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A Depth Sensing Display for Bomb Disposal Robots

Brian Day
Institute for Safety, Security and Rescue Technology at the University of South Florida.
4202 E. Fowler Avenue
Tampa Fl, USA
bjday@cse.usf.edu

Cindy Bethel
Institute for Safety, Security and Rescue Technology at the University of South Florida
4202 E. Fowler Avenue
Tampa Fl, USA
clbethel@cse.usf.edu

Robin Murphy and Jennifer Burke
Institute for Safety, Security and Rescue Technology at the University of South Florida
4202 E. Fowler Avenue
Tampa Fl, USA
Murphy@cse.usf.edu and jburke4@cse.usf.edu

***Abstract*—** This paper describes a visual display that provides depth of objects to be grasped and was developed at the request of a local Bomb Squad for use with a bomb disposal robot. The display provides four key functions: (1) it allows the operator to extract the distance between the object and the robot's grasper that each pixel represents, (2) it cues the operator when the object is within a predefined distance from the robot grasper, (3) it can track the object in the video display, and (4) it can continuously display the distance from the robot grasper to the selected object. The display was designed specifically for the Canesta EP200 mounted on a Remotec Mini-Max robot, but the display functionality is expected to be useful for any robot grasper used in conjunction with a 3D sensor. While the usability of the visual display and its impact on grasper-related performance has not been formally evaluated, the informal feedback from the subject matter experts is that this display meets their requirements.

***Keywords*:** *HRI, Miniature Range Sensor, TOF, User Interface*

I. Introduction

With almost every bomb squad robot there is a lack of an important perception which is critical when manipulating any kind of explosive device. Most bomb squad robot graspers in use do not give the operator a depth reading. Instead, the robots use multiple cameras to obtain different views and then the operator must employ various workarounds to gauge the depth or distances to objects located in the environment.

With different miniature depth sensors available on the market there is no reason not to add the basic functionality of determining depth to such a sensitive and dangerous task. The Canesta EP200 [1] is one such small depth sensing camera which allows the operator to sense the environment in real time. The size of the sensor is 12.7 cm wide x 5.08 cm high x 5.08 cm deep with a weight of approximately 544.3 grams. Due to its relatively small size and lightweight design the Canesta sensor can be mounted easily on a bomb squad robot or any manipulator arm where depth readings are needed.

The primary purpose of this research is to develop an interface that provides necessary depth information to the robot operator. During testing of the interface, the subject matter experts had a second operator in the observer role to relay the depth value from the interface to the main robotic operator. The interface includes the functionality that a local bomb squad indicated was necessary to have in an interface for a bomb robot. Each member of the squad is a certified bomb squad expert and based on their experience and training they are considered subject matter experts (SMEs).

Section II discusses related work. In Section III, there is a discussion of necessary hardware and software used in this research. Section IV describes the software interface. Section V, presents the reported responses from seven SMEs during feasibility testing, followed by conclusions and future work in Section VI.

II. Related Work

Three modalities have been historically used to obtain depth: (1) planer laser ranger, (2) sonar, and (3) stereovision. Of the three modalities, only sonar does not appear to have been applied to robotic graspers. In addition to these modalities a new sensor system has been developed that is small and lightweight, a miniature 3D ranger that uses near infrared laser light. This section describes planer laser rangers, stereovision, and miniature 3D rangers, then compares stereovision with miniature 3D rangers.

The planar laser rangers, such as SICK [2], are routinely mounted on robots to aid in navigation; however, they typically produce only a planer range scan. A 3-d image can be obtained by spinning the laser on one axis [3]; however, this type of sensor tends to be too large and heavy to be mounted on a robotic manipulator arm. Sensors that are to be mounted on the arm of a bomb squad robot should be small and lightweight as to not reduce the amount of weight the arm can lift or impede the arm's range of motion. A 3D picture of the environment would provide the operator with more detailed information of the environment around the grasper instead of a line directly in front of the grasper.

