

Charles University in Prague  
Faculty of Mathematics and Physics

## **BACHELOR THESIS**

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# **3D Computer Vision on the Android Platform**

Computer Science Institute of Charles University

Supervisor of the bachelor thesis: Mgr. Lukáš Mach  
Study programme: General Computer Science

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Dedication.

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# Introduction

The task of reconstructing 3D information from multiple 2D photos of a real-world scene has attracted a lot of research in the last two decades and in the recent years in particular. A great number of algorithms have been proposed to solve problems in this area and several main approaches have emerged. The applicability of these approaches depends mainly on what kind of input we intend to feed the algorithm (an unorganized set of photos, a video stream, a pair of stereoscopic images, etc.) and also on what type of output we expect the algorithm to produce (polygonal model, a disparity map). As a result of this progress, various real-world applications for these algorithms have appeared – e.g., several camera trackers or products like Microsoft PhotoSynth [18].

Simultaneously, both the general availability and the computational power of smartphones have improved significantly. Mobile phones that employ the Linux-based Android software platform are currently very popular. The Android market share increased to almost 69% in the year 2012 [9] (Figure 1). A built-in camera, a relatively fast CPU and various sensors such as the accelerometer are very common in such mobile phones, making it possible to develop a wider range of applications.

Operating System	2012 Market Share	2011 Market Share	Year over Year Change
Android	68.8%	49.2%	104.1%
iOS	18.8%	18.8%	46.0%
BlackBerry	4.5%	10.3%	-36.4%
Windows Phone	2.5%	1.8%	98.9%
Symbian	3.3%	16.5%	-70.7%
Others	2.1%	3.3%	-7.4%
<b>Total</b>	<b>100.0%</b>	<b>100.0%</b>	<b>46.1%</b>

Figure 1: Top five smartphone operating systems and their market share in 2011 and 2012.

The goal of this work is to explore the ways of connecting these two phenomena. Our aim is to create an Android application that takes a pair of photos using the phone’s internal camera, applies a series of computer vision algorithms to reconstruct the depth information, and visualizes the result using 3D graphics. Due to the inherent ambiguity of the problem, it is inevitable that our approach will be limited to particular types of scenes, for example sets of photos of highly textured surfaces. One of our main goals is to investigate how well the solving of such a computation-intensive problem can be done within the limits of a Java-based environment running on a mobile phone or a tablet computer.

## **Outline of the thesis**

The first part of this work analyzes the problem, describes currently available software packages solving related problems, and gives an overview of some of the programming libraries employed in this work (Chapter 1). In Chapter 2, we introduce the mathematical concepts fundamental to the area of computer vision. This part also fixes the notation used in the remaining parts of the thesis. In Chapter 3, we rigorously discuss the problem of 3D reconstruction from images. Furthermore, we describe several algorithms from the literature that have been successfully applied to this problem. Then, we elaborate on the basics of Android development (Chapter 4). The following section is devoted to the implementation of our application. Finally, we evaluate and benchmark the resulting application (Chapter 6).

# 1. Overview

In this chapter, we give an overview of software solutions providing functionality related to our area – namely, the analysis of depth information from photos and videos. Section 1.1 discusses software packages currently available to the end-users, while Section 1.2 describes software libraries implementing relevant algorithms. Section 1.3 is devoted specifically to our solution. There, we discuss what type of input the software processes and what kind of output can the user expect as a result.

## 1.1 Available software packages

### 1.1.1 Matchmoving software

Matchmoving software in the film industry represents one of the earliest widely adopted commercial applications of algorithms extracting 3D information from 2D (video) imagery. In such a software, accurate 3D information about the scene is only a secondary product and the user is mainly interested in obtaining information about the position and orientation the camera had at the time of capture of the individual video frames. The knowledge of these parameters allows artists to add special effects and/or other synthetic elements to the video footage.

Although matchmoving (also called camera tracking) can be achieved using many different techniques, the prevailing method detects easily definable elements – such as corners – in a frame of the video and tracks their movement on the subsequent frames. The camera parameters are then calculated from the 2D movement of these *tracks*. In computer vision this approach is called *structure from motion*, since the structure of the scene (for example, the trajectory of the camera) is determined by the apparent movement of the tracks on the video frames. The 3D positions of the scene-points corresponding to the detected corners can also be calculated, giving the user a very rough point cloud reconstruction of the scene.

Examples of widely used matchmoving applications include 2d3’s Boujou<sup>1</sup> and Autodesk Matchmover<sup>2</sup>. The opensource libmv project<sup>3</sup> aims to add matchmoving capabilities to the Blender 3D modelling application<sup>4</sup>.

### 1.1.2 Microsoft PhotoSynth

Microsoft PhotoSynth, based on a research by Snavely, et al. [18], has been publicly released in 2008. The software solution processes a set of unorganized pictures of a single scene and subsequently generates its 3D point cloud reconstruction. The main purpose of the reconstruction is to allow the user to navigate between the photos in a novel way that respects the physical proximity of the cameras taking the individual photos. Perhaps most notably, the technology has

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<sup>1</sup><http://www.2d3.com>

<sup>2</sup><http://www.autodesk.com>

<sup>3</sup><http://code.google.com/p/libmv/>

<sup>4</sup><http://www.blender.org>

been employed at various times by the BBC and CNN [3]. Recently, the possibility to generate 360° panoramas and to upload the input photos from a Windows 8 mobile phone has been added.

Microsoft PhotoSynth is a closed-source application with most of the computation running on Microsoft’s servers. It extends a system called *Photo Tourism* developed by Snavely, Seitz and Szeliski [16, 17]. To obtain accurate information about the positions of the cameras it applies the SIFT algorithm (discussed in Section ??) to detect points of interest. These are then matched across images using an implementation of an approximate nearest neighbour algorithm and filtered using the RANSAC paradigm [5]. The theory presented in the classical monograph [7] is then applied to obtain external and internal camera calibration (if there is relevant EXIF information associated with the photo, then the software uses this to obtain an initial guess of the internal camera calibration parameters).

### 1.1.3 Autodesk 123D

Autodesk 123D is a bundle of several applications. One of them is 123D Catch, which creates a 3D model from a set of photos taken from different viewpoints. The software is compatible with other Autodesk 123D applications, making it a viable solution for 3D artists who want to include real-world objects in their scenes. The program is available for the Windows, Mac OSX, and iOS platforms. To achieve good results, it is necessary to follow detailed instructions when taking the photos. A failed reconstruction typically occurs when the photos are blurred, do not have solid background, or in the case of insufficient amount of photos.

## 1.2 Available libraries

We now briefly introduce the main computer vision or computer graphics libraries that provide implementations of some of the algorithms necessary to build our software.

### 1.2.1 OpenCV

OpenCV<sup>5</sup> is a cross-platform library originally developed by Intel. It provides an implementation of several hundreds of computer vision related algorithms, including, e.g., camera calibration routines, image segmentation algorithms, clustering algorithms, and linear algebra solvers. The library was originally written in pure C. However, in the recent years the development shifted towards C++. This led to the introduction of a new object oriented API.

The library provides interfaces for C, C++, Python, and Java and supports the Windows, Linux, Mac OS, iOS, and Android platforms. The Android version of the library, called *OpenCV4Android*, provides an access to the OpenCV methods using JNI bindings. The same approach has been used by the competing *JavaCV* library<sup>6</sup>, which actually provides access to a wide range of computer graphics libraries (e.g., FFmpeg, OpenKinect, . . . ).

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<sup>5</sup><http://opencv.org>

<sup>6</sup><https://code.google.com/p/javacv/>

Let us now compare three variants of the same example code for OpenCV, OpenCV4Android and JavaCV to illustrate the difference between these interfaces. A typical C++ code to detect strong corners on an image using the OpenCV function `goodFeaturesToTrack` would be:

---

```
std::vector<Point2f> corners;
goodFeaturesToTrack(img, corners, maxCount, qualityLevel, minDistance,
    mask, blockSize, useHarrisDetector, k);
```

---

An OpenCV4Android version of the same code reads:

---

```
MatOfPoint corners = new MatOfPoint();
Imgproc.goodFeaturesToTrack(img, corners, maxCount, qualityLevel,
    minDistance, mask, blockSize, useHarrisDetector, k);
```

---

The JavaCV version of this would be:

---

```
CvPoint2D32f corners = new CvPoint2D32f(maxCount);
int[] count = { maxCount };
cvGoodFeaturesToTrack(img, eig, temp, corners,
    count, qualityLevel, minDistance, mask,
    blockSize, useHarrisDetector);
```

---

Here, note that the JavaCV binding is derived from the older pure-C interface of OpenCV. For this reason, the function still expects the parameters `eig` and `temp` even though they are actually ignored by the current version of the library. The way in which the `maxCount` parameter is passed to the function is another relict from the old versions of OpenCV, where it was necessary to pass it using a pointer to get back the length of the array `corners` dynamically allocated inside the `cvGoodFeaturesToTrack`.

