Advanced Sensing Towards Improved Forklift Safety

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Abstract

The National Institute of Standards and Technology's Intelligent Systems Division has been researching advanced three-dimensional (3D) imaging sensors and their use in manufacturing towards improving forklift safety. Experiments are presented in this paper and that show how the sensors can augment a forklift operator's perception of obstacles nearby. Interoperability of the obstacle/pedestrian detection information from these sensors to the facility or other forklifts for broader alerts is also possible.

1 Introduction

There are over 1 million forklifts in operation in the United States with an estimated 2 million operators (6 million including part time operators) [1] and nearly 2 000 automated guided vehicles (AGVs) in use in the US. Forklifts are a necessary piece of material handling equipment for many industries. If used properly, they can reduce employee injuries. Unfortunately, they can also pose some safety risks to drivers, pedestrians, and other equipment and goods.

The National Institute of Standards and Technology's (NIST) Intelligent Systems Division (ISD) held a Special Session at the 2009 Performance Metrics for Intelligent Systems (PerMIS) Conference to address the safety of forklifts. A White Paper [2] summarized presentations and discussions from the Special Session on "Performance Measurements Towards Improved Forklift Safety." In this paper, forklift safety statistics were listed along with recommendations for improving forklift safety. For the readers convenience, several of the statistics are listed here:

- OSHA estimates that there are 110 000 accidents each year.
- $135 000 000 immediate costs are incurred due to forklift accidents
- Approximately every 3 days, someone in the US is killed in a forklift related accident
- Almost 80 % of forklift accidents involve a pedestrian
- One in six of all workplace fatalities in this country are forklift related
- According to OSHA, approximately 70 % of all accidents reported could have been avoided with proper safety procedures

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A definition for interoperability [3] is "the ability of systems to provide services to and accept services from other systems, units or forces and to use the services exchanged to enable them to operate effectively together." Interoperability of forklifts with facilities was also discussed in the Special Session and in the White Paper, including:

- automatic barrier guards which can be installed to prevent fork trucks from falling off a vacant receiving dock that can detect approaching forklifts and trucks,
- radio frequency (RF)-tags placed in safety vests worn by warehouse workers that can communicate with RF receivers on forklifts alerting drivers to the presence of any workers within the detection radius of the receiver,
- presence detection sensors of a vehicle being within the detection distance or zone and can indicate potential collisions at intersections and can communicate with other forklifts.

The White Paper also listed two recommendations suggested by NIST to add sensors and cameras to new forklifts and also to retrofit them to the nearly 1 million forklifts in use today. Sensor systems added to forklifts can potentially detect nearby obstacles and pedestrians and provide alerts to drivers and/or, through communication with the facility, to pedestrians or other forklift drivers nearby. Moreover, non-contact sensing devices are discussed in the ANSI/ITSDF B56.5 Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles

Standard draft (currently under ballot) [4] stating that "a sensing device or combination of devices shall be supplied to prevent contact of the vehicle structure and installed equipment with people or objects appearing in the path of the vehicle in the main direction of travel." Also, "if used as a primary sensing device, … (the sensor) shall cause a safety stop of the vehicle prior to contact…" In the case of manned forklifts, the operator is responsible for prevention of accidents. However, the operator's view is sometimes blocked by, for example, the forklift and/or its payload. ISD has performed non-contact 3D imager experiments to recommend language to add to the ANSI B56.5 standard to support sensor and AGV manufacturers. [5]

ISD has, therefore, continued to research advanced sensors applied to forklifts through experiments using forklifts outfitted with 3D imagers and operator alerts (e.g., lights). This paper will discuss these experiments and discuss next steps to collect data in real manufacturing environments. The paper begins with discussion of the advanced 3D imagers used. Following are sections on the experimental configuration, software developed, and experimental results. Last are conclusions and references.

2 Advanced 3D Imaging Sensors

The imaging sensors used in the forklift experiments were 3D LIDAR (light detection and ranging)[1], time-of-flight measurement sensors, [6] each having a 64 x 48 pixel array and photonic mixing device technology to provide data that can be used to identify an object in its field of view (FOV). The sensors measure 122 mm long x 75 mm wide x 95 mm high. The array projects 3072 points of reference onto an object, capturing the entire FOV in three dimensions. The sensors provide their own active lighting with background lighting suppression for use in various lighting conditions. Each pixel within the array is able to compute the phase difference on-board the sensor chip allowing the sensor to pre-process the signal. Variations in color cause challenges with traditional photoelectric sensors. White objects reflect more than dark objects. The sensor manufacturer's specification states that this issue is minimized and creates a more consistent measurement throughout the color spectrum. Without direct comparison and evaluation of this sensor with a different manufacturer's sensor, this claim could not be verified.

