Active Light for a small Planetary Rover

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Master Thesis in the subject

Space Science and Technology

presented by

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

Würzburg, the 28th, February 2008

__________________________
(Canute Mascarenhas)
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<th>Description</th>
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<tr>
<td>MFEX</td>
<td>Micro-rover Flight Experiment</td>
</tr>
<tr>
<td>INRO</td>
<td>Intelligenter Rollstuhl</td>
</tr>
<tr>
<td>MJPEG</td>
<td>Motoin JPEG</td>
</tr>
<tr>
<td>MERLIN</td>
<td>Mobile Experimental Robots for Locomotion and Intelligent Navigation</td>
</tr>
<tr>
<td>OpenCV</td>
<td>Open Computer Vision Library</td>
</tr>
<tr>
<td>IPL</td>
<td>Intel Performance Library</td>
</tr>
<tr>
<td>OD</td>
<td>Optical Density</td>
</tr>
<tr>
<td>WB</td>
<td>White balance</td>
</tr>
<tr>
<td>AGC</td>
<td>Automatic Gain Control</td>
</tr>
<tr>
<td>OF</td>
<td>Optical Flow</td>
</tr>
<tr>
<td>FOE</td>
<td>Focus of Expansion</td>
</tr>
<tr>
<td>CamShift</td>
<td>Continuously Adaptive MeanShift</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>QE</td>
<td>Quantum Efficiency</td>
</tr>
<tr>
<td>RGB</td>
<td>Red Green Blue</td>
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<tr>
<td>HSV</td>
<td>Hue Saturation Value</td>
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Abstract

The planetary rovers must be able to accurately, quickly, and reliably perceive the terrain for navigation. The main objective of the thesis is to realize a laser-based optical system for obstacle detection at unknown terrain for a planetary rover. The optical system consists of an active light emitter that projects a pattern of laser beams onto terrain surface, and a CMOS camera captures images and the image processing software identifies the variations in the pattern as it encounters different obstacles. The proposed Active Light system is deployed on a MERLIN rover. The approach based on active light is expected to offer substantially reduced sensing costs, allowing more reliable navigation through unstructured areas.

The implemented purely vision based algorithms rely on capturing and detecting deformation in the laser pattern. Simple straightforward Template matching method and Boundary masking method are proposed initially. Subsequently optical flow [28] based and CamShift [29] based obstacle detection methods are implemented to overcome the limitations posed by earlier methods. The real world environment is highly unstructured and dynamic, each of the four algorithms, for obstacle detection, have certain advantages and limitations. The dynamics in the captured image due to rover motion is unpredictable, since it is governed by an unknown number of parameters. Obstacle detection becomes a more complicated problem in outdoor scenes, where numerous factors are controlling the scene in a very unpredictable way. A Meanshift [30] based approach is used for estimating pattern shifts in video sequence due to rover vibrations. Active Light sensor reliably recognizes obstacles irrespective of their shape in real-time. The performance of the system is evaluated on wide variety of terrains, for each of the image processing based obstacle detection methods. The results of the experiments demonstrate that the proposed system using CamShift based method is more accurate and efficient compared with other methods, enabling the rover to navigate safely.
Chapter 1

Introduction

Planetary rovers are often the only way to explore hostile remote areas. In traditional applications, mainly space explorations the ability to perceive terrain obstacles is essential for safe and efficient navigation of planetary mobile robots. For successful operation, the vehicle has to dynamically interact with the environment around it. Various sensors have been used to date for detecting obstacles and estimating terrain. Vision based obstacle detection, which is one of the widely used methods, has evolved over the years with the development of new algorithms. Vision is the physical sense consisting of the ability to detect light and interpreting the images. With the cost of CMOS cameras declining and low cost processors with higher speeds, the use of computer vision on mobile robots has taken important role. Vision provides a cheap sensor that can be used with a large variety of applications within robotics. This thesis describes an optical system consisting of a camera and a laser pattern generator for detecting obstacles. This technique is called active based on changing the lighting of the scene by projecting structured light on it. Active Light is largely used in computer vision and robotics. Considering mobile robotic applications in mind, the system provides a low cost, faster and robust alternative over other obstacle detection methods.

1.1 Background

Within the centre for Robotics and Telematics, research in the area of obstacle detection using real-time sensors for autonomous vehicles started with the development of mobile robot platform MERLIN [1] [2]. The MERLIN rover can be operated as autonomous and remotely controlled modes to perform tasks, such as monitoring of given areas, sampling of material probes or navigation. The wheeled MERLIN rover is used as the sensor platform and test bed for this thesis work, further details on the control and electronic architecture are discussed in [section 3.3.3]. Projecting structured light patterns onto the environment is a widely used technique in computer vision and robotics. The term structured light is used to refer to a vision
system taking advantage of active light source which projects a light pattern onto an environment. The pattern aids a computer vision task to be accomplished. The main advantage is that the projected visual features are easily distinguished by a camera. One of the fields of application of structured light is in robotics. In this case, structured light is used in range sensing [2], SLAM [3], obstacle avoidance [4] and other robotics applications which will be detailed in Chapter 2. The laser sensor system used in this thesis is classified into an active light system, and can be used for the navigation environment sensing.

1.2 Motivation

Structured active light based vision system is proposed to avoid the burdensome correspondence problem in the image processing used in the earlier planetary missions. The laser range finder on the other hand operates by measuring the time-of-flight between the sensor and object. Though the laser range finder has more advantages in views of wide measuring range and high relative accuracy at a longer distance, still it maintains the same resolution even at a short distance. In addition, laser range finder’s high cost, high power consumption and relatively high weight need to be compromised for its usage. In order to keep up the advantages of the sensor system using the laser structured light and without degradation of the sensor resolution, it is necessary to develop a new visual sensor system different from the sensors mentioned above. Active light vision is cheaper than laser range finders. The use of structured light solves the limitation of passive vision when observing non-textured objects. The price of colour cameras has fallen in recent years. Vision systems are easily reconfigurable (in response to dynamic behaviour in different conditions), and easily upgradable (with efficient software algorithms). In addition, active light based vision can be used to identify precipice. This is difficult or impossible with Sonar (ultrasonic) or IR (Infra Red based on time of flight /phase shift).

1.3 Objectives

The main goal of this thesis is to design, implement and test an obstacle detection sensor, based on Active light for planetary rover. The sensor system is composed of a
dot-matrix laser pattern generator and a camera. The laser beam generated by a dot matrix laser generator is projected onto a terrain scene. The camera captures the deformation of the laser pattern as the laser beam sweeps over the obstacles. The image processing module detects obstacle by finding any laser pattern deformation in the camera image. Thus the system must resolve the environment sensing problem associated with mobile robots, i.e., detecting obstacles with various shapes and surface conditions, hard to be robustly perceived by using conventional only passive.

The environment is unknown terrain filled with sand, rocky or uneven soil surface. Positive obstacles (stone, heap, rock etc.,) as well as negative obstacles (pothole, precipice etc.,) are randomly spread all over the terrain. The Rover is assumed to be moving at speed of 0-10km/s. For the rover to have smooth navigation, an efficient and robust obstacle detection scheme need to be implemented, capable of detecting both positive as well as negative obstacles.

### 1.4 Thesis outline

The thesis is organised as follows: Chapter 2 covers the state of the art, describing brief survey on previous work done on obstacle detection, mainly laser stripes based approaches. Chapter 3 gives a detailed description of the Active light system overview, giving both hardware and software architecture of the system. Chapter 4 covers the methodology used in this thesis work. Detailed design and implementation of various algorithms are discussed individually. Chapter 5 describes the testing of the Active light system and analysis of the experimental results. Chapter 6 provides a comprehensive evaluation of the Active light system is mentioned here. Experiment results are categorized based on the type of terrain and the kind of algorithm used. A final conclusion is drawn, with possible future improvements.
Chapter 2

Previous work and literature review

There has been a great amount of research carried out on the general obstacle
detection problem for mobile robots. Several active and passive technologies are
available for the task, including fixed light stripe systems [1], mechanically scanned
light stripe systems [7] and stereo vision [8].

Reliability of hardware components is crucial to mission success since repair of failed
components is unlikely after launch. For this reason, solid-state solutions are preferred
over mechanically scanned systems such as Laser range finders that may not survive
the vibration and G-forces of launch, atmospheric entry and landing. Also computing
power is an important factor, as stereo vision approaches are inefficient for
computationally restricted rovers.

2.1 Micro-rover Flight Experiment (MFEX)

Hardware
MFEX under Pathfinder mission [1] uses a laser stripe-based structured light system
as shown in Figure 1. The rover computer is an Intel 8085 with 0.5 MB of mass
memory; its software is a custom executive with a single thread of control. Obstacle
detection is done with a light-stripe triangulation system. Five lasers project stripes
onto the terrain imaged by the rover's stereo camera pair. The cameras have a stereo
baseline of 15cm with a pan/tilt mount on a mast 1.5m above the ground, CCD
imagers with 256x256 pixels, and an angular resolution of 0.001 radian per pixel.

Obstacle detection methodology
Two images are taken for each stripe, one with the laser turned off and another with it
on. The difference between the two images reveals the stripe on the terrain. The lasers
and cameras are arranged so that the height of the terrain relative to the rover can be
determined using simple geometry once the stripes are detected.
The MFEX power budget for hazard detection mode is 7.33 W, which consists of 0.01 W for two lasers at a time, 3.77 W for the CPU and I/O functions, 0.75 W for the CCD, and 0.8 W to run the attitude sensors. Thus, the lasers are a relatively significant part of the power budget. Pathfinder's power budget allows only one of the five laser stripes to be active at a time. Since laser light intensity is reduced as it is spread over a stripe, image differencing is required to find the stripe in an image. These factors combine to require 10 separate exposures for each hazard scan. The process is especially time consuming on the 8085-based system since image acquisition is slow. Time required to perform hazard detection is 20 seconds per scan. Since MFEX will drive about 6.5 cm between scans at a speed of 0.67 cm/sec, the net traversal rate will be around 0.22 cm/sec. For obstacle detection, speed is a key limitation of the sensor, which takes 20 seconds per hazard scan. This stems from a combination of factors, including the slowness of the 8085 processor, the wide fan-out of the light stripes, and the constrained power budget on the rover.

A hazard is declared if any of the following criteria is met:

- either of the nearest two points for any laser are not detected in the images;
- the elevation difference between any two 8-connected neighbours in the 4 x 5 measurement array exceeds a threshold;
The Pathfinder rover Figure 2 scans for hazards once every wheel radius of forward motion (6.5 cm). The rover has to stop to do each hazard scan.

**Pros and Cons**

The main advantage is adaptation of simple methodologies for navigation. The key limitations of the approach were in the quality of rover localization, the slow speed in hazard detection and the ability of behaviour control algorithms for path selection to negotiate the rock frequencies encountered on Mars.

### 2.2 Rocky III and LSR-1

The paper [9] presents a laser-based optical sensor system that provides hazard detection for planetary rovers. The system is derivative of the hazard detection system aboard Mars Pathfinder rover. The sensor can support safe travel at speeds up to 12 cm/second for large (one meter) rovers in full sunlight on Earth or Mars.
Hardware
The primary optical components of the system include the laser, the laser beam splitter (diffraction grating), camera lens, camera filters and the CCD. The LSR-1 rover is equipped with one of the 8085-based computers developed for Pathfinder, while Rocky-III uses a 486-based computer. The rovers are equipped with two laser/camera pairs for hazard detection. Each laser/camera pair operates as an independent hazard sensor. For now, consider one of the pairs by itself. First, laser light is split into 15 cc-planar beams using a commercially available diffraction grating. The central beam is aimed at the ground in front of the rover (50cm ahead for LSR-1). The rest of the beams fan out to the left and right. On flat terrain, the beams form a straight line of spots. The camera is offset horizontally from the laser at the same height above the ground as shown in Figure 3.

Obstacle detection methodology
On-board software finds the spots in the image which are in turn used to determine coordinates of the terrain. From the camera’s point of view, each spot shifts left or right depending on the height of the terrain the corresponding beam strikes.

Pros and Cons
The system overcomes limitations in the MFEX design [1] that require image differencing to detect a laser stripe in full sun. The system ensures the projected laser light is detectable in a single image, eliminating the requirement for additional
difference images. The system found to be more power efficient and also improved the speed of rover motion.

2.3 Vehicle collision avoidance system

The paper [11] describes a vehicle collision avoidance system using laser beams as shown in Figure 4. It is mainly designed for avoiding traffic accidents. A special projection device used to perform projection as a sequence of spot lights. Based on the deformation of laser spots obstacles are detected.

Hardware

The laser projector beams out 20 laser spots. The system captures the positions of each laser beam using a special camera installed in the vehicle.