Since OpenCV4Android is developed by the same group of developers as the original OpenCV and provides access to functions available only in newer versions of the library, we have decided to choose this version for the final version of our project.

### 1.2.2 OpenGL

OpenGL<sup>7</sup> is an application programming interface for developing 2D and 3D graphics applications. It is an open cross-platform environment providing mainly rendering and visualization functions. OpenGL ES, a subset of OpenGL for embedded systems including mobile phones and consoles, has been released in 2012.

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<sup>7</sup><http://www.opengl.org/>

## 1.3 Problem statement

Our application's objective is to provide the user the possibility to create a rough 3D model of a scene pictured on a pair of photos. We expect that:

- both photos are focused, reasonably sharp and not significantly over- or under-exposed,
- the viewpoints the camera had when taking the photos differ only by translation,
- the above-mentioned translation is not negligible – our software certainly cannot reconstruct the depth information from a pair of photos that are identical,
- there is some overlap between the two photos, i.e. some scene elements are visible on both photos,
- the scene on the photos is highly textured – for example, taking photos of historical houses would typically result in an appropriate input.

The output of the application is a visualization of a “depth map” showing the reconstructed depth information for the overlapping part common to both input photographs. The intended purpose of the reconstruction is purely for its visualization. However, we can foresee the extension of the software to offer additional features. For example, the ability to estimate relative dimensions of objects could be provided, although the accuracy of this would depend on how precisely the internal calibration of the phone’s camera (most importantly, its focal length and sensor size) can be estimated.

## 2. Basic Notions

To make this work more self-contained, we briefly introduce basic notions and concepts used in the later chapters. Interested reader is referred to the monographs [1, 7] for further details.

### 2.1 Convolution

*Convolution* is an operation on two functions often encountered in signal processing. In image processing, convolution is typically used to apply a particular filter (kernel) to the image. For example, the output of such convolution can be a blurred image. Convolution with a Gaussian kernel is particularly common.

**Definition 1.** *The convolution of functions  $f$  and  $g$  is an operation defined as:*

$$(f * g)(t) = \int_{-\infty}^{+\infty} f(\tau)g(t - \tau)d\tau.$$

In our setting, the  $f$  from the above definition represents the image function and  $g$  the filter.

### 2.2 Image derivatives

*Image derivatives* of an image function are analogous to derivatives of a real continuous function. They allow us to measure spatial changes in an image by expressing the rate of image intensity change in a particular direction. High values often indicate an edge in the image data. They are defined as

$$\begin{aligned}\frac{\partial I}{\partial x}(x, y) &= I(x + 1, y) - I(x - 1, y), \\ \frac{\partial I}{\partial y}(x, y) &= I(x, y + 1) - I(x, y - 1),\end{aligned}$$

where  $I$  is the input image and  $(x, y)$  are coordinates of the pixel. A generalization of this is often considered since the above discretization is not able to detect significant intensity changes spread across more than few pixels.

#### 2.2.1 Gaussian image derivatives and scale-space

Scale-space of an image is a series of gradually more and more smoothed images obtained by convolving the original image with Gaussian kernels of increasing size. Formally, it is a series of image functions  $L(x, y; t)$  defined as the convolution of the image function  $f(x, y)$  and the Gaussian kernel  $g(x, y; t)$ , where  $t$  is the corresponding variance:

$$L(x, y; t) = f(x, y) * g(x, y; t).$$

To this scale-space representation we can apply local derivatives at any scale. Equivalently, scale-space derivatives can be computed by convolving the original image  $f$  with Gaussian derivative operators which are derivatives of the Gaussian function. For this reason they are often also referred to as *Gaussian derivatives*.

## 2.2.2 Laplacian

As already mentioned, *image derivatives* are useful for the purpose of the detection high variations of image intensity values. After taking the first derivative of the image function, points of highest intensity change are those where we have local maxima. If we go further and take the second derivative, then the corresponding values transform to zeroes. Thus, it might be important to consider the sum of derivatives in the direction of both axes to detect such structures.

**Definition 2.** *The Laplacian of a function with  $n$ -dimensional support is the divergence of the gradient of a function  $f$ :*

$$\nabla^2 f = \sum_{i=0}^n \frac{\partial^2 f}{\partial x_i^2}.$$

*In image processing we usually consider 2-dimensional space, thus the Laplacian becomes:*

$$\nabla^2 f(x, y) = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2}.$$

Similar argument to the above can be used to deduce that local maxima and minima of the Laplacian function indicate the presence of a blob-like structure in the image data. The size of the structure is related to the variance of the Gaussian used in the definition of the Gaussian image derivatives of Section 2.2.1. For this reason, algorithms like SIFT [13] repeat some parts of the computation for varying values of this parameter to detect structures of all sizes.

## 2.2.3 Hessian matrix

The Hessian matrix describes a second-order behaviour of a function around a particular point.

**Definition 3.** *The Hessian matrix of a function  $f : \mathbf{R}^n \rightarrow \mathbf{R}$  at  $\mathbf{x} \in \mathbf{R}^n$  is a matrix  $H_f(\mathbf{x})$  of the second order partial derivatives of  $f$  evaluated at  $\mathbf{x}$ :*

$$H_f(\mathbf{x}) := \begin{pmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n \partial x_1} & \frac{\partial^2 f}{\partial x_n \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_n^2} \end{pmatrix}.$$

*If any of the partial derivatives on the right-hand side are undefined, we say that the Hessian matrix is also undefined.*

Note that the trace of the Hessian matrix is equal to the Laplacian at the same point  $\mathbf{x}$ .

Within the context of image processing, the function  $f$  typically corresponds to the input image and derivatives are replaced either by differences between the intensity levels of neighbouring pixels or Gaussian derivatives.

The Hessian matrix forms a basis for a basic feature detector (called Hessian detector), which selects the image positions  $\mathbf{x}$  locally maximizing  $\det(H(I, \mathbf{x}))$ , where  $I$  is the input image. This leads to a detection of corners and features of size roughly comparable to the variance of the Gaussian kernel used to compute the Gaussian derivatives.

## 2.3 Basic image similarity metrics

We now introduce two simple metrics that can be used to estimate similarity of visual contents of a pair of images. These are often used as a basis for more sophisticated image registration algorithms, e.g. [8].

*Sum of absolute differences* describes the difference of intensities of corresponding areas of two images:

**Definition 4.** Let  $I_1(x, y)$  and  $I_2(x, y)$  be two grayscale images. Then the sum of absolute differences of  $I_1$  and  $I_2$  is the value  $\sum_{x,y} |I_1(x, y) - I_2(x, y)|$ .

Note that this value is going to be zero for a pair of identical images.

For the second metric, we need to recall the definition of *entropy* (sometimes also called *Shannon entropy*). It can be viewed as a measure of information complexity of a random variable.

**Definition 5.** The entropy  $H$  of a random variable  $X$  with probability distribution  $P(X)$  is defined as

$$H(X) = \mathbb{E}[-\log(P(X))] = -\sum_k P(k) \log P(k),$$

where  $\mathbb{E}[\cdot]$  is the expected value operator.

In computer vision, it is used to measure the “complexity” of the image histogram when the underlying random variable is set as  $X = I(\mathbf{x})$ , where  $\mathbf{x}$  is a uniformly randomly generated image position. A constant, uniform image attains minimum entropy while random noise maximizes it.

We can now introduce the *mutual information* of two images. Generally, it measures the mutual dependence of two variables. It expresses how much the value of one random variable predicts the value of the other.

**Definition 6.** The mutual information of two variables  $I_1$  and  $I_2$  is defined as

$$MI_{I_1, I_2} = H_{I_1} + H_{I_2} - H_{I_1, I_2},$$

where  $H_{I_1, I_2}$  is the entropy  $H(X)$ , where  $X = (I_1(\mathbf{x}), I_2(\mathbf{x}))$  for  $\mathbf{x}$  uniformly random. In the context of computer vision, the vector  $\mathbf{x}$  is a random image position.

We can also interpret *mutual information* as a reduction of uncertainty of one random variable given the knowledge of another. High mutual information indicates a large reduction in uncertainty and vice versa. Mutual information of two images depends only on their joint histogram. Again, this value attains zero for a pair of identical images. However, it remains zero even after, e.g., increasing the brightness of one of the images. Thus, this measure is invariant under illumination changes, which is of great importance when matching photos taken in an uncontrolled environment.

## 2.4 Projective geometry

In the standard Euclidean space  $\mathbf{R}^n$ , the infinity does not exist. However, many geometric concepts are simplified when the notion of infinity is included. An example of such a geometry is *the projective geometry*. Projective plane  $\mathbb{P}^2$ , or generally projective space  $\mathbb{P}^n$ ,  $n \in \mathbb{N}$ , is obtained by extending  $\mathbf{R}^n$  by including a point at infinity for each direction.

