Submitted to IEEE/RSJ International Conference on Intelligent Robotic Systems (IROS'98)

A Photo-Realistic 3-D Mapping System for Extreme Nuclear Environments: Chornobyl

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Abstract

We present a novel stereoscopic mapping system for use in nuclear accident settings. First we discuss a radiation shielded sensor array designed to tolerate 10^6 *R of cumulative dose. Next, we give procedures to ensure timely, accurate range estimation using trinocular stereo. Finally, we review the implementation of a system for the integration of range information into a 3-D, textured, metrically accurate surface mesh.*

1 Introduction

In the early morning of April 26, 1986 the worst nuclear accident in history occurred in reactor Unit 4 of the Chornobyl power station. [1] After a heroic initial response to cope with the immediate emergency, an external containment structure, or "shelter" (often referred to as the "sarcophagus" in the West) was constructed over and around the damaged reactor building in little more than six months. An international effort to remediate Unit 4 is now mounting, but major difficulties will have to be overcome.

Specifically, the integrity of the shelter, which rests upon the damaged structure of Unit 4, is dubious. In light of this deterioration, any remediation activities must ensure that no further environmental damage occurs and that areas of major structural weakness are identified and reinforced. To aid in this activity, a robot equipped with a functional three-dimensional mapping system is being constructed to provide the shelter operators with a safe, reliable, and effective means to document the current state of the sarcophagus interior.

The **Pioneer** robot (designed by RedZone Robotics, Inc.) consists of a tracked vehicle approximately 1.2 by 0.75 m with a centrally located mast 1.4 m high. The two tracks, operated by electric motors, can perform skid steering and climb a slope of 45 degrees. The vehicle supports one of several payloads including the mapping sensor package. Other sensors mounted on the vehicle measure gamma and neutron radiation, ambient temperature and relative humidity. Electrical connections between the vehicle, power electronics, control and communication are via a tether of 100 meters in length. In addition to the mapping cameras on the vehicle, a color vidicon camera with zoom lens is used for teleoperation. Finally, a "core-boring" assembly designed at Carnegie Mellon [7] and an associated material analysis system from the Jet Propulsion Laboratory provides structural information.

The primary goals of the **Pioneer** mapping system are to:

- Perform a complete, accurate three-dimensional mapping of the designated target areas.
- Co-register auxiliary sensory information with the 3-D surface maps.
- Integrate color texture information with the 3-D surface maps to provide a photo-realistic rendering of the target facilities.

2 A Rugged Stereo Rig

The hardware of the mapping sensor must withstand an environment which includes radiation, decontamination procedures, and the vibration and shock