Stereovision has been used with manipulator arm(s) on robots. Drascic [4] and Chen [5] have conducted studies to determine the effectiveness of using stereovision over monovision for tasks commonly performed by telemanipulator arms. Their research has shown that the use of depth while using a telemanipulator arm may decrease the time needed to complete a task. Drascic [4] shows that until the user gains enough experience performing the task that the use of stereovision decreases the time needed to perform the task when compared to using monovision. Chen [5] writes, "degraded depth perception affects the teleoperator's estimates of distance and size and can have profound effects on mission effectiveness." The use of stereovision for robotics is not only in the lab, but also in real-world applications. Focus Robotics [6] and MobileRobots Inc. [7] are two companies that create stereovision systems for robots that can mount on telemanipulator arms. The systems produced are light enough to not impede the arm or dramatically decrease the weight the arm can manipulate. These systems provide a stereo view of the grasper and the surrounding environment giving the operator the ability to judge accurately the depth to objects in the environment. The company, ANDXOR [8], has implemented stereovision on a bomb squad robot titled Solid-Look. Solid-Look technology was demonstrated at the 2006 International Association of Bomb Technicians and Investigators. The Solid-Look system was attached to the mast head of the robot. The Bomb Technicians were shown how the use of the system allows for a 3-D view of the environment. Solid-Look uses both stereoscopic displays and stereovision glasses to allow the user to perceive depth in the environment. ANDXOR demonstrated that stereoscopic displays are useful in the field environment [7]. In their system, the stereo cameras mount on a pan-tilt on the top of the robot mast.

The final type of depth sensor is the 3-D miniature range sensors, which use near infrared laser light to create a depth image of the environment in the sensor's field of view. These sensors are lightweight and can mount on a manipulator arm, unlike the SICK ranger. They use time of flight like sonar but do not have the problem with detecting objects that are not perpendicular to the sonar sensor. If the object reflects light, the sensor can detect it. These sensors produce a false color image by giving each depth an individual color value. Two main companies create 3-D miniature range sensors: Canesta Inc., which produced the Canesta sensor used for this research, and Mesa Imaging AG that produces the Swiss Ranger. These sensors appear to have the same outputs, which allow the sensors to be interchangeable. The main consideration is resolution. The Swiss ranger SR3000 produces an image of 176 x 144 pixels. The Canesta EP200 has a resolution of 64 x 64. In mobile robot applications, the Canesta sensor has been used to add autonomous obstacle avoidance and wall following functionalities [9]. The Canesta EP200 is lower in resolution than the Swiss ranger but new models of the Canesta sensor have higher resolution. The Swiss Ranger sensor was utilized mainly for map development and navigation tasks [10].

There has not been any research directly comparing stereovision to 3-D miniature range sensors; however, miniature rangers appear to have three advantages. First, the depth readings produced by the miniature range sensors yield smaller file sizes compared to stereovision. Second, the miniature range sensor's depth reading is directly produced whereas stereovision requires post-processing of video data on a CPU. Finally, initial work with bomb squads indicated that the false color display generated by 3-D miniature range sensors was a desirable feature.

III. Equipment

The display developed and tested for this work was designed for a specific robot and depth sensor, but it is expected to be applicable to other robot/depth sensor combinations. The hardware consists of a Remotec Mini-Max robot and a depth sensor created by Canesta Inc. mounted on the manipulator arm (see Fig. 3.1a and Fig. 3.1c). Figure 3.1a shows exactly shows the small size of the Canesta, only 12.7 cm wide. Figure 3.1b gives a sense of the size of the Mini-Max robot, the black pelican case is 75 cm long by 52 cm wide. Figure 3.1c displays the Canesta sensor's mounting in relation to the robot's grasper.

A. Hardware

Local SMEs provided the Mini-Max to the University of South Florida for testing purposes. After the sensor and interface have been fully developed and tested to determine its benefit, the Canesta sensor and Java interface will be transferred to an Andros robot for the SMEs. Both the Canesta sensor and the Java interface are portable and can be applied to any grasping robotic arm. The Canesta sensor was mounted right behind the grasper to keep it in the line of sight as the grasper moves.

