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3D Range Imaging for Urban Search and Rescue Robotics Research

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***Abstract* — Urban search and rescue (US&R) operations can be extremely dangerous for human rescuers during disaster response. Human task forces carrying necessary tools and equipment and having the required skills and techniques, are deployed for the rescue of victims of structural collapse. Instead of sending human rescuers into such dangerous structures, it is hoped that robots will one day meet the requirements to perform such tasks so that rescuers are not at risk of being hurt or worse. About 5 years ago, the National Institute of Standards and Technology, sponsored by the Defense Advanced Research Projects Agency, created reference test arenas that simulate collapsed structures for evaluating the performance of autonomous mobile robots performing US&R tasks. At the same time, the NIST Industrial Autonomous Vehicles Project has been studying advanced 3D range sensors for improved robot safety in warehouses and manufacturing environments. Combined applications are discussed in this paper where advanced 3D range sensors also show promise during US&R operations toward improved robot performance in collapsed structure navigation and rescue operations.**

Index Terms - 3D range camera, real-time, safety standard, ground truth, urban search and rescue.

I. Introduction

Disaster response has become a standard role of fire departments and other rescue teams in many parts of the world [1]. This has created a sea of change in philosophy and strategies, and a revolution of equipment, training, knowledge, and capabilities. Around the world, the benefits of these changes have been clearly demonstrated in recent years. Earthquakes, other disasters, and the necessity for rescues will certainly provide substantial tests of human rescuers. Rescuers take on very high risk when entering collapsed structures and other confined spaces during these events. Removing the rescuer from this post-disaster relief risk or secondary hazard would surely save lives. Using robots is one way to accomplish this goal. Robots first need to improve their intelligence and maneuverability so that they mimic human rescuer intelligence and capability. Autonomously navigating through debris and around, through, and/or over collapsed walls and rubble remains difficult for robots, and this is in addition to the problem of enabling robots to understand the difference between a victim and other collapsed debris.

NIST has been collaborating with other government agencies and university researchers to develop methods of measuring and evaluating the performance of robotic and other intelligent systems [2]. The community agrees that it would benefit from having uniform, reproducible means of measuring capabilities of their systems to evaluate which approaches are superior under which circumstances, and to help communicate results. One of the efforts in the performance metrics program at NIST is the creation of reference test arenas for mobile autonomous robots. The arenas target the US&R application and are designed to represent, at varying degrees of verisimilitude, a collapsed building.

NIST has built three test arenas, yellow, orange and red, which are focused on the US&R domain [5]. The yellow is the easiest for traversability, with the orange and red arenas providing increasingly difficult mobility challenges for robots. These include different flooring types, such as ramps, stairs and ladders, in the orange arena. The red arena houses debris such as gravel, steel rebar, plastic bags and thin pipes, as well as floors that collapse under pressure.

Robots can not only test their mobility within the arenas, but they can also test their sensory perception. Robots need to sense what is in the environment, detect hazards, and identify victims and exits. A multitude of sensors are expected to be integrated into robots for their use in US&R as no single sensor has yet been developed to provide all the information required in US&R type missions.

As part of the NIST Industrial Autonomous Vehicles (IAV) Project, NIST has been studying one potentially useful sensor for mobile robots and other intelligent systems called the CSEM SwissRanger-2 (SR2), 3D Range Camera[1] [6,7,8]. This device can provide object detection

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

and range to objects that can be critical for robot mobility and other intelligence characteristics.

The IAV project studies standards, measurement and advanced technology for industrial mobile robots, such as automated guided vehicles (AGVs). AGVs are typically used in warehouse and factory applications where they operated alongside people and other vehicles. Sensors for detecting objects within the vehicle path are critical to the safety of workers and other vehicles within this environment. The SR2 camera has recently been used to detect standard size objects defined in British and American standards. The standard and the results of these experiments are detailed further in this paper. As the SR2 camera can detect these standard objects, the authors believe it can also be used in other environments such as in US&R applications.

This paper will discuss the previous research and show results of using the SR2 camera, along with a data processing algorithm, as a potential safety sensor for manufacturing robots. Next we apply the SR2 camera and algorithm to US&R environments within the NIST Reference Test Arenas proving another application for 3D range sensors. We then provide conclusions and outline our continuing research efforts.

