DASA Laser Range Camera Evaluation

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Abstract

The DASA Laser Range Camera is a novel sensor that can be used to capture range images over distances from 0.5 m to 30 m, depending on the configuration. Unlike most laser ranging devices, it captures a whole image at once, rather than scanning point by point. The laser can be used indoors and outdoors and has no movable mechanical parts. It was developed to assist in object recognition, measurement of distances to objects, navigation, and process automation. This paper describes a set of indoor and outdoor tests on the DASA Laser Ranger, and presents an evaluation of the ranging capabilities of the camera.

1. Introduction

There is a growing interest in range measurement for a wide variety of applications, and a number of sensors have been developed to address different aspects of this task. The Appendix shows characteristics of some of the emerging scanning and imaging range finders. As part of an international agreement between the United States and Germany, the National Institute of Standards and Technology (NIST) agreed to evaluate the DASA range sensor, manufactured by DaimlerChrysler Aerospace AG[*]. The evaluation was conducted using a camera provided by the manufacturer and calibrated by them. Due to the inability to carry out calibrations at NIST, some of the tests that were originally planned could not be carried out.

The DASA Laser Range Camera operates using indirect time-of-flight measurement over a full image frame (640×480 pixels) to create two types of images, intensity images and range images. To create an image, the scene is illuminated by a series of laser pulses whose duration typically ranges from 10 ns to 80 ns[†]. The laser pulses pass through a lens to spread the light over the entire field of view. The camera receives the back-scattered light, whose travel time is dependent on distance to the object.

To take account of confounding effects such as surface characteristics and ambient illumination, three images are taken at slightly different times. First, an intensity image, I_1, is taken with the

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[*] Commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

[†] A laser safety report was produced by Dasa in October 1999, and the device was approved for operation at NIST provided the beam is aimed downwards.

laser switched off, to measure the environmental illumination. Then the laser is triggered, and about 50 ms later, a range image, *R*, is captured, where objects closer to the camera appear brighter due to the longer integration times of the returns. Finally, a gray-scale intensity image, I_2, is captured, which integrates the laser light over the whole pulse sequence.

The value of a pixel in the range image should reflect only its range. The returns from the pulses are, however, dependent on the laser power and the surface characteristics of the object. To reduce these effects, a quotient image, *Q*, is computed by dividing the range image by an image obtained by subtracting the intensity image with the laser off from the intensity image with the laser on, that is, $Q = R/(I_2 - I_1)$. The final range is then found through a look-up table created during calibration, which assigns a range to each quotient image value. The intensity image is registered with the range image, and can be used for object recognition, terrain classification, or other application-specific purposes.

The imaging process is controlled by a number of parameters. Parameters that can be changed are the binning mode, laser delay, number of pulses, and the pulse frequency. Each has an allowable range of values, depending on a pre-defined configuration file for each calibrated camera lens and the pulse duration desired. The experiments were conducted using 70 ns (indoors) or 80 ns (outdoors) pulse configurations with a 23 mm lens[‡]. The camera has an exposure time of 17 ms.

Binning mode: The binning mode determines the resolution of the image in pixels (binning averages a local region into a single pixel) and affects the rate at which images can be acquired. Available modes are full resolution (640×480), at approximately 6.7 Hz, half resolution (320×240) at 10 Hz, and half-resolution in one direction, and full in the other (i.e., 320×480 or 640×240). Our experiments were conducted at full resolution (the default for the configuration file used).

Laser Delay: The camera has a maximum and a minimum range for which results are accurate. This range interval can be moved closer or further from the camera by changing the delay. Laser delay sets the interval between laser emission and triggering of the camera shutter in nanoseconds. Adjustment of this parameter changes time of flight, and therefore shifts the range interval up or down. In our experiments, the laser delay was left at its default setting. **Pulse Frequency:** The pulse frequency is the number of laser pulses emitted per second. The pulses are emitted with a maximum 1 % duty cycle. The pulse frequency was left at the default setting for our tests.

Total Number of Pulses: This adjusts the intensity of the laser light. It can increase or decrease the intensity of the pulse train. Changing the number of pulses affects no other parameters, but instead, regulates the amount of laser light and hence the Signal to Noise Ratio (SNR) in range measurements. Too few pulses would result in poor SNR. In our tests, the number of pulses was always set to the maximum.

The range interval over which measurements can be made by the camera is a function of the lens and the parameters (Table I). It depends on which configuration is selected. By appropriate choices, the lower and upper distance limits that define the interval can be shifted to suit the application.

[‡] The camera was only calibrated for a 23 mm lens. Calibration for additional lenses would have required returning the system to the manufacturer.

Maximum Operating Range (m)		***Field of View (Camera Objective Lens)***				
Laser Power	**Lateral Resolution**	42°×32° (f=8 mm)	29°×22° (f=12 mm)	21°×16° (f=17 mm)	16°×12° (f=23 mm)	10°×8° (f=35 mm)
75 Watt	640×480 Pixel	2	3	4	5	7
	320×240 Pixel	3	5	7	9	15
150 Watt	640×480 Pixel	2	4	5	7	10
	320×240 Pixel	5	7	10	13	21

Table I Manufacturer's Specifications of Camera Parameters

2. Indoor evaluation

Evaluation took place in a laboratory in the basement of the NIST Metrology building, designed for testing measuring tapes. The laboratory is long enough to measure tapes of up to 50 m, but only part of the facility was available for our use. The camera was set up on a calibrated position marker, and a target was moved to a sequence of similarly calibrated positions to cover the ranges to be tested. The Laboratory has facilities to measure to thousandths of cm over its length, but the accuracy of the sensor was orders of magnitude less than this, and therefore did not require stringent set-up procedures. Nevertheless, the true distances to the target were known to within 3 mm, which is 10 times the accuracy of the sensor. The manufacturer claims a range resolution of ±2 % of the depth of field, and uncertainties in the measured values in the experiments below are reported as percentages to verify these claims.