Obstacle detection methodology

The system calculates the difference between the positions on normal roads and that of on abnormal roads like an obstacle on the road. The system can identify bumps, hollows and obstacles on the road surface with a high accuracy. The system is also able to detect the laser beams of other vehicles, by doing so it is able to judge whether or not the vehicle will collide, even if the incoming vehicle is not visible at a blind corner. The system could achieve significant detection rate of the laser beams, the obstacle detection rate and the collision avoidance rate with other vehicles.
Taking safety of human eyes into consideration, laser beams projection of the scanned image is only possible at an extremely weak level of brightness. Therefore, a special projection device that controls beam radiating from several openings and performs projection as a sequence of points using a spotlight is introduced. In order to recognize dim projections during the daytime in bright places, projection is performed using two filters; one for strengthening the radiating light, and another for deleting it. The method could able to extract the projected area from the background even in the case of weak illumination, which is hardly seen by the naked eye.

It operates by identifying considerable amount of change within 20 frames. Edge detection is done using Sobel filter [14] and Deriche filter [13]. Noise is detected by subtracting every frame with template frame. After Hysteresis thresholding [15] the sharp image is searched for pattern using dynamic programming matching. When all of laser spots are not detected, system compensates the detected area using estimated laser spots.

**Pros and Cons**

The system provides unique collision avoidance especially head-on encounters at blind corners, using laser beams for preventing traffic accidents even in daylight conditions. There are advantages for nearby people. If nearby people are able to view the projections, they are able to determine whether a vehicle is approaching from head on or from a hidden spot. The system can detect both positive as well as negative obstacles. The limitation is the high power requirement for the laser projector. Any obstacle falling in between laser spots, (i.e., obstacle within laser spot offset length), cannot be detected as laser spots are not incident on them.

### 2.4 Active marking system

The paper [16] provides a survey on different low-cost sensor modules, for increasing safety in mobility for users of electrical wheelchairs. The implemented functionalities include navigation as well as obstacle avoidance support. Different sensor types are used, for reliable operation, over broad range of environmental conditions.
Hardware

The standard electrical wheelchair already integrates sensors, like the encoders for motor control and velocity measurement, the input device (i.e. a joystick). Within INRO (Intelligenter Rollstuhl) additional sensors have been integrated:

- A ring of five ultrasonic sensors for obstacle avoidance, indoor navigation and convoy driving.
- An active marking system to detect low and concave obstacles.
- A differential global positioning system for outdoor navigation.

In addition to ultrasonic sensors, complementary sensor types are used. In the framework of INRO an active marking system is implemented, combined of a laser marker projecting 3 lines vertical to the drive direction and a CCD-camera to detect these lines. For suitable light conditions this approach exhibits good performance also for concave and flat obstacles, thus well complementing the ultrasonic system.

Within the hospital environment, the system assists the nursing staff for:

- convoy driving of several wheelchairs,
- autonomous transports along specified routes,
- in case of emergencies speedy service to disabled person’s

Obstacle detection methodology

Active marking system as shown in Figure 5 composed of laser marker projecting 3 lines vertical to the drive direction and a CCD-camera to detect these lines. From the deviation between expected line position and deformed measured lines, the data processing scheme derives the position and shape of obstacles. For suitable light conditions this approach exhibits good performance for concave (descending stairs, kerb-stones, holes etc.) and flat obstacles. Velocity adaptable within 4 velocity ranges: 2.5 km/h, 5 km/h, 7.5 km/h, 10 km/h, an optical high-pass filter suppresses all wavelengths below the one of the laser. The wavelengths above the visible spectrum are cut off by a filter integrated into the camera, an automatic brightness adaptation is implemented, and a horizontal edge filter is implemented in image processing software.
Pros and Cons
The method provides increasing safety in mobility for users of electrical wheelchairs using low cost components. The implemented functionalities include navigation as well as obstacle avoidance support. Both positive as well as negative obstacles are detected and avoided. The obstacle detection range is limited to the field of view of the camera and the area of pattern spread. The system is operable in the environment where the Laser light is brighter than ambient lighting.
Chapter 3
System Overview

This chapter provides description of building blocks of Active light system. The purpose is to introduce various elements of the system to a new user. Starting from overall architecture till the individual components such as optics, rover hardware and software modules composing the entire system are presented with schematics.

3.1 Physical Layout

Figure 6 shows the schematic of the Active light system and Figure 7 shows the side view, seen from a direction orthogonal to the plane identified by the laser beam and to the focal centre of the lens. The laser pattern source of the optical system, rest on a bar which is mounted on the rover approximately 1m above the ground. A CMOS camera is also mounted on the rover. The laser source is semiconductor laser. When the laser pattern strikes an obstacle, the pattern follows up over the obstacle.
As mentioned previously the optical sensor system is made up of laser pattern and CMOS Camera. The output of the laser is 5mW at a wavelength of 630nm. The output signal of the Axis 212 CMOS camera [section 3.3.2] is motion jpeg [39] sequence. Even though the hybrid system does not require any calibration, its geometry must comply with certain requirements. The camera and the laser pattern are mounted with offset to ensure the largest distance possible between them. This is to ensure maximum amount of reflected laser light to reach the camera imager. The laser is elevated (or lowered) with respect to the camera thus avoiding their horizontal configuration.

### 3.2 Architecture of the system

Figure 8 shows the system architecture of the proposed sensor system. Rover is operated from the host over the wireless communication. Environment sensing sensors as well as obstacle detection sensors which are assembled on the rover collect information and deliver it to the host for decision making. The image processing software is configured to run on the rover PC104 [20].
3.3 Active light sensor specifications

The Structured active light based vision system which is prescribed as basic sensor, detecting obstacles by image processing techniques. The sensor system is comprised of dot-matrix laser pattern and a camera, capturing the deformation of the laser pattern as it encounters obstacles. The sensor is built using off the shelf components. The sensor is expected to point towards the ground surface, thereby reducing the opportunity of undesirable eye contact with the laser beam. An optical filter sheet if glued on top of the camera lens, can reduce the effect of ambient light outside the laser’s bandwidth. The system presumes following conditions are fulfilled:

- The laser pattern is entirely visible (and in focus) inside the field of view of the camera.
- There is no relative movement between the laser pointer and the camera once the system is setup.

The camera must be capable of capturing the laser spots with a colour model in the field of view. The system is divided into four parts:

1. Laser pattern source
2. The observer (the camera)
3. Outdoor MERLIN rover, the mechanical part that gives the system its mobility
4. The underlying vision based program, combines the parts (1), (2) and (3) and avoids collision by detecting obstacle.

The following sections present each of these parts with brief description.

3.3.1 Laser

A semi-conductor laser and its diffraction grating are produced by the vendor Lasiris Inc. [40], and produces red pattern with 5mW output power. The laser is powered by a 5V source with a current of about 100mA. The diffraction grating in front of the laser splits the laser beam into a pattern. This setup provides coverage of the area in front of the rover with dense collection of laser spots near the rover, but sparse coverage of longer range terrain. The laser is an inexpensive module, with nominal divergence of 2 mrads and centre band at 630 nm. This laser is of class III [25].
3.3.2 Axis 212 CMOS Camera

An Axis 212 network camera with CMOS sensor [30] with configurable resolution of 320×240, 640×480 and 1024×768 pixels, frame rate range of 5-30 frames/s, mounted with a 6 mm microlens is used on the MERLIN rover. CMOS is a quite new technique that has several advantages over CCD, it is significantly less expensive to manufacture since it uses almost exactly the same manufacturing processes as those used to produce common memory chips, it is less power-consuming and it is easier to integrate other functions into the CMOS-chip, such as analogue-to-digital conversion and load signal processing. But CMOS also has some disadvantages, the most important ones being more sensitive to noise and having lower light sensitivity [70]. This is why most high-end cameras are equipped with CCD sensors. This is expected to change in the future as the CMOS technology matures.

The camera position and view angle is already preset on the rover. The camera optical axis is roughly parallel to the ground surface. This preset camera position is very close to ground surface with horizontal tilt configuration, resulting in capturing of unavoidable glare reflections from smooth surfaces, eventually blurring the laser
pattern. For better reception of laser spots, it is necessary to have the camera offset from the ground surface in order to sense a deflection in the projected laser pattern. The laser is angled downward so the centre of the pattern is near the centre of interest of the obstacle detection scheme.

The axis camera continuously sends sequence of Motion jpegs (MJPEG) [39] to the subscriber. At the receiver end, the MJPEG frames need to be decompressed and then decoded as shown in Figure 11. An open source package named Ffmpeg [40] is used for processing motion jpegs. After decoding, the image frames are converted to openCV format before being processed by the obstacle detection software. The usage of this camera is obliged for this thesis work, even though it is not suitable for colour based image processing. The camera tends to change its colour mode to grey mode automatically even for slight light intensity variations. The CMOS imager characteristics can be found in [41]. The advantage being no movable parts involved for pan tilt operation.

![Figure 11: Ffmpeg used for decoding Motion JPEG’s from Axis Camera](image)

### 3.3.3 Outdoor MERLIN Rover

The MERLIN (Mobile Experimental Robots for Locomotion and Intelligent Navigation) rover is used as a platform for sensor and navigation tests, as well as for testing various tele-operations scenarios. For the wheeled MERLIN rover details on the control and electronic architecture are discussed in this section.
3.3.3.1 Hardware architecture of Outdoor MERLIN rover

For each module specified in the following block diagram, inputs and outputs are pointed out and a general explanation of their behaviour is presented.

![Block diagram of rover hardware](image)

The robot is controlled by C167 CR 16-bit processor [28] and PC104 [20] 700 MHz Pentium III as shown in Figure 13. A motor with servo control module comprise the
driving and steering control of the rover. The AXIS 212 CMOS network camera is also mounted on top of the robot for live video acquisition and interfaced using Ethernet cable to PC104. The communication between C167 and PC104 is achieved via a serial port. The Debian Linux operating system is running on PC104. Standard TCP/IP protocol over wireless is employed for user-robot communication.

3.3.3.2 Computer hardware

The image processing software runs on Intel Pentium 3 processor at 900 MHz clock frequency and equipped with 512 MB of RAM and 4GB of flash disk. C167 micro-controller to which sensors and actuators are connected collects sensor data and delivers it to PC104.

3.3.3.3 Supplementary sensors

Mobile robots need sufficient sensors to extract information regarding the environment in which they are operated, in order to navigate. The MERLIN robot is interfaced with a number of sensors and also sensors for obstacle detection. Unfortunately, most methods are weak in outdoor environment. The Ultrasound based sensor or expensive laser range finder are considered to be a method for determining the obstacle, but they lack in providing sufficient precision. The sensors connected to MERLIN rover are

- Gyro determining the orientation by integrating the angular velocity of the rover.
- GPS receiver for determining the position.
- Live Video Camera capturing images with Laser pattern.
- One encoder for motor detecting motor revolutions.
- Rear view USB webcam.
- four ultrasonic ranging sensors
- 3D compass

The detailed description for sensors is presented in [37] [38]. Active Light uses only camera and laser source for its operation.
3.3.4 Software architecture

Details on detection algorithm, and performances, are presented here. The block diagram of the software architecture of the system is shown in the Figure 14.

![Figure 14: Architecture of rover software.](image)

The PC104 board runs debian Linux with 2.6 kernel version, and intel’s OpenCV based vision software. C167 microcontroller runs MERLIN OS. The server running on PC104 receives driving and steering commands from the client GUI and delivers the commands to MERLIN OS on C167, for further processing by drive/steering controllers. MERLIN OS interacts with client application program using MERLIN packet based protocol. The communication between the rover and the tele-operator GUI is comprised of UDP data packets transferred over wireless LAN.

**Software**

**Operating System:**

- Debian Linux kernel version 2.6 on PC104 [35]
- MERLIN OS on C167 [36]

**Language:**

The Plugin multi-driver is written in C++.

**Packages:**

- Intel’s OpenCV [20] and IPL computer vision library. [Ref 3.3.4.1]
- Player server [37] a device abstraction layer is also selected for providing drive and steering servo access over the network [Appendix B].
3.3.4.1 **OpenCV and IPL**

The Intel Open Computer Vision Library (OpenCV) [20], is a collection of algorithms for various computer vision problems. The library is compatible with IPL (Intel Performance Library) [20] and utilizes Intel Integrated Performance Primitives for better performance. OpenCV is mainly aimed at real time computer vision, and provides a large number of tools for image analysis, as well as tools for tracking. The Intel Image Processing Library, IPL, contains useful tools for image filtering and transformation, as well as histogram and thresholding functions. More information about IPL and OpenCV can be found in [34].

### 3.3.4.2 GUI for results of obstacle detection

A GUI module has been implemented to show all the results of the system on the screen. It is comprised of 2 windows shown in Figure 15. One for showing background subtracted video sequence and the other window is for live video sequence, with animated obstacle warning as overlay.

![GUI for Active light operator](image_url)

*Figure 15: GUI for Active light operator*
3.4 Laser pattern for surface sensing

Figure 16 shows the projection of the 20 x 20 divergent laser beams on an area of e.g. 200 cm² at a distance of 2 m. Since pattern area and density are proportional to the distance, different obstacles can be captured at full resolution.