II. Previous Research Efforts

A. *CSEM SwissRanger-2 3D Range Camera*

The SR2 camera [9], shown in Figure 1, is based on the Time-Of-Flight (TOF) principle and is capable of simultaneously producing intensity images and range information of targets in indoor environments. Range cameras with capabilities similar to these are appealing for obstacle detection in industrial applications as they will be relatively inexpensive compared to similar sensors when it becomes commercially available. They can deliver range and intensity images at a rate of 30 Hz with an active range of 7.5 m while incorporating no moving parts such as a spinning mirror found in many off-the-shelf laser sensors.

Figure 1 – CSEM SwissRanger-2 3D Range Camera.

The SR2 camera is a solid-state device capable of producing 3D images in real-time. The camera measures 14.5 cm x 4 cm x 3 cm (5.7 in x 1.6 in x 1.2 in), has a field-of-view of 0.7 radians (42°) horizontal x 0.8 radians (46°) vertical, and is capable of producing range images of 160 pixels x 124 pixels.

The camera is equipped with a light source that is ideal for use in dark areas such as within collapsed structures and caves. The camera can provide 3D distance to objects up to 7.5 m (25 ft) including stairs and measurement of step height/depth to within 2.5 cm (1 in), and it can detect negative objects such as stairwells and holes if the camera is angled properly. It can also provide distance to clusters of objects as a whole where individual objects, such as cinder blocks, boxes, etc., are not as important to the robot traversability as is the pile itself.

B. *SR2 use toward Advancing Safety Standards of Industrial Vehicles*

A recent change to the American Society of Mechanical Engineers (ASME) B56.5 standard [10] allows the use of non-contact safety sensors (as opposed to contact sensors such as contact bumpers on AGVs). Prior to this change, the B56.5 standard defined an AGV bumper as a “mechanically actuated device, which when depressed, causes the vehicle to stop.” The recent change allows proven non-contact sensing devices to replace or be used along with mechanical AGV bumpers. The allowance of non-contact safety sensors on AGVs opens new areas of vehicle control generally supporting the safety notion of not only stopping the vehicle but also slowing it near high-risk objects such as humans. For example, should the vehicle’s sensors detect walls, shelving, posts, etc., the vehicle may continue to move at higher speeds than if the sensors detect what could be human arms or legs.

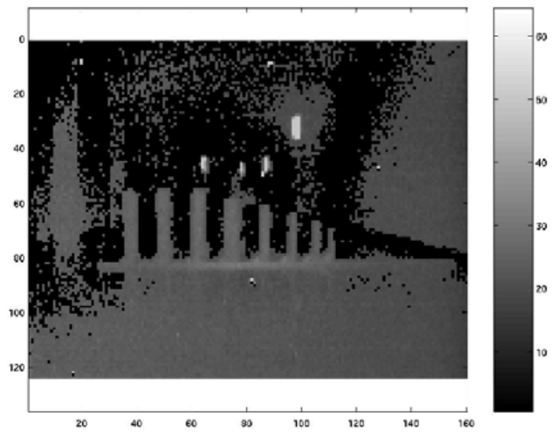
The American ASME B56.5 and British EN1525 safety standards [11] both consider non-contact safety sensors and specify that horizontal test pieces used to test sensors shall be 200 mm (7.9 in) diameter x 600 mm (23.6 in) long lying perpendicular to the vehicle path. Vertical test pieces shall be 70 mm (2.8 in) diameter and 400 mm (15.7 in) tall completely within the vehicle path. Figure 2 shows a photo of the vertical apparatus used at NIST to test the SR2 for compliance with the US and British standards. The horizontal test apparatus and associated SR2 processed data can be seen in [6].

Figure 2 – Test apparatus.

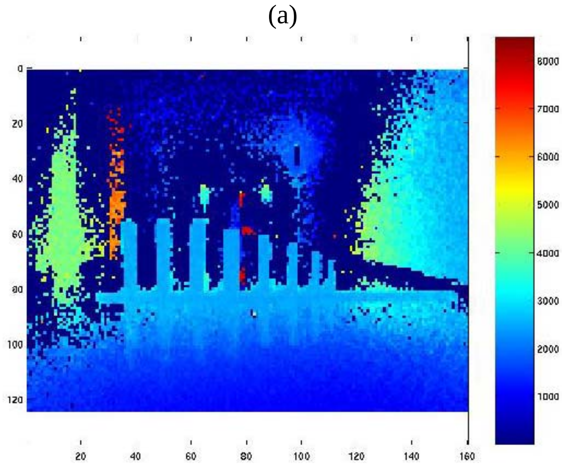
In the tests described in [6], an algorithm processes the SR2 data and determines not only the objects’ range, but also segments the objects from their environment and reorients them to place them in a world model (see Figure 3) – a map of the robot area to be traversed. Generally, the obstacle detection and segmentation algorithm combines intensity and range images from the range camera to detect the obstacles and estimate the distance to the obstacles.

