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Time of Flight Sensors Experiments Towards Vehicle Safety Standard Advancements

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Abstract

The National Institute of Standards and Technology has been performing measurements using 2 dimensional and 3 dimensional time-of-flight sensors, a sonar sensor, and color camera. These measurements are to be used as background information towards changes to the ITSDF (Industrial Truck Standards Development Foundation) B56.5 industrial truck safety standard with regard to non-contact sensors detecting standard test pieces. The B56.5 standard defines the safety requirements relating to the elements of design, operation, and maintenance of powered, not mechanically restrained, unmanned automatic guided industrial vehicles and automated functions of manned industrial vehicles. Optical and acoustic type sensors were tested in these experiments on B56.5 standard test piece sizes as well as, a third flat test piece being recommended here as an addition to the standard.

Keywords: sensors, LIDAR, LADAR, sonar, test pieces, ITSDF B56.5, automated guided vehicles

1. Introduction

For manufacturing, Automated Guided Vehicles (AGVs) are the vehicles of choice and are equipped with automatic guidance systems and are capable of following prescribed paths. In automated factories and facilities AGV's move pallets and containers. In offices they may be used to deliver and pick up the mail. They are even used to transport patrons around in airports.

The main benefit of AGVs is that they reduce labor costs. But in material handling facilities there is another benefit. Material handling has always been dangerous. Injuries occur due to a driver's lack of attention, drivers driving too fast, or other personnel not paying attention. Obstacle detection is therefore a key to allowing AGV's to interact with personnel safely while optimizing vehicle speeds [1]. Emergency controls are then required which would stop the vehicle if an object is detected in the direction of travel. Although workers are trained to mark AGV travel paths clearly, to watch out for AGV's keeping clear when vehicles approach, equipping AGV's with virtual bumpers such as Laser Detection and Ranging (LADAR) sensor systems can be beneficial. LADAR systems must be able to detect 3D objects such as humans and the controller must understand what they are to be safe. Standards for AGV's and other industrial vehicles provide language that describes specific test pieces to use when manufacturing AGV's. However, there may be adjustments to the current standards to consider, especially when using non-contact sensors to detect realistic obstacles and as AGV's begin working closer to humans in more unstructured environments. Detection of humans, [2] as well as obstacles that can be pushed into humans by AGV's all must be detected for safe working environments.

The National Institute of Standards and Technology (NIST) has recently performed measurements with results to be used as background information towards changes to the ITSDF (Industrial Truck Standards Development Foundation) B56.5 Safety Standard for Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles [3] with regard to non-contact sensors detecting standard test pieces. The B56.5 standard defines the safety requirements relating to the elements of design, operation, and maintenance of powered, not mechanically restrained, unmanned automatic guided industrial vehicles and automated functions of manned industrial vehicles. Optical and acoustic type sensors were tested in these experiments on B56.5 standard test piece sizes, as well as a large flat metal, cinder block and other test pieces and test piece coverings. Over 120 data sets from 21 different tests using a variety of test piece configurations, coverings and layouts were performed in a NIST laboratory.

The ITSDF B56.5-2005 Safety Standard section on non-contact sensing devices is as follows:

8.11.1.2 Noncontact Sensing Devices. *If used as the primary emergency device, such device shall be fail-safe in its operation and mounting and shall stop the vehicle travel prior to contact between the vehicle structure and the object detected.*

8.11.1.2.1 Test Pieces. *The following test pieces shall be detected in the main direction of travel:*

(a) a test piece with a diameter of 200 mm and a length of 600 mm lying at any angle to and anywhere on the path of the vehicle. For maximum activation force, see para. 8.11.1.1.

(b) a test piece with a diameter of 70 mm and a height of 400 mm set vertically anywhere fully within the path of the vehicle.

The test pieces described in the standard are of specific size, originally based on the British EN1525 standard. [4] However, there is no explanation of test piece covering that may also be required as various non-contact sensors may react differently to various materials to be detected. Either the sensor will detect a particular material or not and could cause a safety hazard as a result of choosing the wrong test piece covering. Also, only cylindrical test pieces are listed in the standard and perhaps provide better performance than flat test pieces might when positioned at specific angles with respect to the sensors being used to detect the test pieces.

The sensors considered for the NIST experiments were both optical and acoustic to allow a variety of performance characteristics that do not sway measurement decisions and recommendations toward one sensor type. Sensors used are listed in the following section 2. Experiment and sub-section Experimental Setup.

This paper will explain: the experiment performed, the software algorithm used to collect data, the results and provide recommendations towards changes to the B56.5 standard. Ending the paper are summary, conclusions and references sections.

2. Experiment

2.1. Experimental Setup

Two types of sensors were tested: Optical (2D scanning LADAR (Laser Detection and Ranging)) and Acoustic (Sonar) along with an advanced Flash LIDAR (Light Detection and Ranging) sensor and a color camera. All data during each test was collected simultaneously and data sets have been stored and are available upon request. Figure 1 shows a CAD drawing of the experimental setup representing the sensors and test pieces. Test pieces were setup singularly and in sets depending on test pieces and attempting to overlap, in some cases, from one test to the next (i.e., same test pieces used in both sets).

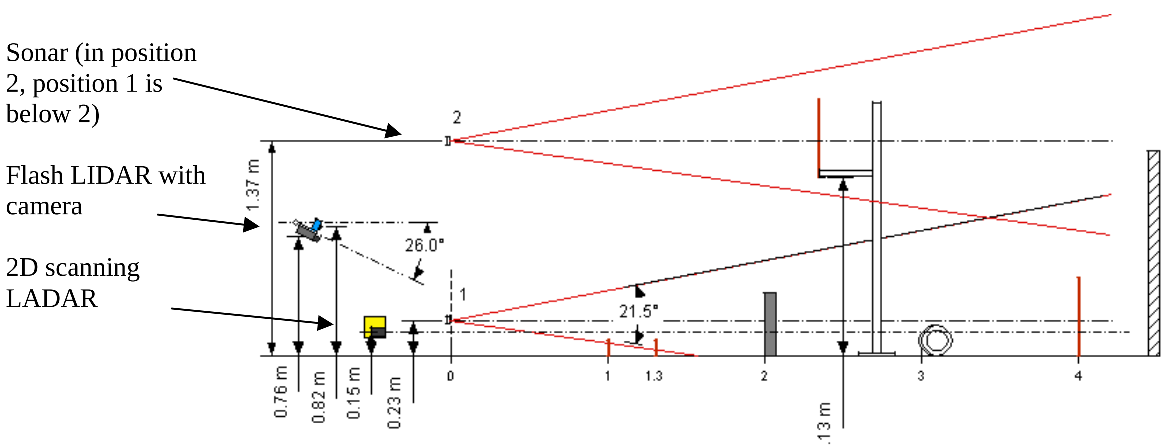


Figure 1 – Graphic of experimental test setup showing dimensions (in meters). Sensors are shown to the left and representing targets in the figure are, from middle to right: a flat target positioned horizontally at 1 m and 1.3 m, a 70 mm dia. x 400 mm long cylinder at 2 m, a raised flat target mounted 1.13 m vertically above the floor and on a floor stand, a 200 mm dia. x 600 mm long cylinder lying horizontally at 3 m, and a flat target vertically at 4 m. The background cardboard wall is to the far right.