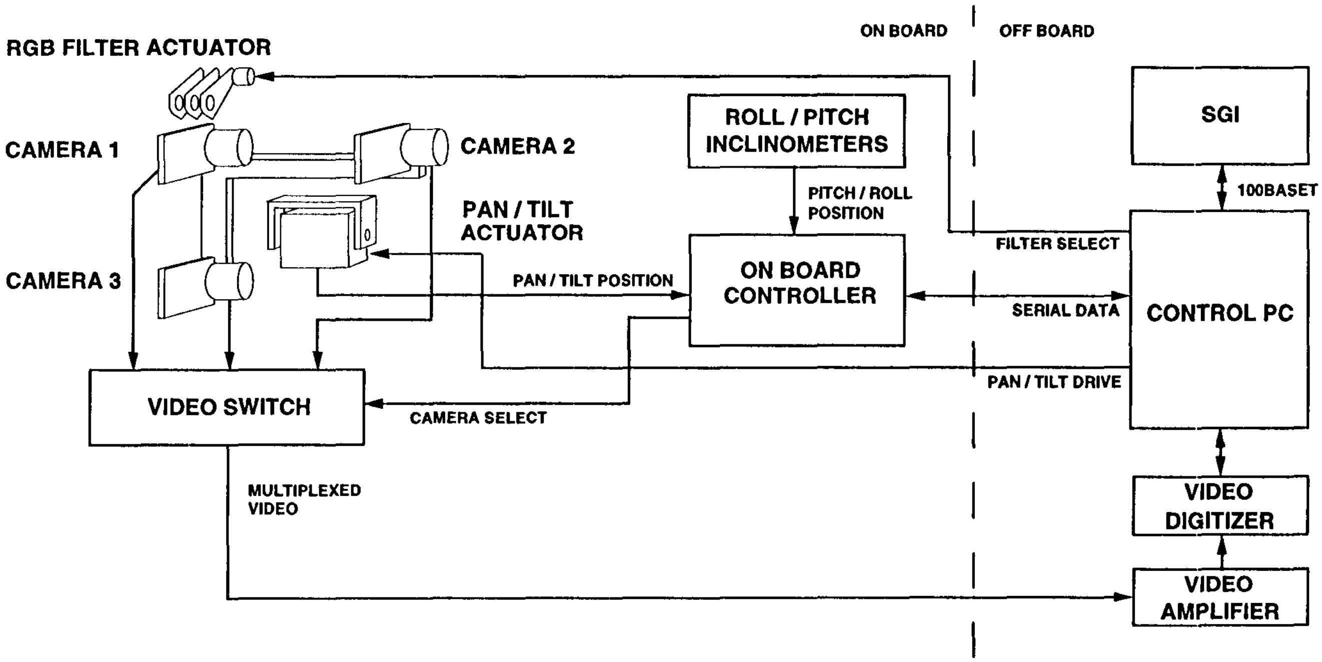

Figure 1: **Schematic of the Pioneer Stereo Mapping System** Components in the left half of the figure are mounted on board.

resulting from vehicle motion. The gamma radiation field results in a 10^6 R total accumulated dose over the mission with dose rates up to 3.5 kR/hr. Neutron dose rates experienced by the components are from 1 to 1000 cm^{-2} sec^{-1}. Electronic components on the vehicle must be either radiation hardened, shielded, or considered sacrificial. The induced effects of radiation must be negligible for the expected dose rates, or transient so that a given mapping session is not interrupted by equipment failure or poor performance of a component. Components deemed sacrificial must be inexpensive enough to be replaced economically and must perform within acceptable limits over the expected component lifetime. The system must be designed to allow any sacrificial components to be easily replaceable under field conditions. The mapping camera system is removable as a unit so that needless exposure of the cameras is avoided when only non-mapping operations are performed by the vehicle.

The raw data for the Pioneer Mapping System is provided by three CCD cameras using stereo vision processing. This has several advantages over competing technologies such as laser scanners, radar sensors, and structured light rangers. Stereo imagery operates passively, requires no moving parts (except for the pan/tilt unit on which it is mounted), requires little power, allows processing to be performed offboard, uses a small number of images, and readily enables registration of video images onto range maps.

2.1 Camera Selection

The requirements of the mapping system and the limitations on the number of conductors contained in the 100 meter vehicle tether combine to preclude the use of commercially available radiation hardened cameras. Fixed image geometry with respect to the optical coordinates is necessary to preserve stereo calibration. Vidicon or other tube based imaging technologies, although radiation hard, do not have sufficient image stability, due to drift of deflection circuitry, mechanically induced misalignment and deflection of the electron beam by fluctuating external magnetic fields, to be used for stereo applications. Alternatively, solid state detectors are available with appropriate radiation hardness and stable image geometry, but require complex control interconnection between the hardened sensor and non-hardened support circuitry. Therefore, this design utilizes readily available CCD board level cameras within a shielding envelope to reduce the amount of on board electrics. The amount of shielding is constrained by the capabilities of the pan/tilt unit carrying the cameras, but provides sufficient attenuation to result in satisfactory performance over the limited lifetime of the cameras. Tests were performed in which board cameras were exposed to a Cs 137 gamma source with dose rates up to 3 kR/hr with noticeable induced noise. The useful lifetime of these cameras is at least 100 hours at the expected dose rates. In addition, the component cost of the cameras is sufficiently low to be neglected over the course of the mission.