We first calibrate the camera with respect to the AGV so that we can convert the range values to 3D point clouds in the AGV coordinate frame. Next, we segment the objects which have high intensity and whose elevation values are above the floor of the operating environment on the AGV path. The segmented 3D points of the obstacles are then projected and accumulated into a grid representation of the floor surface-plane. The algorithm utilizes the intensity and 3D structure of range data from the camera and does not rely on the texture of the environment. The segmented (mapped) obstacles are verified using absolute measurements obtained using a 2D scanning laser rangefinder with a range uncertainty of 3 cm (1.2 in).

Potential obstacles in the world model can be accumulated as the AGV moves. Figure 4 shows an overhead map of the obstacles that is part of the world model. The obstacle map is shown at a 10 cm grid resolution. Further details of the algorithm and SR2 experiments can be seen in [6,7,8] including outdoor experiments with the SR2 in cloudy, shaded conditions and combining two SR2's to make a single, wider field-of-view (FOV) image.



(a)



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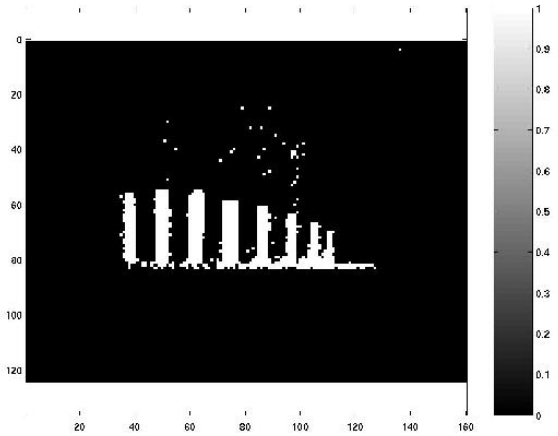


(c)

Figure 3 – Results of the obstacle detection and segmentation algorithm for the experimental setup shown in Figure 2. The resultant intensity, range, and segmented images are shown in (a), (b), and (c), respectively.

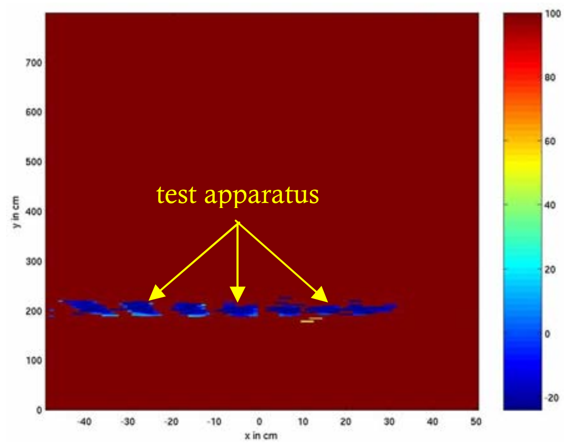


Figure 4 – Segmented objects rotated to show a top-down view for placement in a world model.

III. EXPERIMENTS IN THE NIST REFERENCE TEST ARENAS

A. NIST REFERENCE TEST ARENAS

US&R focuses on finding and removing people trapped in collapsed structures that may result from a terrorist act such as against the World Trade Center in the US, the Kobe earthquake, or more commonly from a cave-in in a trench at a construction site. [3]. This is a domain that is very dangerous to human rescuers, poses an almost infinitely difficult spectrum of challenges, and yet provides an opportunity for robots to play a pivotal support role in helping to save lives [4].

The primary goal of the NIST Reference Test Arenas is to provide challenging and reproducible environments to evaluate mobile robot capabilities and behaviors. Collapsed structures found in the US&R domain provide a huge range of obstacles and features from which to model environments. In an effort to encourage autonomy, the arenas attempt to isolate and test typical sensors used by mobile robots while providing somewhat realistic challenges to robot agility. There are three separate indoor arenas (see Figure 5), each labeled by a color (yellow, orange, and red), forming a continuum of difficulty for robot challenges for both sensing and agility.