The sensor used is stated as having a 40º x 30º field of view (FOV) allowing approximately 11 x 11 mm pixel size with 840 mm x 580 mm FOV at 1 m from the sensor. Distance resolution for white objects at 1 m distance is ± 3 mm versus ± 5 mm for gray objects. Unambiguous object detection ranges are stated to be 6.5 m in the single frequency mode and 48 m in the dual frequency mode. Figure 1 shows images from the sensor brochure of a pallet of boxes and the corresponding sensor data surface map. Range and intensity are available at each pixel and output is via Ethernet to a computer.

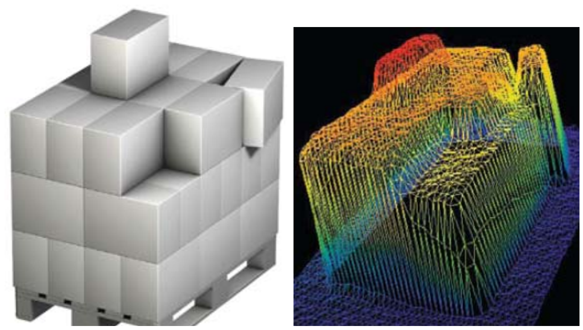


Figure 1 – Images from the sensor brochure showing (left) a pallet of boxes and (right) the corresponding 3D imager sensor data surface map.

Navigation support and collision avoidance on automated guided vehicles (AGVs), among other applications, are suggested as possible applications of these sensors. Based on the product specifications, the sensor appears appropriate for mounting on forklifts to measure objects and pedestrians when they are near the vehicle. Through wireless Ethernet, the object detection information could perhaps be interoperable with facility systems to provide off-board vehicle alerts.

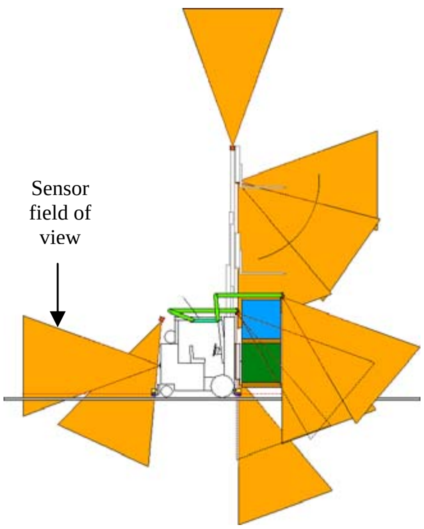
3 Experiments with 3D Imagers on Forklifts

a Sensors Configuration

Experiments were performed using the 3D imaging sensors mounted on forklifts. The sensors were retrofitted to two different commercial forklifts to test the retrofit feasibility, test obstacle detection capability and to provide appropriate operator alerts. Forklift #1 was smaller than Forklift #2. Forklift #1 was retrofit with five sensors and Forklift #2 was later retrofitted with six sensors. Available space between the Forklift #1 front wheels and below the fork frame allowed for a single sensor to be mounted

[1] Commercial systems equipment and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that these materials or equipment identified are necessarily the best available for the purpose.

for detection of the front floor. Forklift #2 did not have this space and instead was retrofitted with six sensors where two sensors, one above each front wheel, detected the front floor. Sensors were mounted to detect the: rear parallel-to-the-floor; rear floor; front parallel-to-the-floor (fork-side); front floor ahead of the front wheels; and the ceiling. Figure 2 shows a concept for ideal forklift sensing and photos of the two forklifts with sensors mounted for use in the experiments. In the concept drawing, 3D imagers are shown on the forks frame and on an extendible boom, among others shown. These tilting-concept (to provide a larger FOV from one sensor) 3D imagers were not tested and instead replaced with fixed mounted 3D sensors and a camera. Figure 2 (b) and (c) show Forklift #1 and Forklift #2, respectively, with red arrows that indicate each of the sensor locations and the directions they sensed.



(a)

(b)

(c)

Figure 2 – (a) Concept for ideal sensing for forklifts; (b) Forklift #1 and (c) Forklift #2 used in experiments showing sensor mount locations and sense directions (red arrows).

The ceiling and front parallel-to-the-floor sensors are mounted to the fork frame and move up and down with the forklift tines. Fork height for the moving 3D imaging sensors, with respect to the forklift, was measured using a one-dimensional (1D) laser measurement sensor mounted to the moving fork frame. This sensor indicates the fork height above the floor to correct for the position of the two moving sensors.