Testing was done with an edge filter, with the laser running in the 70 ns configuration. The configuration was set for a range interval of 0 m to 10 m, and the pulse rate was set to the maximum of 2431 pulses per second.

The first experiments tested the laser's sensitivity to different materials and surfaces as well as its indoor range accuracy. Three different targets were used. Target 1 was a piece of white poster-board with a smooth, slightly glossy surface. Target 2 was a gray, rectangular sheet of plastic foam; and Target 3 was a piece of gray poster-board, similar to Target 1, but with a duller surface. The size of each target was approximately 80 cm by 100 cm.

The laser range camera was set up at the end of the tunnel, and targets were placed in a sequence of measured increments from the camera. The location of the camera's image plane was not known exactly, so the front of the camera, immediately behind the lens, was used as a reference point. This decision was questionable, as is borne out by the consistent under-estimation of range. The images in this experiment were obtained by averaging 50 consecutive range images to reduce noise.

It became clear that the sensor was very sensitive to the material used for the targets. The data from Target 1 were invalid (represented by maximum range values) at ranges from 0 m to 4 m, even though it is easy to make out the shape of the target in the image (the large dark area in Figure 1), and the invalid pixel reading was consistent throughout the whole target. Thus, the sensor is capable of sensing the target, but the laser echo returned by the target is too strong, and invalid data are displayed. This is can be confusing at times, because the invalid range can be mistaken for maximum range. Objects that are shiny and reflect a lot of light may be mistaken

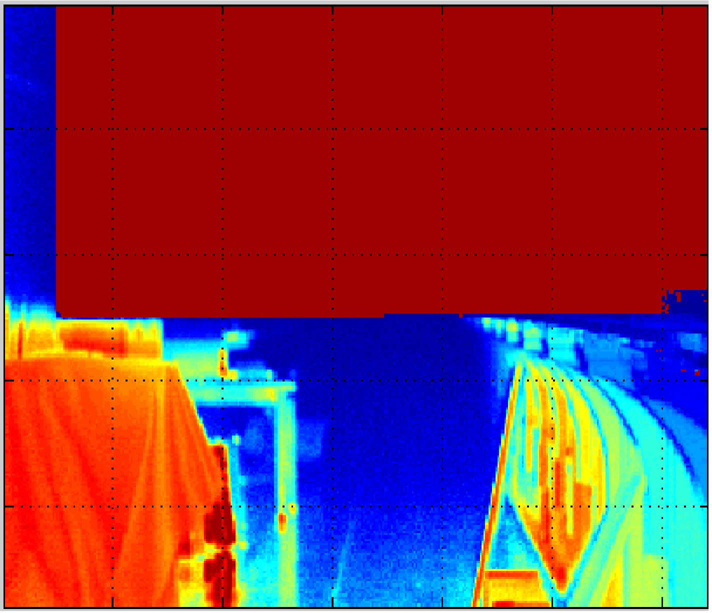

Figure 1 Range Image of Poster Board at 3 m

for objects that are far away.

At a distance of 5 m from the camera (Figure 2), the center of the target registered invalid pixels, but the sides and edges of the target returned valid readings. This is most likely due to spectacular reflections from the target's surface and saturation of the camera. At such close range, the laser echo from the center of the target is too strong or is reflected away from the

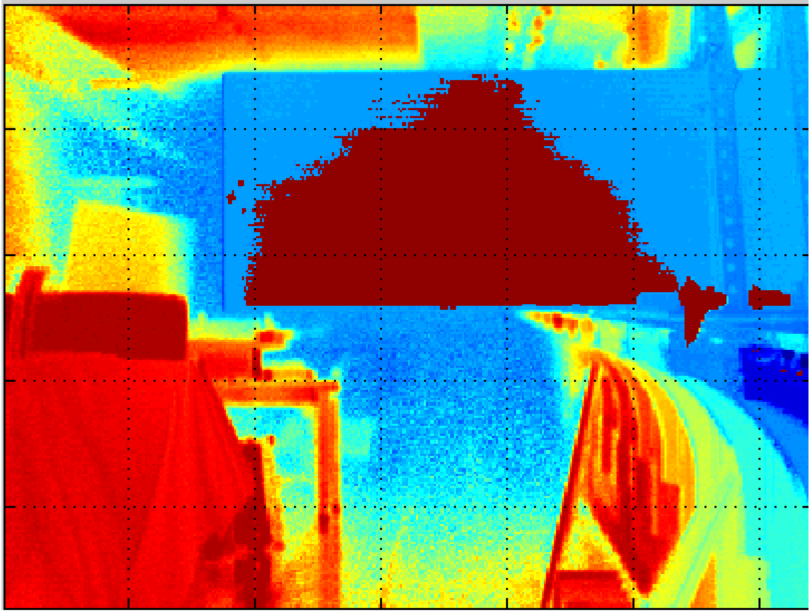

Figure 2 Range Image of Poster Board at 5 m

camera, and results in invalid data at those points. The invalid data at the bottom right corner of the target are a result of the shiny metal clamp used to position the target.

