less processing power is consumed than using the 3D point clouds, but there will still be some delay between the images. In case the images are downsampled to reduce the processing power, small obstacles will be missed. Therefore, It is clear that the computational gain from these operations is not worth the drawbacks in precision that comes with it. In addition to the loss in precision, the conversion from the depth images will cause some problems when calculating the distance to obstacles. DreamVu 3D obstacle detection system provides a compressed 3D planar laser scan (as shown in Fig 22) which is very efficient and provides the information on both 2D and 3D obstacles. Therefore, in our scoring If the 3D vision system has a very high bandwidth requirement, it received 1 point, otherwise, it received 2 points.

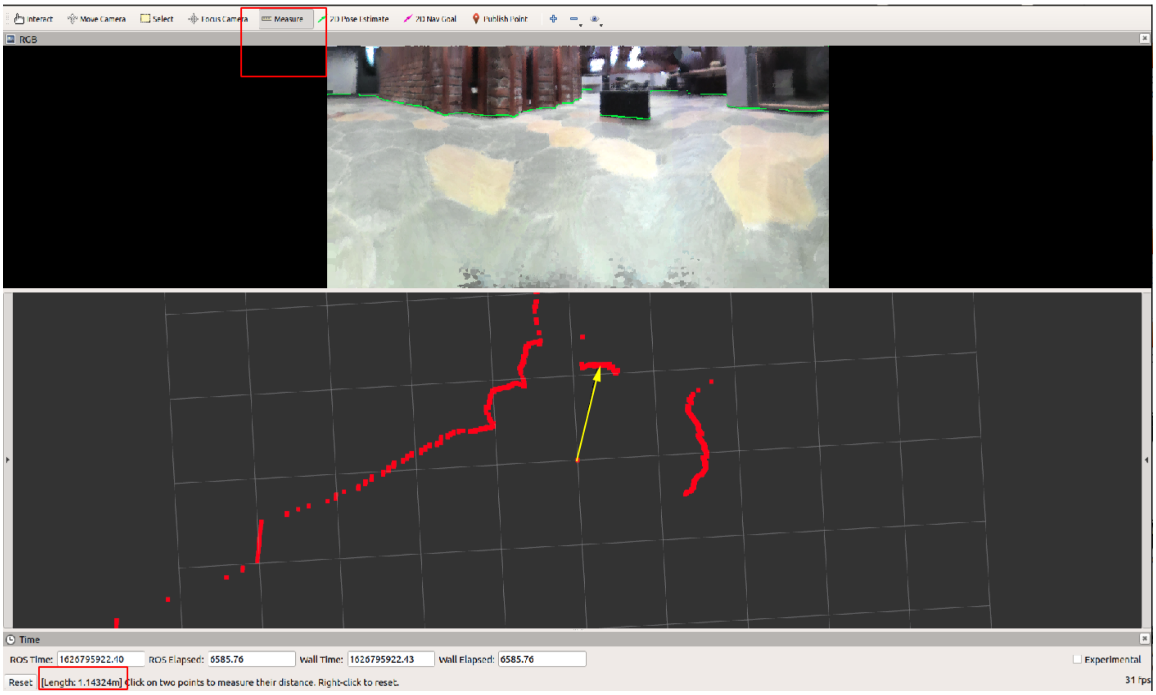

Fig 22: Top- A green laser scan marking the obstacle boundaries on the floor region, Bottom- the 2D representation of the 3D point cloud with the distance to the obstacle measured in Rviz. This representation takes very less memory and compute as compared to the complete 3D point cloud and is much more efficient for an industrial deployment.

19. Extensive APIs

An Application Programming Interface (API) contains premade functions that may be needed by the developer. This usually leads to less time being spent writing trivial code. An extensive API is therefore very useful when implementing any kind of application. Therefore, in our scoring If the 3D vision system included an extensive API, it received 1 point, and 0 points if it did not.

20. Supported Languages for software development using ISO 13849(4.6)

If the software development is compliant with ISO 13849(4.6), the 3D Vision System is given point 1, otherwise 0. ISO 13849(4.6) is important for the components which are important for the safety functions.

21. Complete system including computational units

For faster development and time-to-market, it is necessary to have a complete system which also includes computational units. Therefore, in our scoring if the 3D vision system is complete with software and computational units, it is given 1 point, otherwise 0.

22. Communication

For reliable communication, Ethernet or CANOpen protocol is considered to be the best. Therefore, in our scoring, if a 3D Vision system is compatible with either Ethernet or CANOpen protocols, it was given 1 point. If it was not, it was given 0 points. Though DreamVu PAL Mini is a USB system, since it only uses a single sensor the data is highly reliable, as compared to Intel RealSense USB system which uses multiple cameras and IR projectors inside.

Score Card

Category	Visionary T-AP	RealSense D435	TS3	PAL	PAL Mini	DreamVu + Sick
Range Points	60 m 3	10 m 3	5 m 2	5 m 2	3 m 2	60 m 3
Horizontal Field-of-view Points	69° 1	87° 1	140° 2	360° 3	360° 3	360° 3
Vertical Field-of-view Points	56° 1	58° 1	140° 2	110° 2	80° 2	80° 2
Depth Accuracy Points	1% 3	< 2% 1	10% 0	5% 0	5% 0	1% 3
Different Lighting Points	0	1	3	2	2	3
Human-sized obstacles Points	1	1	1	1	1	1
Pallet-sized obstacles Points	1	1	1	1	1	1
Fork-Sized obstacles Points	0	0	0	1	1	1
Reflective surfaces Points	0	0	0	1	1	1
Non-reflective surfaces Points	0	0	0	1	1	1
Dark surfaces Points	0	0	0	1	1	1
"Will we hit it" Points	0	0	0	2	2	2
"Allowable Speed" Points	3	2	1	1	1	3
Self-calibrated to the floor Points	0	0	0	2	2	2
3D Volume Points	0	1	0	1	1	1
Complete Volume of the Forklift Points	0	0	0	1	1	1
False positives Points	0	0	0	1	1	1
Request-to-response time Points	2	2	2	1	1	2
Data Bandwidth Points	2	1	2	2	2	2
Extensive APIs Points	1	1	0	1	1	1
Supported with ISO 13849(4.6) Points	1	0	0	0	0	2
Complete system Points	1	1	0	1	1	1
Communication Points	Ethernet 1	USB 0	USB UART 0	Ethernet 1	USB 0	1
Total score	**21**	**17**	**16**	**29**	**28**	**39**

Conclusion

The DreamVu PAL 3D vision system provides the best overall-solution in the market for robust and safe obstacle detection and obstacle avoidance. In order for the robot designers to meet the safety standards and performance in dark environments, we also conclude from the above score card that combining Sick and DreamVu complement each other in creating the best 3D sensor combination for the autonomous robot in a warehouse environment, with the combined score of 39 points. Either operating alone or together with Sick, Dreamvu's PAL 3D vision systems are the best choice in autonomous robot navigation sensing.