Numerically, the points in  $\mathbb{P}^n$  are represented using non-zero vectors from  $\mathbf{R}^{n+1}$ . Suppose we have a point  $(x, y)$  in the Euclidean plane. This point in projective geometry is expressed by the vector  $(x, y, 1)$  and any of its non-zero multiples  $k \cdot (x, y, 1)$ ,  $k \neq 0$ . These are called *homogenous coordinates* of the point. In what follows, we identify the point in a projective space with the vector of its homogeneous coordinates. To get back the Euclidean coordinates we simple divide the first two coordinates by the third. We can notice that none of the points  $(x, y)$  from Euclidean space corresponds to a projective point of the form  $(x, y, 0)$ , because the operations  $\frac{x}{0}$  and  $\frac{y}{0}$  are undefined. Such non-zero vectors are used to represent the points at infinity, with each corresponding to a particular direction.

Similarly to points, lines in the projective plane can also be modelled as non-zero  $(n+1)$ -dimensional real vectors. A point lies on a line if the dot-product of the corresponding vectors is zero. It can be easily seen that the line  $k \cdot (0, 0, 1)$ ,  $k \neq 0$  contains all the points at infinity and is therefore termed *the line at infinity*. In higher dimensions, lines generalize to planes and hyper-planes. The question of representing lines in  $\mathbb{P}^3$  is more subtle; we refer the reader to an overview of different approaches in [7].

From the perspective of computer vision, the most important property of projective geometry is that it allows us to express the projective camera using linear algebra. This makes it possible to build on the grounds of this well-understood area.

*Projective camera* represents a model of central perspective projection. It maps points from  $\mathbb{P}^3$  (world) to  $\mathbb{P}^2$  (image). In Figure 2.4 we can see the camera geometry. There, the *camera centre* is positioned at the coordinate origin, while the image plane is in front of the camera. The line perpendicular to the *image plane* with one end-point in the centre is called *the principal axis* of the camera and its intersection with the image plane is *the principal point*. The world point is projected by intersecting a ray going through the camera center and the world point with the image plane. This mapping from  $\mathbb{P}^3$  to  $\mathbb{P}^2$  can be algebraically expressed as multiplication with a real  $3 \times 4$  matrix  $\mathbf{P}$ . Note that the overall scale of the matrix does not affect the result. Thus, the matrices  $k \cdot \mathbf{P}$ ,  $k \neq 0$  represent the same camera.

The simple algebraic model of the action of the projective camera on the world points is the main strength of concept. However, it cannot model some properties of physical cameras applied in practice. Most importantly, non-linear distortion of the image (e.g., barrel distortion) cannot be modeled by a projective camera.

### 2.4.1 Epipolar geometry

Epipolar geometry expresses the geometric constraints encountered when observing a 3D scene by a pair of cameras with known parameters. Suppose we choose

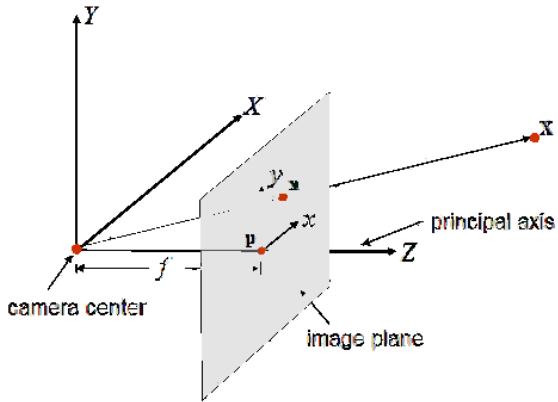


Figure 2.1: (*TODO: tento obrázek jsem stahla z googlu, mel by se nahradit.*)

a point  $\mathbf{x}$  on the image of the first camera from such a pair. The knowledge of its position constraints the position of the corresponding one on the second image. This point, denoted by  $\mathbf{x}'$ , lies on the line  $\mathbf{F}\mathbf{x}$ , where  $\mathbf{F}$  is the fundamental matrix. This line is called *the epipolar line*.

**Definition 7.** *The fundamental matrix  $\mathbf{F}$  for a pair of stereo images is a  $3 \times 3$  matrix which satisfies*

$$\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0$$

*for any pair of corresponding points  $\mathbf{x}$  and  $\mathbf{x}'$ .*

Fundamental matrix for a pair of photos can be estimated from the knowledge of a set of corresponding points since each correspondence is a linear constraint on the values of  $\mathbf{F}$ . Because  $\mathbf{F}$  has 9 real entries and is determined only up to a scaling factor, it has 8 degrees of freedom and thus at least 8 correspondences are required to determine its values. However, in our case, the matrix is going have only one degree of freedom due to the restrictions we have specified for the input photographs.

## 2.5 Integral images

An *integral image*, also known as *summed area table*, allows fast and efficient computation of a sum of image intensity values inside an arbitrary rectangular area. A pixel of an integral image represents the sum of all of the original image's pixels that lie to the left and above the considered position:

$$K_I(\mathbf{x}) := \sum_{i \leq x} \sum_{j \leq y} I(i, j),$$

where  $K$  is the resulting integral image,  $I$  is the input image image, and  $\mathbf{x} = (x, y)^T$  is a location of a pixel.

An advantage of the integral image is that we are able to compute it using only one pass through the original image. Moreover, once we have calculated the integral image, only three integer operations and four memory accesses are required to calculate the sum of the original intensities inside any rectangular region (see Figure 2.5).

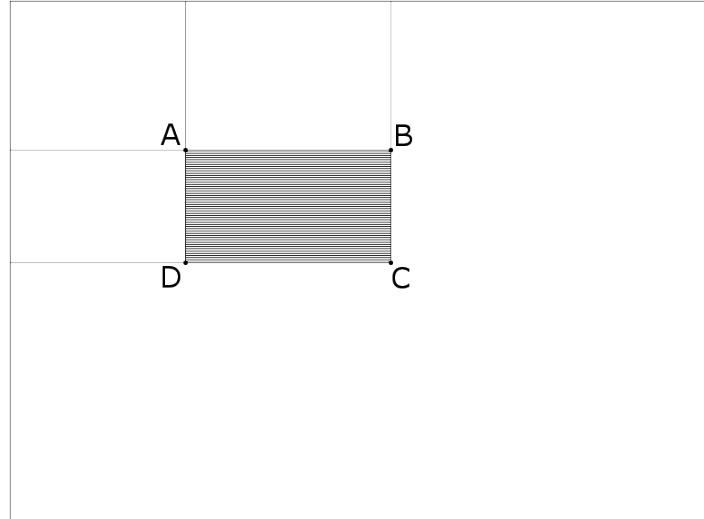


Figure 2.2: The sum of any rectangular region can be calculated by only three additions:  $\sum = C - D - B + A$ .

# 3. Image Processing Algorithms

In this chapter, we introduce image processing algorithms often applied in software solutions with functionality similar to those discussed in Chapter 1. Applications reconstructing depth information from photographs or video sequences typically have at their core an algorithm that detects and tracks image primitives (such as corners, blobs, lines, individual pixels, etc.) across several photos/frames. This knowledge allows one to estimate the camera parameters, which in turn makes it possible to compute the spacial parameters of the tracked primitives.

The approaches to computing correspondences between pairs of photos can be divided into *sparse correspondence* and *dense correspondence* problems. In the former, a relatively conservative subset of only the most stable *features* are considered and paired. In the latter, the objective is to obtain a correspondence in the second image for (almost) every pixel of the first image.

We describe two techniques solving the sparse correspondence problem – the SIFT [13] and SURF [4] feature detectors/descriptors – and then introduce a max-flow algorithm [15] for the dense correspondence problem.

Generally, sparse feature matching algorithms first extract features from each photo. If the feature detection is repeatable, most of the features should be detected in all images where the corresponding scene element is visible. Then, for each feature a *descriptor* is generated, typically a high-dimensional vector. This descriptor is constructed in a way ensuring invariance to various image transformations. For instance, the SIFT descriptor is invariant to translation, rotation, scaling, and image noise. Thus, applying any of those transformations to the image should leave the descriptors unaffected, making it possible to match image features using Euclidean metric. The SIFT descriptor is also partially invariant to illumination changes and to affine transformations, the latter enabling us to perform matching of images capturing the scene from slightly different viewpoints.

## 3.1 Scale-invariant feature transform

Scale-invariant feature transform (SIFT) was introduced by Lowe in [13], building on a previous work by Lindeberg [12]. The paper describes both a feature detector and descriptor. To this day, SIFT remains a popular choice for applications such as panorama stitching and object detection. It is able to detect objects in images even in the presence of clutter.