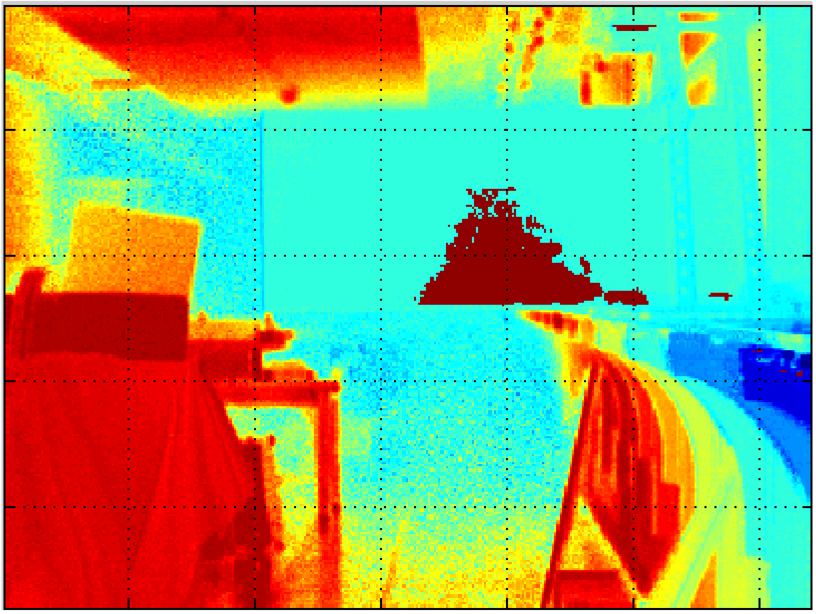

Figure 3 Range Image of Poster Board at 6 m

With the target set at 6 m from the camera (Figure 3), a triangular region at the bottom and middle of the target returned invalid data (about one quarter of the target). Again, invalid data were found at the center, where the laser echo is strongest. At 7 m, there were only small patches of bad data towards the bottom, middle portion of the target. When the target was 8 m away

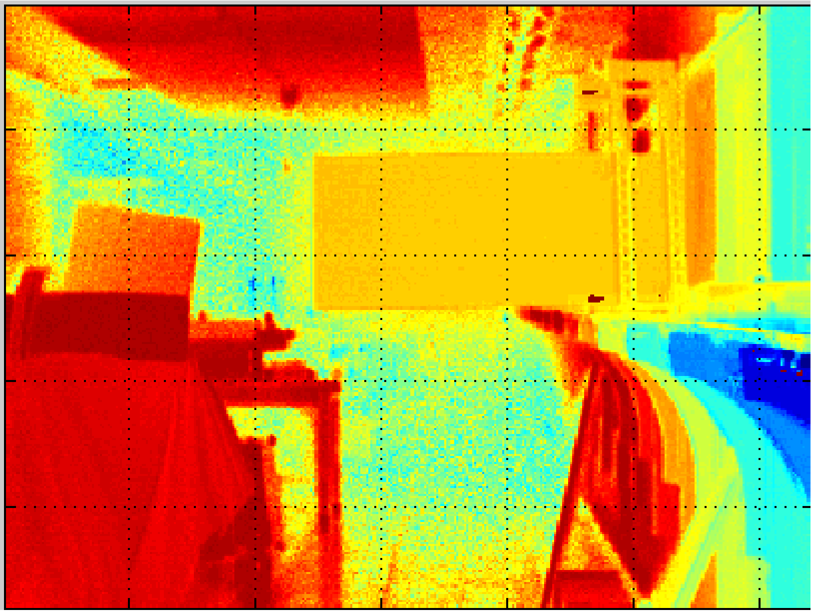

Figure 4 Range Image of Poster Board at 8 m

(Figure 4), it didn't return any distinct invalid data points. For the images that didn't have invalid data, the standard deviation in the range of each image increased with distance from the camera (Table II). In Table II, the standard deviations are computed over the valid points in the image that lie on the target.

Target 1 returned consistent, valid data for ranges of 5 m to 9 m (Table II). All the mean measured ranges had less than 2 % error; the most accurate range reading occurred at 7 m, when the data had 0.7 % error. In all cases, error is characterized by one standard deviation, as shown in Table II, of the set of measured values. The standard deviation in the range data increased steadily from 23 mm at a range of 5 m to 32 mm at a range of 9 m. The further away the target, the greater the deviation in range data.

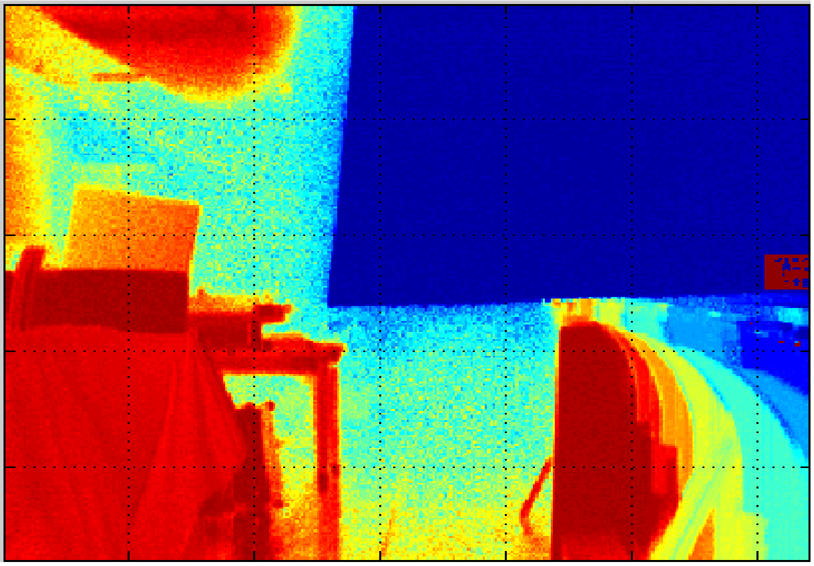

Figure 5 Range Image of plastic foam at 3 m

Target 2 didn't return any invalid data at distances of 2 m to 5 m. This could be a result of the sponge-like nature of the material, which absorbs some of the laser light instead of reflecting it. Although it did not return invalid data, the range camera overestimated Target 2's range for distances less than 3 m (Figure 5). For example, at 2 m, the reported mean range was (2.492 ±0.012) m. At 5 m, Target 2's image loses the fuzziness around the edges (Figure 6). The measured range is (4.817 ±0.050) m, which is well within the manufacturer's claimed accuracy.