The three cameras composing the stereo sensor array are rigidly mounted to a frame in the shape of an inverted "L", which is itself mounted on the pan/tilt head. This frame is machined to provide several prealigned mounting locations for cameras 2 and 3, allowing the baseline of the stereo images to be varied from 15 to 30 cm during the development phase of the project. Camera 1 is fitted with a device that can place any of three filters in the optical path to generate a composite color image of the scene. All of the camera components are housed within an enclosure having a sealed glass port. Not shown in Figure 1 is a set of four waterproof quartz halogen lamps mounted on the pan/tilt unit. Two lamps are mounted above and two below the camera array.

2.2 Baseline and Field-of-View

The field of view was selected by balancing two competing goals. Horizontal precision in the depth maps increases as the field of view narrows, suggesting that a smaller field of view would be better. But the number of images required to completely map an area increases dramatically as the field of view shrinks, so a wider field of view is desired for more timely mapping operations. 28 degrees was found to be an appropriate compromise.

The baseline required between the stereo cameras is determined from the desired depth resolution of the system and its field of view, according to this approximation:

$$b \approx \frac{z^2 r \Delta\phi}{\Delta z} \qquad (1)$$

where z is the distance of a world point from the camera head (5 m maximum), r is the subpixel resolution expected from the stereo system (0.2), $\Delta\phi$ is the approximate field of view of each pixel (1 milliradian), and Δz is the desired depth resolution (3 cm). Thus for this application a baseline of approximately 16 cm is most appropriate.

2.3 Shielding

The shield of each camera consists of 1.25 cm lead, covering the CCD board camera, lens, and a mirror. An aperture is provided in the shield for the lens. The mirror is placed at 45 degrees to the optical path in front of the shield aperture and folds the optical path by 90 degrees. In this design the lead behind the mirror shields the camera and optics from radiation incident along the optical axis of the lens.

3 Trinocular Stereo Processing Suite

The stereo vision sensor provides the raw data required by the **Pioneer** mapping system to perform accurate world modeling. The software component of this sensor has been demonstrated to provide automatic range data with enough accuracy to enable autonomous vehicle navigation from binocular stereo imagery [6]. However, the goal of this project is somewhat different, so certain parts of the automatic system have been made accessible to the user, providing the ability to adjust the environment and tailor the stereo parameters to individual stereo triples. Also, a third stereo camera was added to help reduce disparity artifacts that might occur at horizontal object boundaries; these are much more common in manmade environments than in natural terrain.

3.1 Automatic Stereo Processing

Effective stereo processing is enabled by accurate camera calibration. Our camera model is Gennery's extension of the Yakimovsky/Cunningham linear model [8], and includes radial lens distortion terms [5].

The stereo algorithm used by the **Pioneer** mapping system is a coarse-to-fine correlation procedure using 2-D windows. It will not be described in detail here, but can be found in [6].

3.2 Range Image Evaluator

To assist the user in the acquisition of appropriate map information, a range image evaluator will provide feedback concerning the quality of the raw images and their resulting range data. Some examples of perceived problems and suggested solutions include:

Pixels are saturated Turn the light level down

Pixel intensity range too small Turn the light level up

Sparse range data Adjust lights to improve image texture, or Reposition vehicle closer to target, or Verify calibration.

3.3 User Controls

Several of the stereo processing parameters and environmental controls have been made available to the user to allow for refinement of the range maps.

Lighting Much of the intended mapping operation will take place in an unlighted portion of the reactor facility. Since stereo processing depends on the quality of image texture visible in a luminance image, the user is given dimmer control of the four lights mounted on the stereo camera pan/tilt head. The range image evaluator module will offer suggestions as to how the lighting might be adjusted to improve image quality.

Range Bounds The mapping system was designed to provide range information to a given precision over a fixed range in front of the camera head. The user may increase these bounds if range data at greater distances is desired (at some loss of resolution), or narrow them to reduce the potential for correlation mismatch if all objects are known to lie within more restrictive bounds.