Figure 2 shows a photo of the experimental setup. The entire setup was initially aligned with the floor tiles for simple and approximate positioning of test pieces. We incremented test pieces approximately 1m away from the sensors for each test up to 4 m. Beyond the test pieces at approximately 5 m, was a cardboard wall. Sensors were mounted on two parked vehicles - a large and small robot. The sonar and sonar computer were stock with the

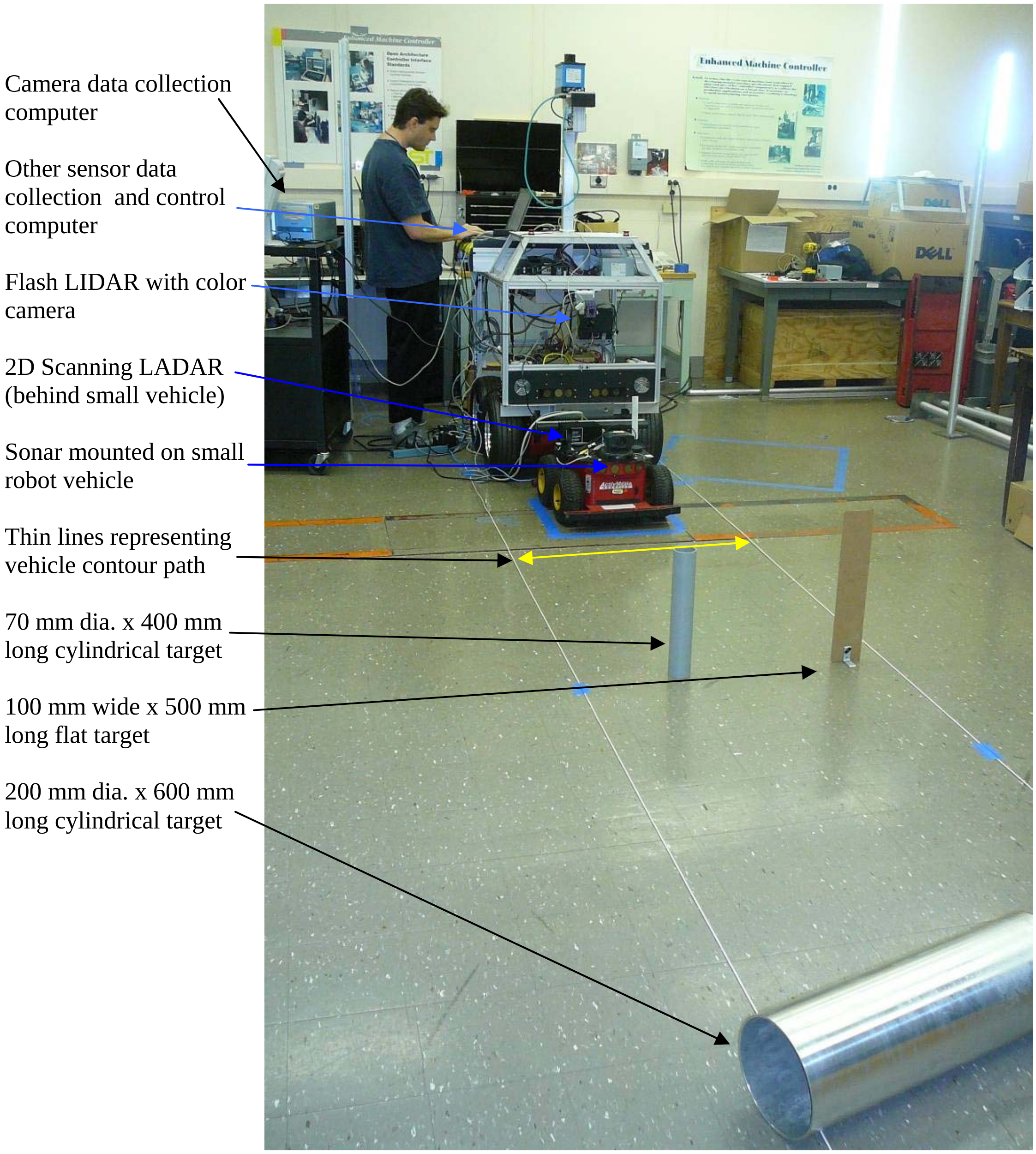


Figure 2 – Test setup. The two cylindrical obstacles are B56.5 standard sizes while the flat obstacle is not.

small robot[1] shown in the figure and were used as is. The sonar maximum range was well beyond the experimental setup of approximately 5 m to the cardboard wall. Two additional computers were used to collect data and control the simultaneous data collection. A color camera (4.8mm 1:1.8 Lens) and a 3 dimensional (3D) Flash LIDAR (Light Detection and Ranging) sensor were mounted at a 26º angle with respect to the horizontal and on the large vehicle. A 2D scanning LADAR was

1 Any mention of commercial products within this document is for information only; it does not imply recommendation or endorsement by NIST.

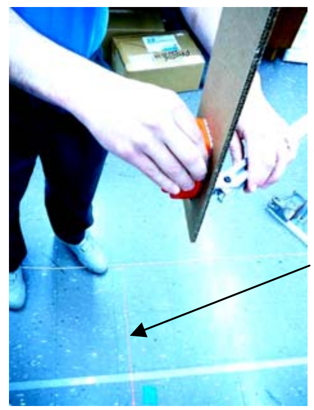
also mounted on the large vehicle and was not used during sonar measurements as it was blocked by the small vehicle. For all tests, one researcher read the distance from the sensor to the obstacle as returned by the sensor program on the control computer. The other researcher typed in the value stated for that sensor/test.

The sonar sensor was mounted in two positions: position 1 at 0.23 m above the floor and position 2 at 1.37 m above the floor. The second position was used to negate any effect that may have been caused by parts resting on the floor. For this, a lightweight stand was built and used to support the flat test piece well above the floor. To ensure that the test stand had no effect on sonar sensor data, the test initially included the test piece followed by removing the test piece with only the test stand in the field of view.

The test stand was setup at an approximate 45º angle with respect to the sensor. The stand included a relatively thin, 25 mm square aluminum post to not be seen or reflect sonar signal away from the sensor. As a result, the test stand had no effect on sonar measurements.

Figure 3 (top) shows the small robot raised to position 2 and shows the point of view from the sonar sensor, camera and Flash LIDAR. For the position 2 sonar tests, the camera and Flash LIDAR were removed from the large robot vehicle and setup on the small robot 127 mm left and 51 mm up (camera) and 127 mm up (Flash LIDAR) with respect to the sonar sensor and facing perpendicular to the test pieces (i.e., parallel to the floor) as viewed from the sensors.

Figure 3 (bottom) shows the calibration technique used to align the flat target to the floor tile grid. A tape measure was used to indicate approximate 1 m, 2 m, 3 m, or 4 m distances from sensors.