Target 3 was similar to Target 1, except that it was gray and not as reflective. Like the first target, it returned invalid data at close range. However, this target could be placed at a closer range before invalid data appeared. Perhaps the target's color made the laser echo weaker or the matte surface had fewer specular reflections. At 3 m away (Figure 7), the target returned invalid data at the center, but over 50 % of the target's image returned valid pixel values. At 4 m, the measured mean range is (3.824 ±0.029) m, similar to the rest of the data collected at close range.

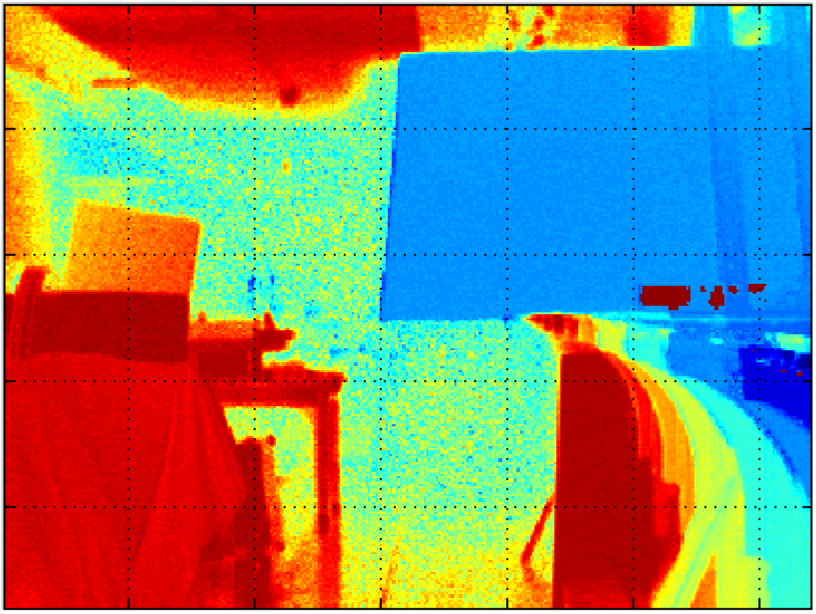

Figure 6 Range Image of plastic foam at 5 m

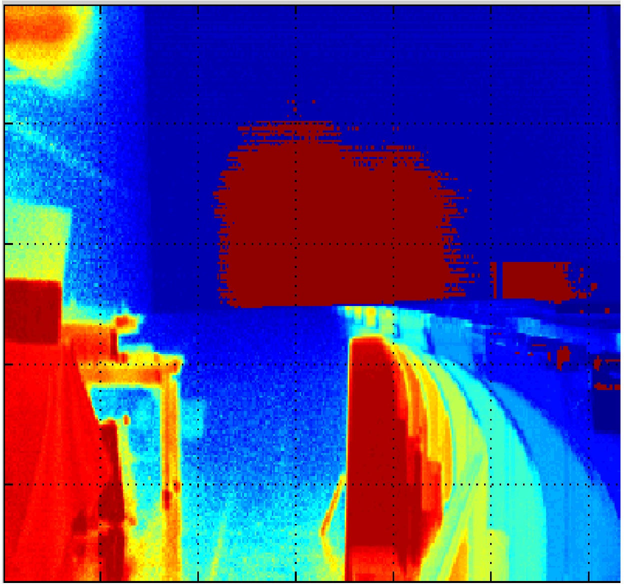

Figure 7 Range Image of Gray Board at 3 m

For all the images, except when the target was closer than 3 m, the range data underestimated the actual range of the target. At 2 m with Target 2, the range returned was greater than the actual range (See Table II). This implies either that the wrong origin was chosen, or that a correction could be made during calibration to improve the range estimates. As an example of the improvement that can be made, a rough correction based on our measurements for Target 3 is shown in the last column of Table II.

Range (m)	Target 1 Mean	Target 1 Std Dev.	Target 2 Mean	Target 2 Std Dev.	Target 3 Mean	Target 3 Std. Dev	Target 3 Corrected Mean Range
2	Invalid		2.492	0.012	Invalid		
3	Invalid		2.799	0.036	Invalid		
4	Invalid				3.824	0.029	3.84
5	4.924	0.023	4.817	0.050	4.860	0.025	4.92
6	5.942	0.024			5.794	0.024	5.9
7	6.950	0.026			6.811	0.024	6.96
8	7.906	0.027			7.815	0.026	8.01
9	8.939	0.032			8.810	0.029	9.05
10			9.408	0.100	9.792	0.032	10.08

