Smooth surface image stitching with use of laser illumination

by

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Declaration

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To my family. To those who makes me tick...

Acknowledgments

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Smooth surface image stitching with use of laser illumination

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Panoramic images constructing algorithms are being used for creating photo-mosaics, environment maps, producing satellite photos and in many other applications. These algorithms utilize either pixel intensity information by counting every pixel contribution, or distinctive features extracted from the image in order to establish correspondence between images to be stitched. There is a whole framework developed to date, and the problem of image stitching has been addressed from different points of view.

However, existing methods for image alignment experience difficulties when applied to smooth surfaces (such as steel, paper, rubber, stone, cardboard etc), where is no features can be extracted, or image intensity varies insignificantly across overlap area.

The current project presents an interesting mixture of computer science and physics, it is intersection of computer vision in part of creating panoramas and optics in part of utilizing techniques from laser speckle interferometry. Speckle phenomenon has been efficiently used to analyze optically rough surfaces, now it is employed to address the problem of finding overlaps and point correspondence in smooth surfaces.

Stitching images with use of laser speckle requires experimental apparatus, where laser illumination system, camera and pan-tilt unit are put together onto optical bench. Dedicated stitching application is developed to account particular properties of smooth surface images to form a panorama.

Experiments demonstrated that laser speckle contains necessary information for creating composite image. Speckle pattern is persistent to surface movement, i.e. it is determined by surface's roughness and moves together with surface. Template matching technique and normalized cross-correlation formula were used to calculate matching points responsible for correspondence between images.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Panoramas are useful. The “panorama” as a new word was coined to describe a show where visitors could see 360-degree view painted on the walls inside circular room and later artists started to sell these “panoramic” scenes painted on canvas [13]. Several panoramas of that time survived the years and still can be visited. Soon after the invention of photography, photographers wanted to capture city scenes in a panorama way, but were unable to do so due to limited angle of view of normal camera, so they came up with idea of making panoramas with cameras placed next to each other, but with slightly changed direction to create composite photos later. Then so-called “panoramic cameras” appeared and allowed photographers to capture elongated fields of view. They were patented and evolved into a variety of models, some of them were very expensive and used only for capturing wide-angle photos.

Today, most of hand-held digital cameras support “panoramic” mode, and even beginner can create beautiful image of his own favorite scene. There is a dedicated software to stitch several photos into one big image seamlessly and almost automatically. Adobe Photoshop (with Photomerge extension), PhotoStitcher, PanoramaTools, or Autopano are the most popular ones. Due to proliferation of mobile technologies in our everyday life, software in modern mobile phones also provides an ability to make panoramic photos by using phone's on-board camera.

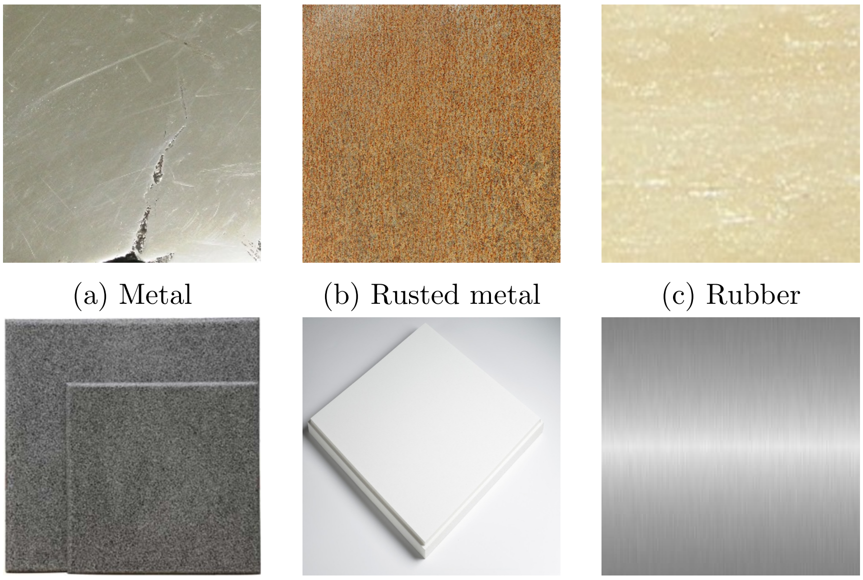
In the same time, humanity make use of devices called "lasers". Lasers appear in our everyday life, they have many important applications. For example, laser beams are used in CD/DVD players, bar code scanners, laser lighting displays and laser printing devices. Lasers are used to measure the distance and speed of target in military devices, help in bloodless surgery, work in industry etc. They were called "a solution looking for a problem" because of their substantial properties [12].

The dissertation in your hands describes an interesting mixture of computer science and physics. On the one hand it explores the ways to acquire high resolution images with the camera of smartphone, on another it applies a study about speckle phenomena which has been investigated since the age of Newton and continued to be examined after invention of lasers.

1.1 Project Motivation

This project is motivated as a way to determine a novel approach of finding overlapping regions in sequence of images of smooth surfaces, i.e. surfaces with very little visual texture like paper or metal. According to the Szeliski [31], existing apparatus for image alignment and stitching developed to date consists of the following steps:

- motion model estimation
- computing the alignment parameters between a pair of images
- stitching images using information about point correspondence



(a) Metal (b) Rusted metal (c) Rubber

(d) Stone (e) Cardboard (f) Steel

Figure 1.1: Examples of smooth surfaces

- remove stitching artifacts, such as ghosting and visible seams

Alignment parameters estimation in apparatus presented above uses either direct or feature-based methods in order to calculate correspondence points between two images. Direct methods are usually based on information from image intensity and experience difficulties when applied to the images of smooth surfaces. Reliable extraction of image features for images of smooth surfaces is often impossible [21].

Project described in this dissertation is intended to compensate drawbacks of existing methods and provide additional information to compute correspondence of such images.

It could be beneficial to obtain panoramic images of surface where neither human eye, nor machine vision systems are able to spot the intersecting areas. You can see some of examples of such surfaces on the figure 1.1. This list can be easily extended with clean metal surfaces as combustion chamber of internal combustion engines and walls inside oil tankers, concrete walls inside radioactive waste storages etc. Note that in some situations the presence of operator taking photos is not recommended, or even potentially dangerous.

1.2 Project Aims

There are a number of existing applications for creating panoramic images, but they are not adapted for stitching images with non-unique and periodic texture.

Assumption has been made that the captured image of surface being highlighted by coherent illumination will contain valuable information about its roughness pattern and this information will help in stitching. The aim of the dissertation is to prove or discard this assumption. To do this we will design and evaluate the system, which will be expected to take high resolution images of surfaces with hardly visible patterns (e.g. concrete wall and metal surfaces) and stitch them together into one panorama. Overlapping regions of neighboring images would be found based on a useful characteristic of laser illumination: *speckle phenomena*.

1.3 Project Approach

We propose a system which will make use of camera and coherent illumination system working together to obtain a panoramic image of smooth surface. In particular, we intend to

- build the apparatus consisting of camera and laser illumination module pointed to the sample surface,
- develop an application for capturing and stitching images,

- evaluate the quality of panoramas stitched with help of introduced apparatus.

We present a description of apparatus build for experiments as well as design and implementation of application for image stitching. We will make decision about the most appropriate method for finding point correspondence and analyze its performance in order to compare it with other methods.

1.4 Project Contribution

We propose use of techniques known from laser speckle interferometry to allow panorama creation for smooth surface.

1.5 Dissertation Structure

Chapter 2 explores the current state-of-the-art in image stitching for smooth surfaces, including existing algorithms for alignment and stitching, study about smooth surface and principles of laser illumination. Chapter 3 provides both the apparatus for experiments and design of image stitching application. The actual implementation of application is described in Chapter 4. Finally, chapter 5 details evaluation of proposed system and concludes this dissertation. Also, possible applications of developed system discussed there.