To generate the set of features and their description, four major steps are followed. At first, features are detected over all scales of the grayscale version of the input images. Then for each detected potential feature, its location and scale model is determined to measure their stability. Only the stable features are selected for further computation. In the next stage, to each feature that passed the previous tests, based on the local gradient directions the orientation assignment is computed. It is used to establish a reference frame for the construction of the descriptor. The last step is the feature description. The SIFT feature descriptor is a 128-dimensional vector determined by the gradients around the feature at the selected scale. Since the computation of the descriptor is performed using

the abovementioned local reference frame, the resulting descriptor is invariant to transformations that affect this reference frame in a covariant manner but only partially invariant to affine transformations and illumination changes. We now proceed to describe both the detection and the descriptor construction steps in more detail.

The first step in feature detection is to identify locations and scales that can be repeatably assigned. It has been shown, that the only possible scale-space kernel is Gaussian function. Hence the scale-space of each input image is defined as a convolution of a Gaussian with it. We can formulate it as a function:

$$L(x, y) = G(x, y, \sigma) * I(x, y),$$

where  $\sigma$  is the deviation,  $*$  presents the convolution operator,  $I(x, y)$  is the input image and  $G(x, y)$  is the Gaussian function

$$G(x, y, \sigma) = \left( \frac{1}{\sqrt{2\pi\sigma_1^2}} \cdot e^{-\frac{x^2+y^2}{2\sigma_1^2}} \right).$$

To extract the features in the scale-space we detect the local extrema in the difference-of-Gaussian function convolved with the image  $D(x, t, \sigma)$ . The difference-of-Gaussian (DoG) is defined as the difference of two neighbouring images of the scale-space. The  $D(x, t, \sigma)$  function can be expressed as:

$$D(x, y, \sigma) = (G(x, y, 2\sigma) - G(x, y, \sigma)) * I(x, y).$$

Each sample point of DoG is compared to its eight neighbours in the current scale and nine neighbours in the scale below and above. If it is larger than all of these neighbours, it is selected as maximum, if it is smaller than all of them, it is selected as minimum.

Usually, the detection of scale-space extrema results in a large number of candidate keypoints. However, some of them are local extrema created by image noise or the responses of the operator along edges. Such structures are unstable and should be discarded from the set of candidate keypoints. To detect such unstable features, we fit a 3D quadratic function to the local sample points and interpolate the location of maximum. This is done using quadratic Taylor expansion of the function  $D(x, y, \sigma)$  around the detected point. By calculating the minimum we get the value of the local extrema. This value is used for rejecting unstable extrema that were detected from  $D(x, y, \sigma)$ . If the 3D parabola is shallow the detected point is a result of noise and we reject it. Otherwise we accept it as a feature.

To achieve invariance to rotation, local orientation must be determined. First, we compute a histogram of orientations of image gradients around the keypoints location. The peaks of the histogram represent dominant orientations. The orientations corresponding to the highest peak are assigned to the feature. If there are several peaks of magnitude within 80% of the highest peak, multiple keypoints are generated – one for each such orientation.

The descriptor is then constructed by considering several histograms in the four quadrants of the reference frame of the keypoint. Typically, each quadrant is divided into four subregions. In each of the resulting sixteen subregions, we

construct a histogram of orientations of gradients sampled regularly in the subregion. Concatenating the values in these histograms results in a 128-dimensional vector.

## 3.2 Speeded-Up Robust Features

Another popular feature detector/descriptor is the Speeded Up Robust Features (SURF) algorithm, introduced by Bay et al. [4]. It is influenced by the SIFT algorithm described above and is based on the computation of Haar wavelet responses and Hessian-matrix approximation. Similarly to SIFT, keypoints are again detected in a scale-space to achieve invariance to scaling. In this approach, however, the scale-space is not constructed explicitly and integral images are employed instead to decrease the computation time.

Similarly to SIFT, SURF determines the orientation of the keypoint. The local orientation and scale is again used to obtain a reference frame ensuring that the resulting descriptor is not affected by rotation and scaling of the input image. Before the point description the surrounding area is

The size of the inspected region around the keypoint is set to  $20s$ , where  $s$  is the scale where it was detected. (*TODO: nemelo by s byt nejak svazane s rozptylem  $\sigma$ ?*) We split the region into  $4 \times 4$  regular square subregions and for each of them we compute Haar wavelet responses  $d_x$  and  $d_y$  in a  $5 \times 5$  grid. (*TODO: tady porad rikame "pocitame Haar wavelet responses" ale jde nam o to vypocitat ty derivace; ja bych to napsal tak, ze se na zacatku nadefinuji ty derivace aproximovane temi integral image a pak uz se jen pouziva dokola od-kazuje se na to nejakym konkretnejsim terminem; navic mi neni jasne, jaky je rozdil mezi temi box filtery a Haar wavelety.*) The sum of the responses for  $d_x$  and  $d_y$  and their absolute values  $|d_x|$ ,  $|d_y|$  separately results in a descriptor  $v = (\sum d_x, \sum d_y, \sum |d_x|, \sum |d_y|)$  for each subregion. Concatenating this for all  $4 \times 4$  subregions gives 64-dimensional vector descriptor.

Matching the SURF descriptors between two images can be speeded-up by including the trace of the Hessian (Laplacian) to the process of finding corresponding keypoints. We exploit the sign of Laplacian that distinguishes bright blobs on dark background from the reverse situation. In the matching stage we compare only features if they have the same sign – type of contrast. This costs no additional computation time since this quantity has already been computed at a previous stage.

## 3.3 SIFT vs. SURF

Both SIFT and SURF are popular feature descriptors based on the distribution of intensity around the interest point. SURF has been shown to have similar performance to SIFT, but being much faster. (*TODO: odkaz na nejakou studii porovnavajici ruzne detektory/deskriptory.*) The work [4] highlights the fast computation of the descriptor. SURF describes image three times faster than SIFT. (*TODO: jestli je tohle napsane v tom puvodnim clanku, tak ty predchozi vety spojme a napisme to tak, at ta informace z toho je patrna.*) The element enabling this speed-up are the approximations using integral images. Also, the SURF

descriptor is a 64-dimensional vector, enabling faster computation of the Euclidean distance between the descriptors compared to the 128-dimensional SIFT descriptors. Furthermore, due to the global integration of the SURF-descriptor, it stays more robust to various perturbations than the SIFT descriptor. (*TODO: potrebujeme napsat presneji, zejmena by se hodil odkaz na to, odkad to tvrzeni je cerpano.*)

SURF offers invariance to rotation and limited levels of image blurring. On the other hand, SIFT is more robust under illumination changes and viewpoint changes. (*TODO: znovu neni jasne, jestli popisujeme vlastni zkusenost nebo neco z nejakeho clanku (jakeho?).*)

### 3.4 Lucas-Kanade algorithm for optical flow

Optical flow algorithms are typically applied in postprocessing software for movies to track an object through a video sequence. We can think of this problem as the image correspondence problem optimized for the situation where there is very little camera movement between the registered pair of photos, as is in the case with two consecutive frames of a video sequence. The output of such algorithm is an array of 2-dimensional vectors  $\mathbf{d}_x$ , where  $x$  is an image position, with the property that the point  $x$  on the first frame corresponds to the point  $x + \mathbf{d}_x$  on the second one. Optical flow is typically not constrained by epipolar geometry, since the assumption is that the video is of a dynamic scene that includes objects moving relative to the camera and each other. The algorithms for optical flow tend to work only when the differences between the images are significantly limited and the registration can be performed only on a small neighbourhood of the original position of a feature.

We now describe a classical Lucas-Kanade method [14] for calculating the optical flow between two images  $I_1$  and  $I_2$ .

The method proceeds by specifying linear constraints on the values  $\mathbf{d}_x$  and then solves the resulting over-determined system in the least squares sense. For each pixel  $x$  that is being tracked, we consider the following equation:

$$\Delta I_1(x) \cdot \mathbf{d}_x = I_1(x) - I_2(x), \quad (3.1)$$

where  $\Delta I_1(x)$  is the image gradient at  $x$ . This is motivated by the observation that the apparent movement should be roughly in the direction of the image gradient for locations with a large jump of the intensity value between the frames. On the other hand, when the intensity of a pixel is approximately the same in both frames, we either expect no movement or just a movement perpendicular to the image gradient. However, the inclusion of just the above equations does not enforce spatial consistency of the movement in any way. This is taken into account by repeating equation (3.1) for each position  $x^i$  taken from the neighbourhood of  $x$  of a fixed size. Specifically, we add the following equation for each  $x^i$ :

$$\Delta I(x^i) \cdot \mathbf{d}_x = I_1(x^i) - I_2(x^i).$$

Note that the differences are read from the position  $x^i$  while the movement constrained is of the pixel  $x$ . Solving the above over-determined system using conventional methods gives us the desired values  $\mathbf{d}_x$ .