For an obstacle to be detected it must be in the path of the laser pattern and in the field of view of the camera. Simple median filtering cannot be used for smoothing because the laser spots cover areas of several pixels in diameter.

3.4.1 Scanning different surfaces

The optical properties of the ground surface significantly determine the performance of the laser scanner. The optimal surface type for scanning purposes is a totally Lambertian surface with a high reflection index. Figure 17 and Figure 18 show how a light ray behaves under both a Specular and a Lambertian surface. Translucid surfaces are often present in our everyday life (certain types of rocks or minerals, etc.). Figure 19 shows how a ray of light behaves when it impinges on such kind of surface. In a translucid surface, light reflects as in a lambertian surface, but it goes through the material until a certain depth. The higher the light power, the deeper the light penetrates inside the material. In addition, the light scatters inside the material, so that a camera observes as if laser reflexions sourcing from inside it. Example of light behaviour and a study of how it affects on marble surfaces can be found in [17].
The laser light impinging on a translucid surface as in Figure 19 induces a lot of undesired light peaks where they are not expected to be. In addition, if the light power is lowered, the noise due to the different sources becomes more and more significant and hence, the laser pattern image quality degrades. In addition material’s excitation wavelength varies with surface type. For optimal performance laser with suitable wavelength range matching that of surface materials excitation wavelength should be chosen.
3.4.2 Identifying obstacles and avoiding collisions

A standard video camera produces 5 to 30 images or frames per second. This is known as the frame rate, which is the sensing frequency for this sensor. Thus a minimum time range from 1/5 to 1/30 second is required to update the model. A video camera also has a relatively low resolution, which means that the laser pattern deformation due to objects is typically very small, which will have consequences for the whole system. The pre-processing part prepares the captured image for the laser detection process, e.g. reduce the size of the image for performance reasons (although this naturally makes it harder to detect small objects). The detection process tries to identify interesting details, or features, in the image. This can be done in a number of ways [section 4.2.4.3]. Here as first step the background information is subtracted [section 4.2.1.3] and later any deformation in the pattern due to obstacles is examined, especially ones that are on collision course. Predictions of the laser pattern shifts due to inherent vibrations of the rover movements, is found from the tracking process, thus aiding the obstacle detection. This will be examined more thoroughly in later [section 4.2.5.3].

3.4.3 Structured light pattern deformation

The laser is equipped with a special optical head (diffraction grating) which generates a high quality dot-matrix pattern from the laser beam. The pattern consists of 20 x 20 dots. As mentioned before, an optimal design of the structured light set gives an optimal safety for navigation.

![Figure 20: Image of structured light deformation against positive obstacle](image-url)
Let us consider an example of the projected laser pattern. The pattern seems to be small when the wall is near and big when the wall is far away. Assume here that the laser source is one meter in front of the wall and assume that the size of the pattern is square with each side one meter. When projected against the lower corner of a wall, a change in the shape of the pattern can be observed, due to angle of the wall as shown in Figure 20. The reason for using the laser beams is to keep the amount of the light energy along the dispersion direction.

The pose of the pattern can be described by five points. One centre point and four points placed on the border of the pattern where there is 90-degree difference between these points. This set of identification points gives us exactly the information of the pose of the pattern that is visible on the wall. These points are the ones that are most important to identify the pose of the pattern. For the negative obstacles similar pattern variation can be observed as depicted in Figure 21. The dot-matrix pattern used provides an acceptable method to successfully establish the reflection projection correspondence needed to detect pattern deformation. Figure 22 shows video sequence of obstacle detection for negative obstacles.

### 3.4.4 Light intensity compensation and intensity invariant operation

For correct detection of the laser reflection off the ground surface, it is imperative that image saturation be avoided. Saturation may destroy the brightness profile information that allows the system to discriminate between the laser return and other
sources of light in the scene. Since the sensor is mounted on moving platform, the light conditions will continuously change, and fast adaptive light compensation must be applied. The system needs to work in all types of lighting environments. By adjusting the shutter rate, gain, exposure and various other settings on each camera it is possible to ensure that the laser pointer is both brighter than the surrounding area in the camera image and displays a minimal blurring effect between frames. This however, is not enough to ensure that the dot can be accurately detected.

![Image sequence from (a) to (f) showing structured light deformation at Negative obstacle](image)

**Figure 22: Image sequence from (a) to (f) showing structured light deformation at Negative obstacle**
The problems observed with using a constant threshold are separated into two groups:

- **Spatial intensity variations.**

  The reflectance distribution function of the laser pattern and ground surface causes large variations in the measured intensity of the laser pattern captured by the camera, when the rover is in motion. This happens because the angle between the laser beam incidence and the camera’s view vector varies significantly as a function of where on the ground surface the laser beam hits. There could be situations in which the ground surface at certain parts of the camera image is brighter than the laser pointer in other parts of the camera image. A constant threshold value is unable to accurately classify the laser pointer in this case.

- **Temporal intensity variations.**

  The captured images may have significant intensity variations from frame to frame, since they are not synchronized to the refresh rate of the laser projector. This can render any automatic gain correction useless. A constant threshold brightness used to identify the laser dot must take these variations into account. Additionally, things such as bright flashing lights in the background can cause significant detection problems. The solution developed is the use of a background removal process.

### 3.4.4.1 Optical bandpass filter

A single chip colour sensor CMOS is relatively inefficient, in terms of light sensitivity. This is due to their colour pixel arrays (e.g. bayer pattern), with only some of their pixels being sensitive to a specific wavelength. Amplitude of such wavelengths would saturate the pixels, loosing the desired signal information. Digital filters can be useful only when the imaging sensor is more sensitive in particular wavelength range and the ambient signal from exposure should not saturate the imager. Thus most of the ambient light (which is noise), should be completely blocked in order to just capture the laser pattern reflections.
Figure 23 A red bandpass filter, blocks ambient light and also provides additional attenuation of infrared and other unwanted longer wavelengths that most camera are sensitive to, resulting in maximum contrast when using 630nm red laser diode. [36]

A band-pass filter [36] as shown in Figure 23 can be used to improve contrast and thus achieve better control over changes that may occur over time in ambient lighting conditions. A broad pass-band allows a filter to perform well when wide-angle or shallow-incident angle is used. The current system does not include any optical filter, inclusion of which would result in performance boost.

3.4.4.2 Linear Polarizer

Light reflected from a non-metallic surface, results in polarization of the reflected light. This polarized reflected light can be the result of uncontrolled ambient light. As the angle of incidence of the light and the camera relative to the subject are about the same and approach 55° to normal, a “glare” and loss of contrast become more of flashy causing distractions. Linear polarization helps in reducing primary and specular reflections off a surface. By using a linear polarizer [36] in front of the laser source, the light emitted from the sensor is oriented in the direction of the polarizer (Figure 24). Only light waves parallel to the direction of the linear polarizer will be transmitted.
When the polarized light bounces off the reflector ground surface, the direction of polarization becomes partially random (depolarized). Some of the returned light then passes through a second linear polarizer (positioned perpendicular to the source polarizer) and lands on the photo detector. When a shiny object blocks the beam, the reflected light remains polarized, and does not reach the photo-detector because it does not have the same polarity as the filter in front of the detector. Thus using polarizer filters, glare and unwanted reflections can be suppressed. The present system lacks usage of linear polarizer, which otherwise improve the overall obstacle detection quality.

3.4.4.3 Neutral-density filters

Neutral-density filters [36] can be used when operating in environments where lighting is extremely bright. They generally appear gray in colour and reduce the amount of light reaching the sensor without affecting colour balance or contrast.
Filters can range from an optical density (OD) of 0.30, which transmits about 50% of visible light, to OD 1.20, which transmits about 6.25% of visible light.

Another common use for neutral-density filters is to decrease the depth of field by allowing wider lens apertures to be used. This helps to separate subjects from their foreground and/or background, as the subject (here in this case laser pattern) will appear in focus, while the background will be out of focus [36]. The use of neutral density filter is highly recommended for improved laser detection, as it is not used in the current system.

3.4.5 Conventional methods for separating reflected laser from ambient disturbance

The reflected laser can be easily separated from ambient lights by intensifying the projected laser which results in improved S/N ratio. A laser source is very desirable for this sensor because of its excellent beam characteristics. The second approach involves increasing S/N ratio by using an optical filter, thus eliminating wavelengths other than that of laser. An interference filter can provide very sharp bandpass characteristic. Sunlight includes, however, plenty of light elements having wavelength the same as laser, and consequently, an optical filter alone cannot perfectly cut ambient disturbance though it can reduce the intensity of the disturbance.

Normalising colours attempts to eliminate illumination effects.

1 Colour normalization based on chromaticity
2 Colour normalization by Histogram Equalization.

However, both techniques are not been very successful in eliminating illumination side effects. Converting RGB to Grey loses information. An obvious problem with greyscale images is iso-luminant surfaces, i.e. surfaces with colors map to the same level of grey scale. One of the main objectives of choosing a colour space is to eliminate the effects of shadows and highlights. Under HSV colour space model, Hue wraps around at 360º, so comparison is not monotonic around Red (which is at 0º or 360º by definition). Also, there is no representation for pure Black and White in Hue.
In fact, any pixel where the R, G and B values are equal, i.e. shades of grey, cannot be represented as a Hue.

### 3.5 Minimum time to avoid collision

As per the requirement specification of this thesis, the rover should be able to avoid collisions moving at a speed of 0-10km/hr. The laser is projected 2m ahead of the rover, and the pattern spreads for about 1m length. Thus the top portion of the laser pattern which is spread on the ground plane is separated by a distance of 3m (2m+1m) from the rover. The outdoor MERLIN rover can achieve a top speed of 50 km/s. Time required for covering 3 m when moving at maximum speed 50 km/hr:

\[
\frac{60 \times 60 \times 3}{50000} s = 216 ms \quad (1)
\]

The maximum speed the outdoor MERLIN can operate in autonomous mode is 10 km/s.

Thus to avoid collision the system must detect presence of any obstacle within:

\[
\frac{60 \times 60 \times 3}{10000} s = 1.08 s \quad (2)
\]

### 3.6 Real Time Processing

Active light optical system must operate in real-time as it is designed to perform obstacle detection task while interacting with real world. The vision provides the most comprehensive information about the outside world. Thus considering the sheer intensity of the flow of video data which has to be processed, an efficient visual processing is a crucial component to achieve the desired goal. This information however is critical, since the usefulness of a laser based obstacle detection depends on its reliable real-time performance. The processing bottleneck here is directly related to the image processing involved in the detection of the laser spots, since it must be repeated at a high frequency. It is important due to the fact that it defines the theoretical lower limit of obstacle detection latency.

Laser pattern deformation detection and tracking algorithms could be used in a real time obstacle detection system. All measures are taken to adapt some of the least computationally demanding algorithms for the system. For our application it is crucial
that the algorithm runs in real-time and reacts predictably to unrehearsed environmental conditions. The computing power allocated for computer vision was that of just one Pentium III 700MHz computer as specified earlier. Furthermore, this computing power is also used for receiving images from the IP based Axis 212 camera, for calculating image statistics to adjust camera parameters, for video compression. Therefore only half of that computing power is available for the actual computer vision part of the algorithm. To achieve performance of about 15fps and to keep the algorithm simple and hence more robust, the algorithm is more predictable for simple parameters. Furthermore, the runtime of the program depends linearly on frame rate and image resolution. The camera optics is zoomed such that the overwhelming proportion of the pattern is visible in the scene, at image resolution of 320 × 240.

The code is written using Open Source Computer Vision Library (OpenCV) [18] maintained by Intel. OpenCV is a comprehensive collection of C code optimized computer vision algorithms under a BSD license, with Intel Integrated Performance Primitives [19] software library containing assembly level optimized routines that OpenCV makes use of can also be utilized.

### 3.7 Sensitivity

Given the spread of the laser pattern, less power is reflected back to the sensor, and reliable/complete reflection detection may be difficult. A popular technique to increase the detectability of the laser reflection is to modulate the light power synchronously with the photoreceptor reading rate. For example, with a simple on–off modulation, frame differencing can be used for reliable detection in static scenes. Note, however, that in the case of highly dynamic scenes (or when the device is moved around, as in our case), frame differencing may yield noisy results, and more complex processing may be needed.
Chapter 4

Video and Image Processing

The main aim of image processing module is to extract laser colour regions in the images where the detected laser spots are supposed to be. This is used to confirm that all the detected laser spots correspond to real laser spots. After extracting laser dots, the resulting image is searched for any deformation in the shape of the laser pattern. This section provides usage of digital processing techniques in order to cope with the detection of laser pattern for the scanning of various types of surfaces with different optical properties and different noise levels.