Chapter 2

State of the Art

We want to determine the key research that has been completed to date which is related to the problem of generating panoramic images of poorly textured or smooth surfaces. The most important part that has to be done to formulate the process of generating such images is image stitching and alignment. We will review the key research results that address that issue, overview the panoramic images construction algorithms and techniques proposed in the literature, analyze their performance and outline the key features (section 2.1). After that, we will look at different aspects of smooth surfaces, discussing the existing problems of image stitching alorithms applied to these surfaces (section 2.2). Finally, we will overview the laser illumination in section 2.3. Chapter ends with research question to be addressed (section 2.4).

2.1 Panoramic Images

Algorithms for constructing panoramic images (or image mosaics, or photo mosaics) have been known for quite a long time in computer vision. Algorithms for image aligning have been used in digital maps creation and producing satellite photos [24], high-resolution photo-mosaics construction, combining all the best photos from a series of shots and in many other applications [1]. At the moment almost all digital photo cameras have "image stabilization" feature, which implements stitching and alignment algorithms to remove ghosting effects on photos or to create wide-angle panoramas. Also, such algorithms have been made use for medical imaging and remote sensing [31]. Finally, panoramic images creation functionality is being included into mobile phones and tablet PCs, which requires refinement of existing algorithms with consideration of limited computation power and energy consumption constraints.

It is worth to mention that image alignment algorithms are not only used to create panoramas, but also to improve quality and make high-resolution image from a set of images containing the same scene. This approach is called *super-zoom* or *super-resolution* [6][19][20].

This section covers main building blocks in panoramic creation process. It begins with discussion about image acquisition techniques, continues with overview of motion model, point correspondence calculation methods and global registration. Section ends with overview of compositing the final panorama.

2.1.1 Image Acquisition

The process of creating a panorama starts from acquiring a series of overlapping images. Complexity of the system for creating photo mosaics depends on the image acquisition methods. Moreover, the acquisition methods in turn depend on the type of panorama to be created.

Images can be acquired in following ways [7]:

- **Camera rotations.** Camera is fixed at one spot and rotated with respect to vertical axis in one chosen direction. Rotation continues until the area of interest is captured. Obtained images should have overlap with the previous ones in order to stitch them. The method is simple and preferably used for modeling 3D environment or creating elongated panoramas of nature.

- **Camera translations.** Camera is being shifted in a direction parallel to the scene plane. This method gives the images where the sizes of objects remain the same for neighboring images. Image acquisition may become difficult for objects which are distant from the camera. Used in creation of architectural walk-through (e.g. Google Street View).

There are several issues exist in image acquisition. The intensity may change from image to image due to change in illumination conditions (it is called *intensity shift*). Also, camera lens may introduce distortions which have to be corrected. These problems have to be taken into account during creation of panoramic image.

2.1.2 Motion Model

Before stitching two images into one, the mapping between pixel coordinates from one image to another must be calculated. Such mathematical correspondence is called *motion model*, a variety of such models exist, including simple 2D transforms, planar perspective models, 3D rotations etc[30].

Among others, cylindrical and spherical motion models are the most commonly used. However, they have limitations: only pure panning motion of camera considered, registration errors due to ill-sampling at north and south pole, information about camera's focal length required. In order to overcome these limitations, Szeliski and Shum propose 8-parameter model which replaces cylindrical and spherical coordinates [32]. Also, authors state the method to recover camera's focal length and provide algorithm to extract environment maps from set of images. This algorithm can be used to project panorama onto any arbitrary surface, which allows to build 3D models of environment. Depending on the type of panorama to be created, straightforward or sophisticated model may be chosen.

As soon as the motion model is selected to describe the correlation between images, it becomes possible to estimate the parameters of image alignment (i.e. position of one image in relation to another). There are two basic approaches to do this:

- **Direct-based.** This approach is based on intensity information and pixel-to-pixel matching.
- **Feature-based.** This approach is based on extraction of distinctive *features* from images and matching those individual features in order to define correspondence.

2.1.3 Direct (pixel-based) Alignment

The pioneer paper in the area of direct alignment have been written by Lucas and Kanade [23]. It addresses the issue of registration of images that have known approximate position in relation to each other (for example, when images have been taken by stereo camera), and explains methods that compute the difference and find a good match between such images. Authors examine existing techniques for registering two images, analyze their drawbacks and provide an algorithm which examines far fewer potential matches comparing to full search across all possible options.

Since the time of Lucas and Kanade, direct-based methods were being intensively researched. M.Irani introduced formal description of direct methods and proposed mechanisms for motion/shape estimation obtained from pixel values processing [18]. Also, properties of direct methods have been explained and comparison with feature-based methods has been given.

The approach of direct methods consists of two steps: select the *error metric* to compare images and choose the *search technique* to find the alignment which minimizes the error metric.

2.1.4 Feature-based Registration

The feature-based approach is the following. Extract distinctive features from each image and match these extracted features to get the global correspondence across all images. Then, calculate the geometric transformation between the images [31]. This technique initially has been used in stereo matching applications, later it was adopted for image stitching applications by Capel and Zisserman [6] and Brown and Lowe [4]. Lowe proposed the method to calculate *scale invariant* keypoints, which are insensitive to scale and rotation of source images. With use of these keypoints he designed an algorithm called *Scale Invariant Feature Transform* (SIFT) [22], it has been proven to be the best across algorithms calculating local descriptors. The list of areas where SIFT is applied is not limited to image stitching, but includes object and gesture recognition, video tracking, 3D modeling etc.

Both direct and feature-based approaches presented above have advantages and drawbacks depending on the application. Feature-based methods considered robust [22] and usually they do not depend on scale and orientation. Direct-based methods use contribution of all pixels from the image, but have limited range of convergence. They can be used in stitching video frames sequence, but fail too often in matching partially overlapped images when overlap is arbitrary [31]. Both approaches can be used together. For example, when approximate alignment of image pair is calculated by one of feature-based methods, followed by warping images into the same reference coordinate system and locally refining alignment results with direct methods.

2.1.5 Global Registration

Usually, there is a need to register more than two images in order to stich them into image mosaic, whereas local registration methods described previously map the relation only between pair of images. There are methods of finding *globally consistent* set of alignment parameters in the way of minimizing errors between all pairs while processing the final panorama[29]. Global registration can be achieved using *bundle adjustment* (Triggs et. al. [33]) to define which of the images in the set will be included into composed panorama. There is also a method of recognizing panorama stated by Brown and Lowe [4], which uses keypoints calculated with SIFT and discovers which images go together to form panorama.

The paper of M.Brown and D.Lowe [4] presents the system for automatic image matching based on Scale Invariant Feature Transform (SIFT), probability model for matching verification. This system recognize multiple panoramas in unordered image sets and stitch them fully automatically. It is robust to camera zoom, orientation change and changes in illumination. However, the approach needs to be tested for cases where source images contain non-unique textures (in other words, images with lack of features). SIFT and its applications are explained in papers [22] and [5]respectively.

2.1.6 Compositing

If the motion model is known and the alignment between all images has been estimated, they may now be placed onto single compositing surface [31]. First, the type of compositing surface has to be selected. Then, depending on the size of field of view, two following approaches are possible. If field of view is small, we can pick one image as reference and warp other images into reference coordinate system. At the end it gives us *flat* panorama. Otherwise, we can use cylindrical or spherical projections to place a big set of images onto them as explained by Szeliski and Shum in [32]. If the goal is to create large panoramic image of arbitrary shape and detail (e.g. *environment map*), the video mosaics technique may be applied [30].