Table II Indoor Data taken from valid regions of the target

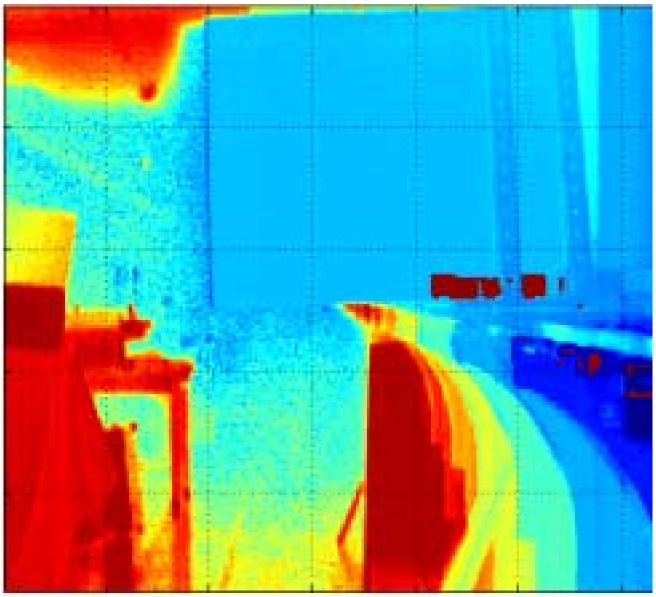

Figure 8 Range Image of Gray Board at 5 m

At distances greater than or equal to the maximum range (10 m with the settings used for these experiments), the targets returned values less than or equal to 10 m (Figure 9). At distances greater than 15 m, the range values start dropping, and the standard deviation of the range data increases. In order to measure these ranges more accurately, the range interval needs to be shifted to 10 m to 20 m instead of 0 m to10 m, by changing the laser delay. If the camera is to be used for unsupervised measurements, however, this out-of-range behavior can cause significant problems. It would be helpful if the values of points outside the working range could be set to a special invalid value.

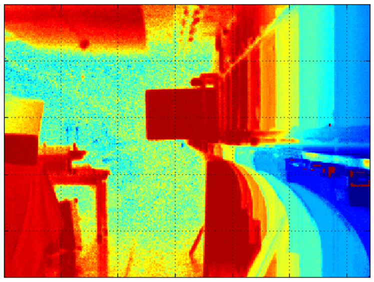

Figure 9.1 Range Image at 14 m

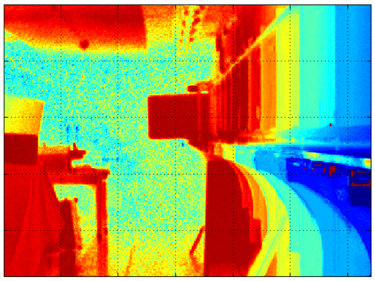

Figure 9. 2 Range Image at 16m

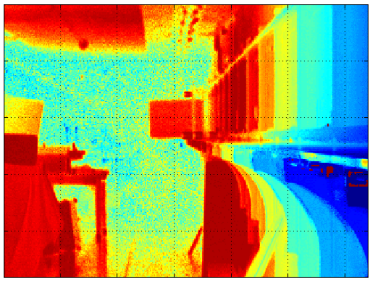

Figure 9. 3 Range Image at 18m

At these greater ranges, the camera consistently displays invalid data for the target. This is because the range is outside the range interval. However, the range image at 18 m (Figure 9.3) shows a lighter colored target, which is probably a result of the reduction in laser echo at this great range.

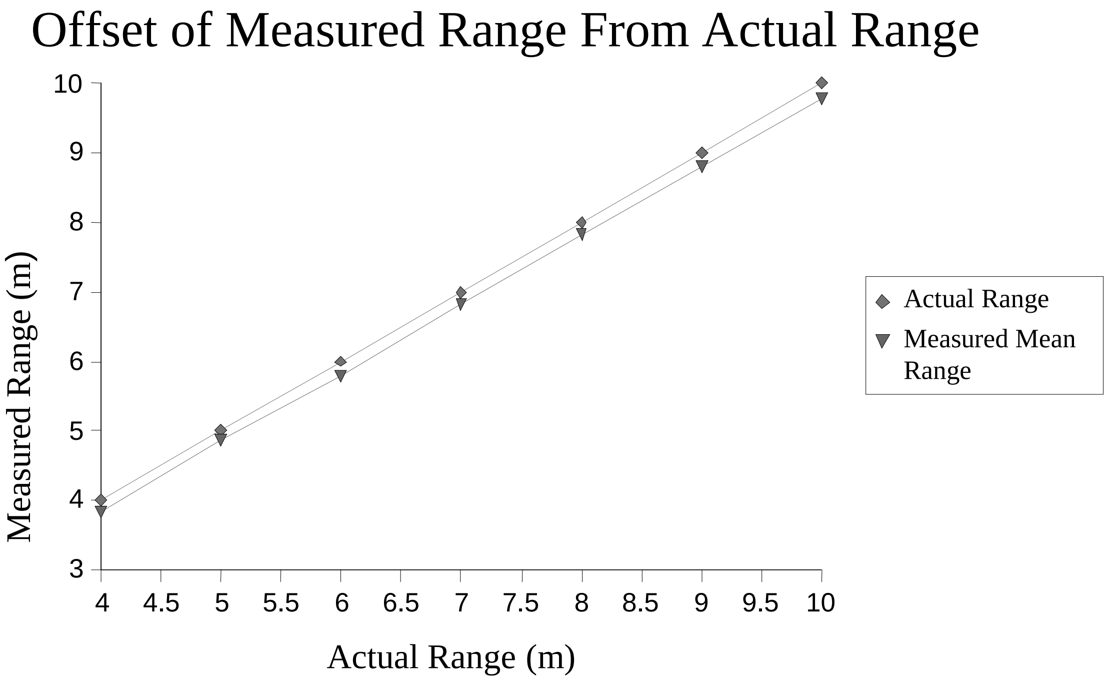

Figure 10 Indoor Calibration Error

The graph in Figure 10 shows how the measured range is slightly less than the actual range. The graph of the actual range is $y=x$. The corrected range in the last column of Table II was attained by applying a least squares fit to all the valid indoor data captured in the 70 ns pulse configuration. This included data from all three targets.

3. Outdoor Evaluation

For outdoor testing, the laser was configured to use 80 ns pulses, with the number of pulses set to the maximum of 2100 per second. The edge filter was replaced with an interference filter, which filters out ambient light with wavelengths different from that of the laser. As in the indoor experiments, the data were averaged over 50 images to reduce noise. For outdoor data, ground truth was not as accurate as for indoor data, and the uncertainty represents one standard deviation about the mean measured range.