The Canesta is an active depth sensor, which produces a pulse/flash of near infrared laser light similar to the effect of the flash of a standard camera. "The distance to objects in the scene can be calculated using the properties of light and the phase shift" [11]. Using this method, the Canesta calculates an independent value for each pixel. If the object reflects the pulse laser light then the Canesta can detect it no matter the orientation or position of the object in relation to the sensor. Craighead, Day, and Murphy [9] describe, "The maximum unambiguous range (resolvable distance) is 11.5 m. This limit is a result of the pulse frequency, which is adjustable and affects the depth resolution. The unambiguous range and depth resolution are inversely related. The maximum depth resolution, about 5 mm, is achieved within the minimum unambiguous range of 1.44 m. This limitation is present in all time of flight sensors that use phase shift for range detection." This means objects within 1.44 meters will have a resolution of 5 mm. This is an acceptable range because the SMEs are concerned about the depth of objects 1.2 m away from the robot, and all precise work with the grasper is performed within one meter. The field of view is broken down into an image of 64 x 64 pixels; each pixel consists of a depth value of that area of space. In addition to depth, the Canesta sensor also produces two other views: the brightness image and the active brightness image. The brightness image is an image of all light detected by the sensor, while the active brightness images are the objects illuminated only by the sensor's light. The brightness image and active brightness image are shown only in grayscale, while the depth image is in color with each color signifying a different depth, red being zero and green being 1.68m. Adding the Canesta sensor to the Mini-Max involves making a mounting bracket and affixing it to the preexisting camera mount on the manipulator arm. A similar mounting bracket can be created for most telemanipulation arms, which means that this interface/sensor system can be utilized with most telemanipulation arms.

The interface design is flexible regarding the type of hardware used. While the Canesta sensor is used in this research, the Swiss Ranger is another miniature range sensor that may be used with this interface. The interface takes as input an array with each node corresponding to the pixel's value in millimeters. The interface design requires the 3-D miniature range sensor to be placed right behind the grasper on the manipulator arm. This interface may be used for depth sensing whenever a 3-D miniature range sensor can be placed just behind the grasper of a robot manipulator arm.

B. Software

The interface design was developed in Java for integration into a Java-based robotic architecture and for portability. The Canesta sensor's drivers were developed in and designed to be used in C or C++ applications. Java's JNI allowed communication between the interface and the Canesta sensor's drivers.

The interface used the array of depth readings produced by the Canesta sensor and assigned a color to each depth value for display in the interface. This produced a false color image; each color represented the depth of the object and not the color of the object.

The Canesta sensor has a software calibration system. The shutter time, frame rate, and modulation frequency are all preset in the interface for the user. The shutter time combines with the modulation frequency to give the best resolution for the distance between the grasper and 1.2m distance range per the SMEs' request.

Fig. 3.1a. A close up of the Canesta sensor with ruler in centimeter scale. The metric ruler shows the sensor is 12.7 cm wide. The Canesta sensor has a 55 degree field of view. There are also 30 degree and 80 degree field of view cameras.