Laser level line on floor

Figure 3 – (top) Raised small vehicle to position 2 with Flash LIDAR (top-right) and color camera on small vehicle and raised target support on test stand (top-left). (bottom) Calibration of flat target with respect to floor tiles using a laser line level.

Figure 4 shows the cart that supports the small vehicle when in position 2. The cart is pushed against the large vehicle and again blocks the 2D scanning LADAR. For all sonar experiments, tape and cardboard was used to cover all but the sonar sensor used for tests.

Figure 5 shows the 2D scanning LADAR sensor mounted on the large vehicle with the 70 mm dia x 400 mm long test piece set in front and covered with a standard 6% black density patch. [5] Density patches used had the following characteristics:

- reflections of 6% (density of 1.22D), 50% (density of 0.30D) and white;
- meet MIL-M-9868E requirements.
- 15.24 cm square

The paper was taped to the standard cylinder test piece at a height allowing the laser line to be approximately at the paper center.

Figure 4 – Small robot vehicle on a cart in front of the large robot vehicle. Left shows the rear of the flat target being supported from the test stand. The large black camera was not used. Note the blue tape covering all except the front facing sonar sensor.

2.2. Experiments

Table 1 lists test pieces and their coverings and positions for all tests. Three different test pieces were used. The two cylindrical test pieces are specified in the ITSDF (Industrial Truck Standards Development Foundation) B56.5 standard. Additional flat test pieces were added in an attempt to cause no or limited detection from sensors. Various coverings over the test pieces were also used to again cause no or limited detection from sensors.

Approximate location of laser line on test piece

Figure 5 – Optical 2D scanning LADAR sensor mounted on the large vehicle with the 70 mm dia. x 400 mm long test piece set in front and covered with a piece of black standard reflectance paper.

The coverings used were representative of clothes and colors that may be worn by people or of manufacturing or other industrial industry materials that may be near robot vehicles in real world situations. Initial tests used the sonar sensor followed by optical sensor tests and then was ended with sonar sensor tests.

2.2.1. Acoustic and Optical Sensor Tests

The initial tests 0 through 10 and final tests 18 to 21 included simultaneous data collection from the 3D Flash LIDAR, color camera and sonar sensors. The optical sensors were used to show the scene on each sonar test using the color camera and to use the LIDAR as an advanced sensor for future full scene detection comparison. For this initial test, our focus was on sonar data collection.

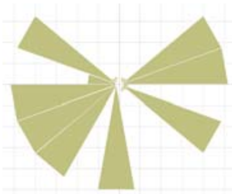
Table 1 – Tests, test pieces, coverings and positions.

test	test piece	size (mm)	covering	position 1 or 2
Sonar Sensor				
0 - 1	flat cardboard	100 x 500 tall	none - brown cardboard	1
2	flat cardboard with sweatshirt cover	100 x 500	50% polyesther, 50% cotton	1
3	vertical cylinder	70 dia. x 400	none - gray plastic	1
4a	vertical cylinder with sweatshirt cover (loose)	70 dia. x 400	50% polyesther, 50% cotton	1
4b	vertical cylinder with sweatshirt cover (tight)	70 dia. x 400	50% polyesther, 50% cotton	1
5a	vertical cylinder with denim cover	70 dia. x 400	100% cotton denim	1
5b	vertical cylinder with denim cover	70 dia. x 400	100% cotton denim	1
6	horizontal cylinder	200 dia. x 600	none - aluminum	1
7	moving box	200 x 460 x 318	none - brown cardboard	1
8	still box	200 x 460 x 318	none - brown cardboard	1
9	flat cardboard laying horiz.	500 x 100 tall	none - brown cardboard	1
10	flat cardboard raised using floor stand	100 x 500	none - brown cardboard	2
Optical Sensor				
11	3 vertical cylinders	70 dia. x 400	none - gray plastic	1
			100% cotton denim	1
			50% polyesther, 50% cotton	1
12	4 vertical cylinders	70 dia. x 400	none - gray plastic	1
			standard black reflectance paper	1
			100% cotton denim	1
			50% polyesther, 50% cotton	1
13	2 vertical cylinders, 2 flat cardboard	70 dia. x 400	cylinder: none - gray plastic	1
		and 100 x 500	cylinder: stnd. blk reflect. paper	1
			flat: foil covered	1
			flat: none - cardboard	1
14	horizontal cylinder with no and covered patches	200 dia. x 600	standard black reflectance paper	1
			standard gray reflectance paper	1
			standard white reflectance paper	1
			none - aluminum	1
	2 Horizontal Cylinders - 1 alum. with 3 stnd	200 mm dia. x 600 mm long	standard black reflectance paper	1
	color covers, 1 cardboard with flat paint		standard gray reflectance paper	1
	or no cover		standard white reflectance paper	1
			none - aluminum	1
		200 mm dia. x 600 mm long	cardboard cylinder painted flat black	1
15	4 flats	100 mm wide x 500 mm high	1-right - none - cardboard	1
		100 mm wide x 500 mm high	2-rt-mid. - foil covered	1
		100 mm wide x 500 mm high	3- lt-mid. - none stainless steel	1
		44 cm wide x 46 cm high	4-left - none - aluminum	1
16	cinder blocks	304 mm wide x 203 mm high	none	1
		304 mm wide x 203 mm high	painted flat black	1
17	framed flat glass panel	914 mm wide x 457 mm high	metal frame, clear glass	1
Sonar Sensor				
18	Horiz. Cylinder - cardboard	200 mm dia. x 600 mm long	cardboard	1
19	large plate	44 cm wide x 46 cm high	none - aluminum	1
20	cinder block	304 mm wide x 203 mm high	flat black painted	1
21	framed glass	914 mm wide x 457 mm high	metal frame, clear glass	1

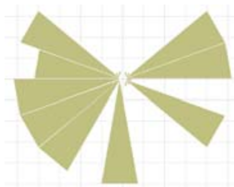
Figure 6 shows a top view of graphical sonar data for obstacle detection at (a) 1 m, (b) 2 m, (c) 3.5 m, and (d) with no obstacle in front of the sonar sensor. The left triangle that changes in each figure is the sonar that was used.

The other sonars were blocked with tape and cardboard where some sonar energy still penetrated the cover. In d, the pattern shows no detection of an obstacle as the cardboard walls were at approximately 5 m from the sensor. Figure 7 shows the data collected with the color camera and 3D Flash LIDAR of the same scene in Figure 8 b.