The target used was a brick wall. Testing had to be done in the shade, because when the sun shone on the wall, the ambient light was too strong, and the wall would return invalid data. The laser delay parameter was adjusted for an initial range interval of 0 m to 15 m.

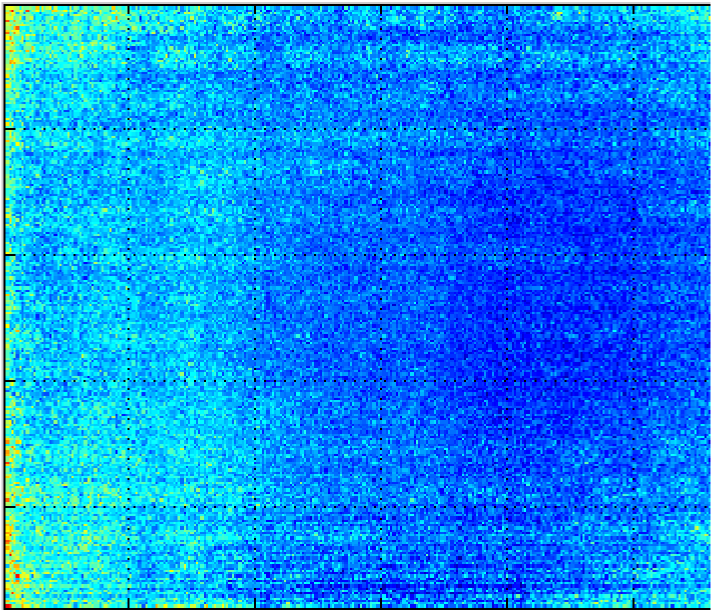

Figure 11 Range Image of Wall at 5 m

The laser range camera couldn't be used to find the range of any shiny, reflective, or metallic objects like cars, metal garage doors, and glass windows. Since the wall took up the whole field of view, it was easy to see how the data varied across the target. Readings at the center of the target were the most consistent and appear in the images as mostly uniform colors (Figures 11 and 14). One would expect the range to increase slightly from the center of the image to the periphery, due to the effects of off-axis angle. The field of view with the 23 mm lens that we used is 16°×12°, so the maximum range at the edge of the image is increased by a factor of *1/cos(8°)*, or about 1 %. As with the indoor tests, the measured range is consistently slightly less than the actual range in this middle region. Values further from the center of the target image show greater variance and tend to overestimate the actual range. The mean range of the target was less than the actual range for ranges greater than 10 m. As the distance from the wall increased, the field of view contained a larger portion of the wall, and there was a sharp increase in standard deviation compared to indoor testing. A small part of this could be due to the mortar joints in the wall, visible at close ranges (Figure 11).

Since the sunlight was so strong, the intensity image could be seen without turning on the laser (Figure 12), even with the interference filter. When the laser was on, the data from the center of the image were mostly invalid (Figure 13). This is why the range tests had to be performed in the shade, or on cloudy days.

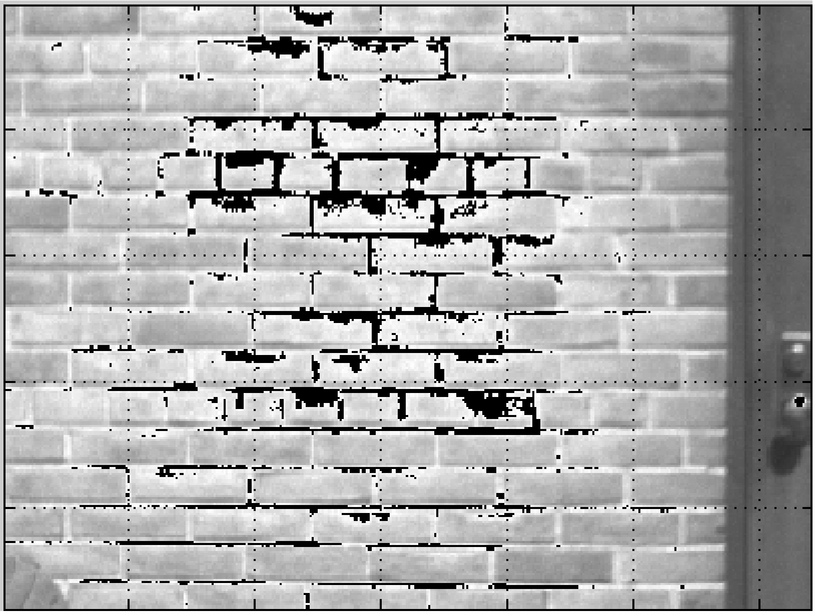

Figure 12 Intensity Image with Laser Off

As range increased, the standard deviation of the range data increased as well. At a distance of 12 m (Figure 14), the mean range of the data was closest to the actual range, at (11.953 ±0.166) m, an uncertainty of about 1.4 %.

Beyond 13 m, the ranges are less accurate. This could be a result of a number of things. At this distance, the field of view consists of a large portion of the wall, so the data could have greater deviation. This is because a larger wall will be affected more by changes in lighting, since different portions of the wall can be exposed to varying amounts of sunlight. During outdoor

Figure 13 Intensity Image with the Laser On

testing, lighting changes very often, due to the shifting clouds in the sky. This could also have an effect on the accuracy of the ranges measured. Another possibility arises from the observation that the closer the distance to the maximum range, the less accurate the data become. Since the range interval maximum was 15 m, the ranges measured at 14 m and 15 m weren't as accurate as they could have been if the maximum range was 20 m.

