DESIGN AND DEVELOPMENT OF A STEREO VISION-BASED DEPTH MAPPING SYSTEM FOR SURVEILLANCE IN UNDERGROUND MINING ENVIRONMENTS

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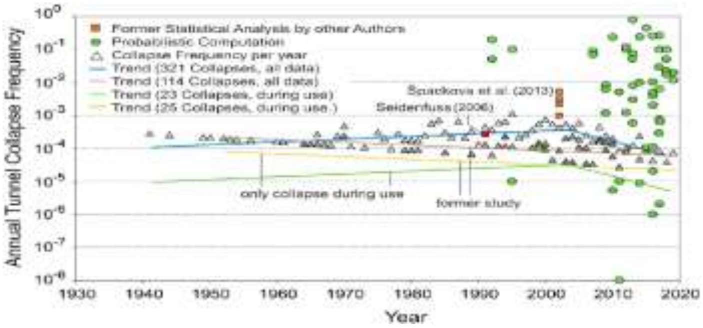
Introduction:

Subterranean mining activities pose distinctive challenges concerning safety, surveillance, and disaster response. Conventional monitoring techniques tend to be inadequate in terms of obtaining real-time spatial details within these dangerous settings, especially under emergency conditions like tunnel collapse. This project counters these issues by creating an affordable stereo vision-based depth mapping system tailored for subterranean mining settings.

Proposed system exploits stereo vision principles to create depth maps and point clouds containing very important spatial information regarding mining tunnels and chambers. Unlike costly commercial hardware-based stereo cameras, our solution brings together consumer-level webcams and advanced software algorithms to produce similar results at a fraction of the expense. This enhances the technology for use in implementing mining operations all over India and helps the country achieve its ambition of becoming a world leader in sustainable and secure mining practices.



Distribution of tunnel collapses frequency over time

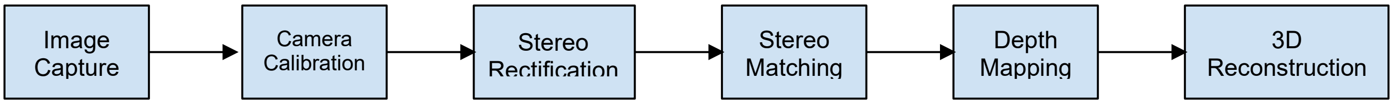
The system developed has various applications in underground mining such as real-time structural monitoring, post-disaster evaluation, planning of rescue operations, and periodic surveillance. With the delivery of accurate spatial information under poor lighting and environmental conditions common in underground mines, the system greatly increases safety procedures and operational efficiency.

Objectives:

- Develop a low-cost stereo vision system based on consumer-grade webcams for use in underground mining settings.
- Apply camera calibration, stereo rectification, and stereo matching processes to produce valid depth maps.
- Construct 3D point cloud reconstructions of depth data to visualize mining tunnel spaces.
- Develop a system able to deliver real-time depth data to aid response in disaster events like tunnel collapses.

Methodology:

The approach to this project is to use a pipeline-based structured methodology for stereo vision-based depth mapping and 3D reconstruction. The two webcams are used, which are Zebronics Sharp Pro(720p) and are mounted with a fixed baseline distance from each other. They are used to capture stereo image pairs. These images pass through a series of processing steps to extract depth information and create 3D point clouds.



The stereo vision pipeline includes the following major steps:

- **Image Acquisition:** Synchronized acquisition of image pairs from the stereo cameras with synchronized software triggers.
- **Camera Calibration:** Calculation of intrinsic and extrinsic camera parameters by Zhang's method with multiple chessboard pattern images.
- **Stereo Rectification:** Registration of image pairs by Fusiello's algorithm to have epipolar constraints for efficient stereo matching.
- **Stereo Matching:** Matching of corresponding points between rectified images to calculate disparity maps.
- **Depth Map Generation:** Disparity information converted to depth values based on triangulation concepts and the parallax effect.
- **Point Cloud Creation:** Conversion of depth maps into 3D point clouds for spatial visualization.

Hardware setup: The stereo vision system used in this project utilizes two Zebronics Sharp Pro(720p) webcams placed on a stiff frame with a separation of 90 mm to provide an accurate reproduction of human binocular vision. The two webcams are interfaced to a processing machine through USB interfaces to permit real-time image acquisition and processing.