When source pixels have been mapped into the final compositing surface, it is required to perform additional operations to reduce visible artifacts after stitching: remove ghosting (this process is called *de-ghosting*) and exposure artifacts [34], and smooth the image if needed [24]. Ghosting being introduced to the photo when the object moves between different views of dynamic scene. Exposure artifacts appear in the panorama when the illumination levels of adjacent photos are different. At this stage, optimal seams should be found. Graph-cut technique and vertex cover mechanism, and Dijkstra algorithm may be applied to solve this issue [1]. The *parallax removal* procedure can also be applied to avoid the *parallax* caused by unmodelled radial distortion in the image.

Agarwala et. al. [1] proposed a framework for combining a set of photographs into one composite image. They concentrated on analysis of two techniques: graph-cut optimization to find optimal seams when stitching the images (this mechanism is also reviewed in paper of Boykov et al.[2]) and gradient-domain fusion to reduce visible artifact that left after stitching (proposed by Perez et al.[27]). Their contribution was to design an algorithm to minimize a cost function for graph-cut optimization and improve gradient-domain fusion.

Davis [10] studied dynamic scenes and addressed the problem of stitching images in case of movement within the scene by using Dijkstra algorithm for optimal seams search, He proposed a registration method which is unbiased by movement and a method for finding globally consistent registration for all images.

Uyttendaele et al. [34] analyzed existing methods for ghosting removal and applied vertex cover mechanism to represent overlapping regions in order to eliminate ghosting by selecting minimal vertex cover. Additionally, they smooth the luminance across all source images to achieve nice looking composite image.

2.2 Smooth Surfaces

Previous section described the steps for creating panorama in general. However, when extraction of image features is impossible, general methods experience difficulties with surfaces like presented on the figure 1.1.

There were several attempts to deal with smooth surfaces. Veeraraghavan et. al.[35] studied smooth mirror-like surfaces and addressed the problem of finding invariants associated with parabolic curvature points. They show that invariant curves can be extracted from arbitrary image without any a priori information about the shape of such surface. Kupervasser [21] presents methods to recover epipolar geometry, which are based on examining illumination characteristics, correspondent tangency points, curve characteristic points and curve tangent points. Another researchers, Cross et.al.[8] investigate parallax geometry of smooth surfaces by applying bi-tangents between the homography registered occluding contours and computing the trifocal tensor.

Study about smooth surfaces is mainly applied in computer graphics and visualization in order to convert images of real objects into 3D models. One example of such study is work of Hertzmann and Zorin [15], where authors introduce algorithm for finding silhouettes based on geometric duality, and an algorithm for segmenting the silhouette curves into smooth parts with constant visibility.

2.3 Laser Illumination

Generally speaking, lasers are intensively used in industry. The phenomenon we are planning to use is called *speckle*. Speckle is a high contrast, fine scale granular pattern seen when laser light is reflected from a surface [14]. The images of speckle patterns presented on the figure 2.1, where scattered green laser beam is directed to a surface.

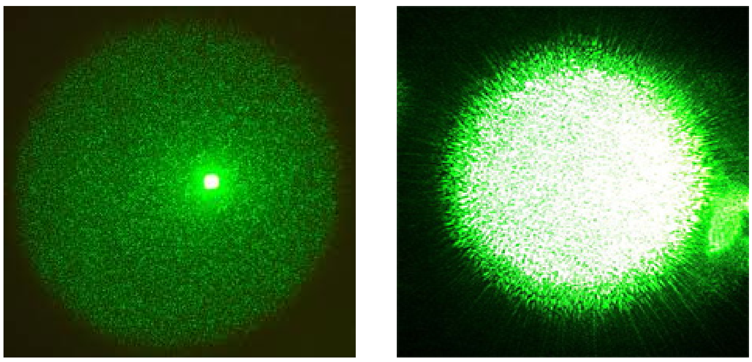


Figure 2.1: Examples of laser speckle

Speckle gained prominence due to Laser Speckle Interferometry (LSI) or Electronic Speckle Pattern Interferometry (ESPI), where speckle helps to visualize static and dynamic displacements of components with optically rough surfaces. LSI allows to measure the surface roughness up to optical interferometric precision (i.e. to fractions of a wavelength of light). The speckle effect is exploited in holographic interferometry, also it is used in stellar speckle astronomy [9], speckle imaging and in eye testing.

2.4 Research Question

Inspired by use cases of speckle phenomena applied to measurement of surface roughness, we hope to utilize existing LSI techniques in stitching smooth surface images. The goal of the current project is to examine the laser illumination in application to smooth surface panorama creation. It is proven that this process experiences difficulties, when the scene contains non-unique and poorly textured areas. We aim to build a system, which will overcome the limitations of methods to estimate point correspondence. In order to do this, we aim to:

- build an experimental apparatus to be used in capturing images,
- state the assumptions and requirements for the apparatus and images,
- make decision regarding the method for finding image correspondence,
- develop an application for panorama stitching,
- analyze the photos obtained with the support of laser illumination, and
- evaluate constructed system.

Chapter 3

System Design

The previous chapter covered the current state of the art for the project, including image stitching approaches and details about smooth surfaces and speckle phenomenon. In this chapter, we propose design of the system for obtaining stitched images of smooth surfaces with use of laser illumination. Chapter begins with short explanation of project approach and continues with overview of apparatus required for experiments, also it presents the functional design of stitching application.

3.1 Approach

Current dissertation aims to determine whether the image of smooth surface placed under laser illumination will contain unique roughness patterns. Image stitching becomes extremely difficult without such patterns, because surface itself do not provide any information to calculate points of correspondence between overlapping images.

In order to build a system for finding intersecting regions or correspondence points, we propose to:

- Build an experimental apparatus,
- Develop an application for stitching images, and
- Access whether application can stitch images under coherent illumination.

The apparatus will consist of laser illumination system, high resolution camera and sample surface and will be used to undertake experiments. With use of apparatus, a program will be developed in order to control the camera parameters, capture images and stitch them into one panorama. Firstly, images will be stitched under daylight conditions, later the coherent laser illumination will be involved into the process.

3.2 Apparatus

The initial intent for the system is to have the camera and laser illumination system placed on the robot arm. The camera takes pictures and moves together with illumination device with respect to the surface. The robot arm is used for precise movement operations. It is important that all components are fixed at optical bench and the distance between surface and camera remains constant. In these circumstances, we can configure parameters of camera (i.e. focal length, exposure compensation and shutter time) and characteristics of laser illumination (i.e. speckle parameters). Also, it would help to avoid of complex motion estimation techniques and potentially could keep the need of warping away.

However, there is no difference from stitching point of view between (1) fixed surface and camera is moving, and (2) surface moves relative to the fixed camera.

The general structure of the apparatus is presented in the figure 3.1[1]. The source

[1]Image inspired by V. P. Ryabukho and his article "Speckle Interferometry"

of laser light is directed to the sample of smooth surface. Light is reflected from the surface, and this reflected light contains speckle pattern, which is captured by camera.

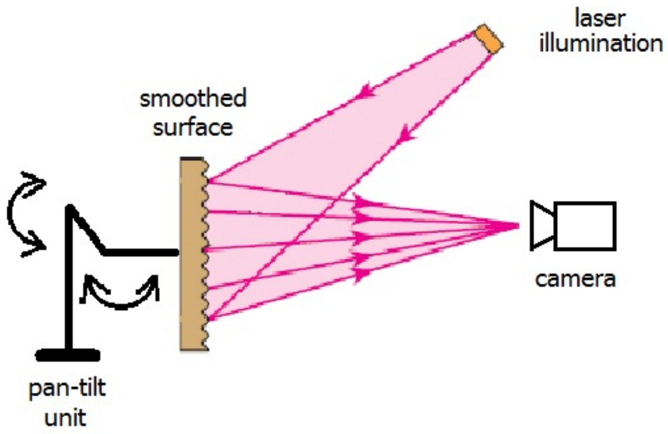


Figure 3.1: Scheme of the apparatus for image stitching

The technique applied here is the same as in laser speckle interferometry, when the roughness of surface is being examined. The characteristics of the speckle depend on several factors:

- Distance between source of light and surface,
- Distance between surface and camera,
- Wavelength of light, and
- Parameters of viewing system, including lens aperture size etc.