To test the maximum range capability of the laser range camera, the distance interval was set to its maximum in the 80 ns configuration, at 22.5 m to 37.5 m. Data were taken for distances from 34 m to 38 m. However, in each case, the maximum range returned was approximately 30 m. Relative range could still be distinguished, despite the inaccurate range readings. Closer objects returned a smaller range than further objects, although the data couldn't accurately tell you how much closer one object was than another. Ranges below 30 m were more accurate, but could be off by as much as 1 m (3 % to 4 % uncertainty). As in the indoor testing, the ranges returned were always less than the actual range, except at close distances (5 m or less). The results would most likely have been better with a 35 mm lens, but this could not be tested because only the 23 mm configuration was calibrated.

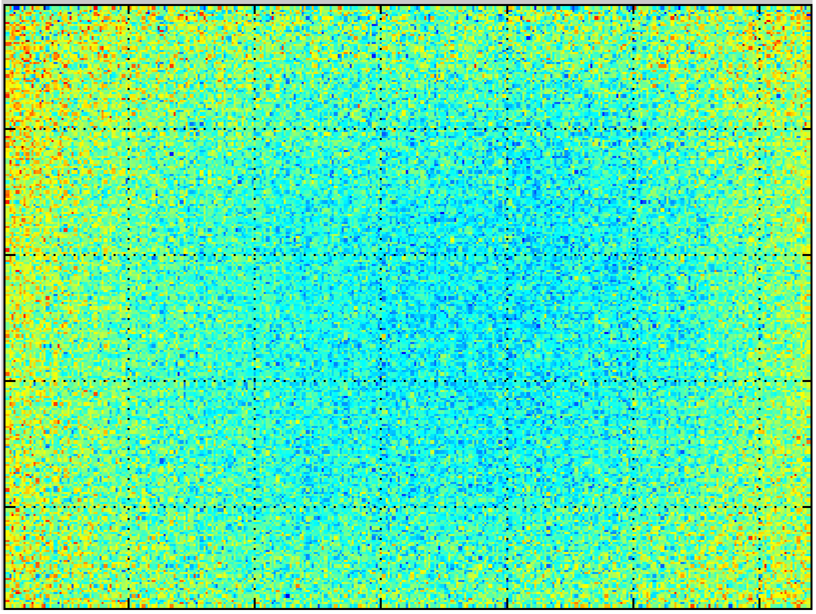

Figure 14 Range Image of Wall at 12 m

Finally, the range interval was set for distances from 15 m to 30 m. With the camera 28 m from the wall, range readings were more accurate, with the mean range being less than 1 m from the actual range.

In outdoor testing, there was little evident calibration error except at the limits of the range interval (Figure 15).

Range (m)	**Mean**	**Std. Dev.**
5	5.026	0.021
6	5.891	0.057
7	6.906	0.070
8	7.904	0.082
9	8.906	0.096
10	9.916	0.121
11	10.953	0.147
12	11.968	0.166
13	12.919	0.194
14	13.514	0.351

Table III Outdoor Data, 80 ns configuration

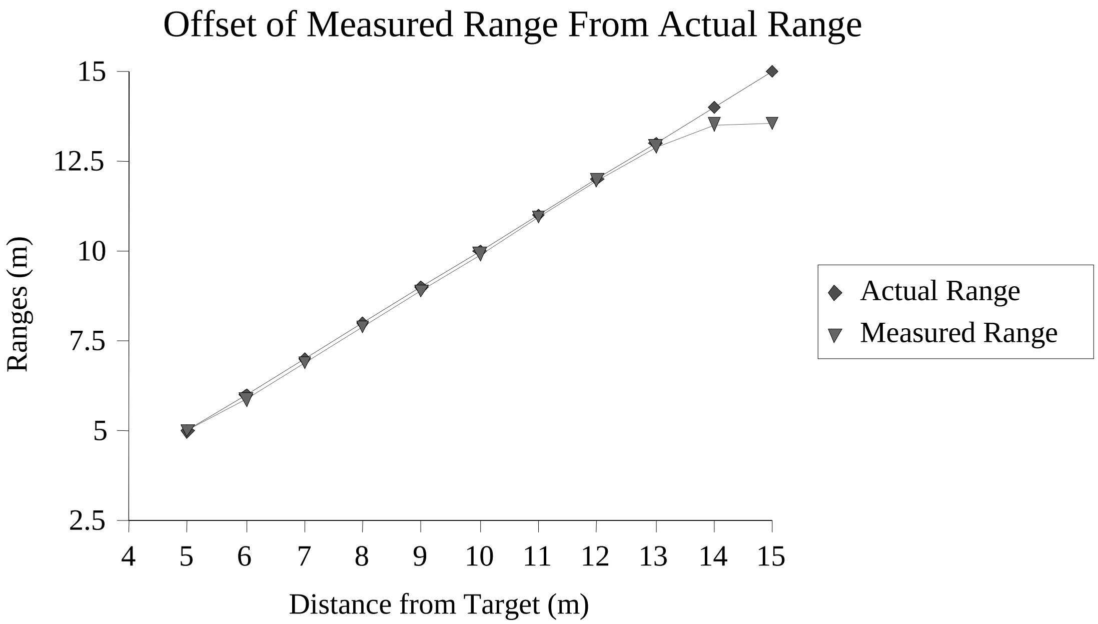

Figure 15 Outdoor Calibration Error

4. Summary and Conclusions

The DASA Laser Range Camera was tested in both indoor and outdoor environments. There was less scatter in range data when the camera was used indoors, but this can probably be attributed to the smaller size of the target area measured as well as the fixed lighting. The manufacturer claims a range resolution of ±2 % of the depth of field. In our experiments, this claim was found to be correct for most of the valid measured points, but in some cases, typically at the limits of a range interval, the range was off by as much as 5 % of the selected depth of field. The deviations are partly due to calibration error (or our selection of the wrong origin), since the measured range is usually less than the actual range. Though standard deviation of the range data increased with the range, the deviation was still within 1 % of the range.