4.1 Noise

Once the video sequences are captured as image frames, the frames are scanned for laser spots. The laser spots are affected by the superposition of certain amount of undesired external lighting. There could be 4 noise sources:

- Electrical noise
- Quantization noise
- Image blur
- Speckle

The first 2 noise sources are associated the image sensor, Electrical and quantization noise are very significant when the S/N is very low (i.e., when the laser spot power is very low). A thorough study about the performance of CMOS image sensors and how electrical noise affects the image quality can be found in [26]. This is commonly found when the surface exhibits a very low reflection index or when scanning at very high speed. The Speckle is related to reduced wavelength of light compared to the surface roughness and the mono-chromaticity of the laser light [27]. The image blur is inherent in the wide angle cameras due to the lens curvature. Noise level plays an important role in the results evaluation of any sensor device. In standard cameras, the most influencing noise has been found to follow a Gaussian probability distribution
[26] (which is a consequence of point spread function), due to the imperfections in the lenses and the grey level digitization. These noise sources combine together and make the observer see the constructive and destructive interferences within the laser pattern.

An accurate obstacle detection process needs precise laser deformation detection. Optical properties of the surface significantly determine the performance of laser detection process and thus identification of laser pattern deformation, for obstacle detection.

## 4.2 Implementation of obstacle detection algorithms

The theoretical aspects presented earlier provide a basis for obstacle detection, which is transformed into an operational system. As preliminary work a prototype design is developed as a proof of concept described by the theory. Later more advanced methods are used for baseline version of the system.

### 4.2.1 Pre-processing steps

#### 4.2.1.1 White Balancing

White balance (WB) is the process of removing unrealistic colour casts. The Active light system suffers from sudden changes of image intensity due to the illumination noise. The camera can be configured for automatic white balancing. Most cameras have AGC (Automatic Gain Control) or Automatic White Balance. WB improves colour image capturing under a wider range of lighting conditions.

#### 4.2.1.2 Frame Rate

The purpose of this section is to determine the needed frame rate for the system. A high frame rate makes it easier to capture minute variations in the pattern correctly. However, a high frame rate leads to higher computational requirements.

#### 4.2.1.3 Laser detection approach

The laser pattern intersects the obstacles in the scene and produces a visible contour of deformed pattern. For example, the projection of laser onto a plane produces a pattern with a different shape than if the laser is projected onto a ball. Thus the deformation of the laser pattern reveals information on whether obstacle is present.
Therefore, the first goal is to detect the laser pattern with a maximum accuracy. Here a fast laser spot detection method that can be used for real-time obstacle detection is presented. The capturing of reflected laser spots can be improved by optical filter in front of the camera lens [Ref section 3.4.4.1] and to the light compensation mechanism that reduces the chances of saturation. However, other image points may be brighter than the reflected laser. Typically, this occurs in correspondence of specular reflection from shiny surfaces. Hence, the brightness profile over a whole region must be analyzed for robust detection. Different background subtraction methods implemented for extracting laser spots. Figure 26 shows block diagram of Background subtraction process. Each video frame is fed to the background subtractor to get the output frame with only laser spots.

![Figure 26: Background subtraction](image)

**4.2.2 Obstacle detection by Template matching method**

Obstacles must be detected at early stage to avoid collision. This means that slight variation in the laser pattern as small as a couple of pixels must be pointed out as presence of obstacle. It is important to have in mind that this will be severe under outdoor conditions. Low contrast, e.g. objects with a similar colour or intensity as the laser will be almost impossible to detect using a single detection method.

**4.2.1.1 Segmentation by intensity**

This method uses information based on the light intensity of the laser spot to detect it on camera images. Segmentation by intensity aims to separate the background from the laser pattern that can be found within the image using the assumption that background is darker than the laser as shown in Figure 27 (a) image. For this task, threshold is an appealing method as by this means it is computationally inexpensive.
and fast. The success of background subtraction by thresholding is however solely depending on our knowledge of the background intensity properties. For the (a) image in Figure 27 any pixel intensity dimmer than laser spot intensity is turned null, and the resulting (b) image (with red laser dots) is found.

![Figure 27: Background subtraction using Segmentation by intensity (a) source image (b) result image](image)

Even the parallel use of several different detection methods may not be accurate enough to robustly detect objects. The captured images contain intensity information divided into three colour components: Red, Green and Blue. The detection process uses this intensity information to separate foreground objects from the background, and then uses Template matching process for obstacle detection. Figure 28 shows a reference laser pattern template.

![Figure 28: Laser pattern template](image)

The thresholding algorithm results with an image with pixels having a value of zero (black colour) or one (white colour). The threshold is set above this maximum intensity value by a margin that is adjusted to be close enough to help laser spot detection without hampering the binarization process due to variations in light measurements by the camera that could be related to noise or reflections on the display.
Figure 29: Block diagram of conceptual design of Laser pattern deformation identification.

Matching is performed with the help of OpenCV’s function cvMatchTemplate [34] as it can be easily modified to perform other standard matching functions such as the sum of squared differences and cross correlation. Once matching has been completed, any deformation in the laser pattern indicates presence of obstacle. Figure 29 shows the schematics of template matching based obstacle detection. The input frames are background subtracted and matched with a predefined template frame. The obstacle detection method can be divided in 3 steps, illustrated in Figure 30.

Figure 30: Obstacle detection steps

In template matching the detected laser pattern is matched to a predefined template as shown in Figure 31 for a typical scenario. Any mismatch is treated as presence of obstacle and the exact position of disparity is highlighted to indicate possible location of the obstacle. It is a simple method easy to implement but not a robust method as it fails in cases where the entire pattern shifts due to rover vibrations. Figure 33 shows flow chart of Template matching method.
Figure 31: Laser pattern deformation identification using template matching. The input image (a) is background subtracted to get image (b) which is later compared with template (c), and the location of disparity is highlighted in (d).

Figure 32: Flow chart of Template matching method

Video Capture (new image frame)

Thresholding (as per configuration range)

Set region of interest (ROI) and perform template matching

Any Laser spots in region of interest ?

Obstacle found ?

result
4.2.3 Boundary Masking based method

4.3.2.1 The vision and the identification using masking

The most crucial part of this vision system is how the projected light sources are affected by the geometrical form of obstacles in the field of view. So the most important part of the image that is observed by the camera is the pattern of the laser beam that is deformed due to the object. One way get only the pattern is to filter these images for laser dots. The filter techniques that are usually used are computationally challenging. Instead of using complex methods that demand high computing, simple methods are experimented. One way to identify only the pattern from the laser beams is to set the region of interest as the area covering only the pattern in the captured image.

\[ C = B \ast A \]  

Where the picture A is the image with projected light sources, the picture B is the mask of the standard pattern created when the laser was projected on horizontal reference surface. By masking onto the frame A, information of the position of each laser dot displaced off its original pattern can be found. The mask that is used in this thesis is simply a zero matrix of the same size as the filtered image except for the interesting regions where there are ones. As given in equation (1), by element-wise multiplying the mask with the image C, a result frame having information only in the region of interest that is chosen in the mask where the pattern is visible is obtained. In other words, after the masking process the resulting frame contains patterns that are affected by the geometrical form of the obstacles. An example on masking strategy is shown in [Appendix A.3].

4.3.2.2 Global thresholding

In this method a simplest approach for background subtraction by Global thresholding of the image is used. In brief this operation examines each of the input image’s pixels. If the input pixel’s intensity is above the chosen threshold level the corresponding output pixel is set to one and if the intensity is below the threshold level it is set to zero, i.e. thresholding is the transformation of an input image (a) to a binary (black and white) output image (b) defined as in Figure 33.
The RED channel of the RGB colour model of i/p image in Figure 33 is extracted. Any pixel value dimmer than laser spot value is turned null and others to 255 (white colour), and the resulting (b) image is found. Correct selection of threshold value is crucial for successful segmentation. Pixels with intensity above this threshold are treated as background. The threshold operation in OpenCV can only be used for one of the image’s colour components, at a time.

**Detecting Positive obstacle**

Figure 34: Image sequence from (a) to (d) showing positive obstacle identification by boundary masking
In this method imaginary boundaries around the laser pattern is presumed as shown in Figure 34 (a). The positive obstacles as they approach the laser pattern as in Figure 34 (b), due to ego motion, the pattern appears to climb up as it encounters the obstacles, hence entering its outer boundaries Figure 34 (c). Thus positive obstacles can be easily detected by just masking outer boundaries of the laser pattern and searching for any laser spots presence. Figure 34 (d) shows the result of application of boundary masking method for positive obstacle. Masking method when applied for positive and negative obstacles found to be working reasonably well, but the only shortcoming is, it fails to detect any variation within the pattern i.e., any deformation in the laser pattern other than boundary region is not detected.

**Detecting Negative obstacle**

Similarly negative obstacles can also be detected by taking interior boundary, within the laser pattern as shown in Figure 35 (a). But in this case the inner boundary is checked for absence of laser spots. If the laser spots are absent within inner boundary then it indicates presence of negative obstacle depicted in the frame sequence (b) to (d) in Figure 35.

![Image sequence from (a) to (d) showing negative obstacle identification by boundary masking](image)
4.2.4 Optical Flow method

Optical Flow (OF) produces a set of vectors at every point in the image that indicate the direction of pixel movement. The flow vectors are not calculated over the entire image for computational reasons. It is based on two basic assumptions [28]:

1. The observed brightness (intensity) of any object point is constant over time.
2. Nearby points in the image plane move in a similar way.

Ego motion estimation and relative depths toward the obstacles can be derived from optical flow. The key feature is the use of the temporal derivative of the flow field to compute the normal surfaces of the obstacles. OpenCV provides two popular algorithms Horn & Schunck [37] and Lucas & Kanade [38]. The OF would appear to originate from the Focus of Expansion (FOE) on the horizon. A tilt in the camera indicates that the FOE is not in the centre of the image, i.e. not at the horizon. Given the geometry of the camera, it is possible to calculate the flow field of the laser pattern at a particular speed. Optical flow follows “Structure from Motion” paradigm in computer vision. Computing the optical flow field of two consecutive images of a
video yields the approximation of the motion field. While the computation of optical flow generally means to compute the flow vector of every pixel of the image and thus obtain an exhaustive global flow field, it is possible to do this computation only for an exclusive number of features. This results in a sparse optical flow field. Although there are chances to lose out laser pattern pixels, but those are exception cases. As the laser pattern approach positive obstacles, due to ego motion, the pattern appears to climb up and resulting in distinct flow field vector which stands out over entire flow field. This can then be subtracted from the overall field and obstacles will stand out as having maximum flow field vectors for positive obstacles and least flow vectors for precipice. In practical terms OF is an expensive computation that is noisy and not reliable in many circumstances as in Figure 37.

![Figure 37: OF image for the wide variations](image)

The OF using correlation-based techniques is similar to disparity mapping using Stereo-vision. The difference is that in OF the images are separated temporally, whereas for Stereo Vision they are separated spatially. Unfortunately, the task of correlating images for OF is complicated by the fact that robots in the real world are subject to vibrations. The main concern in OF is the sampling rate. A faster sampling gives smaller differences, and therefore it is easier to find correspondences. However, this also means that the flow vectors will be relatively small. OF is ineffective when
the image flow is small compared to the image noise. Figure 38 shows flow chart for obstacle detection using L&K optical flow method.

Figure 38: Flow chart for obstacle detection using L&K optical flow method

4.2.4.1 Analysing grey level image Histogram

The following Figure 39 (b) and (d) are the intensity histograms of frames (a) and (c) respectively. As from the Figure 39 (b) the histogram has a distinct peak, which is due to the laser pattern in the foreground. The distinctiveness of this peak is solely dependent on the size of the pattern and, of course, its intensity properties. The second peak which is slender belongs to the background, whereas the rest may contribute noise. By using this information a threshold close to, but below, the intensity of the background can be applied, leaving only the pixels with a lower intensity than the surface. This selection of threshold value is made upon the doubtful assumption that laser to be found are brighter than the background. It is true in most of the cases but not all, due to the different daylight conditions. One simple way to handle this is to use two threshold levels and by that remove pixels within an intensity range around the intensity of the background. The selection of a suitable threshold level is, for that
reason, more difficult. The thresholding using histogram is computationally inexpensive method. The limitation is that sensitivity to non-uniform lighting. It is hard to detect laser spots with same intensity as the background.

Figure 39: The image’s (b) and (d) are intensity histograms of the images (a) and (c) respectively

4.2.4.2 Threshold of each colour component

A simple improvement would be to use different threshold levels in each of the three different colour components of RGB colour model. In Figure 40 the histogram of each colour component of the Image is shown. The red-component contains higher intensities than in the other two components. By selecting a higher threshold in the latter component it is possible detect pattern with a high intensity that otherwise would have been lost during the threshold. Another way to use the intensity information in the separate components is to classify each pixel with red as a dominant component, i.e. pixels with blue < red, and red > green, as foreground. This requirement can easily be extended to only set pixels with red > u * blue and red > v * green, where u, v > 1, as foreground and by that require the red-component to have a
certain level of dominance (aiding in laser extraction). The method is simple as colour information is taken into consideration.