The Yellow arena is the easiest to traverse. Researchers using non-agile robots to test their sensory perception, mapping, or planning algorithms can explore the entirety of the Yellow arena. It consists of a planar maze with isolated sensor tests (tactile, audible, sonar, infrared, visual, LADAR) in the form of obstacles or simulated victims. The maze is easily reconfigurable to form a variety of passages. It has doors, blinds, and simple collapses to block passages during missions, specifically challenging mapping and planning algorithms.

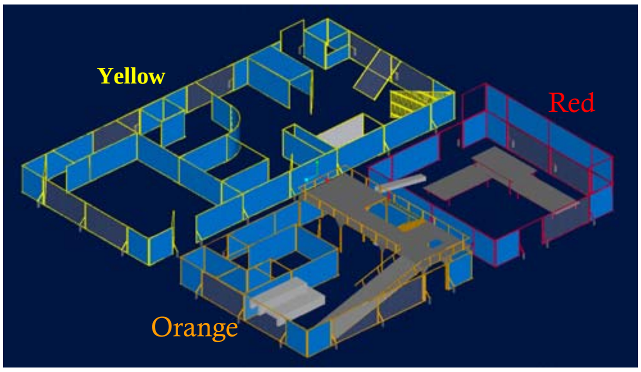


Figure 5 – Graphical model of the NIST reference test arenas for autonomous mobile robots.

The Orange arena provides more difficult challenges for both sensing and agility. Assorted types of flooring materials are introduced. There is an elevated floor section, reachable via ramp, stairs, or ladder, requiring considerable agility to negotiate. Holes in the elevated flooring provide negative obstacles to avoid. Leaning collapses provide perceptual and physical obstacles to negotiate without causing a secondary collapse. Robots must consider the entirety of this three-dimensional maze to successfully map the environment and plan their way through the arena.

The Red arena provides the least structure and the most challenge to robot agility. It is essentially a rubble pile with assorted debris throughout the arena and is a very difficult environment in which to sense and maneuver. The debris, which includes steel wire, gravel, plastic bags, pipes, etc., is very problematic for robot locomotion, and even harder for sensory perception algorithms. There are leaning and pancaked collapses (floors collapsed onto lower floors). Tactile obstacles such as unstable flooring may collapse under the weight of a heavy robot.

First responders could also use mapped data from a sensor passing through these US&R areas showing access ways, victims and hazard locations. The key here is getting information back to humans in some manner. As robot traversibility through these areas may be difficult, onboard data registration mapped to its surroundings (hallways, doorways, etc.) may be one method for responders to understand what the robot brings back.

B. Experimental Setup and Data Collection

As evidenced from the IAV Project efforts, the solid state range imaging cameras appear to be a promising sensor technology for robots for autonomous mobility within the US&R setting. The SR2 was used to take data in all three NIST arenas to consider its operation within the US&R environment. Figures 6, 7, and 8 show photos and processed SR2 data taken in representative areas in each of the three arenas.