Since the goal of project is to use speckle phenomenon in image stitching, we can skip the study about the most appropriate speckle parameters for stitching and concentrate more on the computer vision details.

3.2.1 Camera

Camera parameters can affect the speckle characteristics. Also, the images should be taken when camera is focused on the surface. Depending on the type of panorama needed, monochrome or colour camera may be used. Different types of lenses have varying distortion parameters. In our scenario, we will need the camera with lenses, which minimize distortions and allow aperture setting.

3.2.2 Sample Surface

There are many possible choices of smooth surface exist for conducting this research. Amongst others, we may use clean piece of steel, construction materials like concrete, plastic or even glass. However, the paper seems to be the most appropriate one, because it is easy to get, easy to give it a shape, crop and place on the fixed platform. Blank piece of paper demonstrates no visible details or features to be used in stitching.

Additionally, during experiments, we can put marks and text, draw lines or any arbitrary shapes in order to test the stitching application. Such tests should be performed first when the paper is under the daylight. We should get the stitching application working well and performing good match of correspondence points under normal light (for example, when application makes panorama of piece of paper containing printed text). After that, we will assess the stitching results for surface under coherent illumination.

3.2.3 Laser Illumination System

Lasers (acronym of *Light Amplification by Stimulated Emission of Radiation*) is a source of coherent[2] light. The beam produced by laser source is thin, so there is

[2]Coherence is an ideal property of waves that enables stationary (i.e. temporally and spatially constant) interference [36].

a need to scatter it. In order to do this, phase randomizing deformable mirror of Dyoptyka [28] will be used. This mirror reflects laser beam and produces illumination with controllable divergence from 0.5 to 5 degree. Also, this mirror reduces the speckle, and therefore speckle characteristics expected to be more reliable.

The structure of laser illumination system is presented in the figure 3.2. Here, laser source is directed to deformable mirror, which scatters thin laser beam and reduces the speckle.

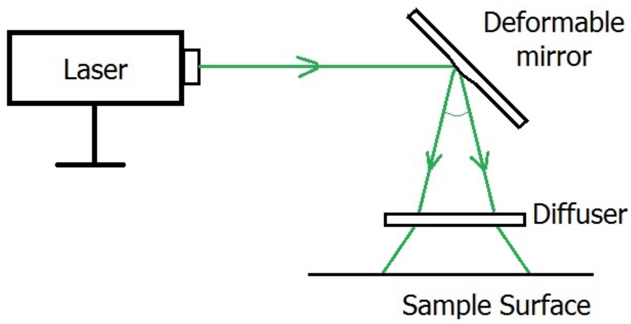


Figure 3.2: Structure of the laser system

Presented configuration is similar to one used in laser interferometry except that deformable mirror is replaced by lenses or prism to scatter the beam.

3.2.4 Pan-Tilt Unit

The speckle pattern characteristics depend on several factors, in particular on two distances: (1) laser-to-surface and (2) surface-to-camera. To keep these distances constant, pan-tilt unit will be used in apparatus. This unit is fixed on the optical bench (as well as other parts of the system). The unit at our disposal is PTU-46 (see figure 3.3) produced by Directed Perception Inc. It has 2 degrees of freedom and precise control of position with resolution 0.0129°.

Figure 3.3: Pan-tilt Unit used in apparatus

The PTU can be controlled manually and from PC, when user can set initial position and then send command to set desired pan and/or tilt position. Therefore, the experiments can easily be repeated with assurance that speckle characteristics remain the same from one experiment to another.

Apparatus Summary

The apparatus is required for observing speckle patterns due to following reasons. Firstly, to fix the position of camera, sample surface and laser illumination system in order to have constant pattern, which can be used in image stitching. Secondly, to provide repeatable configurations, and to achieve this pan-tilt unit is used. As soon as apparatus has been built, we will concentrate on the application for image stitching. This topic is covered in next section.

3.3 Application

General approach for creating panoramas consists of (1) acquisition of images, which have overlap; (2) search of correspondence between them; (3) motion model estimation;

(4) warping these images into same reference coordinate system; and (5) copying pixel values onto compositing image.

The acquisition part of stitching process is simple. Camera and laser illumination have fixed positions. Only pan-tilt is responsible for change of image contents, and this change is controlled very precisely from PC. Pixel values copy becomes straightforward as soon as images are warped into same coordinates. What's more, camera lens may be chosen in a way when distortions are kept minimal, and sample surface plane can be put parallel to the camera plane. This, along with small rotation angles (i.e. 10°–15°) of pan-tilt unit, will keep the coordinates of overlapping images at the same system. Hence, no warping will be needed.

As we can neglect the warping, attention must be paid to the task of finding intersecting regions and points of correspondence between overlapping images. Considering assumptions from previous paragraph, we can conclude that direct methods of alignment estimation are the most suitable for correspondence calculation. And here are the reasons:

- Rotation angle is known, and pre-processing *rotate back* can be performed to transform next captured image to same coordinate system;
- Scale of overlapping patches is the same, template matching algorithms best suited for that;
- Speckle pattern has uniformly distributed intensity, so there is no changes in lighting conditions, and the error of matching will be minimized.

The idea of template matching is based on matching an actual image patch against an input image by "sliding" the patch over the input image using one of the matching methods [3]. These methods are based either on square difference, or correlation between patch and image. We will use normalized cross-correlation (NCC), which is proven to obtain more accurate matches and reduces the effects of lighting differences between the template and the image. The equation 3.1 is used to calculate correlation coefficient when template is placed to position with coordinates (m,n):

$$N(m,n) = \frac{\sum_i \sum_j \mathrm{g(i,j)} * \mathrm{t(i-m,j-n)}}{\sqrt{\sum_i \sum_j \mathrm{g(i,j)}^2} * \sqrt{\sum_i \sum_j \mathrm{t(i-m,j-n)}^2}} \tag{3.1}$$

where $g(i,j)$ - pixel value at position (i,j) in the image, $t(i,j)$ is a value of pixel in the template. The perfect match will be 1 and a perfect mismatch will be -1; a value of 0 means that there is no correlation [3].

The speckle pattern is expected to be an instrument for matching the corresponding points of overlapping images. However, the purpose of the system is to build panorama of smooth surface, not the speckle pattern itself, so we propose to utilize laser illumination in the following way:

1. capture image of sample surface under normal light conditions;

2. capture image of surface under coherent illumination;

3. do steps 1 and 2 for next region of surface;

4. use "laser" image version to find coordinates for stitching and use this information to stitch images together.

Since we control the motion of pan-tilt unit, we can also restrict areas where to search for correspondence. These areas will depend on the rotation angle of pan-tilt, therefore will be chosen at experiments time.

Application Summary

In controlled environment, we can assume that apparatus will produce no or small distortions and no warping would be needed. It simplifies stitching process and transforms it into acquisition-alignment-composition line. Images have known rotation parameters, so direct based methods for alignment will be used, in particular, normalized cross-correlation seems to be best choice. Speckle pattern will help to find coordinates of overlaps between images, then real images of surface will be stitched.