Sonar cones shown in Figure 8 are from a program called "Playerv" that comes with "Player" [6] and was used as part of the sonar data collection. “The Player Project creates Free Software that enables research in robot and sensor systems. Player is developed by an international team of robotics researchers and used at labs around the world."




a b



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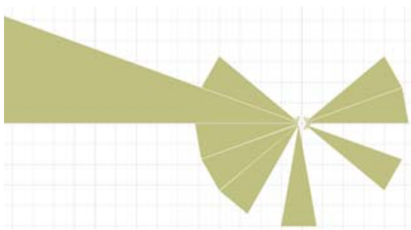
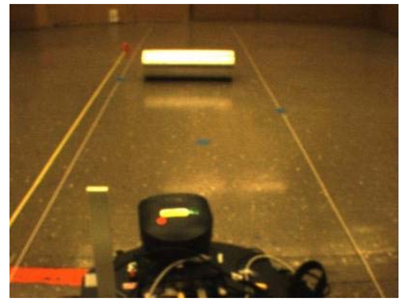


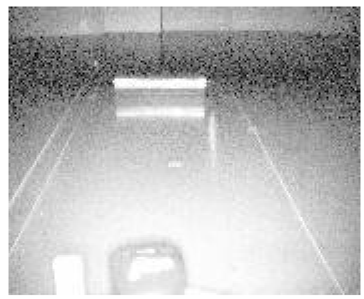
d

Figure 6 – Top view of graphical sonar data for obstacle detection at (a) 1 m, (b) 2 m, (c) 3.5 m, and (d) with no obstacle in front of the sonar sensor. The left triangle that changes in each figure is the sonar that was used.

2.2.2. Optical Sensor (LADAR) Tests

Two types of reflection were tested: specular and diffuse optical reflection. Specular surfaces (like tin foil or a mirror) make the angle that the light hits the target and either reflect the light back to the sensor or away from it. Diffuse reflection, like white paper, scatters the light back more uniformly regardless of the angle that the light hits the target. There is a at least one point on specular spherical or cylindrical objects that reflects the light strongly back to the sensor, while objects with flat surfaces reflect the light away from the sensor unless the surface is close to facing the sensor/light source.





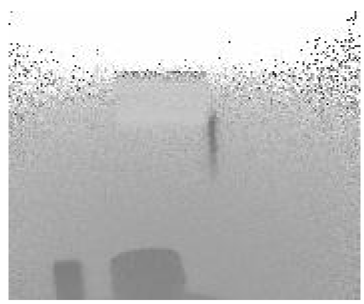


Figure 7 - Data collected with the color camera (top) and 3D Flash LIDAR (middle and bottom) of the same scene in Figure 6 b. The middle image is intensity data and the right image is range data.

The optical tests included no sonar data collection and instead focused on the 2D LADAR sensor data collection. However, simultaneously the researchers again collected data from the 3D Flash LIDAR and color camera for comparison. Figures 10 and 11 are from data set 101 collected of 4 obstacles placed at 2 m and Figures 12 and 13 are from data set 111 collected of the same 4 obstacles placed at 4 m from the sensors. Figures 8 and 10 show data captures from the 2D LADAR and Figures 9 and 11 show data captures from the 3D Flash LIDAR. The four obstacles are from left to right: 100 mm x 500 mm cardboard angled at 30º, 100 mm x 500 mm cardboard covered with tin foil and angled at 30º, 70 mm dia. x 400 mm high gray plastic cylinder, and 70 mm dia. x 400 mm high cylinder covered with standard black reflectivity paper as shown in Figure 5.

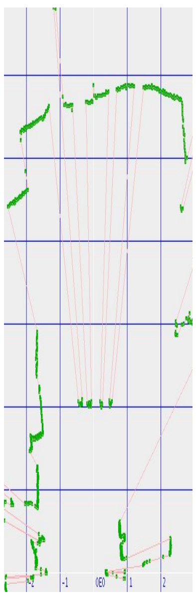
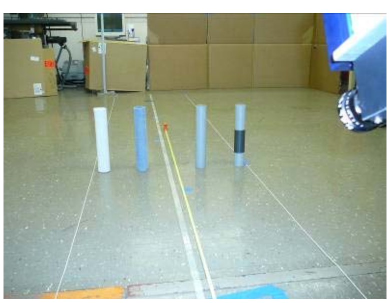


Figure 8 – Scanning LADAR data from data set 101 of the 4 test pieces at 2m. Grid are in 1m blocks.



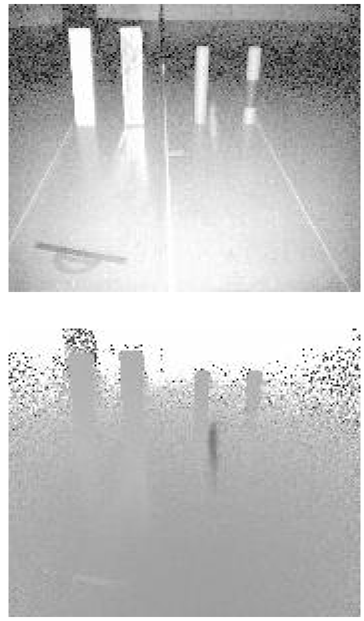


Figure 9 – 3D Flash LADAR data from data set 101 of 4 test pieces (2 flat left, and 2 cylinders right) at 2 m. The top photo was taken with a separate color camera. The middle image shows the intensity data and the bottom image shows the range data to the targets.

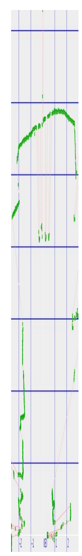


Figure 10 – 2D scanning data from data set 111 of the 4 obstacles (2 flat turned 30º left, and 2 cylinders right) at 4 m.

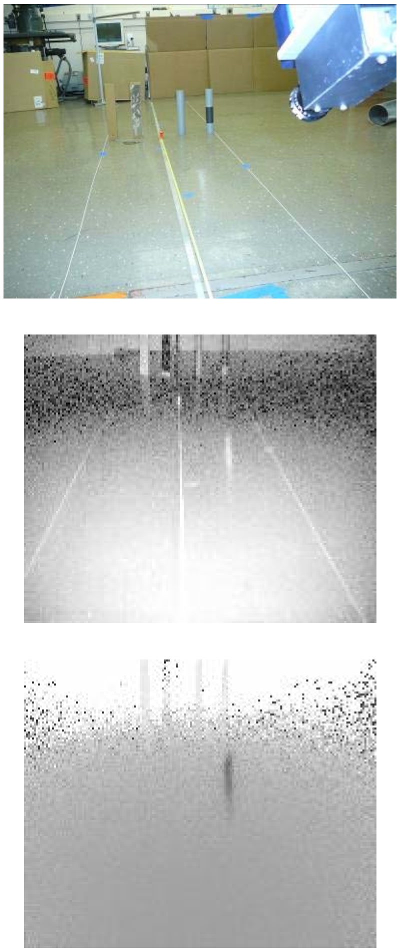


Figure 11 - 3D Flash LADAR data from data set 111 of 4 test pieces (2 flat turned 30º left, and 2 cylinders right) at 4m. The top photo was taken with a different color camera. The middle image shows the intensity data and the bottom image shows the range data to the targets.

Figures 12 and 13 show results of data set 118 of the horizontal cylinder lying at 2 m away, rotated to 15º and covered left to right as follows: uncovered aluminum (left end) and covered (left to right) with patches of standard reflectivity paper of white, gray and black. Although Figure 12 shows no difference with the standard reflectivity coverings, the 3D Flash LIDAR does show a difference in the intensity image whereby black stands out as a dark spot much more than the lighter colors. For advanced 3D sensors that may soon appear on the market, it may be critical to include these findings in the standard. A side note is that for sonar sensors, as shown in test 6, no returns were seen from angles even close to 15º or above. In our opinion, these sensors are not ready to be the only safety sensor on robot vehicles that work around humans or even other obstacles where they can cause harm.