![Image](image.png)

Figure 40 Histograms of each colour component for (a) Image. Histograms of red (b), green (c) and blue (d) components of the source image (a) respectively

### 4.2.4.3 Feature Extraction

Rather than processing all pixels belonging to an image frame, it's efficient to focus on few coordinates containing distinct features, that can be assumed to occur in two consecutive images, for example laser spots. In OpenCV the method GoodFeaturesToTrack is designed to find pixels with big eigen values in the image. This is done in four steps:

a. The method first calculates the minimal eigen value for every pixel (indicating magnitude of colour intensity change at each pixel) in the source image and stores them in a temporary image of the same size as the input image.

b. It then performs a non-maxima suppression, a routine that suppresses (to zero) all but the local maxima in a in 3 x 3 neighbourhood.

c. By submitting a “quality level”, the method then rejects weaker regions, i.e. regions with an eigen value less than the required quality level multiplied by max(eigImage(x,y)).

d. The method’s last step is to ensure that all the regions found are distanced enough from one another and checking that the distance
between the newly considered feature and the features considered earlier is larger than a submitted minimum distance, i.e remove the features that are too close to the stronger features.

This method found to perform reasonably well for feature extraction in the pattern deformation detection process. A way to reduce the information for each detected object even further is to consider only the centre position of each object along with their size and orientation. The method CvFitEllipse [34] available in OpenCV calculates an ellipse that fits best, in a least square sense, to the extracted features. Since the size of the ellipse is available after this operation, a useful property like growth-rate can be computed. The size be used to make comparisons between frames. This change in the size is the key for speculating pattern deformation, hence presence of any obstacle.

4.2.4.4 Detecting obstacles using optical flow

It is possible to calculate the expected optical flow in every point, or at least its expected direction and maximum value (it is always possible that there is no optical flow at all). Considering images frames with laser spots, the spots optical flow depends on the nature of the surface it is being projected. When the rover is in motion on plain surface, all the laser spots have same OF. But the OF values change when obstacles encountered. This is due to the expansion of the focus and it is in the direction of heading. One can then calculate the actual optical flow in the image sequence with one of the optical flow methods in OpenCV and compare it to the expected optical flow. If any laser spots OF is found to differ significantly from the expected optical flow, and this is not because of noise, it should be likely that this comes from an obstacle. Using OF precipice can be easily detected. The main limitation is its higher complexity.

4.2.5 Obstacle detection by using CamShift

4.2.5.1 Introduction

The Continuously Adaptive MeanShift (CamShift [29]) algorithm is generally used for tracking the shape and orientation of a single colour object. Here an obstacle
detection method using CamShift is proposed and the algorithm is tuned for detecting laser pattern deformation. The principles of the method are shown in Figure 41. Input video image frames are converted to HSV colour model. The frames are segmented for a suitable range of hue and passed to the CamShift algorithm in order to locate the centre of the laser pattern blob.

4.2.5.2 Red colour segmentation by hue

The HSV colour space provides us with a component containing the colour wavelengths called hue. In brief segmentation by hue is archived by setting all pixels that have a hue in a specific range around the background’s hue to belong to the background. Those pixels with a different hue are by that set to be laser spots. The range of hues that will be classified as background is selected by examination of the hue component’s histogram looking for the background’s distinct peek. Figure 42 shows, captured image and its hue histogram.
The main advantage using this method is that effects of lighting and shadow can be reduced, since the intensity and saturation information are separated from the hue component in the HSV colour space. In case segmentation does not produce high quality regions or the regions have been fragmented, CamShift will treat each region as a probability distribution and locate the centre of the region. This hue based matching scheme provides a robust method for laser pattern deformation detection.

![Figure 43: Histograms of hue (b), saturation (d) and value (f) components of the reference image (a) (top image with laser pattern). It is possible to detect pixels distributions in each channel.](image)

On the other hand, a great disadvantage is that hue is undefined for grey-scale colours, which is unfortunate, since grey colour may occur in operational scenario. It is true that completely grey pixels are very rare in natural images, since there is often some small amount of colour present, but since noise occurs in the image it still would be unfortunate to use hue for these pixels. Segmentation by hue will perform better when the laser is reddish. Figure 43 shows, reference image and its hue, saturation and value histograms corresponding to HSV space. Reference image is divided into Hue, saturation and value component images. Later for each of these images respective histogram is found. As expected, hue can be a good criterion for classifying between
laser and background surface when the surface has a high saturation and the laser has a different hue than the background, as in the first two images. However, the method is more inaccurate when the background is covered with greyish texture. In the later case the image contains a great portion of pixels that, by the threshold mentioned above, would be classified as undetermined due to its low saturation. The method is insensitive for non uniform lighting and shadows. Handles surface as background. Hue is undefined for grey, which can be a problem when operating in dull lighting conditions. In low saturated image areas the performance is weak. Laser pattern with the same hue as the background cannot be detected. The HSV colour space is used as a basis for representing colours in the following figures.

4.2.5.3  Laser Pattern Tracking

The active light is built with a main objective for obstacle detection in outdoor environment. Since the outdoor surface is uneven and randomly bumped. Due to this the Outdoor MERLIN would capture shaky, tilted, rotated image of the laser pattern as it moves on the rough surface. The laser pattern shifting due to inherent vibrations must be handled. Tracking is the process of estimating the motion (shift) of laser pattern (in this case) on ground surfaces, using preceding observations. In the obstacle detection case projected laser pattern on the ground surface is tracked for deformation with the help of video images. The output signal from the video source is not reliable, as they are noisy and have limited accuracy. Thus, in order to be able to estimate the pattern shift, a robust and efficient algorithms need to be used to keep track of pattern between consecutive frames. The output from this algorithm can then be used as a description of the laser pattern’s path across the image. For this obstacle detection system the laser pattern tracking stage is as fundamental as the detection stage.

4.2.5.4  The CamShift algorithm

The CamShift [29] is an adaptation of the MeanShift algorithm [30]. The CamShift is an iterative technique, operates by finding the mode of probability distribution. For each frame in a video sequence, the image is first converted to a colour probability distribution function by manipulating the image's histogram. The centre, size and orientation of the distribution will be found by CamShift and this new information will be feedback as initial condition for processing subsequent frame as specified in
the flow chart Figure 44. The frame captured from the camera is first converted to the HSV colour space and the hue channel of the image is thresholded so that only the red colour (laser colour of interest) is retained. Colour is undefined for pixels with neutral shade (white, grey or black). Colour can be computed for pixels that are almost neutral, but their colour values are unstable and these pixels contribute as noise. This noise is screened out by thresholding those pixels which are too close to neutral. Almost black, white and almost grey pixels are ignored.

Next, the histogram of the image is calculated and will be used to calculate the colour probability distribution image of the desired red colour which is called the back projection image. The back projection replaces each pixel in the frame with the probability that it is a red (colour of interest). Once the back projection image has been obtained, it will be used for the MeanShift operator. In the CamShift technique, it is required to specify an initial window, in this case the region of laser pattern spread. Information on the distribution of red colour probability within the search window is used for the MeanShift operator. MeanShift is fed with the last-known bounding rectangle of the laser pattern (or the initial search window in the case of the first frame) and the new position (the centroid) of the region is produced. Using MeanShift, CamShift calculates the centre of the local distribution and expands the search window size slightly until convergence. Finally, new bounding box, size, orientation, indicating the laser pattern region is determined. This is done by calculating the moments of the region. Updated information about the pattern is used as feedback for the MeanShift operator in the subsequent frame.

The MeanShift algorithm described briefly as follows:

1. Select an initial search window size for the laser pattern.
2. Determine the initial location of the search window in the image
3. Compute the mean location in the search window
4. Focus the window at the mean location obtained in step 3
5. Repeat step 3 and 4 until convergence, i.e. the difference between the old and new location is smaller than the chosen threshold or a certain number of iterations has been reached.
The CamShift algorithm described briefly as follows:

1. Apply MeanShift and store the zeroth moment (Zeroth moment, is the laser colour probability of pixel value at position (x, y) range over the search window)
2. Reset the window size according to the zeroth moment found in step 1
3. Repeat step 1 and 2 until convergence (mean location moves less than a threshold)

Steps for obstacle detection using Camshift as follows:

1. Create a colour histogram of the Laser Pattern
2. Calculate “Laser colour probability” for each pixel in the incoming video frames.
3. Shift the location of the laser bounding box in each video frame.
4. Calculate the size, position and angle of the laser pattern
5. Check the new values with threshold for any deformation in the pattern.
   Deformation in the pattern indicates presence of obstacle.

![Reference laser pattern image](image1)
![hue histogram](image2)

![Laser pattern with obstacle](image3)
![hue histogram](image4)

Figure 45: Comparison of reference laser hue histogram (top) against laser with obstacle hue histogram (bottom).

Create a colour histogram of the Laser Pattern

Figure 45 shows two example histograms. The height of each coloured bar indicates how many pixels in an image region have that “hue”. In the image region represented
by top histogram reddish hue is most common. The bottom histogram shows a region in which bluish hue is the most common and pinkish hue is the next most common.

**Calculate “Laser colour probability”**

The histogram of the reference laser pattern is created only once at the beginning. Later it is used to assign “Laser probability” value for each pixel in the video frame that follow. Figure 46 shows the hue bars from a histogram stacked one to the other. After stacking them, it is clear that left most bar accounts for 40% of the pixels in the region. That means the probability that a pixel selected randomly from this region would fall into the rightmost bin is 40%. That is the “Laser probability” for a pixel with this hue. The same reasoning indicates that the “Laser probability” for the next histogram bin to the right is about 35%, since it accounts for the 35% of the stacks total height.

As new video frames arrive, the hue value for each pixel is determined. From that, the histogram of reference laser pattern is used to assign a “Laser probability” to the pixel. This process is called “histogram back-projection”. Black pixels have the lowest probability value and red the highest, Grey pixels lie somewhere in the middle.

![Figure 46 Laser probability, bars in histogram stacked one top the other. The probability associated with each colour is % of that colour bar contributes to the total height of the stack](image-url)
**Shift the location of the laser bounding box in each video frame**

For each new video frame, a new estimate of the laser pattern location is done, keeping it centred over the area with the highest concentration of bright red pixels in the “Laser probability” image. The new location is found based on the previous location and then computing the center of gravity of the “Laser probability” values within a bounding rectangle. The rectangle is shifted such that it always stands right over the center of gravity. This process of shifting the bounding rectangle to correspond with the center of gravity is based on the algorithm called “MeanShift”, by Dorin Comaniciu [29].

**Calculate the size and angle**

The size and the angle of the bounding rectangle for the laser pattern is adjusted each time it is shifted (by Meanshift). It does this by selecting the scale and orientation that are the best fit to the “Laser probability” pixels inside the new rectangle location. After the segmented image has been available, (the Suzuki-Abe [45] algorithm is used) determine the search window region. For each connected region in the image, the initial search window is set equal to the bounding box of the region.

![Figure 47: Two scenarios for obstacle detection by using Camshift, (b) & (e) are hue images of (a) & (d), and their background subtracted images (c) & (f) respectively.](image)
Check the new values

Compare the new values with threshold values for any deformation in the pattern. Deformation in the pattern indicates presence of obstacle. Figure 47 shows laser detection considering the system as a whole, in order to analyze the usability and effectiveness of the application. The system is able to detect obstacles in a scene image and output the resulting image with an alert message is also displayed at the bottom of the display.
Chapter 5

Experiments and Results Analysis

This chapter focuses specifically on the experiments of the real-time Active light obstacle detection under different circumstances and environments. The results of the experiments conducted towards evaluating the performance of the system are presented. The Active light sensor is evaluated by conducting system level tests. This chapter is divided into sections, each one to show the performance results and analysis of the data collected as part of test scenarios. Each section starts by addressing how the experiments are to be conducted. The experimental environment and setup are described. A discussion on the results is given at the end of the section in graphical and tabular formats.

5.1 Testing

The Active light system is evaluated for its operation by taking various factors under consideration and testing the system against each of them. The experiments are performed using each of the schemes, considering tests for indoor and also outdoor environment under different terrains. The experimental setup, procedure, results of individual test cases and evaluation criteria are described for each of the schemes.

5.1.1 False detection

Any miss detection of obstacle during normal operation is considered as an error. The number of obstacle detection errors, depends very much on several factors, the speed of the rover, the type of the terrain, surface property, nature of the obstacle and lighting conditions. In another word, in a less complicated background there will be fewer faults. Since laser spots are detected by using their geometric or colour characteristics, there might be the case that some other objects of the same characteristics exist in the scene. In this case, it is difficult to avoid false detections. Besides, when obstacles are too narrow, it is hard to detect their presence as the laser spots are offset by 2 to 3 inches between them with respect to camera position. For the
Obstacle detection based on CamShift, it is assumed that the background which is ground surface must not have the same red colour hue characteristics as the laser.