This chapter was dedicated to detail design decisions made regarding apparatus for utilizing laser illumination in stitching images of smooth surfaces. Also, the background knowledge was collected in order to build stitching application. The next chapter presents a proof-of-concept implementation of design stated above.

Chapter 4

Implementation

Since we described design of experimental apparatus and have chosen alignment method to be used in stitching, we can proceed to implementation of software. First, we have to choose the platform for application development and library for image processing. Then, provide detailed architecture of application. At the end of this chapter we demonstrate our apparatus and test it together with developed application on images taken under normal conditions and coherent illumination.

4.1 Platform

There are two ways to build stitching application. First, is to take standalone camera device with lens and develop PC application consuming captured images and stitching them together. This would involve the use of specific camera drivers, which are different for all camera producers. Therefore, the application will be device-dependable and require more development effort. Second option is to use the camera of smartphone, e.g. Android-based phone. This way has two main advantages:

1. Modern Android smartphones have cameras of high resolution (e.g. 8 mega pixels in LG Nexus 4, 13 mega pixels in Sony Xperia-Z [17]);
2. Android SDK affords full control of camera parameters from API functions;

Additionally, Android application later can be run on Android working on embedded system, thus may be used to get the panorama of the dangerous areas like oil tankers or radioactive storages. For example, snake-arm robots (like robots developed by OCRobotics[25]) can carry embedded system on board and take pictures inside these places. Modern smartphones also can define location, measure spatial position, acceleration and speed. This information may be potentially useful to reduce the computational complexity by utilizing additional data about operating environment.

To date, number of researchers conducted study about panorama stitching for smartphones. Generally, they addressed stitching problem by using feature based methods(e.g. Gansawat et.al. [11]), however, you can find solutions for high resolution images based on direct methods (e.g. Xiong et.al. [37] and [38]). This demonstrates that mobile devices have specific constraints due to limited computational power and energy consumption, though can be a good platform for panorama stitching.

Industry standard for computer vision applications is to be developed with use of OpenCV (Open Source Computer Vision Library). OpenCV is free for both academic and commercial use, has C++, C, Python and Java interfaces and supports Windows, Linux, Mac OS, iOS and Android [26]. The library helps professionals to implement projects efficiently and fast by providing infrastructure for processing, which has been tested and is proven to be efficient.

The functions of openCV to be used current project are image manipulation and template matching.

4.2 Application

Development for Android platform differs from application development for PC. The main building block of Android application is activity. The Activity class is an important part of an application's overall lifecycle, and the way activities are launched and put together is a fundamental part of the platform's application model[16]. According to Android Developer Guide [16], Activity is a single, focused thing that the user can do. Almost all activities interact with the user, so the Activity class takes care of creating a window for you in which you can place your UI. Activity lifecycle is presented on the figure 4.1 below[1].

Activity calls method *onCreate()* when created, here all initialization of resources performed and UI is prepared. Execution of activity ends after *onDestroy()* is called. User can change the current state of activity by launching another application, by pausing current activity and by finishing working with application.

Our application has only one class derived from activity, where we put camera control and stitching functionality. We override activity methods, presented in the table below (see table 4.1).

[1] Image is taken from Android Development Guide

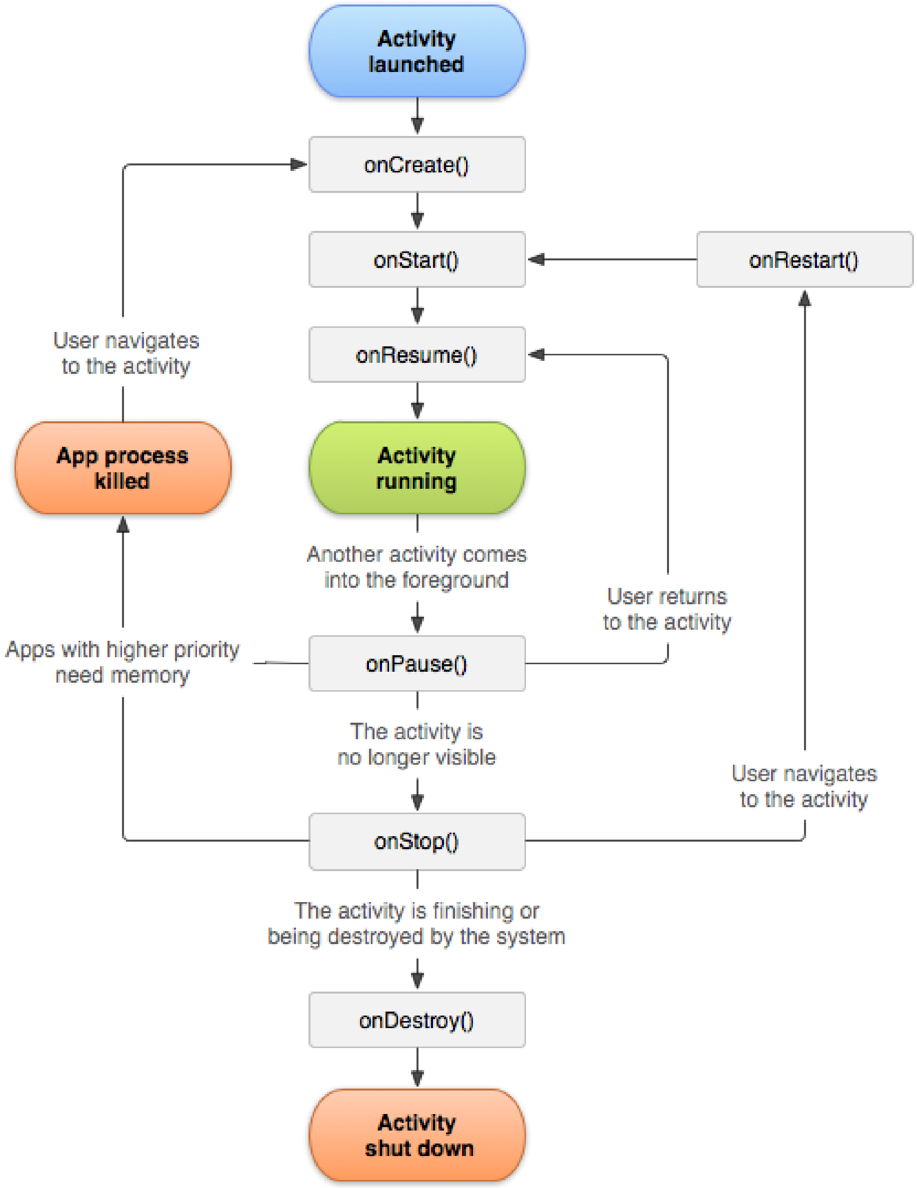


Figure 4.1: Android activity lifecycle

Table 4.1: Activity methods overridden

Method name	**Functionality**
onCreate()	UI initialization, preparing camera preview and directory for saving images
onResume()	load OpenCV manager, initialize camera device and start preview from it
onPause()	stop camera preview and release camera
onDestroy()	finalize the work and ensure that resources released correctly

The structure of application you can see at the class diagram below (figure 4.2). Class *Panorama* extends Android class *Activity* in order to create custom user interface and provide new functionality. The class called *Stitcher* uses OpenCV library to perform image rotation, template matching and panorama stitching.