Correlation Window Size Although not recommended, the user may change the size of the correlation window used in the stereo computation.

Pyramid level The pyramid level indicates the size of the resulting range map. Pyramid level 0 will generate a range map at full resolution, 1 means the range map will be half as large in each dimension (and thus only one quarter the size), and so on. Higher pyramid levels reduce dependence on the calibration and speed up processing, but provide a smaller number of polygons to the mesh generator.

4 Flexible 3-D Cartography

A mapping scenario consists of maneuvering the **Pioneer** robot to discrete positions within a particular target location. At each position an overlapping set of range and color imagery will be acquired, fully exploiting the available pan and tilt angles. The primary goal of the cartography system is to integrate an entire set of range and intensity imagery from multiple mapping positions and merge them into a textured, three-dimensional rendering of the target space. Data sets acquired from individual robot positions are trivially referenced to the local robot coordinate frame. However, no direct or accurate transformation between separate robot positions is made available to the mapping system from the **Pioneer** robot. In such cases where no global estimate of position is available, the mapping system has the ability to register two related data sets, and to derive the "best" possible estimate of the transformation between them. The **Pioneer** mapping system offers these capabilities through a suite of mesh processing and analysis tools.

4.1 Mesh Creation and Processing

Surface meshes are a common way of representing 3-D data, and when the points from a 3-D cloud have an easily recovered, common, coplanar projection, such as in stereoscopic imagery, creating a simple mesh is a relatively easy process. In most cases, these meshes are not suitable for subsequent analysis without additional processing. Mesh processing in the mapping software consists of four separate stages: *Texturing*, *Cleaning*, *Smoothing*, and *Resampling.*

Texturing Application of texture gives reconstructed scenes a more realistic feel, and allows the user to more easily recognize salient features. It is done by relating three dimensional mesh points to the co-registered color image obtained by the filter sweep of the central camera of the stereo rig.

Cleaning A mesh may have several unwanted features upon creation, such as small, insignificant noise patches and jagged boundaries. Cleaning is the processing of removing long edges, small unconnected surface patches, and restructuring the boundaries.

Smoothing Range data can be noisy. Mesh smoothing attenuates the high frequency noise structure and (ideally) preserves important mesh structures and boundaries.

Resampling Most 3-D vision applications perform either more efficiently or more accurately given a uniformly sampled surface at a lower resolution than the original mesh data. Resampling takes a clean, smooth mesh and outputs a lower resolution, more uniformly sampled mesh [3].

The mesh processing sequence depends only upon the acquisition of a single range image referenced in sensor coordinates. Subsequent processing stages group and assemble individual meshes into a coherent 3-D map. Figures 2 and 3 show renderings of input meshes after application of the mesh processing suite.

4.2 Position Integration Module

At a discrete robot position, the relative transformations between individual sensor positions can be

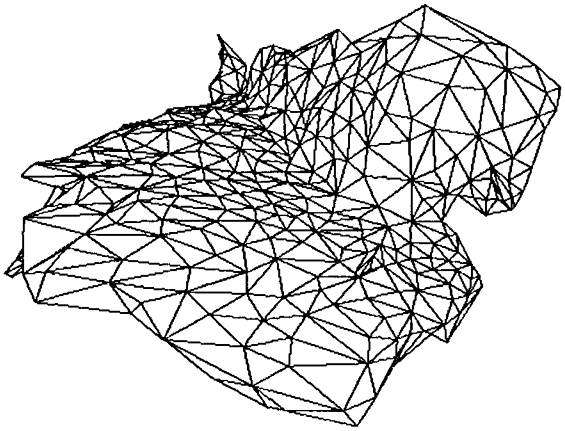

Figure 2: **Fully Processed Mesh Wire Frame** Input points have been triangulated, cleaned, smoothed and resampled.