### 5.1.2 Criteria for evaluation

The system is developed with an intention for planetary navigation, the underlying approaches can be generalized to solve other real-world problems and bring Computer Vision into production systems. However, systems can be designed such that it gracefully falls back to base functionality provided by other modalities. The main criterion used for evaluating Active light system is the detection ratio, which is given by equation (4).

$$\text{Detection ratio} = \frac{\text{number of correct obstacle detections}}{\text{number of attempts made}} \quad (4)$$

For ideal scheme the detection ratio is 1, in reality it is hard to achieve 100% success rate in obstacle detection. To evaluate the working of the developed system, indoor experiments [section 5.2.3] and outdoor experiments [section 5.2.4] are performed. The [section 5.2.1] through [section 5.2.1] cover the experiments performed for evaluating generic performance such as obstacle detection time, CPU usage, etc., of the system.

### 5.2 Experiments and Performance results

#### 5.2.1 Obstacle detection accuracy

##### 5.2.1.1 Detection of obstacles with different shape

Obstacles with different shapes such as square box, sphere, cylinder and cone are considered for testing. Each of the obstacles placed along the rover path 5m ahead of it. The camera is configured with image resolution of 320x240, 5 fps, 100% colour depth and 30% of image compression. The rover is made to move at 5km/hr speed so as to approach the obstacle along a straight track. The average detection ratio for every algorithm is found over 10 test runs. A comparison of methods for Active light based on obstacle shape is presented in Figure 48.
5.2.1.2 Accuracy for positive and negative obstacle detection

In this experiment the accuracy of obstacle detection based on the type of the obstacle is evaluated. Box, wall surface, tree can be used as positive obstacle. As negative obstacle downward stairs is considered. The camera is configured at 5fps frame rate, compression rate of 30%, colour depth and with 320x240 image resolution. For each of these obstacles one at a time, the rover is moved towards them starting at 5m distance off the obstacle on straight path at 5km/hr velocity and detection hit or miss is recorded for every algorithm. Detection ratio is calculated for 10 test runs and presented in Figure 49.
5.2.1.3 Obstacle detection performance based on placing of the obstacle

In this experiment the time taken for obstacle detection based on the placing of the obstacles with respect to the laser pattern is evaluated. From the moment the image with obstacle captured till the algorithm detects deformation in the laser pattern is considered as obstacle detection time. Timer system calls are invoked at the start of image capture and at the completion of algorithm iteration for that particular image. The difference in the timer values is noted down. A cylinder type obstacle is placed to the left, right, front of laser pattern approaching direction. The camera is set at image resolution 320x240, compression at 30%, 5fps and 100% colour depth. For each trial as described above the obstacle detection for every algorithm is found. Figure 50 shows typical placing of obstacles for various laser pattern approaching directions.

![Illustration of obstacle placing with laser pattern approaching direction](image)

**Figure 50** Illustration of obstacle placing with laser pattern approaching direction

![Detection based on the placing of the obstacle](image)

**Figure 51**: Detection based on the placing of the obstacle
As special case the obstacle is dropped at the center of laser pattern and near the rover’s front face. Detection ratio is found and presented in Figure 51.

### 5.2.1.4 Obstacle detection accuracy based on level of camera image compression

High image compression rate of the camera tends to degrade the quality of the captured image. Thus laser spots in the highly compressed image may not be even clearly visible, thus degrading overall laser detection process. The camera image compression rate can be configurable from 10% to 100%. The rover is moved towards a box type obstacle placed 5m ahead on its straight line track at 5km/hr velocity and probed if at all the rover stops on encountering the obstacle. The camera image compression rate is varied between 10% to 100%, as shown in the Figure 52. In every test case as mentioned above the obstacle detection hit or miss is observed for all the algorithms at 320x240 camera image resolution, with fixed frame rate 5 fps and 100% colour depth. The test case is performed for 10 times and finally detection ratio is calculated. The Figure 52 shows accuracy level for obstacle detection based on the level of image compression.

![Obstacle detection based on the level of image compression](image)

**Figure 52:** Accuracy level for obstacle detection based on the level of image compression.
5.2.1.5 Obstacle detection accuracy based on level of camera image colour depth

For better colour contrast the camera imager colour depth must be set to higher value, which in turn increases the chances of laser spot detection, thus improving overall deformation detection process. The camera colour depth value can be configurable from 10% to 100% colour depth. A box type obstacle is placed along the rover path 5m ahead of it. The rover is moved at 5km/hr towards the obstacle in a straight path. The camera colour depth is varied between 10% to 100%, as shown in the Figure 53. In each trial as described above the obstacle detection hit or miss is recorded for every algorithm at image resolution 320x240, compression at 30% and 5fps camera configuration. Detection ratio is found for each algorithm after 10 test runs and presented in Figure 53.

![Obstacle detection based on the image colour depth](image)

Figure 53: Accuracy level for obstacle detection based on the image colour depth.

5.2.2 Obstacle detection time

The assumptions for all the test cases under this section are as follows. The experiments are conducted under dark conditions (lights off in indoor or during night for outdoor) unless otherwise specifically mentioned. The main concern here is to detect obstacle detection time. This is due to the underlying algorithm runs through same steps irrespective of testing environment i.e., the complexity of the algorithm is unaltered. Every test case is performed for 10 times and all the other test case
conditions are presented specific to test scenarios. The obstacle detection time test cases are covered in the [section 5.2.2.1, section 5.2.3.1 and section 5.2.3.2].

5.2.2.1 Obstacle detection time for different image resolution

With higher camera resolution, more information needs to be processed, thus delaying overall deformation detection process. The camera resolution rate can be configurable and is verified only for 320x240 and 640x480. The time taken to detect obstacle is considered from the moment the image captured till the algorithm detects deformation in the laser pattern. In order to find this time accurately for every algorithm, timer system calls are invoked in the beginning of image capture and at the completion of the algorithm as shown in Figure 54. The difference in the timer values is noted down.

In this experiment each algorithm is checked against camera image resolutions (320x240 and 640x480) with fixed frame rate 5 fps, 100% colour depth and image compression rate of 30%. A box or cylinder type obstacle is placed on the rover path and the rover is allowed to move forward with a velocity of 5km/hr. At the instance the obstacle is detected and alert is displayed at the user interface, the timer difference value indicating the detection time is printed on the console. The test is conducted for each of the algorithms and detection time is noted as shown in Figure 55.

![Flow chart for obstacle detection time calculation](image-url)

**Figure 54: Flow chart for obstacle detection time calculation**
5.2.2.2 Obstacle detection time for different frame rate

If the frame rate of the camera is set high, more information needs to be processed by underlying image processing algorithm, in turn delaying obstacle detection process. The camera frame rate can be configurable from 5fps to 30fps. In this experiment the algorithms are checked against different camera image frame rates. A box type obstacle is placed on the rover track and the rover is driven at 5km/hr speed. Timer values as described [section 5.2.1.1] earlier are noted down as soon as the obstacle alert is displayed at the user interface. The test case is conducted for every algorithm with pre-conditions as camera image compression rate of 30% colour depth and image resolution as 320x240. The Figure 56 shows the time taken for obstacle detection based on camera frame rate.
5.2.2.3 Obstacle detection time for different image compression

For low camera image compression rate, high amount of information needs to be processed, thus slowing deformation detection time. The camera image compression rate can be configurable from 10% to 100%. A box type obstacle is placed 10m in front of the rover and rover is moved towards the obstacle with 5km/hr velocity. The time taken to detect obstacle is considered from the moment the image with obstacle captured till the algorithm detects deformation in the laser pattern. Timer system calls are invoked at first during image capture and at the completion of algorithm for that particular image. The difference in the timer values is noted down for every algorithm. For each trial as described above the obstacle detection time is observed for camera image resolution 320x240, with fixed frame rate 5 fps and 100% colour depth. The Figure 57 shows the time taken for obstacle detection based on the level of image compression.

![Obstacle detection based on the level of image compression](image)

Figure 57: Average time taken for obstacle detection based on the level of image compression.

5.2.3 Indoor specific experiments

5.2.3.1 Accuracy under different lighting conditions
To judge the accuracy of the methods against different lighting conditions, the indoor scene is illuminated in different lighting intensities. Figure 58 shows the behaviour of the laser detection methods in different lighting conditions. Normal lighting implies the lighting condition of a normal working office with all the windows closed and lit by ceiling neon lights. Bright lighting is when the office is lit by the ceiling lights and has the windows open to allow ambient sunlight to come in. Low lighting is obtained when half of the ceiling lights are turned off. Ultra-low lighting indicates the office with all the lights turned off and one desk lamp is placed in the far side of the room. A box type obstacle is placed 10m ahead of the rover, along its straight line path. The test case is conducted for every algorithm with camera pre-condition as of 30% of image compression rate, 100% colour depth, and 5 fps frame rate and image resolution as 320x240.

![Accuracies of the methods in different lighting conditions](image)

**Figure 58: Graph showing accuracies of the methods in different lighting conditions**

Figure 60 and Figure 61 show sample images captured during test phase to give pictorial idea on sample test setup. Three box type obstacles are considered and are placed at the left, right and at the center along the laser pattern approaching direction of the rover. The rover is driven in straight track towards the obstacle with all the room lights kept off and doors closed. In Figure 60 (b) is the background subtracted image of Figure 60 (a). The pattern has noisy extensions off the main square pattern, but in all the cases only the center pattern which is square dot matrix of 20x20 laser spots is considered rest is treated as noise. The laser pattern doesn’t encounter any of the obstacles as shown in Figure 60 (a), thus no alert is raised. When it comes to Figure 60 (c) the pattern’s top right corner is incident on the obstacle and is alerted with detection message, Figure 60 (d) shows the background subtraction of the same. Figure 61 shows indoor experiment similar to above except that one neon light is kept
on and the results can be inferred as above. The test case is conducted 10 times for each of the algorithms and detection ratio is calculated. A performance based comparison of methods based on detection ratio for indoor operation is presented in Figure 59. The axis camera automatically changes to grey like mode under dark conditions, thus losing laser pattern red colour information, eventually degrading the performance, except for Camshift where hue and saturation values are reconfigurable to compensate this camera capture behaviour.

![Image of performance chart](image)

**Figure 59: Performance of algorithms for indoor operation**

![Image of frames](image)

**Figure 60: Frames (a) and (c) extracted from the recorded videos. The system performs the detection of the deformation of a laser pattern as in (b) and (d) resulting frames.**
Figure 61: Frames (a) and (c) show Indoor obstacle detection in dark and fluorescent light conditions and respective background subtraction results are (b) and (d).

5.2.3.2 Detection of obstacles at different rover speeds

In this experiment, a box type obstacle is placed 10m ahead of the rover, along its path. The robot is driven along straight line at different speeds ranging from 2 km/hr to 10 km/hr. The robot velocity is increased by 2 km/hr and each trial is run for different algorithms. The camera is configured for 30% of image compression rate; 5 fps frame rate, 320x240 image resolution and 100% colour depth. The experiment is conducted in dark room (lights off) as the concern here is detection depending on rover speed. At the end detection ratio is calculated. The Figure 62 provides test results of obstacle detection when the rover is at different speeds, using different algorithms.
5.2.4 Outdoor specific experiments

Outdoor experiments were conducted at the university test field, an uneven ground surface with sand, stone, wooden planks and vegetation. The results of each experiment is evaluated for various factors eg., overall execution time, the number of errors during the test. The camera is set at 30% of image compression rate, 5 fps frame rate, 320x240 image resolution and 100% colour depth for all of the test cases covered in this section. A set of images are shown in Figure 63 and Figure 64 in order to give an idea on the obstacle detection for outdoor environment (during sunset lighting conditions) on stone covered surface. Figure 63 (a) shows input image with stone surface and the laser is deformed due to wall, and Figure 63 (b) showing the output of Camshift based obstacle detection algorithm indicating an alert message.

![Figure 63: Outdoor obstacle detection during sunset lighting conditions, frame (b) show the result of the detection of the deformation of a laser pattern in outdoor or input frames (a)](image-url)
Though the performed experiments are not quite general, the experimental results show the feasibility of applying this sensor system to sensing mobile robot navigation environment. Figure 64 show images taken during similar test as mentioned above in this section but only difference being concrete surface. The image Figure 64 (a) being the input image to camshaft based obstacle detection algorithm and the output images are Figure 64 (b).

![Image](image_url)

**Figure 64**: Frame (b) show the result of the detection of the deformation of a laser pattern in outdoor or input frames (a).