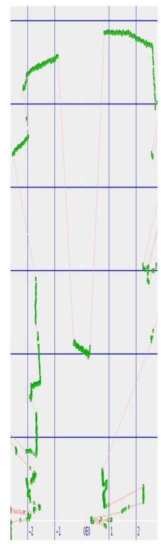


Figure 12 – 2D scanning LADAR data detecting the horizontal cylinder rotated to15º and covered left to right as follows: uncovered aluminum (left end) and covered (left to right) with patches of standard reflectivity paper of white, gray and black.

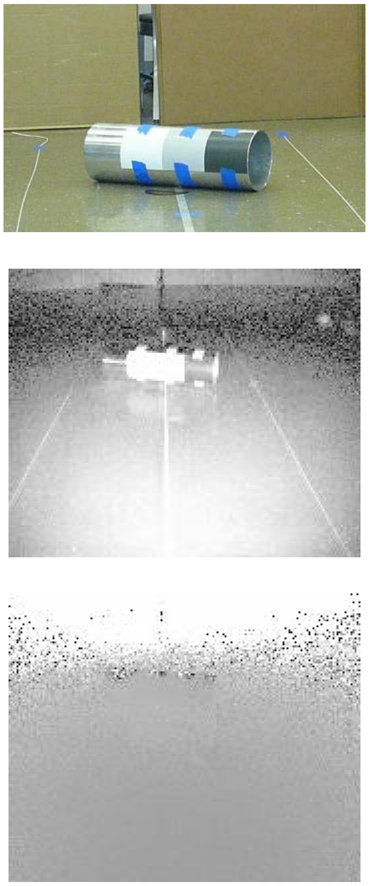


Figure 13 – (top) Closeup of the test piece ¾ covered with standard reflectance paper. 3D Flash LIDAR intensity (middle) and range (bottom) data of the horizontal cylinder as in Figure 12.

3. Data Collection Software

3.1. Architecture

The data was collected from four sensors on four different computers in the configuration shown in Figure 14. It is not necessary to have a different computer for each sensor however the sonar and safety sick were both already integrated with an existing robot each of which already had its own computer. A separate computer was used for the firewire color camera since none of the other computers had firewire ports. The same computer was used to display the live data, allow the operator to start/stop data collection, and to read the SR3000 Flash LIDAR via the USB port.

The system is designed to take data continuously from all four sensors simultaneously. This is not necessary for static tests described here where nothing in the scene nor the sensor itself moves, however we are reusing much of the system from previous dynamic tests and we will likely extend these tests to moving objects at some point in the future.

3.2. NML Producers

For each sensor a different custom program was written specifically for that sensor to read the sensor periodically and write a corresponding message to a communications system called the Neutral Messaging Language (NML). [7] These programs are called Sr3000_nmlProducer, sickS3000_nmlProducer, fwCamera_nmlProducer, and sonar_nmlProducer. Each nmlProducer also periodically checks a command buffer that allows parameters for that sensor to be set. NML uses shared memory to communicate between processes running on the same computer/backplane and either TCP or UDP to communicate between computers on a network. NML allows both queued and non-queued buffers. The non-queued buffers only contain the latest frame from each sensor and are used by display programs and in autonomous systems by the higher level programs of the autonomous system. The queued buffers are read by the log recorder. The queuing allows the log recorder to be intermittently delayed without missing any frames. The nmlProducers are kept as small and

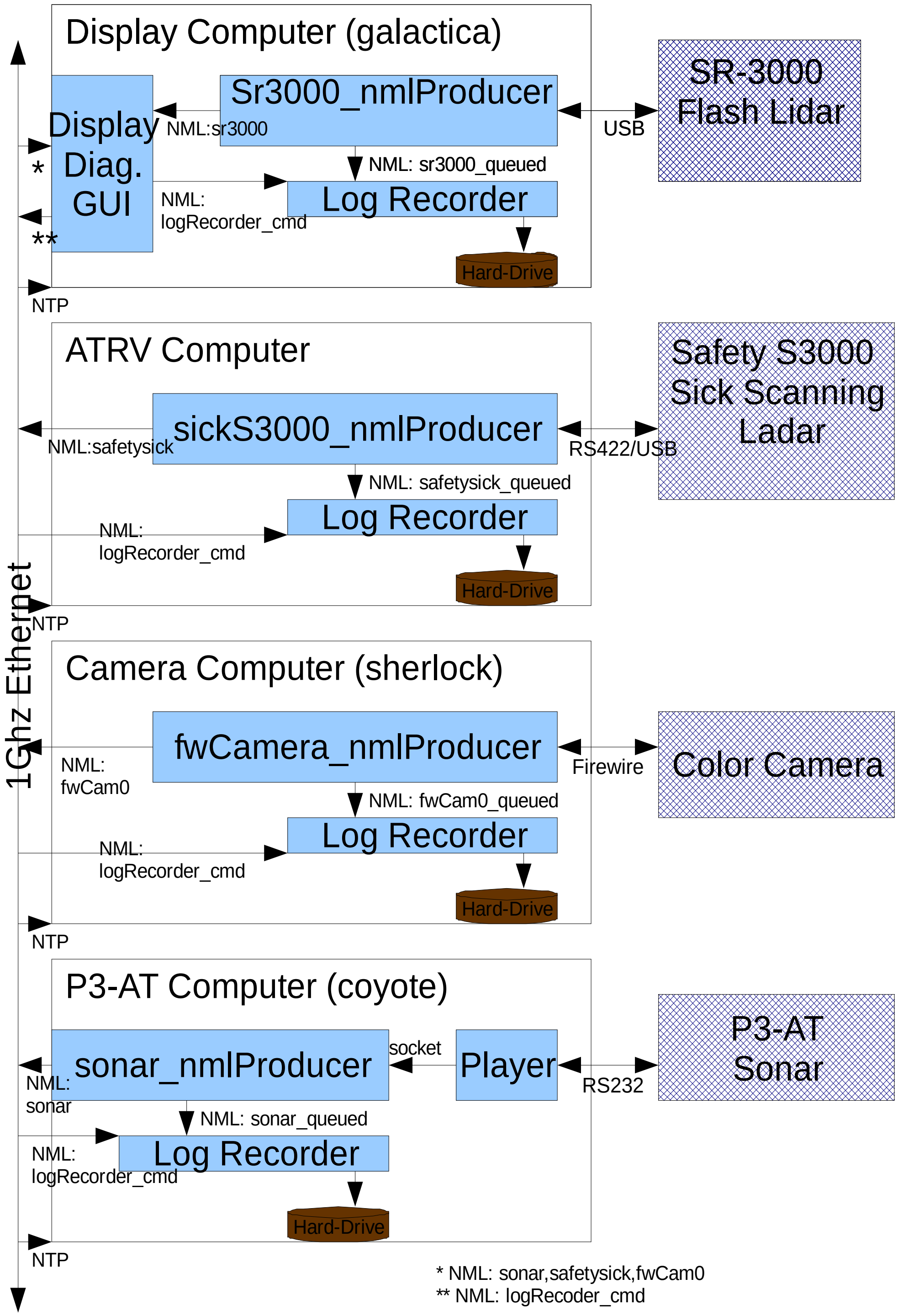


Figure 14: Software/ Computing Hardware Architecture -- Shows 4 computers for the 4 sensors with the major custom programs running on each computer and data paths between them.