Fig. 3.1b. Mini-Max approaching a box 75cm x 52cm x 48cm

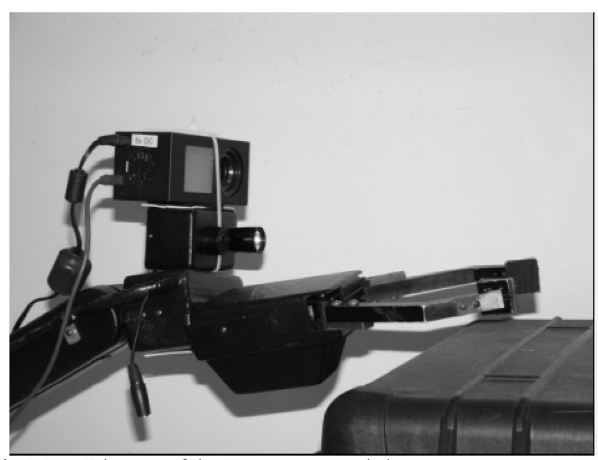

Fig. 3.1c. Close up of the Canesta mounted above grasper

IV. Software Interface Design

The software interface is designed to clearly display depth information of objects detected in the environment, which is needed by the robot operator. The interface incorporates four basic features: (1) a distance display of the depth at the cursor's location in the false color depth display; (2) a distance display which provides the distance of the center of an object identified by the user; (3) a tracking mode for tracking objects in the depth display; and (4) object cueing, an alert box turns yellow and red when the selected object is closer than the predefined safety distance (See Fig. 4.1). The use of color in the depth display is applicable due to the SMEs job requirement that users may not be colorblind. The interface creates a real time video of the depth of objects located in the environment that the sensor can detect. It should be noted that the units the Canesta sensor produces were converted from metric to English measurement units for ease of use by the SMEs.

A. Depth Display

When the Canesta sensor was introduced to the SMEs, they indicated that at times, there is a need for an exact depth. This functionality has been included in the interface design. When the operator moves the mouse cursor over the sensor output display, the depth represented by the pixel is displayed in a text box below this display (see Fig. 4.2).

B. Distance to Object

A requested feature is the ability for the user to click on a blob in the display; each blob represents an object in the environment. The program will automatically track and display the distance to the object represented by the selected blob. When the user clicks on a blob in the sensor output display a pink dot will appear on the center of the blob (See Fig. 4.3a). The dot is to show the operator what object is being tracked and the color is a high contrast to the other colors used in the display for visibility purposes. The center of the blob was calculated using a very basic method. The user will click somewhere on a blob in the sensor output display. The mouse listener gives the program the location of the click and considers this point u_c.

To determine the edges of the blob the program searches in both the positive and negative directions of both the horizontal and vertical axes for the first pixel that has a difference in range from u_c of greater than 30mm. This difference we will call delta. The boundary points determined on each axes are points b_l, b_r, b_u, and b_d, for boundary_left, boundary_right, boundary_up, and boundary_down respectively. These four locations form the boundaries of the blob. The center is then found by taking the midpoints of both the X and Y axes and its value is displayed as the depth from the grasper to that object.

The center position of the blob, C_X and C_Y, are calculated as follows:

$$C\_X = b\_l + ((b\_r - b\_l)/2)$$
$$C\_Y = b\_d + ((b\_u - b\_d)/2)$$

This center position is displayed to the user by placing a pink dot at that point on the blob in the sensor output display (see Fig. 4.3a). This method for calculating the centroid of the blob will be replaced by an improved algorithm developed as part of future work.

The delta value was determined to be 30 mm based on a series of approximately ten informal test runs. The informal test involved driving the robot toward and grasping a bottle placed on a table. If at anytime, the program stopped tracking the blob, signified by the disappearance of the pink dot (Fig. 4.3a) on the blob, then that delta value failed. The informal test was based off a scenario that was observed at a training day exercise when a bottle disrupter was used to open the training explosive device.

Delta started at 10 mm and increased by 5 mm until the program was able to continuously track the blob. Using a delta value of less than 30 mm caused the tracking to fail as the blob moved in the display. With a delta of 30 mm the program tracked the object without breaking the object tracking lock for five consecutive tests and has not disrupted the lock since. The authors note that 30 mm is an arbitrary value; however, a more robust process for identifying objects will be implemented in future work.

C. Tracking Distance to Object

The last feature requested by the SMEs is an extension of the distance to object feature. They wanted to be able to track a blob through successive frames in the sensor output display, of the software interface. The same method was used as discussed in the distance to object feature except the center found in the previous frame was used as the location of the mouse click in the subsequent frame. This method continues until the user turns off the tracking mode by double clicking in the sensor output display. While this method of finding the center was very basic, it provided all of the functionality necessary to find the center of a detected object and track it. When this method found the midpoint of the two axes and used it as the base point for the next frame, it allowed the program to handle side-to-side motion of the object in the display. Additionally, this method allowed the displayed object to shrink and grow as the Canesta sensor on the robot moved closer or farther away from the detected object.