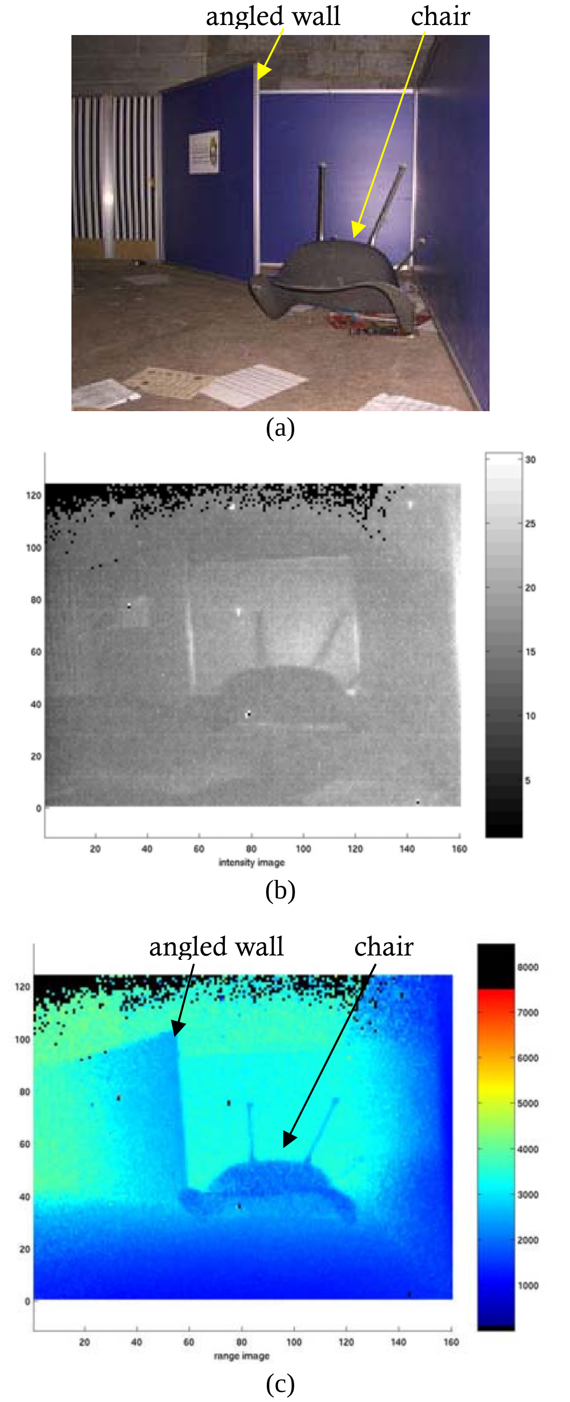
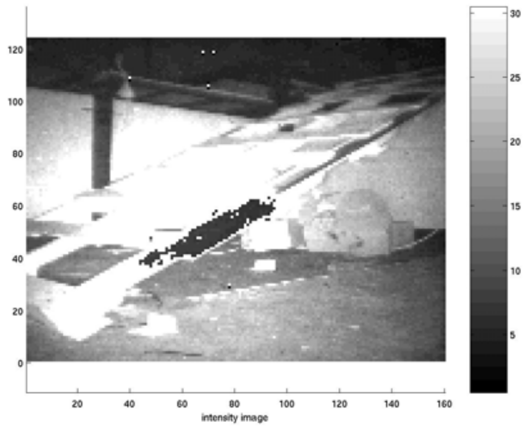


Figure 6 - (a) Photo of a chair upside-down and angled wall with background walls in the Yellow arena, (b) SR2 intensity image, and (c) SR2 range image.

Figure 6(a) shows a chair that has been turned upside-down, a rear angled and perpendicular walls and floor in the Yellow arena. These objects were clearly detected along with range information to these objects. Note that the 19 mm (0.75 in) diameter chair legs are detected using the SR2.

Figure 7(a) shows a ramp and walls in the Orange arena. A clear representation of these objects can be seen in the intensity image in Figure 7(b) and in the range image in Figure 7(c). The ramp is a pallet leaning against a wall in the arena. Note the detailed range information of the pallet slats detected, the holes through which the rear wall is detected and even the hole between the rear wallboards.

(a)



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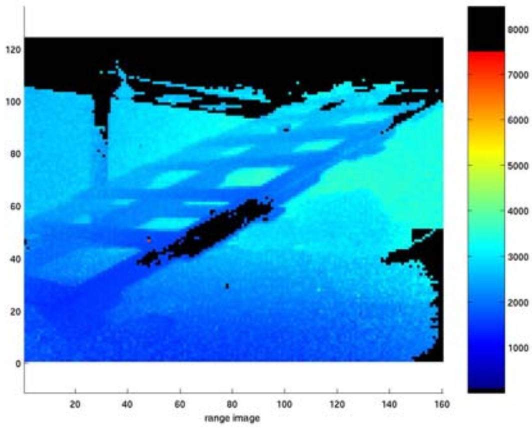


(c)

Figure 7 – (a) Photo of a ramp in the Orange arena, (b) SR2 intensity image, and (c) SR2 range image.

Figure 8(a) shows a rubble pile containing a pallet, wire, and other typical construction objects in the Red arena. Relatively clear intensity and range images shown in Figures 8(b) and 8(c) of the pallet within the pile and of the back wall can be seen in the processed images along with range information to these objects. However, the SR2 does not provide sufficiently detailed information regarding other objects within the rubble pile. For example, unless a human arm, leg, head, torso, etc. were protruding clearly from the rubble pile similar to some of the protruding boards, the SR2 may not be able to detect them. Higher resolution imaging, object recognition algorithms, and/or heat signature or other types of sensors may help improve object detection in the Red arena for these situations.