# 4. Developing for Android

Android, Inc. was founded in October in 2003 by Andy Rubin, Rich Miner, Nick Sears, and Chris White. At first, the company planned to develop an operating system for digital cameras but ultimately decided to focus on smartphones instead. HTC Dream, the first phone with the Android operating system, was sold in autumn 2008. Majority of Android's code is released under a free license. This allows developers to modify and (with certain exceptions) freely distribute the software. Due to this, Android became the most popular operating system for smartphones. In this chapter, we introduce this system from programmer's perspective and give a brief description of how to implement an Android application. The purpose of the chapter is to highlight the main architectural differences of Android and conventional desktop platforms rather than providing a complete programmer's manual.

## 4.1 Introduction to Android development

Android is a product of *The Open Handset Alliance*, which develops open standards for mobile devices and is led by Google. The Android platform is a layered environment built on the foundation of the Linux kernel. It includes a user interface library featuring various types of elements (views, windows, display boxes, lists, etc.), an embedded web browser, and support for OpenGL ES. Most Android-powered devices have built-in sensors to measure, e.g., motion, orientation or temperature. These include an accelerometer, a gyroscope or a barometer. It also provides an array of connectivity options, for example Wi-Fi, Bluetooth or cellular data. A built-in camera support is also included and most Android handsets indeed feature a camera. The data storage support is provided by SQLite, a relational database management system in the form of a library implementing self-contained and server-less SQL database engine.

Linux kernel, the first architectural layer of the platform, is used for memory and process management, device drivers, and networking. Above this, we have the native libraries, which include graphics support, media codecs, a SQLite and WebKit. These are written in C or C++ and called through a Java interface. The actual applications are running on the Dalvik Virtual Machine (DVM), an implementation of the Java Virtual Machine optimized for low processing power and memory resources. The Android Runtime Layer consists of this DVM and the core Java libraries.

The next level is the Application Framework, which manages functions fundamental to running applications. Its major part is formed by the Activity Manager (managing the life cycle of the applications) and various Content Providers (managing data sharing between the applications). Other notable parts are the Telephony Manager (handling voice calls), the Location Manager (specifying location using GPS or cell tower) and the Resource Manager. The final layer is formed by the individual applications. Some of them are preinstalled and provided by Google while the rest are third party applications created by the community. The structure of the system is illustrated in Figure 4.1 below.

Android applications are written in the Java programming language and run

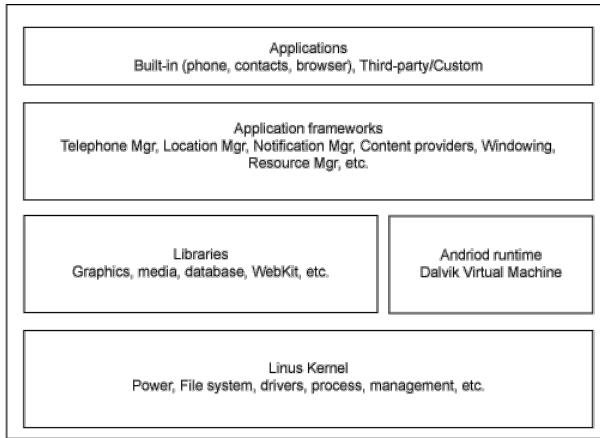


Figure 4.1: The architecture of the system.

within an instance of the Dalvik Virtual Machine. A key part of the application is the `AndroidManifest.xml` file containing installation meta-data, including the permissions needed to run. An example of such permission is the ability to use the phone's camera or to access the Internet. We concentrate more on activities and their development in the following sections. (*TODO: O aktivitach jsem zatím nic nerekli. Proc ted rikame ctenari, ze se na ne vic zamerime v dalsi sekci?.*)

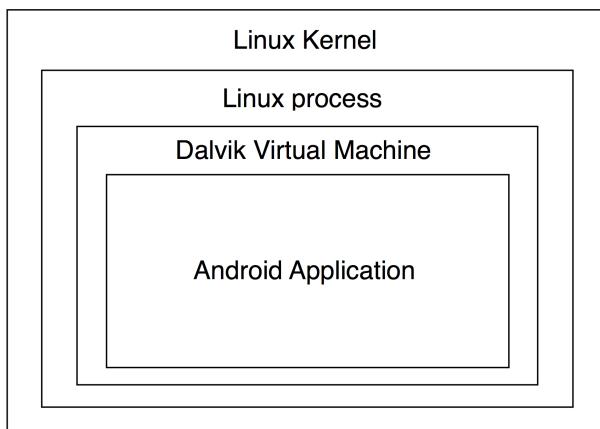


Figure 4.2: A typical Android application runs within an instance of the Dalvik Virtual Machine.

The tools required for the development of an Android application are the Android Software Development Kit (SDK) and a Java IDE, such as Eclipse<sup>1</sup> or the Android Studio<sup>2</sup> based on IntelliJ IDEA. The Android SDK contains an Eclipse plugin supporting Android development, documentation, sample code, and various tools, such as Android Debug Bridge used by the programmer to communicate with an application running on a device.

---

<sup>1</sup><http://www.eclipse.org>

<sup>2</sup><http://developer.android.com/sdk/installing/studio.html>

## 4.2 Application components

When an application is installed to a device, it lives within its security sandbox. Android offers a secure environment where the applications are isolated and can safely run their code. To each application the Linux system assigns a user ID number. Android is a multi-user operating system, meaning that each application corresponds to a different user with a different ID. This number is known only to the system that sets permissions to all files so they cannot be accessed by any other applications. Each application runs in a unique Linux process initiated when the application or any of its components need to be executed. When the system needs to recover the memory or the application is not used for some time, the process shuts down. Releasing memory is governed by the “oldest first” principle – the system starts by killing the apps that were inactive for the longest time.

The security is driven by the principle of least privilege and the application is allowed access only to the resources specified in the manifest file. This protects the whole Android system and the applications from each other.

A typical application is built from several components. These basic building blocks can be divided into four different groups:

- activities,
- services,
- content providers,
- broadcast receivers.

An *activity* is can be thought of as a UI screen providing elements such as views, lists, buttons, labels, etc. along with the implementation of their functionality. The layout of an activity and the widgets placed in the window is described in a separate XML file (we reveal more about user interface later) (*TODO: Tu zavorku rozhodne nahradme odkazem na sekci.*) Most applications consist of more than one activity. Although the activities form one application, they are all independent from each other. If another application has a permission to do so, it can start an activity of a different app.

Usually in a application there is a one main activity that shows up to the user at first after launching it. To this one are all other activities linked. Each activity in android will be subclass of Activity class defined in Android SDK.

A *service* is a component used to perform operations in background. It can be invoked by an activity for example. If the application needs to run long-term process, user can switch to another application and our process can continue to run in background. This can be exploited to develop an application to play music or an application which needs to fetch data in the background.

A *content provider* manages sharing data across the applications. When the app is storing any data - in file system, SQLite database or any online storage, through the content provider they can be accessed or even modified from other applications. An example when a content provider is used is an application working with the contacts database.

A *broadcast receiver* is a component broadcasted by the Android system. It usually inform applications about some basic actions such as turning the screen

off, running out of battery or changes of timezone. Applications can also initiate broadcasts to let other apps know about some action, that there some data ready to use or about completed downloading for example.

From these mentioned components, activities, services and broadcasts are activated by intents. An intent is a message to the system to invoke new activity, service or a broadcast. It is a component activating mechanism in Android.

A very important part of an application is `AndroidManifest.xml` file, where are specified all permissions of the application. Each activity we create must be defined in it. Basically, every component that is used in the application must be declared in the manifest.

## 4.3 The Activity Lifecycle

Any application switches between different states of its life cycle. (UPDATE: jak souvisí to, že aplikace má aktivity s tím, že aplikace prechází mezi nejakými stavami? V dalsim se pak hovori stavech aktivit a ne aplikaci.) Compared to desktop platforms, the programmer has only limited control over the state transitions. (UPDATE: napsat příklad toho, co se může stát na Androidu a nemůže se stát na desktopu.) On the desktop computer we can handle minimizing or closing a window of an application or quit the entire app. This we can not affect on the Android device. The life cycle is a collection of functions operating system calls on the application while it is running.

There are five stages of the life of an application:

- the starting state,
- the running state,
- the paused state,
- the stopped state,
- and the destroyed state.

The starting state and the destroyed state are phases of the activity when it is not in the memory. To launch the app, the method `onCreate()` is called and eventually it is in a running state. When the activity is in a running state it is actually on the screen seen by the user. The activity is in foreground and handling all user interactions such as typing or touching the screen. An activity in this state has the highest priority of getting memory in the Android Activity stack to run as quickly as possible. It will be killed by the operating system only in extreme situations. This transition from starting to running state is the most expensive operation in terms of battery requirements. That is also the reason why we do not destroy every activity when it gets to the background, because it is probable that it is going to be called back in a while and we don't want to create all of it again.

