**An Operator Interface for a Robot-Mounted, 3D Camera System:
Project Pioneer**

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Abstract

The purpose of Project Pioneer is to develop an exploratory robot capable of creating a three-dimensional photo-realistic map of the inside of the damaged Chornobyl Nuclear Reactor, measure the environmental and radioactive conditions, and collect samples of concrete from the physical structure to determine its mechanical stability. This paper describes the Virtual Reality interface for Pioneer's three-dimensional mapping system. This interface addresses a wide variety of technical challenges, including several that are unique to the hostile Chornobyl environment.

The Chornobyl Mapping System provides two modules: Acquisition and Analysis. The Acquisition module (CMAP Acquire) allows the operator to collect a series of images for later processing into a three-dimensional mesh. CMAP Acquire also provides a suite of tools that assist the operator in collecting useful data, including an expert system for image analysis, a graphical overlay for distance estimation, and a three-dimensional image mosaic for situational awareness.

The Analysis module (CMAP Analyze) provides access to the image database. The user can navigate a menu structure, and select a set of images for processing into a three-dimensional, photo-realistic mesh. The program provides a suite of tools that measure the dimensions of hazardous materials and physical structures without risk of radiation accumulation. The user can also combine three-dimensional meshes from different robot locations to build a "Virtual Chornobyl." Plant managers can then use this data to plan additional Pioneer robot missions, and formulate strategies to stabilize the building.

1   Introduction

On the morning of April 26, 1986, the worst nuclear power accident in history occurred in Unit 4 of the Chornobyl nuclear power plant in northern Ukraine [4]. After ten days of fighting fires, the U.S.S.R government constructed a concrete sarcophagus around the damaged structure, established a 36 mile restricted zone around the accident site, and evacuated neighboring cities and towns. Unfortunately, dangers still exist at Chornobyl today. The concrete sarcophagus has rapidly deteriorated, igniting fears of radioactive dust rising into the atmosphere, and contaminated water entering the drinking water supply.

On June 29, 1997, the G-7 nations ratified the Shelter Implementation Plan, an international commitment to prevent a future accident at Chornobyl. Project Pioneer, a collaboration between government, corporate, and academic institutions (footnote with list of contributors), is the first initiative of the Shelter Implementation Plan. The Pioneer robot, designed by RedZone Robotics, Inc., is a tracked vehicle (approximately 1.2m x 0.75m) with a centrally located mast 1.4m high (Fig 1) [3]. The robot contains a number of payloads, including a core boring drill, environmental and radiation sensors, and a trinocular stereo, three-dimensional mapping system. The 3D mapping system consists of three cameras that would be posted at the 1:30, 7:30, and 10:30 positions on a clock face. The 10:30 camera has a filter wheel that provides a choice of
collecting images seen through red, green, or blue filters, or no filter. A complete set of images from this system, a sextuplet, has three black and white images, and three filtered images. The Imaging system has an effective 35° horizontal and 28° vertical field of view, and produces range maps accurate to within 3cm at 5m depth from the camera. Wider view volumes may be imaged by rotating or tilting the cameras to collect overlapping images, which can be later processed as a single viewing region. This paper will focus on the Virtual Reality (VR) user interface developed by the authors for the three-dimensional mapping system.

The Chornobyl Mapping System operation interface is an extension of Marsmap, the visualization software developed for the 1997 Mars Pathfinder Mission [2]. Both systems make use of the unique capability to rapidly generate and interactively display three-dimensional, photo-realistic VR models of real-life geometries; however, Project Pioneer faces several additional challenges. Pathfinder scientists could rely on ambient lighting for stereo processing.
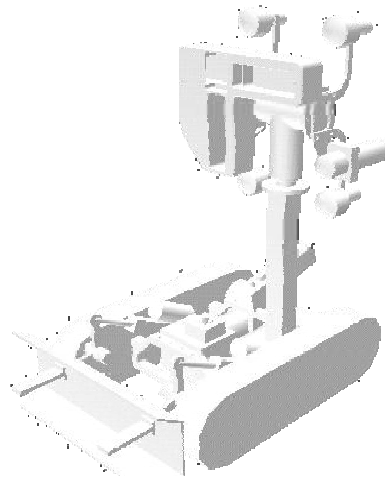

Figure 1 – Pioneer Robot

The Chornobyl environment, however, is completely dark. The Pioneer robot has four user-adjustable lights on the camera mast, but the user must practice extreme care in setting the lights to an optimal level for stereo processing. Also, the Pathfinder Carl Sagan Memorial Station provided a consistent view of the Sojourner robot's path. Pioneer will have to track its own movement without an external view. Finally, the acquisition of the Pathfinder data was directed by a team of highly trained scientists from a comfortable office

environment. The acquisition of Pioneer's stereo images will be handled by Ukrainian technicians in a lead-lined "saferoom" a few hundred meters from the damaged reactor core. Standard keyboard/mouse input devices are not appropriate for gloved technicians working in an environment with high humidity and without temperature controls.