Commercial-off-the-shelf forklift camera systems also mount rigidly to the fork frame or forklift frame and provide extended views (e.g., forward and rear) to the driver. A payload, however, can block at least the front camera. For ISD's experiments, a camera, instead of a 3D imager depicted in Figure 2 (a), was mounted to a manual sliding boom to place the camera in front of payloads to see around them. Figure 2 (b) shows Forklift #1 with a camera mounted on an extendable boom wrapped in safety tape, with a monitor in the cab to allow the operator to see in front of the payload. This concept was tested with a payload blocking the driver's FOV. The driver was able to use the camera and monitor, along with viewing side to side of the load, to drive from one room, through doors, through a machine shop, through another set of doors and through a metal storeroom to a loading dock without any safety personnel support. This concept was tested with good results and is a minor extension to commercial forklift camera systems. As opposed to 2D cameras displayed to the operator, 3D imagers could process the data, instead of the driver, and simply send an alert to the driver and others through interoperability of forklifts with facilities if/when there is a safety issue.

b Data Processing Software

The sensor positions and orientations are calibrated by starting with values taken with a tape measure and level and then fine-tuning using the display of overlapping data on simple recognizable targets. This step is needed since some sensors FOV overlap one another. Some of the sensors are mounted on the fork's frame and the positions of those sensors need to be updated in real-time based on the height of the forks. This height is measured with the 1D laser range sensor on the fork frame.

The software processes the 3D LIDAR sensor data so that if a sufficient number of data points are within that volume, the volume is assumed to be obstructed and an operator alert could be provided. Otherwise the entire volume is considered clear with no alert provided. Similarly, signaling negative obstacles when the floor is not detected (e.g., at the loading dock edge) is important and accomplished with the software. The threshold for each volume is determined after data are collected for both known clear and known obstructed data sets.

For each 3D LIDAR sensor a process is run dedicated to reading and time-stamping each frame of data from that sensor. The data are converted from a vendor specific XML-RPC (eXtensible Markup Language-Remote Procedure Call) network protocol to NML (Neutral Message Language) [7], configured to use shared memory. The data structures used within NML have been used with 3D LIDAR sensors from several other vendors and therefore tools written to work with this interface can be easily configured to work with other sensors.

A separate process reads all of the NML buffers and combines the data from all sensors. Each sensor provides both a range image and an intensity image. Data points can be excluded if the intensity is too high or too low since both conditions may indicate the range value is likely to be invalid. Also, data points may be excluded if the range value differs too much from all their neighboring pixels in the image. Data points not filtered are converted from range to a 3D Cartesian point relative to the center-front-bottom part of the vehicle using a calibrated position and orientation for each sensor.

Each 3D Cartesian data point is then checked to see if it is within a 3D rectangular volume associated with each of the warning lights that will be shown to the operator (see Figure 3).

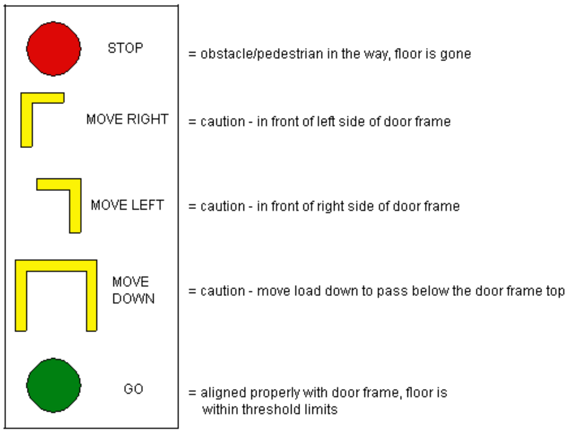


Figure 3 – Forklift operator alerts provided on an onboard vehicle laptop

Another alert panel (shown in Figure 4 (b)) was built and installed as opposed to the Figure 3 laptop-based alerts tested. This panel is potentially simpler for the driver to interpret quickly because the lights indicated the general area an obstacle was detected so that the operator could immediately check that area for issues. In Figure 4 (a), an obstacle is behind the forklift. Figure 4 (b) shows the operator alert panel with the rear light lit indicating that an obstacle is directly behind the vehicle. The obstacle was detected by the rear parallel-to-the-floor sensor and interpreted by software to indicate that an obstacle was in the sensor FOV. The simpler light panel was remote from the computer and connected through a USB interface eliminating the need to include a laptop onboard the forklift. A series of lights also appear adequate to provide the information shown in the Figure 3 operator alerts although this was not tested.

Wired Ethernet was used onboard the vehicle to interconnect all sensor data with the onboard laptop computer. However, wireless Ethernet or other cable-less data intercommunication could interoperability between forklifts and facilities, such as:

- Onboard forklift sensors sending alerts to nearby persons using facility alerts (e.g., lights, audibles).
- Off-board forklift sensors sending alerts to forklift drivers.
- Forklift to forklift communication.

(a)

(b)

Figure 4 (a) – An obstacle is directly behind the forklift and (b) is indicated on the operator alert light panel used in forklift safety experiments.