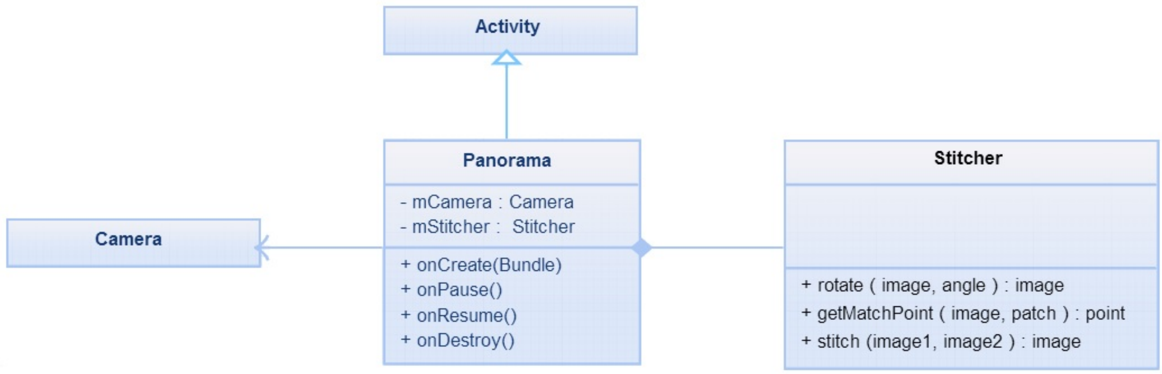


Figure 4.2: Class diagram

To control the camera we use class *Camera* provided by Android API and functions:

setPictureSize() to set the resolution of captured image, *setExposureCompensation()* to configure duration of image acquisition, *setPictureFormat()* to specify the output format of image file and *autoFocus()* to get focused image of the surface.

To use image processing functions of OpenCV we use OpenCVManager, which is a class containing code ported for Android platform. Activity launch is accompanied with OpenCVManager asynchronous loading, and as soon as loading if finished, OpenCV is ready to work.

OpenCV library provides convenient data structure for image manipulations – *Mat*, which represents 2D numerical array [3]. Mat structure contains all required information about image, including Region Of Interest (ROI), image depth, size and pixel format. Functions developed for image rotation, load/save and stitching consume or produce images in *Mat* format.

We would like to note that stitching is being performed in background with help of *Async Task* – simple wrapper around Thread for short operations. In this case, user interface remains responsive and stitching performs faster due to full usage of available resources.

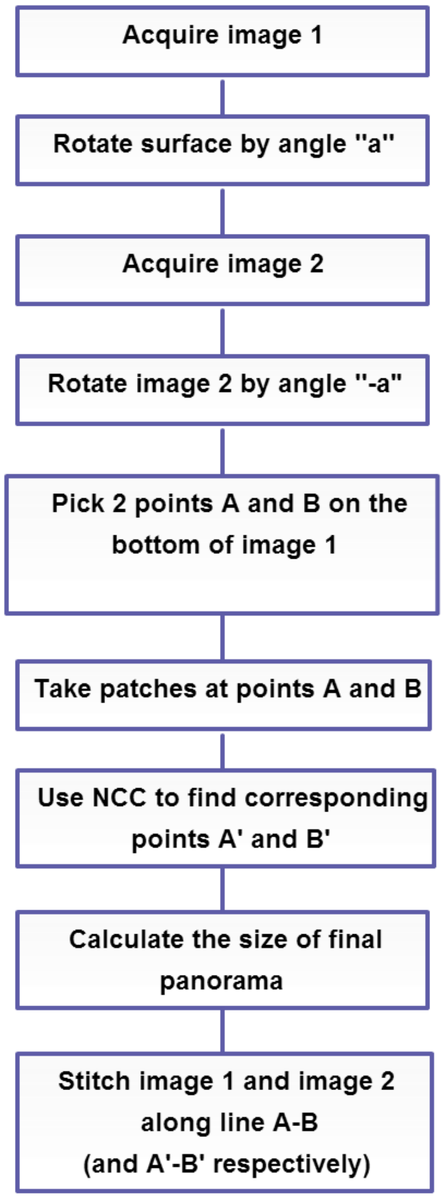


Figure 4.3: Stitching steps

The sequence of actions to stitch two images together into panorama is presented on the figure 4.3. Process starts with acquiring these images, considering that they have been rotated with respect to each other by known angle “a”. Then, second image is *rotated back* by angle “-a”. To align these images, we pick two patches of size 30x30 (faster matching, low precision) or 50x50 (higher precision, takes more time to match) and match those patches with second image. Finally, we calculate the final size for compositing image and copy images 1 and 2 pixel-by-pixel.

The choice of patch size is driven by the performance requirements. Patch positions are dependent on the rotation angle of image 2 with respect to image 1. In experiments, we assume that rotation angle can be from 15° to 20°, therefore points A and B will be located in bottom part of the image at center. During experiments, we found out that patches at positions stated below corresponds to both images and can be used for matching:

Point A(2/8 * image width; image height - patch size)

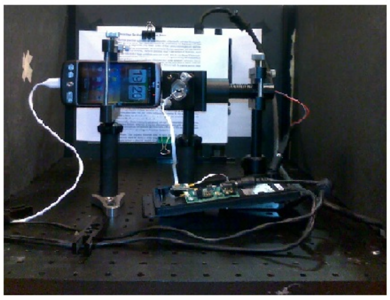
Point B(6/8 * image width; image height - patch size)

4.3 Results

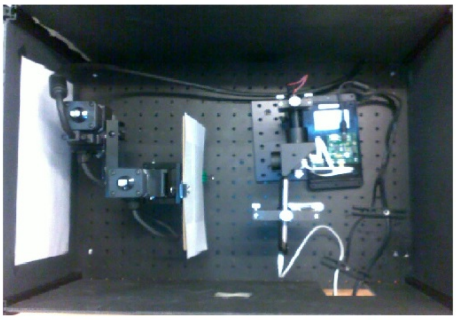
According to design chapter of current dissertation and platform chosen in previous section, after putting all components together the following experimental apparatus has been built (see figure 4.4).

You can see Android phone with embedded camera, laser illumination system and pan-tilt unit holding sheet of paper. Paper with printed text works as a sample surface for experiments. Distance from surface to camera is 11.5 cm. Camera elevation is 14 cm.