The application is paused (in a paused state) when it is not interacting with user at the moment, but still visible on the screen. This state does not occur that often, because most of applications cover entire screen. But when a dialog

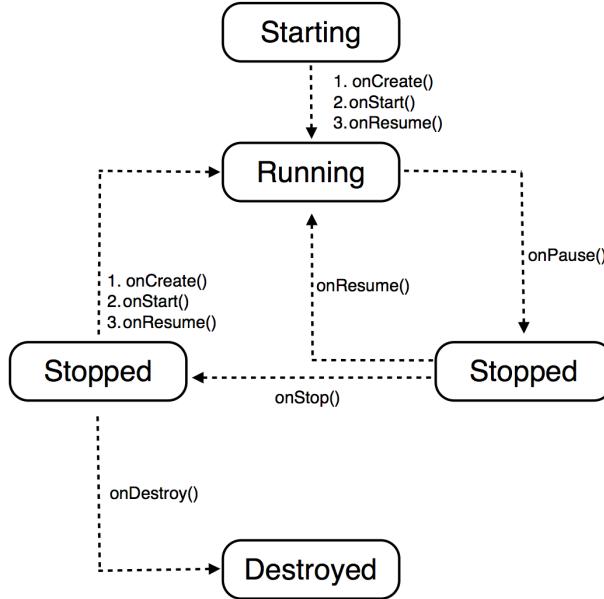


Figure 4.3: Life cycles of an application.

box appears or another activity is on the top of this one but not hiding it all, the underlying activity is partly visible and it is paused.

When the application is not visible, but still in memory, it is in a stopped state. Then it is easy to bring it up to the front again or it can be destroyed, removed from the memory and brought to the destroyed state.

(*UPDATE: Přibýly nasledující sekce - User Interface, Sensors a Data Storage.*)

## 4.4 User Interface

The user interface is part and parcel of an Android application. Basically, an application can not live without the user interface.

All elements of the user interface are built using *View* or *ViewGroup* objects. By using them we also define the hierarchy of used components - a *View* can be nested within a different *View*. The layout describing the visual structure of the *Views* of the user interface is declared in separate XML file. Each *View* is represented as a XML element in its corresponding to the *View* class or subclass. The user interface can be declared also right in the code of an application. Defining it separately make the user interface more flexible to changes without any modification of the code though. Also, the structure of XML corresponds to the structure of UI and makes it more inspectional and easier to debug. In the XML file declaring layout can be only one root element. It must be a *View* or *ViewGroup* which is *LinearLayout* or *RelativeLayout* for example. *LinearLayout* is a layout that arranges the inner elements in a single row or a column depending on the set orientation, while in *RelativeLayout* are positions of its children described in relation to parent or each other.

The developer tools for Android gives us an option of creating other parts of UI beside sketching the layout such as *Menus*, *Action Bars*, *Dialogs* or *Toasts*. There are several types of *Menus* such as *options menu* or *context menu*. The

*options menu* is an user interface component commonly used in many applications collecting menu items for an activity. It appears when a user touches the menu button. From the Android version 3.0 higher, options menu items are part of the action bar after touching the action overflow button. The *context menu* is a floating menu associated with an particular element in a view that is displayed after touching the element.

*Action Bars* are a proper way how to navigate the user through the application. The *Action Bar* is located at the top of an activity and can display the activity title, icon or other actions and items. Some Android devices have a hardware action overflow button which opens the *options menu* at the bottom of an activity (as we mentioned above). *Action Bars* are superiors to *options menus* since an *Action Bar* is always visible while *options menu* shows only on the user request.

*Dialog* is a small window informing the user about some action. Unlike the *Toast* it usually requires the users action before continue by confirmation or giving some additional information. The *Toast* provides only feedback about some action in a small popup that disappears after a moment.

## 4.5 Sensors

Most Android devices have build in motion, environmental and position sensors. Motion sensors are sensors measuring rotation along three axes and give us an opportunity to detect motion, shaking or tilt. For measuring temperature, illumination, or humidity we use environmental sensors. Build-in magnetometers and orientation sensors provides information about current position of a device and can be used in application for GPS navigation or map browsers. We can access sensor events within an instance of the *SensorManager* class.

## 4.6 Data Storage

We have several possibilities how to store our application data. The way we choose depends on the needs and the level of privacy. If we use private files in the application and do not want other application to access them, we prefer using the internal storage. We read and write private data simply by using *FileOutputStream* and *FileInputStream*.

The media files such as pictures, video or audio records are usually expected to be shared and accessible from other applications. In that case the external storage is used. These files are readable and can be modified by user. Methods on the *Environment* class provide the access to the external storage. The function *getExternalStoragePublicDirectory()* depending on the argument given to it returns the path of the root directory where we can write our data, for example

- .. /Music /
- .. /Pictures /
- .. /Movies /
- .. /Download /

- etc.

As an argument we pass the type of the director we want to access, for example *Environment.DIRECTORYMUSIC*, *Environment. DIRECTORYPICTURES*, or *Environment. DIRECTORYMUSIC*.

## 4.7 Developing Android Application

In this section we give an outline of implementing the bases for an Android application.

When developing an Android application usually we need to define some user interface. Some of the components of the UI are described in section 4.4. The layout of all components is defined in a .xml file. All .xml files are stored in */res/layout* directory.

The file consists of one root and other descendant xml elements. Each element is described by the inner attributes of it. We can see an example of such layout below.

---

```
<?xml version="1.0" encoding="utf-8"?>
<RelativeLayout
    xmlns:android="http://schemas.android.com/apk/res/android"
    xmlns:tools="http://schemas.android.com/tools"
    android:layout_width="match_parent"
    android:layout_height="match_parent" >

    <org.opencv.android.NativeCameraView
        android:id="@+id/camera_view"
        android:layout_width="match_parent"
        android:layout_height="match_parent" />

    <RelativeLayout
        android:layout_width="200dp"
        android:layout_height="match_parent"
        android:layout_margin="10dp"
        android:layout_centerInParent="true">

        <Button
            android:id="@+id/captureButton"
            android:layout_width="90dp"
            android:layout_height="90dp"
            android:layout_alignParentBottom="true"
            android:layout_centerHorizontal="true"
            android:background="@drawable/circle_button"
            android:onClick="callTakePicture"/>

        <Button
            android:id="@+id/startCapturingButton"
            android:layout_width="90dp"
            android:layout_height="90dp"
            android:layout_alignParentBottom="true"
```

```

        android:layout_centerHorizontal="true"
        android:background="@drawable/circle_button"
        android:onClick="start_stopAutoCapturing"
        android:visibility="invisible"/>

<ToggleButton
    android:id="@+id/toggleAutoCaptureButton"
    android:layout_width="wrap_content"
    android:layout_height="wrap_content"
    android:layout_alignParentTop="true"
    android:layout_centerHorizontal="true"
    android:textOn="AutoCapture on"
    android:textOff="AutoCapture off"
    android:onClick="autoCaptureStateChanged"/>

<TextView
    android:id="@+id/startCapturing_textView"
    android:layout_width="wrap_content"
    android:layout_height="wrap_content"
    android:layout_above="@+id/captureButton"
    android:layout_centerHorizontal="true"
    android:text="@string/startcapturing_text"
    android:visibility="invisible"/>

</RelativeLayout>

</RelativeLayout>

```

---

In our example the root element is *RelativeLayout* element which allows us to describe the relative position to each other or to a parent. Inside the *RelativeLayout* we can find *org.opencv.android.NativeCameraView* which is an element of OpenCV library used for camera view and another *RelativeLayout* with *Buttons*, a *ToggleButton* and a *TextView*. All of the elements have defined the width and height by using *android:layoutwidth* and *android:layoutwidth* attributes. The value of these attributes can be *matchparent* or *wrapcontent* or the specific number of dp units.

It is also possible to define different layout of one activity depending on the screen orientation. If we need to define different layout for landscape orientation, we save a xml file of the same name with new layout into *res/layout-land* folder.

In the *src* folder are stored all .java files representing activities or classes. Every Android application has at least one activity which is called by the system when the application is launched. Due to the activity lifecycle (see 4.3) it is necessary to implement the following methods:

- *onCreate()*,
- *onPause()*,
- *onResume()*.

The `onCreate()` method handles what happens when the activity is started. Usually only the basic startup instructions should be completed in this method, for example setting the layout or initialisation of some class variables. The particular layout into an activity is loaded by `setContentView(name-of-the-xml-file)`. We can see an example of `onCreate()` method below.