The authors have developed two Virtual Reality (VR) interfaces for Project Pioneer. The first, the Chornobyl Mapping Acquisition System (CMAP Acquire), provides for supervisory control over the trinocular stereo data acquisition process inside the harsh environment of the damaged reactor. It offers the operator a "pseudo-live" image stream from the robot mapping cameras, and an estimation of distances from target acquisition areas. The interface also analyzes the quality of the image data, subsequent range data, and provides suggestions on how to improve poor or incomplete data. A three-dimensional image mosaic gives the operator strong situational awareness. This interface is controlled with a custom pushbutton box and joystick.

The second interface, the Chornobyl Mapping Analyze System (CMAP Analyze) provides scientists and plant managers with tools to visualize the data. This interface processes images collected in CMAP Acquire to produce a geometrically accurate three-dimensional, photo-realistic map. The software evaluates image quality, generates range data, builds a polygonal mesh from the range data, reduces the polygon count of the meshes, and applies surface texture to the mesh. The user can make accurate measurements of features in the mesh using a suite of point-and-click tools. The interface also allows a user to combine several meshes from one or more robot positions to build a "Virtual Chornobyl." Plant managers can use the Virtual Chornobyl model to measure and assess features that are too large to be processed from one robot position.

The following operating scenario will demonstrate how the two interfaces will work together to create a three-dimensional model of the structure.

2   Inside the Structure – CMAP Acquire

The goal for CMAP Acquire (Figure 4) was to develop an interface that takes advantage of the situational awareness made possible through VR technology in a manner simple enough to be used by a high school educated Ukrainian technician in an extremely hostile environment. Technicians work 1.5 hour shifts to limit their exposure to radiation, so the interface must allow for either quick data acquisition, or acquisition by many technicians over several 1.5 hour shifts.

This interface was written in C using the World ToolKit software libraries from Sense8 Corporation [6], and designed for use on a dual processor Octane (2 195 MHZ RS10000, 256 MB RAM) from Silicon Graphics. The Octane is configured to run the CMAP Acquire program at system startup.

The current operating scenario includes two operators: one drives the robot with the robot's Driving Console, while the other controls the mapping system. Before entering the structure, the operators are given detailed instructions on which mapping targets to acquire. This may include verbal descriptions, photographs, or printouts of previous mapping sessions. Inside the structure, the robot driver moves the robot until the desired target has been identified in the driving cameras on the front of the robot.

The mapping operator can also view the scene through the mapping cameras, which are mounted on a pan and tilt gimble that can be panned plus/minus 183.3° and tilted from −35° down to 70° up. A Video Window (Figure 2) provides a fresh image from the mapping cameras every three

seconds. The operators cooperate to direct the robot within 1.5 and 5 meters of the target to ensure reliable data capture. A Heads-Up-Display (HUD)helps the operator estimate distances between the robot and targets.

Lab experiments demonstrate the effectiveness of the HUD. A video camera was placed on a cart with the back end elevated to a tilt angle of 10°. The horizontal field of view was set to 35°, and the corresponding vertical field of view measured at 24°, which approximates the viewing area of the Pioneer camears. Test subjects (n=7) estimated the distance of several targets at varying distances both with and without the HUD. Tests using this procedure indicate an operator can estimate distances approximately 50% more accurately with the HUD than using the image alone, when the ground has a uniform slope (Figure 3). The overlay is less effective in regions of rapidly changing slopes, or when the target is above the plane of the robot.

Figure 2 -- HUD with target at 2.5 meters

Figure 3 - Distance Estimation Error (%)

Through a series of button presses, the operator can define a pan/tilt range for the acquisition of adjacent, overlapping images. The range can be from a single sextuplet of images, to a full set of over 70 sextuplets, imaging a full 360-degree hemisphere of the room. The operator can verify designated pan/tilt ranges both numerically and graphically. In the graphical representation, the box illustrates the accessible imaging area in angular coordinates. As the operator selects a pan/tilt range, the red overlay shows the data capture area, and the number of pan/tilt positions required to cover the selected area. This display also shows the current pan/tilt position of the camera head, both numerically and graphically. The operator can confirm the data capture area, and tell the robot to begin image acquisition.
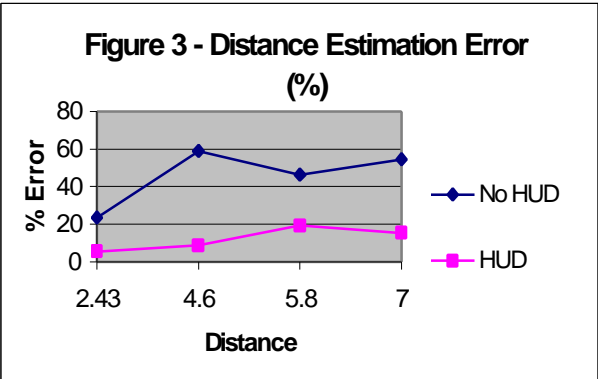
The image acquisition process is largely automated. Image sextuplets are collected at each pan/tilt position. The operator is able to scroll through the images and examine