### 5.2.4.1 Detection of obstacles at different outdoor surfaces

Similar to indoor operation, a series of experimental tests are performed in outdoor to verify the effectiveness of the active light sensor system for a variety of detection techniques, testing environments and the sensing results are discussed in detail. All the experiments are conducted during night conditions. A positive obstacle for example cylinder is placed 5m ahead of the rover, the rover is moved at 5km/hr along the direction of obstacle so as to coincide laser with the obstacle. The hit or miss detection by each algorithm is noted for every trial. Detection ratio is calculated at the end and recorded. A negative obstacle such as trench (ditch) or precipice is considered and the experiment is carried out similar to positive obstacle test conditions as described earlier. Detection ratio is tabulated. Figure 65 show the detection ratio for each method is calculated for the test trials.
5.2.4.2 Detection of obstacles at different rover speeds

In this experiment, the robot is driven at different speeds ranging from 2 km/hr to 10 km/hr. The robot velocity is increased by 2 km/hr and each trial is run under different surface types. Here only the positive obstacle is considered as the main reason for this test case is obstacle detection depending on rover speeds. The test case conditions are similar to the indoor test case described in [section 5.4.3.2] except that tests are conducted during night at the outdoor surfaces like sand, stone, grass and concrete. The Figure 66 provides test results of obstacle detection when the rover is at different speeds, using different algorithms.

5.2.5 Amount of CPU resource usage

The different algorithms are examined for their percentage of CPU usage. The rover drive and steering controls are stopped. Per process CPU usage system calls are invoked to get the CPU percentage by the algorithm. The camera is configured for 5 fps frame rate, resolution of 320x240, 30% of image compression rate, and 100% colour depth. The Figure 67 describes algorithm performance based on amount of CPU usage. The average value is calculated after 10 readings.
5.3 Performance Evaluation

The performance evaluation is done based on the results obtained for the experiments described in [section 5.2]. The criteria used to evaluate the performance of the system are: reliability, accuracy and latency each of them described below.
5.3.1 Reliability

Reliability refers to the proportion of frames where the laser pattern is present on the ground surface and detected correctly. With a reliability of 100%, meaning that the laser pattern is detected in every frame, the system shows a perfect reliability. Due to vibrations and abrupt illumination change some of the frames may not capture complete laser pattern. This could seriously degrade the performance of the system. From the results for the experiment described in section 5.2.3.1 it is clear that Camshift based algorithm is most reliable considering abrupt illumination changes.

5.3.2 Accuracy

Accuracy refers to the distance, measured in pixels, between the laser spot location on the ground surface and the corresponding display coordinates computed by the system. The average of overall detection ratios calculated from the result set in the section 5.2 is found and considered as the overall accuracy of the system. It is clear from the results of the experiments covered in section 5.2.1 the overall system considerably good accuracy with detection ratio as shown in Table 4.

5.3.3 Latency

Latency refers to the time duration between a laser deformation (sensor data acquisition) and the detection of such deformation by the obstacle detection algorithm. To measure latency, laser pattern deformation is applied at arbitrary region within laser pattern and the time required for the response is found using timer system calls. An average of detection time found as a result of experiments presented in section 5.2.2 is calculated and considered as overall accuracy of the system.

<table>
<thead>
<tr>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>20%</td>
<td>40%</td>
<td>20%</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.2</td>
<td>0.41</td>
<td>0.18</td>
</tr>
<tr>
<td>Latency</td>
<td>381ms</td>
<td>218.6ms</td>
<td>113.5ms</td>
</tr>
</tbody>
</table>

Table 1: Performance results
Due to computation and communication times, the latency found to be superior to the theoretical lower limit of 1.08s [Ref section 3.5]. In all cases however, the latency is well under the limit. The performance results obtained are summarized in Table 1.

### 5.3.4 Overall performance of obstacle detection

An overall performance based comparison of methods for indoor operation is presented in Table 2. Template matching method works reasonably fine for indoor operation. Unfortunately this doesn’t work as desired when it comes to outdoor surface. As any translation or rotation of laser pattern yields erroneous results in matching. Boundary based method found to consume huge amount of processing time. This method is also not suitable for outdoor operation for the same reason as template matching case. Optical flow based method assumes smooth rover movements to avoid vibrations, which otherwise produces poor and coarse optical flow data. This causes large errors. The Camshift based method allows obstacle detection for rover speed at 10km/hr, which is a major achievement, considering rover speed limits presented in previous works. This approach still suffers from a few other complications that need to be addressed. Camshift based approach is tested with a very extensive set of experiments, which showed that the method is able to perform obstacle detection with reasonably good precision and robustness at a recognition time per frame of 16 ms (processing time).

<table>
<thead>
<tr>
<th>Indoor obstacle detection</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser pattern deformation</td>
<td>Fails to detect Interior deformation</td>
<td>Cannot separate laser deformation with noise due to vibration</td>
<td>Detects laser pattern deformation</td>
<td>Detects laser pattern deformation</td>
</tr>
<tr>
<td>Detection time</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
</tbody>
</table>

Table 2: Comparison of obstacle detection algorithms based on performance
Camshift based method found to work considerably well on sand, mud, rocky, road, indoor surface, concrete, tiles and grass terrains, detecting both positive as well as negative obstacles with higher accuracy at rover speeds ranging 0-10km. It is observed that the magnitudes of error rates are higher on a rougher terrain. The result obtained from the Camshift based algorithm is very promising. It is noted that at 5fps frame rate, 320x280 resolution, 100% colour and 30 compression rate the algorithm gives optimal results. The robot can successfully detect the precipice in all approaching directions of the rover.

5.3.5 Performance of background subtraction methods

This section shows the results of the recognition of laser colour regions. The main point to consider is capability to segment laser colour from background.

<table>
<thead>
<tr>
<th></th>
<th>Global thresholding</th>
<th>Adaptive thresholding</th>
<th>Hue histogram based thresholding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Intensity invariant</td>
<td>-</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Thresholding time</td>
<td>++</td>
<td>+</td>
<td>+++</td>
</tr>
</tbody>
</table>

Table 3: Comparison of background subtraction methods

Performance of background subtraction to detect laser pattern projected on the surface is tested. Background is subtracted using thresholding to detect laser pattern projected on the surface. Both global threshold and adaptive threshold are available in OpenCV and was used on each captured frame from the camera. Some parameter tuning, of course, needed to optimize the processing. The Table 3 provides comparison between various types of background subtraction methods adapted in Active light system.
Chapter 6
Conclusion and Future Work

This thesis describes the development and implementation of obstacle detection sensor based on using structured light and a camera. Visual servoing based on visual features provided by structured lighting is still a research area and this thesis intends to investigate and contribute into this field. The major steps pursued are, developing vision based algorithms to identify laser pattern deformation, deploying the developed vision module on a small rover (MERLIN) platform as obstacle detection sensor and finally conducting validation and performance tests to evaluate the entire system. The following section describes the major strengths, current limitations and suggestions on possible future improvements of the proposed system.

6.1 Summary

The use of structured light offers reliable visual features independent of obstacle appearance. A comprehensive survey on state of the art work on this subject is presented and a thorough explanation of the design, implementations and results is described in the prior chapters of this report. The major strength of the proposed system is its ability to function robustly in realistic environments with very few constraints. The experiments are performed to evaluate the accuracy and consistency of Active light sensor for real-time obstacle detection on different surfaces indoor as well as outdoor, for both negative and positive obstacles under well defined illumination conditions [section 5.2]. There are a number of sensor related parameters that would depend on the vehicle on which these sensors are implemented. Some of these sensor related parameters are:

1. Placement of each of the sensor hardware (camera & laser patter source) on the vehicle [section 3.1] and Sensor tilt angles towards the ground (Sensor field of view).
2. Camera type (CMOS, CCD, quantum efficiency, capture properties etc.) [section 3.3.2], configuration (frame rate, resolution, colour depth etc.) and laser power [section 3.3.1].
3. Minimum time to avoid collision [section 3.5].
The obstacle detection depends highly on the quality of the video. The sensor parameters would also be affected by the terrain conditions:

1. The surface characteristics (Roughness, reflectivity etc.) [section 3.4.1]
2. Brightness profile [section 3.4.4]

The captured images may have significant intensity variations from frame to frame. A constant threshold brightness used to identify the laser dot must take these variations into account. Additionally, things such as bright flashing lights in the background can cause significant detection problems [section 3.4.4.2]. The system is tested for robust operation at changing illumination conditions as well as to other variations that may occur in real-world environments [section 5.2.3.1]. The performance suffers from the surface with a large area of glare reflections. The design leaves room for future modifications and optimization. The current set of vision algorithms are namely Boundary Masking based method [section 4.2.3], Optical flow based [section 4.2.4], Template Matching based [section 4.2.2] and CamShift [section 4.2.5] based method. The approaches are compared through quantitative and qualitative results in order to validate their performance and the advantages and disadvantages of each are discussed.

6.1.1 Template matching

A straight forward technique for finding pattern deformation from a forehand known reference laser pattern model is to use correlation technique. The template is extracted when laser pattern projected at zero degree orientation on almost perfect even surface. During normal operation any laser pattern deformation in image sequence is found by computing a correlation score with the template image. Also fixed threshold value for laser pattern detection, cannot handle variation in illumination changes. Correlation takes considerable amount of computing resource. Also there is a need for a template image for every surface. This method is not suitable for outdoor operation pattern shifts due to uneven surface, image blur due to vibrations and abrupt illumination changes give unexpected results. Positive and negative obstacles can be detected for indoor only on almost even surfaces.

6.1.2 Boundary masking

Here outer boundaries (to detect positive obstacles) and inner boundaries (to detect negative obstacles) are predefined. The boundary regions are checked for encroaching
of laser pattern. This method eliminates the need for a template image. Both positive and negative obstacles can be detected on indoor surface but tests conclude poor results. The method found to consume huge amount of processing time. This method is also not suitable for outdoor operation for the same reason as template matching case.

6.1.3 Optical flow
The optical flow reduces the amount of focusing to essential portion i.e., laser pattern. Thus some pixel patches are followed. All others are neglected. The method takes considerable amount of computation resource. Any vibration, rotation or rotational disturbances and lens distortion will add a constant optical flow vector to each point of interest. The problem of lens distortion also has an affect on the optical flow. Both positive and negative obstacles can be detected. The results of indoor operations are better than outdoor operations.

6.1.4 Camshift
The Camshift based method is robust and independent of additional information, such as template images. The algorithm presents a method for reducing the overhead involved in searching for the laser shifts by using a predictive searching. It exhibits few errors that could’ve been addressed more thoroughly. It is found to be translation, rotation and vibration invariant approach. Both positive and negative obstacles can be detected for indoor as well as outdoor operation. This approach still suffers from a few other complications that need to be addressed. Potential improvements might tackle the issue of brightness that greatly affects laser pattern recognition.

6.2 Achievements
The results presented in chapter 5 have shown that the main goal of this thesis has been accomplished.

- It is possible to detect positive as well as negative obstacles in both the indoor & outdoor environment.
- The vision module improves the robustness of the system.
- The system can perform its task in complicated real scenarios as long as laser pattern is visible in the captured video sequence.
This system can perform its obstacle detection task and thus can be useful for future developers to use it in their projects. For the vision system, irrespective of its complexity, can provide a rover with a limited support for its visual sensing needs. However, adaptation of the vision system to specific environmental conditions permits the rover to move around successfully with simple visual processing.

6.3 Limitations

The inherent disadvantage of proposed system is that, the obstacle detection region is limited by the size of the pattern, which can be improved by omni-directional pattern or using omni-directional mirror. Another shortcoming of the proposed vision based sensor is the sensing range. The laser source used here is not visible at distances greater than 3m due to the limited capture ability of CMOS sensor. Usage of stronger/more powerful laser, more sensitive CCD/CMOS camera and optical band-pass filter could overcome this problem. The only concern about increasing the laser strength is the eye safety restriction that might apply in certain environment where humans present. The current system is operational only for colour based cameras. Typical cameras cannot handle a large dynamic range from night to bright sunshine; or indoors to outdoors. The primary disadvantage, versus other types of sensors, is that vision is not as reliable for detecting obstacles. Usually area in the middle of the image is brighter than the edges. This is a side-effect of the camera lens which results in the light intensity falling off towards the edges of the CMOS. A black/grey/white coloured ground surface might not be good “colour” selections because they have no representation as a Hue in HSV space. However, the system must be able to cope with natural changes in illumination.

The current limitations of the system are coarse image capturing camera, brightness profile, glare reflections from shiny surface, which may lead to poor feature extraction and matching. The last section describes how those problems may be addressed in future work. Systems are much more robust if they integrate using multiple sensor modalities in a way that takes the advantages and disadvantages of each sensor into account. Vision should be treated as an add-on to a system, and as such it can play a role that extends capabilities significantly. At the current development level, vision
may still have failure modes if the unfavourable conditions don’t allow for it to operate.

6.4 Conclusion and Future Work

This thesis is focused on the visual perception of obstacle detection by means of active light and camera. The technique is reliable only when the captured image of the scene contains projected laser pattern. Active light makes obstacle features to be identified easily in a scene. As per the experimental observation the accuracy of the sensor depends notably with pattern detection under various illumination conditions and under different surface properties. The results obtained prove that the sensor can be successfully used in a variety of real applications for obstacle detection.