---

```
@Override  
public void onCreate(Bundle savedInstanceState) {  
    super.onCreate(savedInstanceState);  
    setContentView(R.layout.activity_gallery);  
  
    adapter = new Adapter(this);  
    ArrayList<GridImage> db_update = new ArrayList<GridImage>();  
    for (String s : files) {  
        ...  
    }  
    ...  
}
```

---

Depending on the needs of our application, we can add some code into the other overriding methods handling the activity lifecycle.

---

```
@Override  
public void onPause(){  
    super.onPause();  
    ...  
}  
  
@Override  
public void onResume(){  
    super.onResume();  
    ...  
}
```

---

To make our user interface interactive we need to set some functions that will be executed when clicking on the elements of the user interface. This can be done either in the xml file or in the code of the activity. To demonstrate these two approaches, we added an example:

```
/* This is the definition of a button in the xml file.  
When clicking on the button, takePicture() method will be executed.  
The method must be defined in the .java file of the activity. */  
<Button  
    ...  
    android:onClick="takePicture"  
    ... />  
  
/* This is the example how to define
```

```
the method directly in the code. */  
  
Button my_button = (Button)findViewById(R.id.button);  
my_button.setOnClickListener( new View.OnClickListener() {  
});
```

---

# 5. OpenCV

OpenCV (a short for Open Source Computer Vision) is an open source library covering the area of computer vision. It was designed mainly for real-time applications and computational efficiency. OpenCV is written in C and C++, can take advantage of multicore processors and (*TODO: aby chom si touhle zminkou ale nenabehli a nekdo se neptal, jak pouzivame na tom androidu parallelismus.*) runs on various platforms including Linux, Windows, and Mac OS X. Bindings for Python, Matlab and other programming languages have been introduced as well. OpenCV contains over 500 functions spanning many areas of computer vision, for example medical imaging, camera calibration, robotics or stereo vision.

## 5.1 The Origin of OpenCV

OpenCV was developed by Intel and the first alpha-version was released in 1999. At first, the project was an Intel Research initiative to advance CPU-intensive applications, part of a series of projects including real-time ray tracing and 3D display walls. That time, several university groups developed open computer vision infrastructure, code that every student could reach and use to his or her own vision application. This code was adapting by the students, building on the top what was implemented before. When one of the OpenCV authors noticed this, OpenCV was conceived as a way how to create computer vision infrastructure universally available.

The team developing OpenCV included experts from Russia (e.g. Vadim Pisarevsky) and Intel's Performance Library Team. The goals supporting the reason why to concern with this research were to provide not only open but also optimized code for computer vision, disseminate knowledge about computer vision by providing easily accessible open library and to advance vision-based commercial applications.

The first 1.0 version was released in 2006. From 2008 OpenCV is supported by Willow Garage, who are notable for their Robot Operating System. As of today, the latest version of OpenCV is 2.4.5 released in the April of 2013.

(*TODO: tady ted zase rikame neco, co bych cekal bud maximalne v uvodnim odstavci.*) Since the first release, OpenCV has been used in many applications. It has even been used in sound and music recognition area where the vision techniques were applied to sound spectrogram images.

## 5.2 Structure of OpenCV

OpenCV consist of image processing functions and algorithms and because computer vision and machine learning often go hand-in-hand, OpenCV also contains Machine Learning Library(MLL). This part of OpenCV library is focused on statistical pattern recognition and clustering.

Basically, we can structure OpenCV into four components, illustrated on Figure 5.2. First of all, it would be the CXCore component containing the basic data structures and operations on them. The HighGUI component ensures I/O rou-

tines and functions for loading and storing images. ML is the machine learning library. Finally, the Computer Vision component containing basic image processing and vision algorithm. CXCore provides the core functionality including

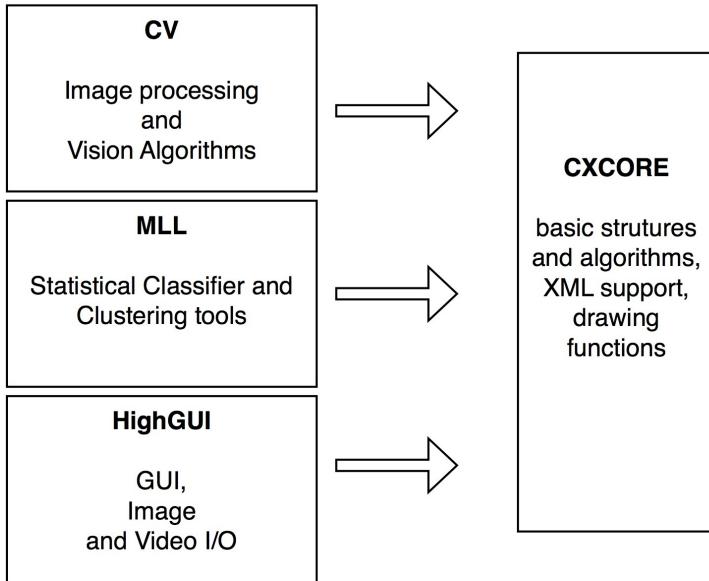


Figure 5.1: The basic structure of OpenCV library.

(*TODO: ten seznam prosim predelejme tak, aby byl spravne typograficky: mala pismenka a carky na konci radku krome posledniho zakonceneho teckou.):*

- Basic Structures
- Operations on Arrays
- Dynamic Structures
- Drawing Functions
- XML/YAML Persistence
- Clustering and Search in Multi-Dimensional Spaces
- Utility and System Functions and Macros.

In this part of OpenCV library we can find the basic structures that are needed for image processing. They are represented as structures in the class Basic Structures. For example `CvPoint` defines a point, `CvSize` is a set of two numbers representing size of rectangle, `CvScalar` is a container of double values, `IplImage` is a structure inherited from the Intel Image Processing Library designed for loading images, or `CvMat` is a data structure for storing a matrix.

As we can presume, the basic methods to work with these structures are implemented. We can find there functions for mathematical operations on matrices such as multiplication (`void cvMul()`), transposition (`void cvTranspose()`), or others like dividing multi-channel array into several single-channel arrays (`void cvSplit()`).

Available are also drawing functions working with matrices or images including `void cvCircle()` which as arguments takes an image, centre point of the

circle, and a colour and draws a circle in the image. Similarly `void cvEllipse()` or `void cvDrawContours()`.

The section with functions for image processing and computer vision provides these functionalities:

- Image Filtering
- Geometric Image Transformations
- Miscellaneous Image Transformations
- Histograms
- Feature Detection
- Motion Analysis and Object Tracking
- Structural Analysis and Shape Descriptors
- Planar Subdivisions
- Object Detection
- Camera Calibration and 3D Reconstruction

### 5.3 OpenCV4Android

(*UPDATE: uprava nasledujici kapitoly.*)

Since 2010 OpenCV was also ported to the Android environment, it allows to use the full power of the library in the development of mobile applications. In this part we will list the important structures and functions of OpenCV4Android library used in our implementation.

Images are commonly stored in `Mat` structure from the `org.opencv.core` package as a matrix of individual pixels of the image. For reading and writing images from saved files, we can use `imread(String filename)` and `imwrite(String filename)` functions from the `org.opencv.highgui` package.

In comparison with desktop version OpenCV4Android also includes the `opencv.android` package containing all the additional functions for the Android platform. This package provides mainly an environment for work with camera by offering classes such as `NativeCameraView.java` or `CameraBridgeViewBase.java`. It controls the frame process, camera adjustments and drawing the resulting frame to the screen.

The following packages contain basic methods used in image processing and implementations of commonly used algorithms (some of them we described in chapter 3):

- `org.opencv.imgproc`,
- `org.opencv.features2d`,
- `org.opencv.calib3d`.

In the image processing package are functions for image scaling (`Imgproc.pyrDown()`, `Imgproc.pyrUp()`), bluring image (`Imgproc.GaussianBlur()`), histogram calculation (`Imgproc.calcHist()`) or methods for converting images between different colour definitions (`Imgproc.cvtColor()`).

With an instance of `FeatureDetector.java` and `DescriptorExtractor.java` classes and calling `compute()` function we can detect keypoints in a set of images. There are several options for selecting descriptor type (such as `BRIEF`, `BRIS`, `FREAK`, `ORB`, `SIFT`) and algorithm for keypoint detection (`BRISK`, `DENSE`, `FAST`, `ORB`, `HARRIS`, `STAR`). All keypoints can be stored in a `KeyPoint` structure. Since the keypoints in all images are detected, we can match them using `DescriptorMatcher.java` class.

The `StereoSGBM.java` class included in `org.opencv.calib3d` package is defined for computing stereo correspondence using the semi-global block matching algorithm, which is a modification of algorithm by Heiko Hirschmüller [8].