C. Current Range Imaging Limitations and Planned Experiments

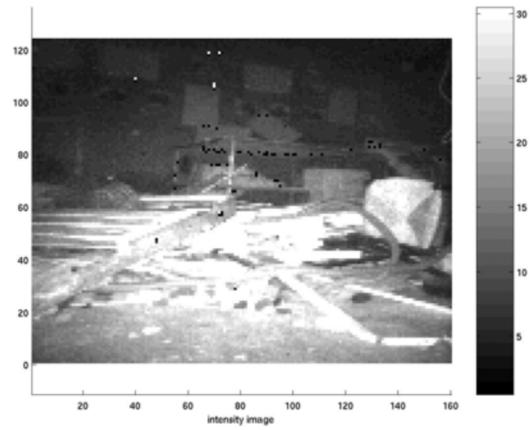
Range imaging appears to be a useful tool in both manufacturing and US&R environments where even with its known uncertainty it is appropriate for detecting large objects in the path of AGVs or mobile robots used in US&R. However, further experiments are required to establish the full capabilities of this technology. For example, optimizing integration times can provide real-time intensity and signal thresholding to adjust the camera to specific applications. In turn, threshold adjustments can help segment out known, detected objects (e.g., wooden boards, cinder blocks, irregular-shaped gypsum boards, etc.) within a room or a rubble pile from known human forms and can provide further benefits for US&R. These and other objects can be sufficiently similar in size and shape to human arms, legs and torsos where robots may provide false rescue information to rescue crews. Also, long and short integration times and even lens focus adjustment parameters can have significant impact on valid sensor data. Experiments to vary integration time and stock, manual lens focus may provide even clearer range imaging data than that shown in the above figures. And testing auto focus and perhaps even narrower-focus lenses that could provide higher resolution data from the stock lens-produced data may prove effective. Therefore, additional experiments and software algorithm development (beyond those detailed in this paper) to adjust sensor parameters in real time, process sensor data in real time, and distinguish human forms in-situ from other typical US&R objects may also provide useful results.

IV. Conclusions and Future Research

The use of 3D range imaging for US&R tasks was the primary theme of this paper. Sensory perception becomes critical in such tasks where first responders have to act to save people within a given amount of time while trying to minimize personnel injuries and losses. The CSEM SwissRanger-2 3D range camera is a versatile sensor capable of delivering range images at data rates that are sufficient for US&R tasks while keeping the cost incurred to a minimum.

We described our previous research with the CSEM range camera on industrial mobile robots such as AGVs for increased safety by reliable obstacle detection. Then, we extended our research to the NIST reference test arenas where the value of the range image camera was made evident by examining its utility in the yellow, red, and orange arenas. The results clearly demonstrated the attractiveness of employing the 3D range camera for US&R tasks. We also described some limitations of current range imaging technology, and the experiments we have envisaged in our continuing research.

(a)



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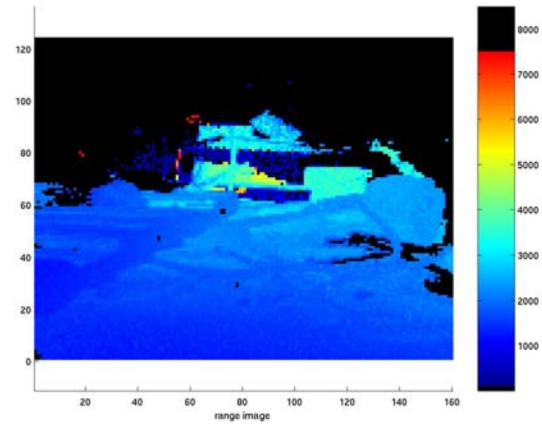

(c)

Figure 8 – (a) Photo of a rubble pile in the Red arena, (b) SR2 intensity image, and (c) SR2 range image.

In addition, we believe that better range imaging capabilities are required to analyze the following areas within US&R:

- To send data to a remote, robot tele-operator in a meaningful form. For non-fully autonomous robots, providing a video combined with 3D range data back to the robot operator is extremely valuable verses only 2D video.
- To evaluate the effectiveness of human-robot interaction [12, 13] in US&R tasks where ground truth is extremely important to compare and analyze the actions taken by a mobile robot while autonomously navigating areas similar to the ones described in this paper. 3D range cameras can provide this competency by enabling us to better map the environment.
- To combine the SR2 with the NIST Ultra Wide Band (UWB) tracking system [14] to register the SR2 within the NIST US&R Arenas. This would enable captured range and intensity data to be registered with known arena locations and even perhaps other sensor data sets for more robust environment information.

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