(a) Front view



(b) Side view



(c) Top view

Figure 4.4: Apparatus constructed for experiments

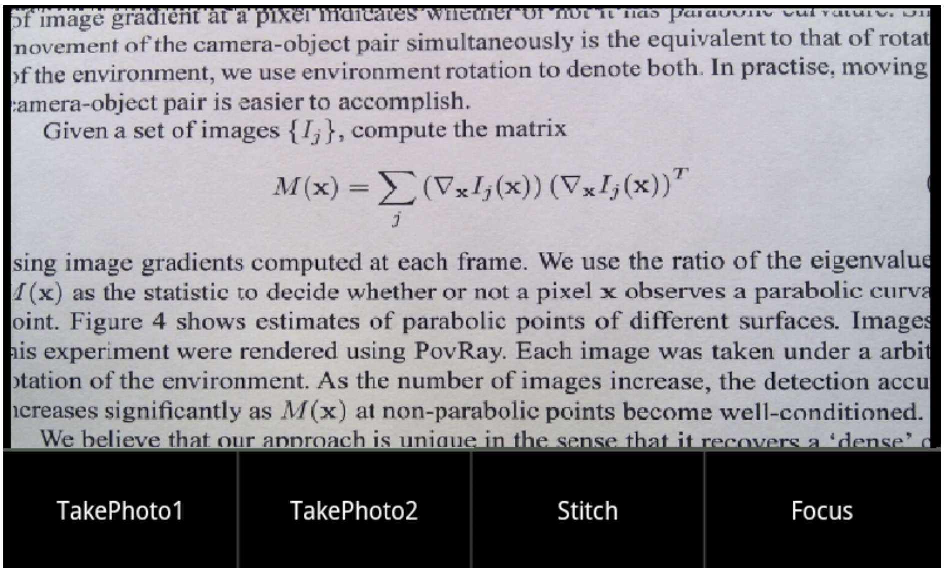
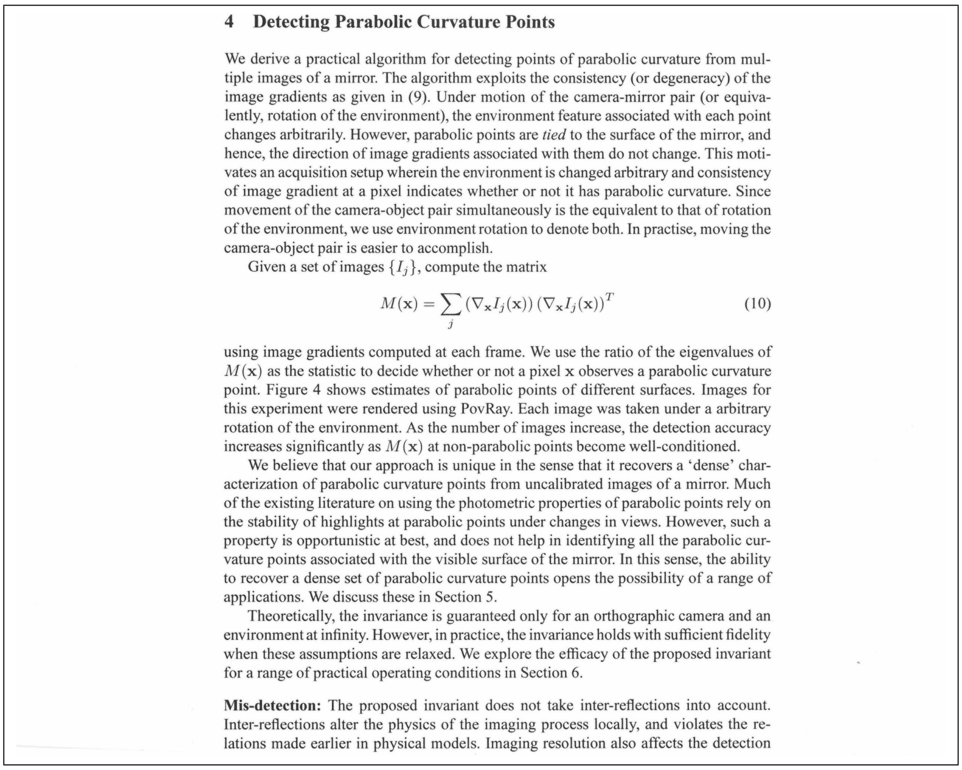


Figure 4.5: Android application screen

We plan to stitch images of paper with text so that we can debug the program, and review the quality of panorama obtained. User interface of Android application developed for this purpose is presented on the image 4.5. Sample for experiment has sizes 21 x 16.5 cm and presented on the figure 4.6.



4 Detecting Parabolic Curvature Points

We derive a practical algorithm for detecting points of parabolic curvature from multiple images of a mirror. The algorithm exploits the consistency (or degeneracy) of the image gradients as given in (9). Under motion of the camera-mirror pair (or equivalently, rotation of the environment), the environment feature associated with each point changes arbitrarily. However, parabolic points are *tied* to the surface of the mirror, and hence, the direction of image gradients associated with them do not change. This motivates an acquisition setup wherein the environment is changed arbitrary and consistency of image gradient at a pixel indicates whether or not it has parabolic curvature. Since movement of the camera-object pair simultaneously is the equivalent to that of rotation of the environment, we use environment rotation to denote both. In practise, moving the camera-object pair is easier to accomplish.

Given a set of images $\{I_j\}$, compute the matrix

$$M(\mathbf{x}) = \sum_j (\nabla_{\mathbf{x}} I_j(\mathbf{x}))\,(\nabla_{\mathbf{x}} I_j(\mathbf{x}))^T \qquad (10)$$

using image gradients computed at each frame. We use the ratio of the eigenvalues of $M(\mathbf{x})$ as the statistic to decide whether or not a pixel $\mathbf{x}$ observes a parabolic curvature point. Figure 4 shows estimates of parabolic points of different surfaces. Images for this experiment were rendered using PovRay. Each image was taken under a arbitrary rotation of the environment. As the number of images increase, the detection accuracy increases significantly as $M(\mathbf{x})$ at non-parabolic points become well-conditioned.

We believe that our approach is unique in the sense that it recovers a 'dense' characterization of parabolic curvature points from uncalibrated images of a mirror. Much of the existing literature on using the photometric properties of parabolic points rely on the stability of highlights at parabolic points under changes in views. However, such a property is opportunistic at best, and does not help in identifying all the parabolic curvature points associated with the visible surface of the mirror. In this sense, the ability to recover a dense set of parabolic curvature points opens the possibility of a range of applications. We discuss these in Section 5.

Theoretically, the invariance is guaranteed only for an orthographic camera and an environment at infinity. However, in practice, the invariance holds with sufficient fidelity when these assumptions are relaxed. We explore the efficacy of the proposed invariant for a range of practical operating conditions in Section 6.

Mis-detection: The proposed invariant does not take inter-reflections into account. Inter-reflections alter the physics of the imaging process locally, and violates the relations made earlier in physical models. Imaging resolution also affects the detection

Figure 4.6: Sample surface used in experiment

Results of stitching under normal light conditions are presented in the figure 4.7. Camera plane and sample surface are kept parallel. As one can notice, optical distortions introduced by camera are small enough and not taken into account when panorama is being created. Image 2 rotated by angle 20° with respect to image 1.

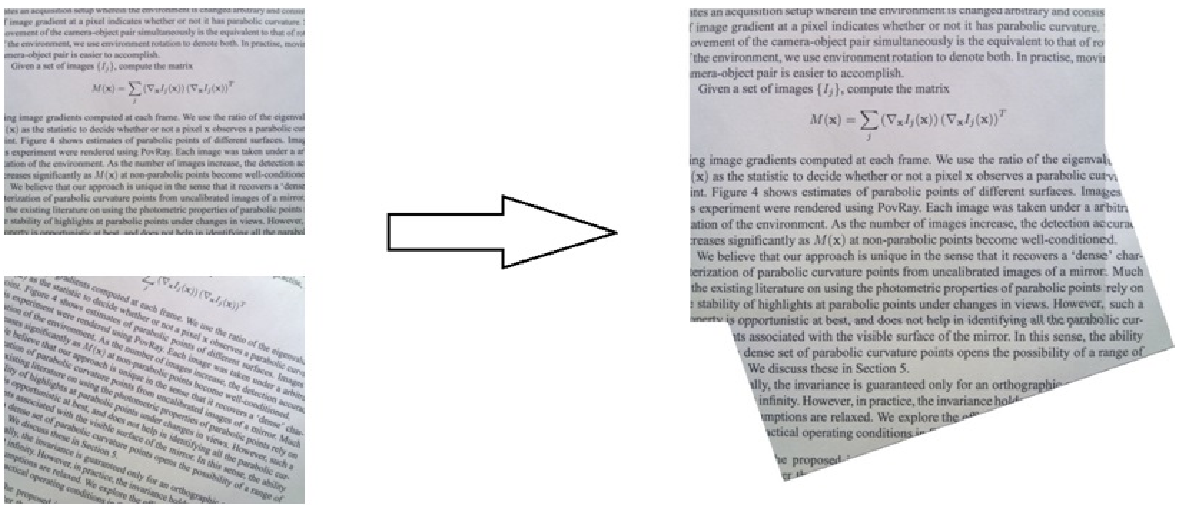


Figure 4.7: Two images with printed text were stitched into one

We defined that point A and point B positions have same y coordinate, thus additional test may be performed to ensure that points A' and B' also have y coordinate the same or slightly different (i.e. 5-10 pixels). This would be an evidence that rotation subroutine correctly transformed second image and the perfect match is found. Another evidence of correctness is the distance between patches. If it remains constant, i.e. distances A-to-B and A'-to-B' are the same, then result is trustworthy.