There are some failure modes in the system; this technique is not developed to be a standalone method but a subsystem of a complete vision obstacle detection system. Here a list of possible improvements is presented. An important improvement could be to endow the vision system with the capability of dynamic laser colour model selection, for segmenting the images. This could be very useful to deal with sudden changes in the light sources that may happen while the rover is moving in such environment. Efficient video image stabilization and blur removal techniques can also be implemented. A high power laser with a suitable optical band-bass filter combination significantly improves the overall laser spot detection problem, with a caution on human eye safety measures. A distinct CCD camera with true colour capture substantially improves the performance of the system.

However, some improvements have to be done on this system to become optimal system in terms of simplicity, accuracy and cost. It is hard to construct a system that achieves all of these three conditions at the same time. Depending on the application the system, upgrades can be made to meet the requirements. Better the equipments used, better the results obtained. Automatic terrain recognition and adaptation can be realized in the existing vision software to address the re-configuration for new terrain model. Another challenge to the visual system will be posed by detection of the thin rods. Given the performance results obtained, further research is necessary, especially to improve the accuracy of the system. Also, the use of a faster image grabbing
camera could reduce the latency of the system therefore reducing the lag for deformation detection. Also, more research is needed to characterize the effect of different parameters such as lighting conditions, display size and camera resolution on system performance. The active light optical system provides a novel method for detecting obstacles in difficult, uneven, and inconsistent terrain. There is a wide scope to improve the performances of the current system. It is important to note that the system can also be used for both front and rear obstacle detection by addition of additional camera at the rear or usage of omni-directional camera/mirror pair.
Appendixes

Appendix A

A.1 CMOS quantum efficiency

Quantum efficiency (QE) is a quantity defined for a photosensitive device as the percentage of photons hitting the photo reactive surface that will produce an electron–hole pair. It is an accurate measurement of the device's electrical sensitivity to light. Since the energy of a photon depends on the photon wavelength, QE is often measured over a range of different wavelengths to characterize a device's efficiency.

![QE RESPONSE](image)

Figure 68: CMOS sensor quantum efficiency [69]

A.2 Colour spaces

The different colour spaces [64] are designed for different purposes each having their pros and cons. Some of the most common colour spaces are CMYK (Cyan Magenta Yellow blacK) suitable for printing, YIQ, YUV and YCrCb used in television broadcasting and several spaces defined by CIE (Commission Internationale d’Eclairage) [Tortora & Grabowski 00]. However these colour models are of little interest for this thesis work. Computer hardware like monitors, scanners and digital video cameras primary uses the RGB (Red Green Blue) colour space. Hence we will take a closer look at this model and one its derivates, which can be used in OpenCV.
A.2.1 RGB

The RGB-model describes images in the tree components Red, Green and Blue. The RGB-model can be described as a cube with black in the origin and the three components represented by each axis, see Figure 69. If each colour channel is assumed to have a range between 0 and 1 then (0,0,0) is black, (1,1,1) is white, (1,0,0) is ‘pure’ red and so on. An important property like brightness cannot be separated from the other important property ‘colour’, but is to be found in all components. All components will hence be affected when lighting conditions changes.

![Figure 69: The RGB cube][67]

A.2.2 HSV

HSV (Hue Saturation Value) and HLS (Hue Lightness Saturation) are similar variants of the same colour space based on the concept of tone, shade and tint. In HSV space hue defines the colour according to wavelength and saturation is the strength of colour. A high saturation means a rich, deep tone of the colour. Value and Lightness correspond to brightness (a stop sign is ‘bright’ red and a glass of wine is ‘dark’ red). This representation is closer to the human understanding of colours and is often used in computer applications during interaction between the application and a human, for example when the user is about to choose a colour in a paint program. Transforming RGB to get HSV extracted from [68].
A.3 An example of how the masking strategy works

Figure 71 depicts an example on masking strategy. The picture A is the image with projected light sources, the picture B is the mask of the standard pattern created when the laser was projected on horizontal reference surface. By masking onto the frame A, information of the position of each laser dot displaced off its original pattern can be found. The mask that is used in this thesis is simply a zero matrix of the same size as the filtered image except for the interesting regions where there are ones. By element-wise multiplying the mask with the image C, a result frame having information only in the region of interest that is chosen in the mask where the pattern is visible is obtained. In other words, after the masking process the resulting frame contains patterns that are affected by the geometrical form of the obstacles.
Appendix B

B.1 Player Server

Player is a networked robot server. It provides a convenient interface to a set of device drivers for real robots and sensors. The Player network protocol is modelled on the UNIX file model, each device supports three basic client (Data), write (Commands) and control. The actual communications layer is hidden from the client applications through a client proxy library which processes the low level Player messages. Control messages are implemented as a request and a server response, these are used for a range of tasks such as delivering drive commands and configuring steering parameters. A plugin position2d driver for Player is written for forwarding drive and steering commands from player client to the MERLIN OS drive control module. Details regarding writing plugin drivers for Player Server can be found in [49]. Player server is used get bi-passed access to drive motor and steering servo connected to C167 running MERLIN OS. Methods for serial port access, connection management, parsing MERLIN protocol [29] packets from C167 over RS-232 link, and MERLIN packet creation are implemented.
Appendix C

C.1 Contents of the enclosed CD-ROM

The enclosed CD contains the following folders and documents

**Content description.pdf**
This pdf document contains description of CD contents.

**Development Environment setup.pdf**
This pdf document contains step by step instructions to setup the development environment of Active Light system.

**Documentation.pdf**
This pdf document contains source code documentation.

**Licenses**
This folder contains all the licenses of the libraries used.

**Videos**
This folder contains video and images taken during the system operation. It illustrates different cases and conditions under which system is operated and tested.

**Sourcecode**
This folder contains image processing source code as well as source code for client side of Active light system.

**Papers**
This folder contains scientific papers used as references for this project.
Appendix D

D.1 Experimental Results

This appendix presents detailed results summarized in Chapter 5:

<table>
<thead>
<tr>
<th>Algorithm Type</th>
<th>Percentage of CPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary Masking based</td>
<td>30.1</td>
</tr>
<tr>
<td>Optical flow based</td>
<td>21.3</td>
</tr>
<tr>
<td>Template Matching based</td>
<td>18.2</td>
</tr>
<tr>
<td>CamShift Based</td>
<td>11.6</td>
</tr>
</tbody>
</table>

Table 4: Percentage of CPU usage for each algorithm

<table>
<thead>
<tr>
<th>Shape of obstacle</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square Box</td>
<td>0.38</td>
<td>0.52</td>
<td>0.52</td>
<td>0.96</td>
</tr>
<tr>
<td>Cylinder</td>
<td>0.59</td>
<td>0.77</td>
<td>0.43</td>
<td>1</td>
</tr>
<tr>
<td>Sphere</td>
<td>0.48</td>
<td>0.9</td>
<td>0.42</td>
<td>1</td>
</tr>
<tr>
<td>Cone</td>
<td>0</td>
<td>0.5</td>
<td>0.07</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5: Detection based on the shape of obstacle

<table>
<thead>
<tr>
<th>Algorithm Type</th>
<th>Positive obstacle</th>
<th>Negative obstacle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Box</td>
<td>wall</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>Detection ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boundary Masking based</td>
<td>0.38</td>
<td>0.63</td>
</tr>
<tr>
<td>Optical flow based</td>
<td>0.52</td>
<td>0.83</td>
</tr>
<tr>
<td>Template Matching based</td>
<td>0.52</td>
<td>0.45</td>
</tr>
<tr>
<td>CamShift based</td>
<td>0.96</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6: Accuracy of obstacle detection based on the type of obstacle
<table>
<thead>
<tr>
<th>Placing of obstacle w.r.t. laser pattern</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift based</th>
<th>Detection ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>0.48</td>
<td>0.83</td>
<td>0.48</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>0.56</td>
<td>0.71</td>
<td>0.38</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td>0.48</td>
<td>0.83</td>
<td>0.43</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Center</td>
<td>0</td>
<td>0.56</td>
<td>0.48</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Near</td>
<td>0</td>
<td>0.17</td>
<td>0.4</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Detection based on the placing of the obstacle

<table>
<thead>
<tr>
<th>% of frame compression</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift based</th>
<th>Detection Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.5</td>
<td>0.63</td>
<td>0.33</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.38</td>
<td>0.67</td>
<td>0.31</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.17</td>
<td>0.59</td>
<td>0.13</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>0.13</td>
<td>0.5</td>
<td>0.1</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>0.56</td>
<td>0.1</td>
<td>0.31</td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Accuracy level for obstacle detection based on the level of image compression.

<table>
<thead>
<tr>
<th>% of frame colour depth</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift Based</th>
<th>Detection Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.1</td>
<td>0.37</td>
<td>0.1</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.1</td>
<td>0.43</td>
<td>0.1</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.17</td>
<td>0.5</td>
<td>0.13</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>0.36</td>
<td>0.67</td>
<td>0.38</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.48</td>
<td>0.77</td>
<td>0.3</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: Accuracy level for obstacle detection based on the image colour depth.

<table>
<thead>
<tr>
<th>Frame Resolution</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>320x240</td>
<td>246.7ms</td>
<td>124ms</td>
<td>72.6ms</td>
<td>16.9ms</td>
</tr>
<tr>
<td>640x480</td>
<td>573.2ms</td>
<td>266ms</td>
<td>128.6ms</td>
<td>26.1ms</td>
</tr>
</tbody>
</table>

Table 10: Average time taken for obstacle detection depending on camera resolution.
<table>
<thead>
<tr>
<th>Camera Frame Rate</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift based</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 fps</td>
<td>246.7ms</td>
<td>124ms</td>
<td>72.6ms</td>
<td>16.9ms</td>
</tr>
<tr>
<td>10 fps</td>
<td>537ms</td>
<td>253.7ms</td>
<td>128.3ms</td>
<td>17.4ms</td>
</tr>
<tr>
<td>15 fps</td>
<td>725.6ms</td>
<td>289.7ms</td>
<td>193.3ms</td>
<td>18ms</td>
</tr>
<tr>
<td>30 fps</td>
<td>938.8ms</td>
<td>747ms</td>
<td>323.6ms</td>
<td>16.9ms</td>
</tr>
</tbody>
</table>

Table 11: Average time taken for obstacle detection based on camera frame rate.

<table>
<thead>
<tr>
<th>% of Frame Compression</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>324.8ms</td>
<td>202.7ms</td>
<td>94.5ms</td>
<td>22.5ms</td>
</tr>
<tr>
<td>40</td>
<td>200.5ms</td>
<td>115.4ms</td>
<td>67ms</td>
<td>15ms</td>
</tr>
<tr>
<td>60</td>
<td>164ms</td>
<td>95.8ms</td>
<td>61.3ms</td>
<td>14.6ms</td>
</tr>
<tr>
<td>80</td>
<td>131.1ms</td>
<td>93.2ms</td>
<td>55.1ms</td>
<td>13.9ms</td>
</tr>
<tr>
<td>100</td>
<td>102ms</td>
<td>92.6ms</td>
<td>51.5ms</td>
<td>13.5ms</td>
</tr>
</tbody>
</table>

Table 12: Average time taken for obstacle detection based on the level of image compression.

<table>
<thead>
<tr>
<th>Rover Speed (km/hr)</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift based</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.8</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>0.9</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>0.9</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0.6</td>
<td>0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 13: Obstacle detection based on rover speed.

<table>
<thead>
<tr>
<th>Indoor Operation</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor (lights off)</td>
<td>0.56</td>
<td>0.76</td>
<td>0.61</td>
<td>0.92</td>
</tr>
<tr>
<td>Indoor (single neon light on)</td>
<td>0.58</td>
<td>0.8</td>
<td>0.66</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Table 14: Performance of algorithms for indoor operation.
<table>
<thead>
<tr>
<th>Surface type</th>
<th>Obstacle type</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor/grass</td>
<td>Positive obstacle</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Outdoor/road</td>
<td>Positive obstacle</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Outdoor/mud</td>
<td>Positive obstacle</td>
<td>0.1</td>
<td>0.3</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Outdoor/grass</td>
<td>Negative obstacle</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>Outdoor/road</td>
<td>Negative obstacle</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>Outdoor/mud</td>
<td>Negative obstacle</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Table 15: Obstacle detection based on rover speed

<table>
<thead>
<tr>
<th>Surface type</th>
<th>Obstacle type</th>
<th>Boundary Masking based</th>
<th>Optical flow based</th>
<th>Template Matching based</th>
<th>CamShift Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor/grass</td>
<td>Positive obstacle</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Outdoor/road</td>
<td>Positive obstacle</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Outdoor/mud</td>
<td>Positive obstacle</td>
<td>0.1</td>
<td>0.3</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Outdoor/grass</td>
<td>Negative obstacle</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>Outdoor/road</td>
<td>Negative obstacle</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>Outdoor/mud</td>
<td>Negative obstacle</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Table 16: Performance on various types of outdoor surfaces.
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