D. Distance Cueing

Although not specifically requested by the SMEs; however for safety purposes, the addition of cueing an operator when objects are getting too close to the grasper was included in the interface design. This functionality was based off the paper written by Welsh and Edmonds [12]. They write that "… the addition of a laser depth cueing system to aid in manipulation tasks" is a possible improvement that should be added to the Andros robot. This functionality is necessary to aid the operator in manipulating the arm. The operator predefines a safe distance for both the grasper and the disrupter; it is usually a preset distance for each model of robot. If the distance of the pixel the cursor is positioned over is closer than the predefined safety distance the alert box turns yellow for caution and if the robot proceeds to a closer distance, the alert box then turns red (see Fig. 4.2 and Fig. 4.3a). Meier et al. states “Color provides a natural and efficient means for encoding multi-dimensional information. We can use color to provide specific display functions, e.g., red shading to indicate danger or to provide warning” [13]. The SMEs need to be able to quickly and easily switch between the grasper and the disrupter. The grasper and the disrupter each have different points where depth is measured from, the zero point or base distance. To accommodate this, two buttons were added to the interface: one marked grasper and one marked disrupter. Clicking on a button will switch the current base distance to the base distance used for the grasper or to the base distance used by the disrupter.

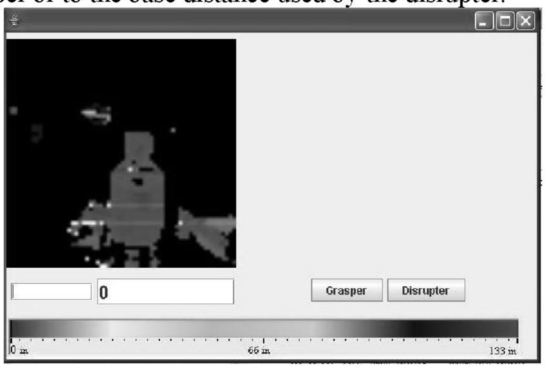

Fig. 4.1. The interface has the Canesta display, color value bar, buttons for grasper and disrupter, alert box, and distance display.

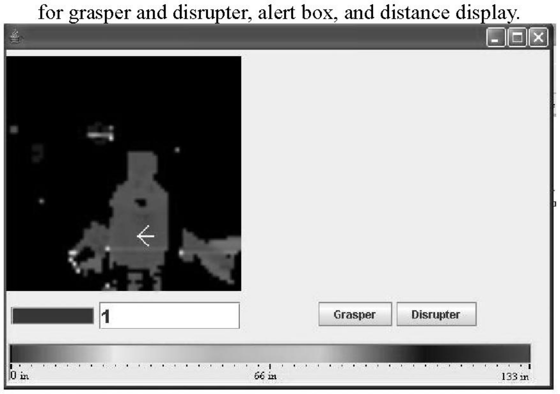

Fig. 4.2. The arrow is the position of the curser over the display. The bottle is one inch way from the grasper

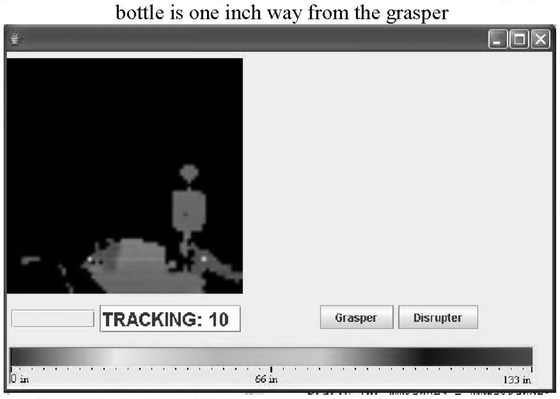

Fig. 4.3a. The bottle is 10 inches away from the grasper and is being tracked by the program. The pink dot on the bottle is the program’s point of tracking