Results of stitching under coherent illumination are presented on the figure 4.8. Surface containing printed text being illuminated by laser light. Text on the paper is used for visual control of the speckle, so one can compare speckle *features* and note similarities or differences in grain pattern[2].

[2] The size of image segment is 294x96. This part is enlarged for better visibility

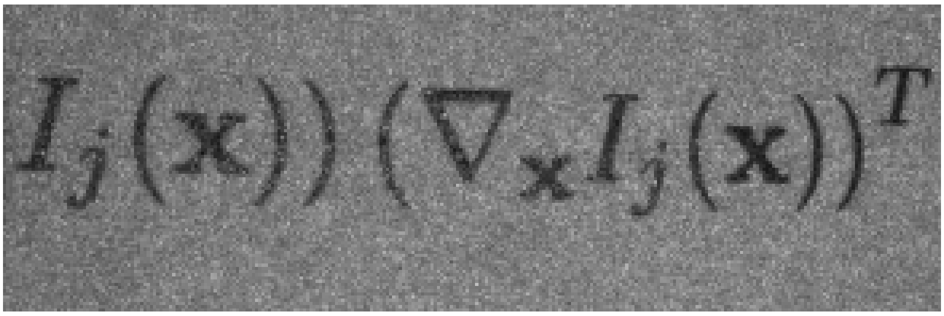


Figure 4.8: Paper with printed text under laser illumination

The form, spatial and relative positions of grains presented here are caused by roughness of the surface and other factors mentioned in Chapter 3. At first sight it looks like there is no pattern at all, but for normalized cross-correlation every pixel contribution is valuable, and the match can be found.

The figure 4.9 shows comparison of images of surface under normal light and under coherent illumination. If we would look at the paper and no text would be placed, obviously, we can see no data for stitching at surface under normal light. However, we can notice some details (circled with red) on the illuminated surface, which are possibly could help to find correspondence.

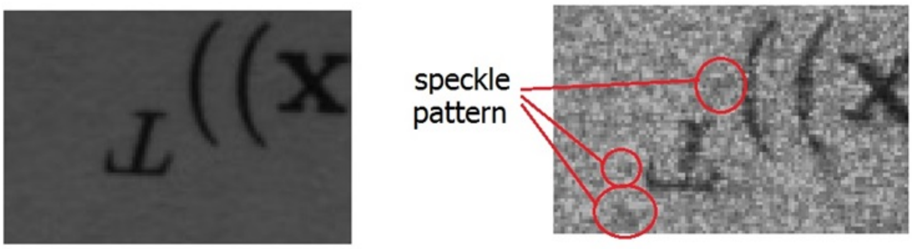


Figure 4.9: Fragment under normal and laser illumination

To demonstrate that speckle pattern is persistent to surface movement, i.e. moves together with the surface, we present the figure 4.10. Here, the sample surface was rotated by 5° degrees and the *features* (circled with red) of the speckle remained.

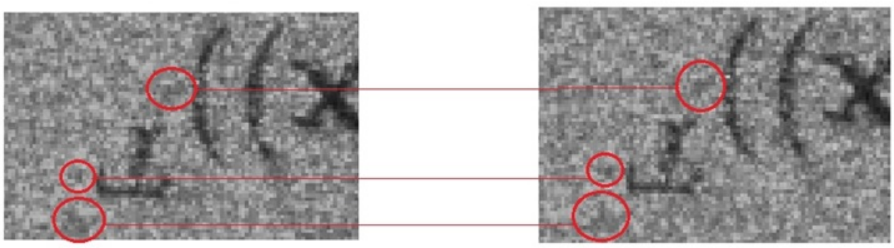
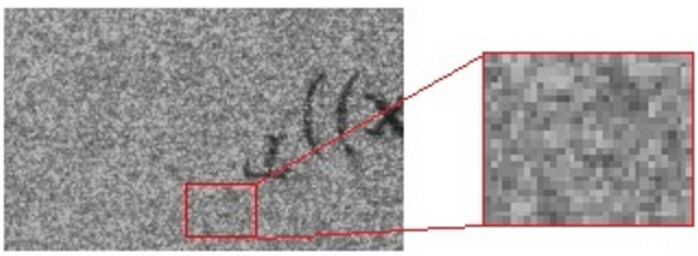
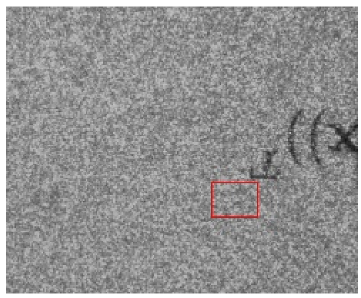


Figure 4.10: Persistence to movement

On the figure 4.11 below, we provide results of normalized cross-correlation applied to the image of surface rotated by 5° degrees. Figure 4.11a contains source image captured when pan-tilt unit was in initial position. Figure 4.11b presents the image of the same area of paper, but rotated with respect to initial one.



(a) Source image with patch



(b) Surface rotated by 5°

Figure 4.11: Results of normalized cross-correlation applied to source and rotated images

We took a patch of size (32x24) from initial image and applied normalized cross-correlation algorithm to find position of this patch on the image of rotated surface. Segments of the source and rotated images presented here have sizes (183x111) and (247x201) respectively.

Chapter 5

Evaluation and Conclusions

In the beginning of this dissertation we stated that there is a substantial need in apparatus for stitching images of smooth surfaces. Especially, it is important when such surfaces lack of any details which may help to establish point correspondence between images with overlaps. Despite the research conducted to address the issue of obtaining smooth surface invariants, and study about curve points in silhouettes, the problem of stitching remains unsolved.

Inspired by laser speckle interferometry, we attempted to perform image stitching with use of information provided by speckle pattern, with the hope that such pattern will be unique and represent the surface roughness.

To address the problem of smooth surfaces, we have built an apparatus for conducting experiments. Time allocated for the project was mainly utilized to settle the pieces of the apparatus together. Every part of experimental mechanism has its own substantial properties and takes time to be adjusted. For example, we tried 3 different cameras with 4-5 lenses until get clean focused speckle pattern appeared on the screen of PC.

We succeeded in stitching images of surfaces with printed text under normal lighting conditions, therefore the stitching part of application has been tested. The only step to be changed is the search of correspondence points: under the normal light we used visible to human eye letters of text, speckle pattern would give unique surface roughness details.

Results of stitching smooth surface being illuminated by laser were not obtained. There was a reason for that: building the apparatus, trying different configurations of camera and lenses, dealing with Android and Android camera took almost all of the time allocated for this project.

However, obtained results demonstrated that solution for stitching smooth images can be found, and speckle pattern provides necessary information for smooth surface image stitching when compared to existing methods of image alignment.

In the future, it is worth to continue the work with experimental apparatus and stitching application. Complete images of smooth surfaces have to be stitched, and the expectation about performance are great.

Additional help is scenario of smooth surface can be provided by Android position and acceleration sensors, which can be used along with information from speckle. As well as feature-based methods are used in conjunction with direct-based ones (when first ones give approximate correspondence and second ones refine it), sensor data can be used to obtain rough location of the overlap position. Then, presented technique will refine it and produce perfect correspondence points search.

Appendix A

Abbreviations

Short Term	**Expanded Term**
API	Application Programming Interface
ESPI	Electronic Speckle Pattern Interferometry
LSI	Laser Speckle Interferometry
NCC	Normalized Cross-Correlation
PTU	Pan-Tilt Unit
ROI	Region of Interest
SIFT	Scale-Invariant Features Transform
UI	User Interface

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