each one separately during the mapping operation. The Trinocular Stereo Processing Suite developed by NASA Jet Propulsion Laboratory, calculates image disparity information, and generates 3D range data of the target area [1]. The range data point cloud rotates sinusoidally in the interface, providing a sense of depth through parallax. This gives the operator immediate feedback on the quality of the data. A Range Expert (REX) performs a variety of statistical tests on the six images and the range data to determine if lighting levels are adequate for mesh processing. If REX finds the images or range data to be inadequate, it pauses the acquisition sequence, and suggests changes in lighting to improve data quality. A graphical icon displays average pixel value and standard deviation. A stacked bar graph icon will display the percentage of zero level pixels, saturated pixels, and valid pixels. The user can then scroll through the low quality image(s), readjust lighting levels and retake images, or tell the system to continue on to the next pan/tilt position. This process is repeated for all pan/tilt positions in the selected range. During the capture process, images from the central camera are pasted on the inside of a virtual sphere, forming an image mosaic. The operator can use the joystick to adjust the viewpoint of this virtual image map, providing further situational awareness of the data capture process. Once the entire capture area has been photographed, the images are copied to a Jaz disk, which the operator will carry back to the "office" for 3D mesh creation.

CMAP Acquire is currently in its third generation of development. It has been tested and refined in a series of usability tests with novice operators, consisting of project managers, Ukranian Scientists, and high school students. In each test, the participants were introduced to the display, and encouraged to work with its features. Comments and suggestions from each session were considered and incorporated in the next generation of the display.

3   Outside the Reactor – CMAP Analyze

CMAP Analyze (Figure 5) and its predecessor, Marsmap, share a suite of core features:

- Real-time, interactive navigation of the virtual viewpoint through the 3-D model of the mapping site
- Measurement of topographical features, including 3D positions, distances, and angles
- Catalog and display of the sequence and location of many mapping locations

Mapping data can be visualized with CMAP Analyze using a 2D mouse and pull down menus. The user can also use a Magellan device, a six-degree of freedom mouse, to manipulate CAD models and mapping data in the virtual environment.

Upon opening, CMAP Analyze displays a CAD model of the 9m Level of the Unit 4 reactor. This is the heart of the damaged area, and a likely target for the Pioneer robot. The operator can scan the image database (indexed by robot position, date, and time), and select a set of images for texture mapped mesh creation. The mesh appears on top of the CAD model; the operator can use a Magellan Device [5] or mouse to position the mesh in relation to the CAD model or previous mesh data. CMAP Analyze utilizes three levels of detail to help keep the frame rate of about 10 frames per second. Single meshes from multiple pan/tilt positions can be combined to form a *Supermesh*. Supermeshes from several robot positions can be combined to form *Megameshes*. The operator can then use the virtual measurement tools to ascertain the geometry of features, help determine the stability of the structure, and plan future robot missions.

When combining multiple supermeshes, it is clearly important to know the location of one supermesh relative to the other. Software developed by the Carnegie Mellon University Field Robotics Center takes two

meshes, performs matching operations, and returns a transform matrix from one mesh to the next. This software requires an estimation of the origin of one the 3D coordinate system relative to the other. CMAP Analyze helps the user attain this estimation by projecting the mesh image texture out of the virtual CAD model of the Pioneer robot. The image shines out of the virtual camera light a spotlight, onto the photo-realistic supermesh. The user can slide the robot model around the supermesh until the projected image lines up with the texture on the mesh. Tests indicate operators using this projected texture technique can locate the position of the robot relative to a textured mesh within an accuracy of ten centimeters, compared with two meters without. The operator can use projected texture to slide the robot model around, until the required precision is met and the mesh matching software snaps the robot model into place. The interface, therefore, capitalizes on the human capacity of pattern matching to get close to the correct position, and lets the computer correct the position to a high degree of accuracy.

4   Conclusion

The Mars Pathfinder project demonstrated the utility of Virtual Reality interfaces for remote 3D cartography. The CMAP interface extends this utility while overcoming a variety of unique requirements:

- Simplified graphical interface for non-expert users
- Custom user control for use in a high temperature/high humidity environment
- Expert system for image and range data evaluation
- Separate data acquisition and processing modules for short technician shifts

- Accurate measurement of hazardous environment with minimal risk to human life

The software is still in development and will be more rigorously tested during integration with the robot this fall. Our initial findings indicate that Virtual Reality based interfaces offer substantial improvements over more traditional mobile robot controls and visualization techniques.

References

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Figure 3 -- CMAP Acquire Interface

Figure 4 -- CMAP Analyze Interface