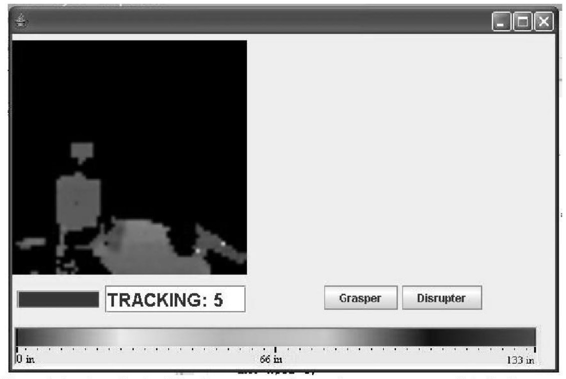

Fig. 4.3b. The bottle is 5 inches away from the grasper and is being tracked by the program

V. RESPONSES OF SMEs

The robot, sensor, and computer was taken to a local bomb squad for feasibility testing at there deployment site. Each member of the squad is a certified and trained bomb squad expert. The squad members are the SMEs and they were requested to conduct an initial evaluation of the display to determine if the display met none, part, or all of their requirements provided at the start of the project. They wanted a way to track an object, obtain its depth in relation to the grasper, and to know when to close the grasper onto the object. Though refinements were needed, they were pleased with the display and supported continuation of the research project.

During their interaction with the interface, during a feasibility test of the interface, each SME practiced grasping a metal pipe using the robot grasper. Seven operators took turns running the robot while using the interface. In this evaluation, one person operated the robot while a second person read off distances from the grasper to the object. The ability of the interface to display depth correctly using two options (holding the cursor over the blob, and using the tracking feature of the interface to track the blob as it moved in the sensor output display) was viewed as a positive attribute of the interface. They SMEs were able to determine the distance between the grasper and the object to be grasped, allowing the robot operator to place the grasper in the position needed to grasp the object without going past the grasping position.

As part of the feasibility testing the SMEs suggested additional improvements to the interface. They requested the creation of a better method of finding the center of the blob. While in the object tracking mode the depth display box will display the word “Tracking” before the depth reading (see Fig. 4.3a). As the object moves across the screen it is tracked. In addition, as the sensor approaches the object it continues to be tracked (see Fig. 4.3b). As the image of the object moves around in the output screen, for example when the robot moves, its depth will continue to be displayed without the user having to keep the cursor hovering over it

IV. CONCLUSION AND FUTURE WORK

This paper describes a depth display with four functions defined by bomb squad experts. First, the addition of depth sensing with a Canesta sensor to a bomb squad robot will increase the functionality of the robot. Second, it will make the task of explosive ordinance disposal an easier and safer task. Third, the user can selectively display the distance to any object that appears in the sensor output display. Finally the interface can also track an object in the sensor output display when the user selects it.

Initial feedback from the SMEs suggests that the addition of the Canesta sensor supports their desire for a means of depth perception and that the developed interface represents a marked improvement over current methods. The addition of a depth sensor with an intuitive interface is expected to enhance performance in robot operations.

Future work includes incorporating some additional suggested improvements made by the SMEs as part of their evaluation of the interface. The primary suggestion is for a greater variance in color between depth changes. For example, restricting depth information to within a one-meter range of the grasper would allow the color gradient to be compressed giving a larger color contrast. Other suggestions included a graph to display past distances, cross hairs, and a grid on the screen. They also had suggestions for the appearance of the interface, such as varying the background color options to promote ease of use in different lighting conditions, adding a negative color indicator if the operator overshoots the object, and including a way to switch settings when the sensor is moved to another model of robot. Future work will also include extensive field testing with the SMEs with statistical analysis of any effect of the sensor on their performance.

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