When used indoors, various objects may interfere with the laser echo, which would cause problems in the range data. To insure accurate data at various ranges, the target's surface and composition have to be accounted for. This requires too much operator involvement, and could probably be avoided by reducing the laser illumination level at close ranges. It would be helpful if the camera controller included an automatic power control feature that reduced the reflected signals to a level that would allow valid measurements.

An undesirable side effect of changing the range interval is that the range estimates change for the same actual distances. If the interval is set so that the target's range is near the middle of the range interval, the image is clearer, and data become more accurate than when the target is close to the limit of the interval. If an object's range is outside of the interval, it is difficult to differentiate between the object and other objects that are within the range interval. Often, objects outside the range interval are given values that are within the range interval, usually near the maximum range.

Our original goal was to evaluate the sensor for use in mobile vehicle applications. Our conclusion is, however, that the current configuration is not suitable for such applications. In an outdoor environment, there may be too much ambient light from the sun at the same frequency as the laser. Unless the pulse intensity is increased, the camera won't be able to differentiate between the laser echoes and the ambient light from the sun. Consequently, the laser isn't very effective outdoors, unless it is dark or cloudy. Data accumulated from the outdoors was closer to the actual range than the indoor data. However, the standard deviation in the outdoor range data was considerably greater than the indoor data, so the range of a small portion of the target would not be a very accurate. The speed at which images are acquired makes the sensor very sensitive to motion, and rules out its use on mobile vehicles. The camera uses three images, taken about 50 ms apart, to construct a range image. This introduces motion blur because the images are not taken from exactly the same position. The effects are particularly noticeable when the camera rotates, but are visible even with small translations. A summary of the advantages and disadvantages of the sensor is shown in Table IV. Overall, however, the sensor is fast, reasonably accurate, and has a wide field of view. It can be expected to perform well in applications where motion and illumination can be controlled.

Advantages	**Disadvantages**
Scannerless Operation	Sensitivity to Material
Large Field of View	Sensitivity to Motion
Registered Gray Scale and Range Images	Sensitivity to Ambient Illumination
Comparatively High Frame Rate	Low Range Resolution compared to scanning systems (see Appendix)

Table IV Advantages and Disadvantages of the DASA Sensor

Appendix

Comparison of some of the LADAR range sensors currently available:

		Flash		**Scanning**		
		Daimler-Benz-DASA	**Lincoln Lab**	**Cyrax**	**Mensi- Soisic**	**K^{2}T**
λ (nm)		850	1064 (1500 in future)	Proprietary. Green, passively Q-switched	640	780
Pulse duration (ns)/ Power		10-80 150W max	2W @ 0.3		< 5 mW, CW	40 mW
Dist. computation		Time-of-flight	Time-of-flight	Time-of-flight	Time-of-flight	
Beam divergence (mrad)					3	
FOV: Horiz / Vert		±21 / ±16		40 / 40	320 / 46	360 / 60
Min. range (m)		0.5		0.5	2	2.3
Max. range (m)		30	70 - 80	50	25	60
Range resolution		±2 % of depth of field		±6 mm	±0.2 mm	1.755 mm
Vert. spatial resolution			32 x 32 pixel	2 mm @ 50 m	1 mrad	0.1° - 0.04°
Horiz. spatial resolution				2 mm @ 50 m	1 mrad	0.0225°
Speed	**Meas. rate**			800 Hz	100 scans/s	100 kHz
	Frame rate	10 Hz. (320 x 240 pixels) 6.7 Hz. (640 x 480 pixels)				
Power requirements		230V, 24V		90 - 240 VAC 24 VDC	220/110 V, 50/60 Hz 250 W	120 VAC, 220 VAC, or 24 VDC
Power consumption (W)		175		125		
Weight (kg)		1.1 (sensor head) 9.2 ("local end")		29.5 (scanner) 21.4 (electronics & power)	14 (scanner)	25.5 (Scanner) 20.4 (Electronics)
Laser Classification		I or IIIa		II	III a	III b
Output					x, y, z	

		Scanning			
		Riegl – LPM-25HA	**Riegl LMSZ210**	**Riegl – LPM98**	**Metric Vision 100B-60m**
λ (nm)		≈ 900	900	903	700
Pulse duration (ns)/ Power			1 mW @ 17	1 mW @ 17	
Dist. computation		Time-of-flight	Time-of-flight	Time-of-flight	
Beam divergence (mrad)			3	3	
FOV: Horiz / Vert		±180 / ±150	±170 / ±40	±180 / ±150	±220 / ± 60
Min. range (m)		2	2	2	2
Max. range (m)		20 / 40	350	150	60
Range resolution		±8 mm / ± 25 mm	±2.5 mm (best) ±10 mm (worst)	±20 mm (best) ±50 mm (worst)	± 2.5 ppm
Vert. spatial resolution		0.009°	0.24°	0.09°	
Horiz. spatial resolution		0.009°	0.24°	0.09°	
Speed	**Meas. rate**	1000 Hz	100 kHz		Psuedo Vision Mode: 10-125 scans/s Metrology mode: 5-50 scans/s Enhances mode: 1-5 pts/s
	Frame rate				
Power requirements		11 - 18 VDC	11 VDC – 18 VDC	11 VDC - 18 VDC	
Power consumption (W)		50	50	50	
Weight (kg)		9.5 (scanner)	13 (scanner)	8 (scanner)	40 (sensor) 190 (cart)
Laser Classification		I when scanning	III b	III b	Class I
Output		x, y, z, intensity	x, y, z, intensity, rgb	x, y, z, intensity	