simple as possible since they contain no graphical or interactive output and no facility for logging data to the hard-drive. Since the log recorder is located on the same computer as the nmlProducer it will read from the communication occurs entirely through shared memory for better performance. All of the nmlProducers add a timestamp to the output message. The timestamps are double precision floating point numbers representing the number of seconds since January 1, 1970 UTC. A Network Time Protocol (NTP) daemon is run on each computer to ensure the timestamps are correct and synchronized at least more accurately than is required for matching video frame rates.

3.3. Log Recorder

The logRecorder is the same generic program for all sensors with one instance running on each computer. It checks a command buffer to determine when to start/stop data collection. The collect_data command also includes parameters to start collection after a given number of seconds delay, to stop data collection after a given number of seconds, and a label and data set number embedded in the name of the directory used to identify the data on the hard-drive later. Each message is written to a binary packed message file. These files are faster to write and take up less space than an ASCII text representation of the same data. However just as with text files the file can be read back on systems with a different byte-endian, operating system, or from a 64-bit program when written by a 32-bit system of vice versa. This is accomplished by passing the data through the NML data-marshalling software which will if necessary swap the byte-order or add/subtract structure padding. The logRecorder also writes a text file describing the position of each variable in the packed message file for NML-independent software to use. Figure 15 shows how a C++ data structure is processed by NML to produce a memory map file and how generic tools can display one of the corre packed message files.

3.4. Displays and Diagnostics Graphical User Interface (GUI)

There are several display programs that run in parallel on the display computer. These programs are important to verify that the sensors are working and the targets of interest are in the field of view of all of the sensors before each data set is taken. One of these programs, the diagnostics tool also allows the operator to enter a text label for each data set and send the command to logRecorder to start/stop the data collection.

The viewer for the SR3000 Flash LADAR viewer also allows certain statistics to be computed for an area within in image as shown in Figure 16. It can display either live data obtained through NML or open one of the packed message files created by the log recorder. A rectangular area can be selected by dragging the mouse in the image. Once an area is selected the min/max and average range values in the area can be displayed. This was used to estimate the range to the target.

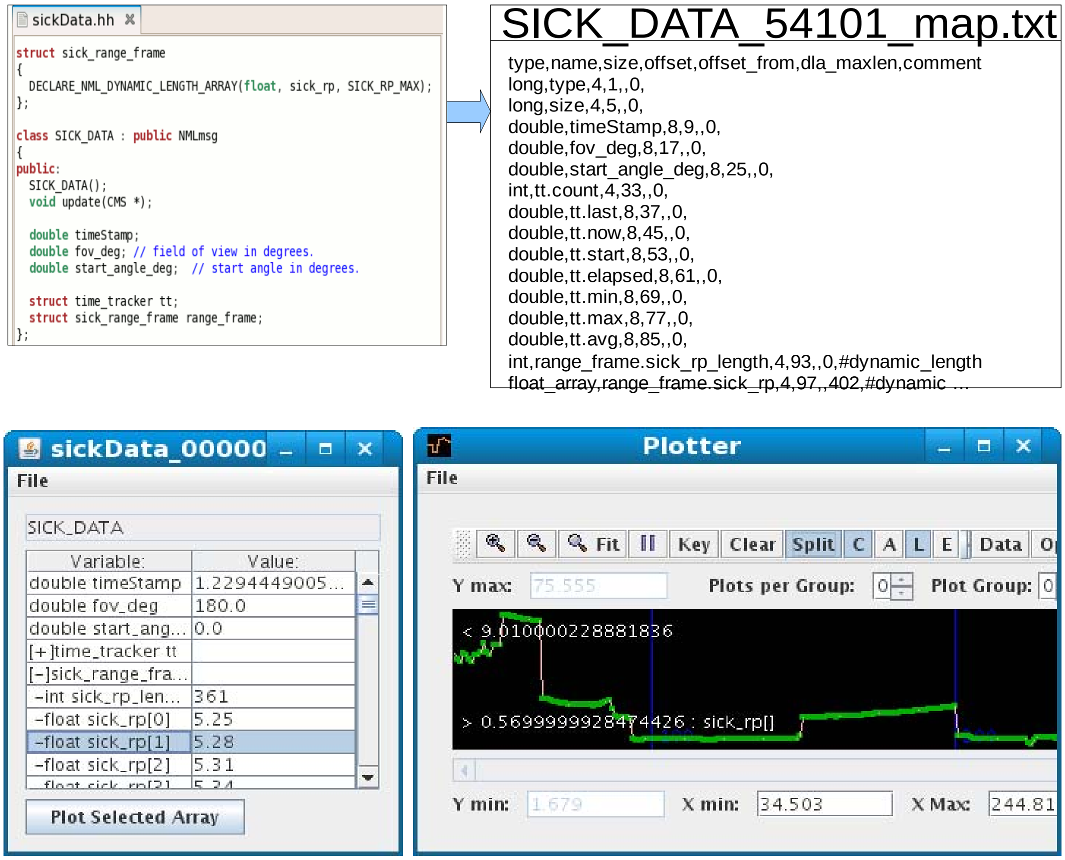


Figure 15: Top left - C++ data structure in sickData.hh, Top right -- corresponding map of the byte offsets into binary packed message file created by logRecorder, on the bottom a particular file is opened and plotted.