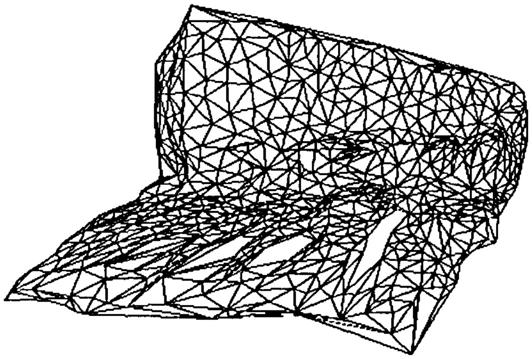

Figure 3: **Fully Processed Mesh Wire Frame** Input points have been triangulated, cleaned, smoothed and resampled.

recovered from the pan and tilt angles. The fundamental technology uses a sensor and noise model for applying the vertices of the surface mesh into a 3-D occupancy grid [2]. Each surface mesh from the current robot position is transformed to a local sensor coordinate reference and sequentially distributed into the voxel volume. Surface normal information is likewise encoded with each voxel and is used to extract a replicate, integrated surface from the grid. Overlapping texture components are then blended using a weighted average. Figure 4 displays the integration of Figures 2 and 3.

4.3 Registration Module

No direct means of measuring the transformation from two distinct robot positions is available in the **Pioneer** robot; however, technology to compute the relative transformation from two featured surface meshes has been developed at Carnegie Mellon. This method derives an approximate transformation between two surface meshes through a correlation of "spin-images" obtained at oriented points on the surface of the mesh [4]. This rough transformation is then refined using a modified version of the Iterative Closest Point algorithm that registers 3-D and color (texture) jointly. Figure 5 illustrates a sample registration and integration of stereo-derived range data using a 16 x 2 image sweep of the "mudpit" mockup at RedZone Robotics, Inc.

5 Summary and Conclusions

Three components of an integrated system for 3-D mapping in extreme environments were presented. A rad-hardened stereo rig and its associated electronics designed to tolerate 10^6 R form the core acquisition system. An interactive trinocular stereo system outputs timely and accurate range information to a linear accuracy of 3 cm. Finally, a 3-D cartographic system for conversion of raw range data into integrated 3-D surface structure maps was presented and preliminary results were detailed. The **Pioneer** robot will be deployed in the Chornobyl facility during the fall of 1998.

Acknowledgments

The authors would like to thank Frank Ruddy for his help in characterizing the radiation sensitivity of our cameras and the use of the Westinghouse hot cell. We also thank Eric Rollins his expert design of the stereo mechanical assembly, Andrew Johnson for his mesh tool box, Todd Litwin for his help in porting the stereo code, and the rest of the Pioneer mapping team at NASA Ames Intelligent Mechanisms Group, the Iowa Grok Lab, and RedZone Robotics for their input, advice, and criticisms. The work described in this

Figure 5: **Sample Integrated Surface Map** Thirty two individual range maps have been registered and integrated into a single coherent surface. Obvious features include the far wall in light grey, an occluding planar piece of sheet metal resting against the wall in the middle of this image, and the corner of a large concrete cube in light grey on the near right.

paper was partially carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract to the National Aeronautics and Space Administration. The **Pioneer** project is sponsored by the US Department of Energy and the National Aeronautics and Space Administration.

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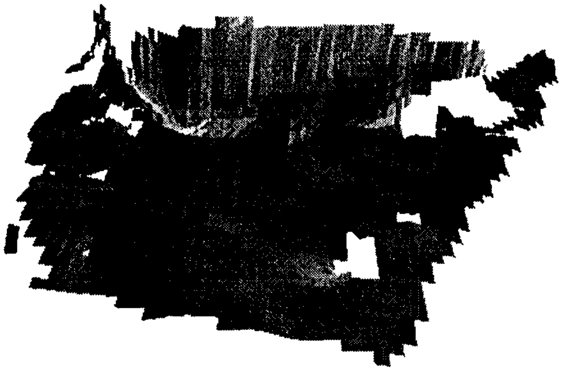

Figure 4: **Integrated Mesh:** A sample integration of the meshes from Figures 2 and 3.

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