Stereo vision setup

testing setup

Software Implementation: Software units of the system were programmed based on Python utilizing robust computer vision libraries like OpenCV and Open3D for processing various aspects of stereo vision. A synchronization script was put in place that allowed both cameras to capture the image simultaneously while providing correct stereo input. A calibration module adopted Zhang's algorithm to calculate intrinsic and extrinsic camera parameters with respect to the multiple images taken of a chessboard pattern. To match the stereo image pairs, Fusiello's algorithm was used to rectify the stereo images, so that corresponding points are on the same horizontal line. The computation of disparity was performed utilizing the semi-global block matching algorithm, which is a compromise between accuracy and computational costs. Depth maps were then created with triangulation principles, calculating the depth of each pixel from the disparity. Lastly, depth information was utilized for point cloud generation with the help of Open3D to allow 3D reconstruction of the recorded scenes.

Result and Conclusion:

Stereo vision system built with the designed framework produced reliable depth maps and 3D point clouds under test environments simulating underground mining environments. Key results are:

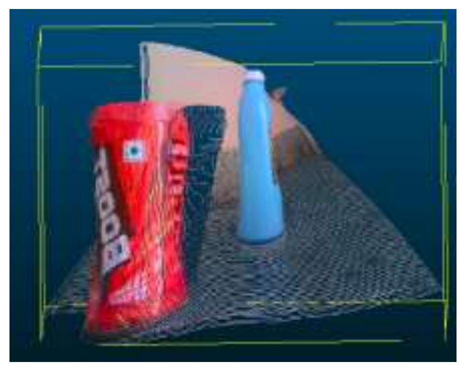
- **Depth Map Quality:** Achieved visually smooth depth maps with a spatial resolution of approximately 640x480 pixels, effectively distinguishing features in simulated tunnel systems and obstacles with a depth accuracy of ±1.5 cm within a range of 1-3 meters.
- **Point Cloud Reconstruction:** Reconstructed 3D point clouds with a density ranging from 8,000 to 12,000 points per frame, suitable for structural analysis and real-time spatial awareness in constrained environments.
- **Real-time Performance:** Achieved near real-time performance at 10–15 frames **per second** using off-the-shelf hardware with GPU acceleration, ensuring timely updates for surveillance or navigation tasks.
- **Cost Effectiveness:** The entire stereo vision-based system was deployed at 15–20% (approx Rs. 6000) of the cost of comparable commercial solutions such as

LIDAR based systems, while delivering viable depth and 3D reconstruction performance for underground mining scenarios.

The system was demonstrated to perform particularly well in the accuracy of depth estimation under low-light conditions prevalent in underground environments. The software solution was advantageous in that it enabled algorithmic tuning to compensate for environmental challenges without hardware modifications.

Overall, the stereo vision-based depth mapping system provides a cost-effective and efficient solution to enhance safety surveillance and disaster relief capabilities in underground mining. By combining consumer-level hardware with sophisticated software algorithms, a technology that can be implemented on a mass scale in India's mining activities is provided.

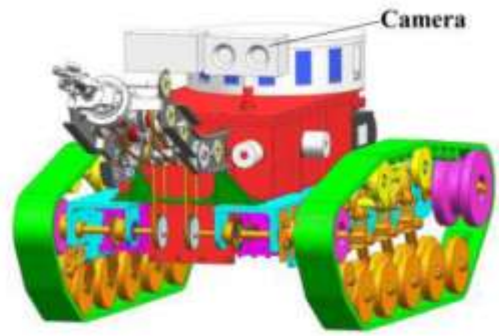
Disparity map



3D point cloud

Future Scope:

The future scope of this project includes several promising directions for enhancement and extension:



CMRR equipped with stereo vision system

1. **Wireless Deployment Options:** Designing battery-powered wireless units which could be quickly deployed in emergency situations. Using ESP-32 camera modules which support the ability to set up web servers to stream the live feed.
2. **Integration with Autonomous Mining Vehicles:** Modifying the system to offer spatial awareness for unmanned vehicles used in underground mines. In subsequent applications, the stereo vision camera system will be mounted on a mobile platform, i.e., a rover or a Compact Mobile Robotic Rover (CMRR), which will be specifically designed for underground mining conditions. The system would be able to travel autonomously or semi-autonomously through complicated and dangerous tunnel systems, providing continuous depth data and creating real-time 3D reconstructions of the environment.
3. **Advanced Machine Learning Modules:** Using advanced deep learning algorithms for more accurate depth estimation in highly difficult situations.
4. **Incorporation of Thermal Imaging:** Merging stereo vision with thermal sensors for improved perception in smoke or dusty surroundings.
5. **Automated Structural Analysis:** Deploying algorithms for automatic structural deficiency or tunnel geometry change detection.
6. **Seamless Integration with Existing Mining Management Systems:** Creating APIs and interfaces for easy exchange of data with complete mining operation management systems.

These improvements would continue to expand the system's capability and applicability to different industrial situations, especially in dangerous situations where human access is restricted or hazardous.