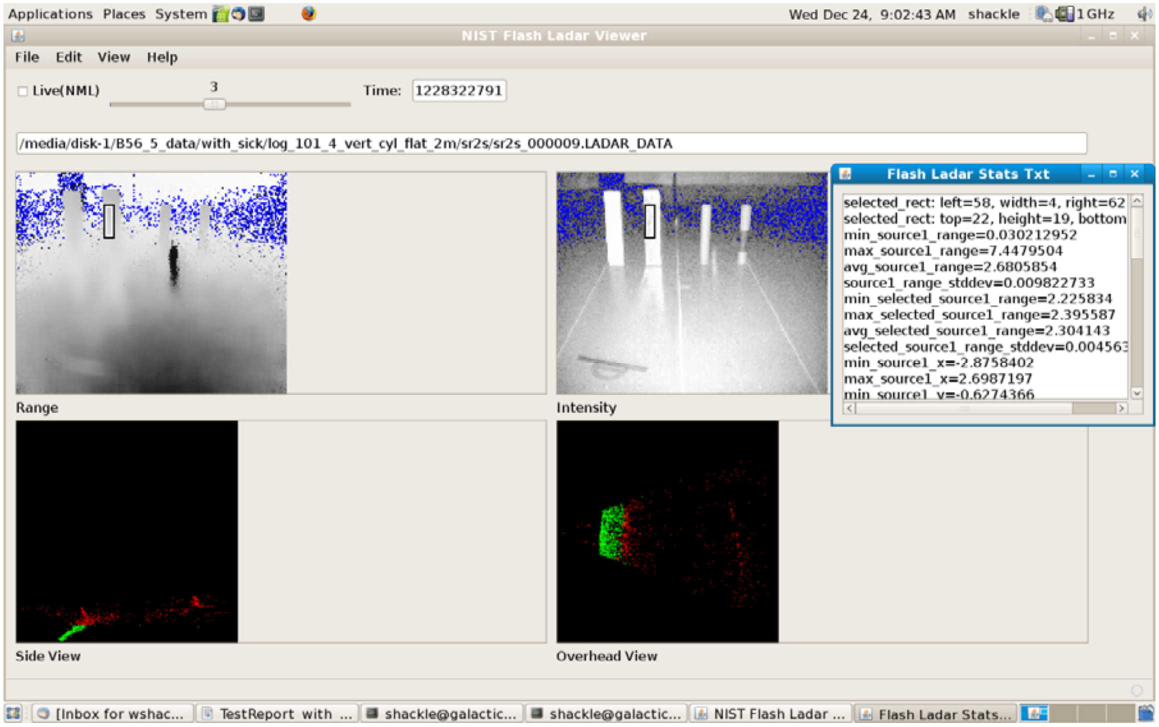


Figure 16: Using Flash LADAR Log Viewer to determine range to target. User dragged the black rectangle over an area of one of the targets in the intensity image. The program computes the average range to pixels within the rectangle in the stats window as avg_selected_source1_range=2.30 (Range values are in meters but have not been adjusted for the tilt of the sensor and therefore need to be adjusted to compare against the horizontal distance.)

The display also includes a facility for segmenting the obstacles above a certain height threshold from the ground and a 3-D rotating view of the point cloud as shown in Figure 17. The 3D view often shows problems with the range data that are not noticeable in the 2D range image. For example, the floor is far from flat and planer and targets on the floor with close to vertical surfaces appear far from vertical in the 3D view.

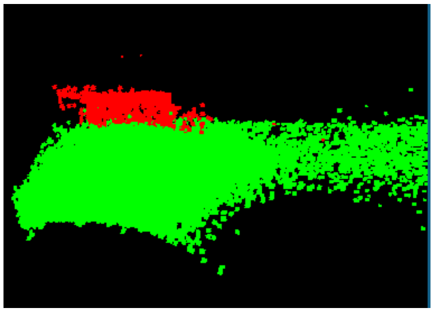


Figure 17: Rotating 3-D display of Flash Lidar point cloud segmented by obstacle detection. Green = ground, red = obstacle (Data was taken from the same scene as Figure 20, framed glass)

Multiple sensors can be overlaid in the same display by finding the file for the second sensor the file with the closest timestamp to the first sensor as shown in the overlay of the range data and camera. Figure 18 shows the black and white range image from the Flash LIDAR overlaid on top of the color camera image.

Figure 18: Range data overlaid with color camera data taken of a framed glass cabinet window. (Data was taken from same scene as Figure 17).

Additional offline tools can be used to generate plots from the packed message files with line scans and images in JPEG form from the files that contain images, the color camera files and flash LIDAR files. Scripts that can generate movie files from set(s) of messages with these images were also written.

4. Summary of Test Results

Sonar Sensor

Sonar could detect all targets, covered or not covered although not at all orientations. However, there are some interesting results for the various test pieces, their orientations with respect to the sonar and coverings.

- in test 6, the angle of incidence with the 200 mm dia. x 600 mm long cylinder lying horizontal on the floor and the flat target received no detected signal for even 15º from perpendicular for the cylinder and 30º (with one exception at 20º) for the flat 100 mm wide x 500 mm high target. Also, as shown in test 9, the flat test piece, when laid horizontal (i.e., 500 mm long x 100 mm high), provides similar results.
- test 8 verified the results as seen in test 9 that a large, flat, cardboard surface (e.g., box) is undetected at angles much larger than even 5º.
- test 10 showed no indication of change when raising the flat target above the floor.
- test 2 displayed no difference when the flat test piece was covered, that is until the 4 m test, indicating that less signal is returned at longer ranges when the test piece is covered with material.
- none of the data taken of the vertical 70 mm dia. x 400 mm high test pieces showed a noticeable difference in range when the test piece was covered or uncovered.
- Tests 18 (horizontal 200 mm x 600 mm cylinder), test 19 (large flat), test 20 (cinder block), and test 21 (flat glass panel) all demonstrated similar results. That is, these obstacles were all detected at 0º and barely or not detected at all when they were rotated to 45º. Test 18 showed when the horizontal 200 mm x 600 mm cylinder was rotated to 45º it was never detected with sonar whether it was made of metal or cardboard. In test 19 and test 21, incorrect data was produced at 1 m and 2 m ranges and no obstacle was detected at 3 m and 4 m ranges when the large plate or the glass panel was at 45º angles to the sonar. In test 20, the black painted cinder block was rotated to 45º angle to the sonar and was undetected at all ranges. This was also true for the unpainted cinder block tested at 4 m as a quick comparison to the painted block.

4.1. Optical Sensors

2D Scanning LADAR

- As in test 12, there was no noticeable difference in 70 mm dia. x 400 mm high test pieces being covered with material, standard black reflectance paper or uncovered plastic. However, for the same test, the 3D Flash LIDAR did return a noticeable reduction in intensity when viewing the black paper versus the lighter color paper or no covering (i.e., shiny metal surface).
- Test 13 showed that even covering the flat test piece with foil returned minimal difference in range from the

uncovered cardboard test piece. Figures 9 and 11 show the change in data being a broken line on the test pieces at longer range. However, what is clear is that the test piece was detected whether covered or not.

- Test 14 revealed no detectable difference whether using a cardboard or metal horizontal 200 mm x 600 mm cylinder.
- Flat obstacles like those in tests 15 and 16 were detected at all tested angles to 45º. Little or no effect was determined for paint or foil covered parts, cardboard, or metal parts.
- Flat glass used in test 17 was not detected at 45º but, was detected at 0º. All measurements saw the frame supporting the glass at both 0º and 45º.

<u>3D Flash LIDAR</u>

- All of the range data from the 3D Flash LIDAR requires adjustment due to sensor location and angle with respect to the sonar and 2D scanner. However, as in test 10, the ranges should be the same as the sonar but, are noticeably different – sometimes by as much as 0.35 m.
- For advanced sensors that may soon be or already are being marketed, these sensors do show a noticeable difference between highly reflective versus relatively low reflective targets.
- In test 14, the dual cylinders were difficult to detect at 2 m range and undetected beyond 2m with the flat black painted cardboard cylinder being much more difficult to detect than the metal cylinder. The cylinder appears to blend in with the floor. The cylinders are detected only when they are in front of a background obstacle or wall.
- In test 15, the 1 m, 0º test produced poor results. The obstacles at this distance and angle were difficult to detect by the researcher in the range data although were detected in the intensity image. However, at 1m and tilted at a 45º angle was detected in the range and intensity data. Beyond 1m, all flats except the foil covered obstacle were detected. There were no problems detecting the painted or unpainted cinder blocks in test 16.
- In test 17, the glass was never detected where the data showed range and intensity that penetrated through the glass. The frame was detected.