4 Experimental Results

Figure 5 shows a snapshot of results of the merged data from sensors used in the experiment. The results show that the sensors clearly detect the ceiling above the forks, obstacles behind the forklift, and the missing floor in front of the forklift (obstacles are shown in red). The forward facing sensor mounted parallel to the floor was blocked by the carried load as indicated by the blue box. When not blocked, this sensor detected obstacles similar to the rear sensor. A height threshold for the floor can be selected in software as indicated by the red and green dots. The slope in front of the forklift indicates either that the floor is sloped or drops-offs. Either case is not safe for the forklift. The detected missing/sloped floor and the obstacles can be processed using software to send alerts to the operator and/or others.

Just as important is to detect if a truck is not completely backed to the loading dock. In this case, the forklift must detect that there is a gap that cannot be crossed between the dock and truck and stop prior to the gap. The 3D sensors clearly detected the gap as shown by the sloped green dots on the lower right of Figure 5.

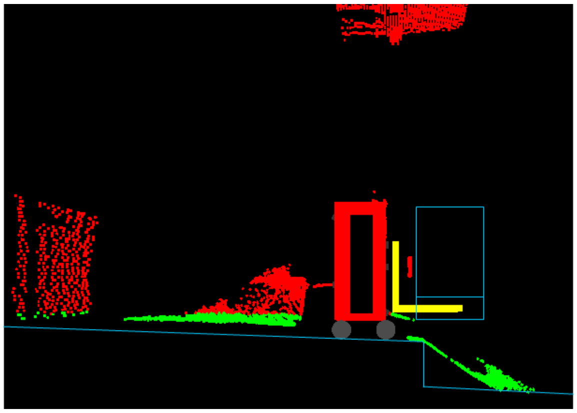


Figure 5 - Snapshot of results of the merged data from sensors used in the Forklift #1 experiment.

Important to note is that while the sensors detected the gap, their front, low mounting locations and angles between or just above the front wheels may not provide enough stopping time when the gap or missing floor is detected depending upon vehicle speed. There may be a better mounting location for these sensors if vehicle speed is allowed to remain high or sensors mounted low may be combined with forced slow speeds in these situations. The rear sensor can detect sloped or gapped floors in either case since it is mounted on top of the vehicle roll-cage and therefore, measures far enough from the vehicle for an appropriate operator alert at higher speed.

Both forklift operator alert panels functioned properly and as expected. Several videos were captured [8] of the Figure 3 panel to prove that when a load was carried and for example, could not fit through a doorway, appropriate indicator lights would alert the operator to move the load left, right, or down to fit through the opening. Similarly, stop and go (path is clear) indicators worked well when the path was blocked or not, respectively. Similarly, the Figure 4 panel control software indicated appropriate lights when obstacles were detected.

Another experiment using Forklift #2 provided similar results to the previous experiment using Forklift #1 with sensors being mounted above each of the front wheels. However, in this experiment the sensors also detected the fork frame when the forks were lowered to the ground since these two sensors were mounted above each front wheel. Software, therefore, was developed to mask the pixel lines viewing the forks and only view the pixels that were in front of the wheel and behind the forks to detect missing floor or obstacles. There was also a concern as to whether these two sensors would return useful data due to too much light returned from the fork frame. In past experience with 3D LIDAR sensors, for example in [9 and 10], we found that the sensor light-emitting diodes can 'wash-out' the data when they are too close to an object. However, these two sensors provided useful returned data without wash-outs. This may be due to the steep angle of the sensor with respect to the forklift frame or from manufacturing differences of different sensors.

5 Conclusions

Forklifts are useful and widely-used material handling tools. However, their safe use is being researched due to the high number of accidents that occur. The ANSI/ITSDF B56.5 standard states that the operator of a manned forklift is responsible for prevention of accidents. Augmenting forklifts with safety devices may be useful to support accident prevention.

Several types of interoperable (forklift with people and/or facility) safety systems have been or are being applied to forklifts. NIST ISD has been researching advanced 3D imaging sensors mounted on forklifts. Ideally, 3D sensors could surround forklifts and provide drivers and those nearby with alert information when obstacles and pedestrians are detected with these sensors.

In experiments performed at NIST, 3D imagers were mounted on two different sized forklifts and obstacle detection data were collected from sensors that viewed the front, rear, and overhead forklift areas. Data processing software was developed to interpret the sensor data as obstacles, including negative (missing or steeply sloped floor) obstacles, or clear space and to send driver alerts. Initial experimental results show that the 3D imagers used can provide enough information to detect obstacles with promising results. Various operator alerts were also tested providing simple obstacle detection (light on) or no detection (light off) alerts as well as showing the operator which way to move the load to clear a passageway. Early results showed that processed 3D image sensor data can augment a forklift driver's perception of his/her surroundings and can provide knowledge of obstacles to the driver through alerts.

Planned next steps for this research are to retrofit the sensors to a forklift in a real manufacturing facility, collect data and determine whether 3D imagers can play a useful role in forklift safety.

6 Acknowledgements

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7 References

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