5. Recommendations for ITSDF B56.5

Based on the test results from these experiments, we recommend the following:

1. When using sonar sensors to detect flat obstacles in front of a robot vehicle, a cardboard or metal target larger than 100 mm wide and preferably 500 mm wide by at least 100 mm high should be used to verify detection at greater than 0º perpendicular to the sensor.
2. When using optical or sonar sensors, covered test pieces had little effect when they are placed at ranges closer than 4 m to the vehicle, within the vehicle path and when using current off-the-shelf 2D scanning LADAR technology. However, to advance the B56.5 standard to also include advanced 3D optical sensor technology that may soon be ready for use on vehicles, it is recommended that language be written to include the use of low reflectance test piece coverings, as well as flat, high reflectance/highly

specular test pieces at multiple angles. Although the effect of the specularity and angle on the 2D scanning LADAR was subtle and inconsistent with the 3D Flash LIDAR, there still seemed to be enough of an effect to be worth testing on future optical sensors.

3. Since the tests were done using static sensors and test pieces, it is recommended that the same tests be duplicated with moving sensors and/or test pieces to ensure safe vehicle operations around covered and uncovered obstacles.

Suggested ITSDF B56.5 Standard language is recommended to be changed, with inclusion of a figure for additional clarity, as follows:

8.11.1.2 Noncontact Sensing Devices. *If used as the primary emergency device, such device shall be fail-safe in its operation and mounting and shall stop the vehicle travel prior to contact between the vehicle structure and people or objects.*

8.11.1.2.1 Test Pieces. *The following test pieces shall be detected at 0% through 100% vehicle speed in the main direction of travel and be positioned to be within the contour area of the vehicle (including onboard payload, equipment, towed trailer and/or trailer payload) as shown in Figure 1:*

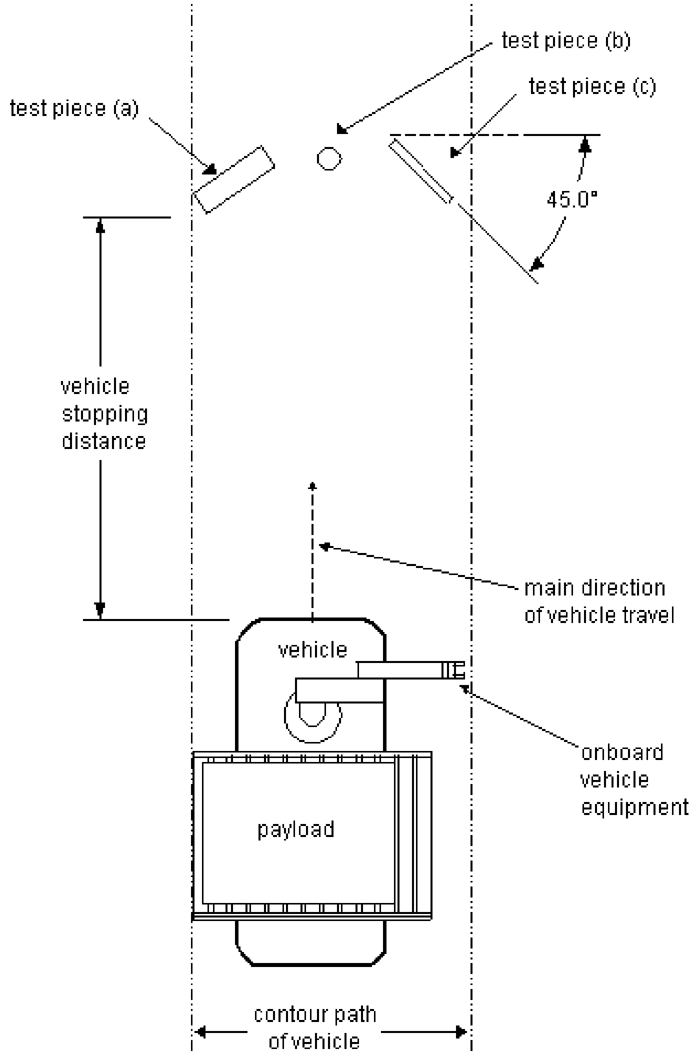
(a) a test piece with a diameter of 200 mm and a length of 600 mm lying at any angle to the path of the vehicle,

(b) a test piece with a diameter of 70 mm and a height of 400 mm set vertically anywhere within the path of the vehicle,

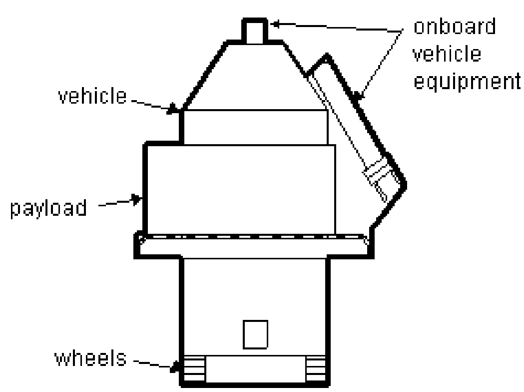
(c) a test piece with a flat surface measuring 0.5 m square set vertically and at test angles of 0 deg and 45 deg perpendicular to the path of the vehicle,

(d) (a), (b), and (c) test piece surfaces must be covered as follows:

- *If optical sensors are used as object or person detection devices, the test pieces must have an external surface reflectance of 6% or less and optical density of 1.22 (e.g., black) or less as referenced in MIL-M-9868E.*
- *If ultrasonic (sonar) sensors are used as object or person detection devices, the test pieces must have a highly reflective surface (e.g., aluminum foil).*



Top view of vehicle, vehicle path and standard test pieces.



Rear view of vehicle contour (bold outline) with overhanging payload, and onboard equipment. Contour could also include a trailor and/or trailor payload (not shown).

6. Conclusions

NIST performed measurements using 2 dimensional and 3 dimensional time-of-flight sensors, a sonar sensor, and color camera on standard sized test pieces, coated and uncoated with materials and standard colors. These measurements were used as background information towards recommended changes to the ITSDF B56.5 industrial truck safety standard with regard to non-contact sensors detecting standard test pieces. Until this experiment, two standard sized cylindrical test pieces were considered. Experimental results determined that a flat, acoustically-reflective test piece positioned at 45° to the sensor provides minimal detection while minimally affecting detection by optical sensors. Therefore, a third flat test piece is also recommended in this paper as an addition to the standard where sonar sensors may be integrated on vehicles. To provide additional clarity, a graphic drawing showing the vehicle, contour path and representative test pieces is recommended. A glass test piece may also be considered as a possible test piece as it produced poor obstacle detection results for both optical and sonar sensors.

7. References

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