# 6. Implementation

This chapter is devoted to implementation of our software. The result of this work is an Android application that allows to shoot pictures with a camera, browse them and pick photos for further processing. The output is a 3D model representing the disparity map which was calculated on the base on the selected input data. In the first section we enumerate the subtasks and chosen algorithms and then describe the structure of the software resources.

## 6.1 Implementation outline

To implement the Android application, several subtask must be completed. At first it is the graphical user interface and handling the camera which is managed through Android Activities and xml files as we described in chapter 4.

Secondly, we deal with the calculation, which consist of the image registration, the keypoint detection, the keypoint matching and solving the dense correspondence problem.

Image registration (finding the relative position of the pair of the images) is implemented by using Sum of absolute differences (described in 2.3). At first, we create a scale-space from the input pair of images, so we can find relatively fast the overlap with minimal difference of intensities of the image pair by comparing each possible overlap in the lowest scale. When we have the approximate overlap, we take the image of the scale above and try to find better result by shifting the matched area in the 5-pixels range. This we repeat until we look over all of the levels of the scale-space or for computational efficiency we estimate the result satisfiable when the width or hight of the investigating scale image is higher then a constant value. Because we expect the image input in the size of approximately  $1000 \times 800$  pixels, for the experiments in our work we set the constant to 200.



Figure 6.1: Left: The result of the registration where the process of upscaling was stopped when the height of the image was over 200px. Right: The division of an image into square-boxes.

The next step of the process is detection of keypoints which are detected with the SURF detector. We divide the images into square-boxes of the same size

and to each square-box we assign an array of keypoints situated in it. Because of the previous calculation of approximate overlap we do not have to match all keypoints in the image, but we choose only the keypoints lying in the overlap. To identify the relative position of the image pair better we detect the most robust keypoint match from our SURF keypoint set and calculate the vector defining the direction of the shift of the keypoint. To find this robust match we choose only the keypoints with response higher than 4000 and each of them we try to match with one keypoint extracted in the second image but only in the corresponding  $30 \times 30$  pixels area determined due the previous image registration. To decrease the computational time we use the pre-calculated square-boxes to find the keypoints of the second image lying in this area. To avoid mismatches we reject the matches where the matched keypoints differs too much in the orientation or if there are more than one obvious potential points for the match.

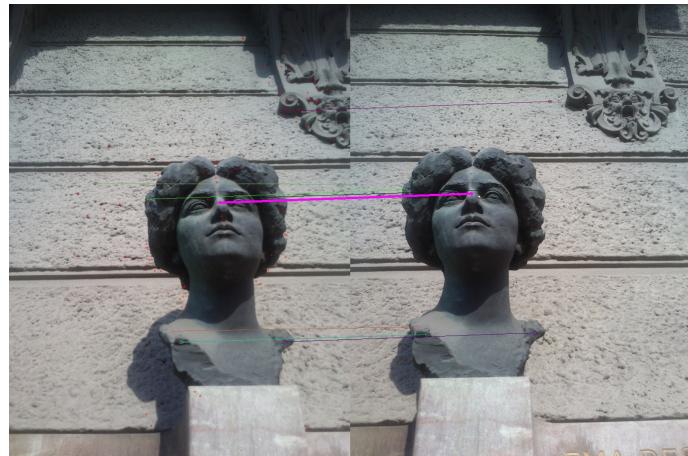


Figure 6.2: The most robust match chosen from the keypoints with response higher than 4000. According to this match the more accurate relative position of images is estimated.

When we know the more accurate relative position of the images, we investigate the keypoints one more time. Now we iterate all of them. Each keypoint in the first image we try to match with a keypoint in the estimated corresponding surrounding area in the second image in the shape of oriented rectangle computed based on the more accurate relative image position. Matched keypoints which differs too much in the orientation or are not obviously the best match we reject again.

At this point we have relatively robust matches for sparse correspondence. For the calculation of the depth information we need to extract more corresponding points. For this purpose we use optical flow algorithm. For each SURF keypoint in the first image we detect corners or other features acceptable for the tracking algorithm in its  $70 \times 70$  pixels area.

Calculating the optical flow we get the corresponding points in the second image. With high probability some of the results will be influenced by noise. To avoid these mismatches we calculate the variation of the distances between each match. If the variation is higher than 300 we discard all of the detected optical flow matches.

The result is visualized in OpenGL ES. Every keypoint is represented as a



Figure 6.3:  $70 \times 70$  windows of the pair of the input images with optical flow matches.

triangle in a space with the depth calculated from the correspondence. At first, the user can view the rough model created from the results of SURF matching. Each time some of the dense corresponding points are calculated with optical flow algorithm, the model is updated.

## 6.2 Project structure

The project resources can be divided into four parts:

- Activities,
- Classes,
- Structures,
- xml files defining layout and other files in the /res folder.

# 7. Evaluation

Our sampling data for testing our application were especially highly textured images of sculptures. In this chapter we sum up the results given by our implementation. We demonstrate it on the input data shown in Figure 7.1.

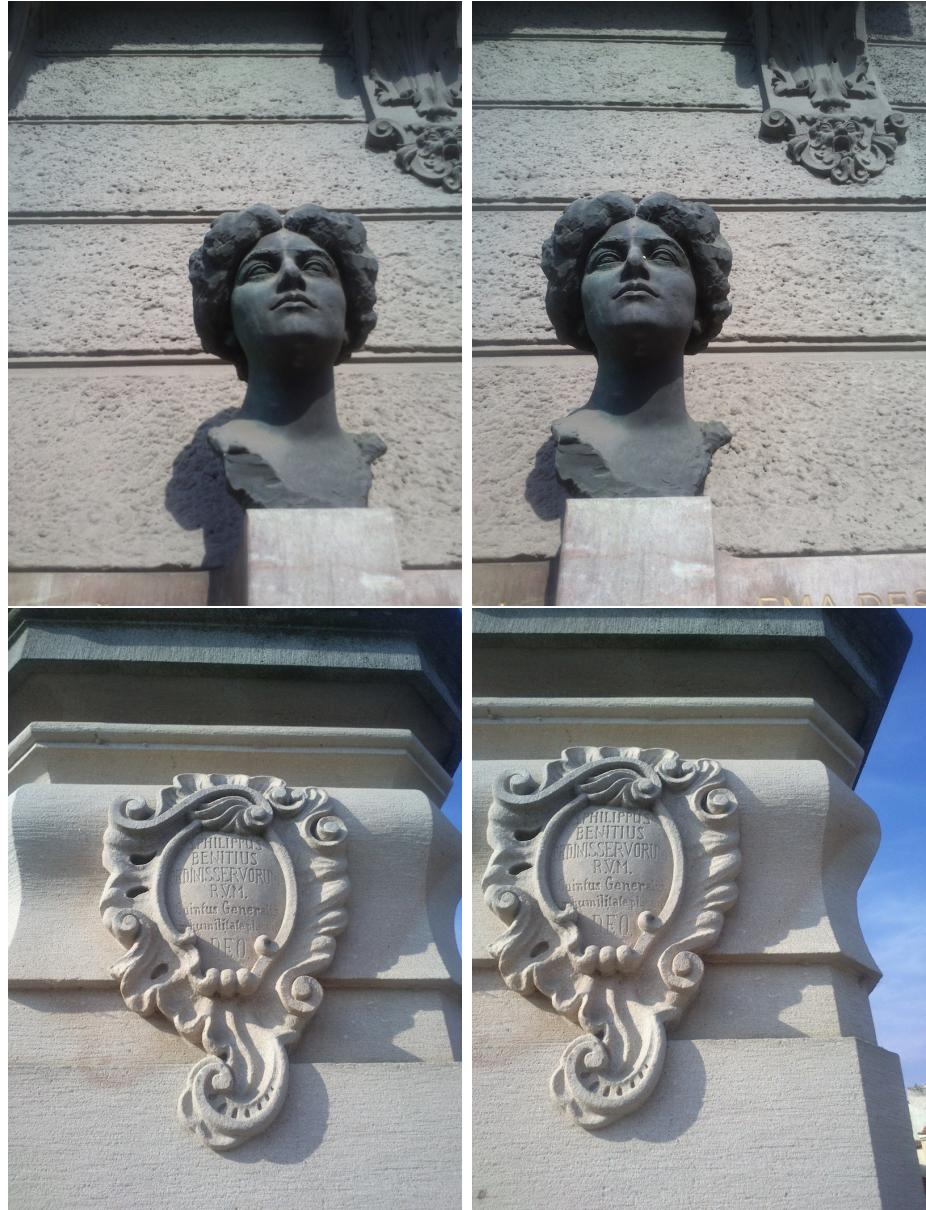


Figure 7.1: An example of input data.

## 7.1 Results

In Figure 7.2 is visualization of the calculated overlap. In the first two images we can see the result of the registration - an rectangular area where the difference of intensities was minimal. In the third one is the overlay of the input images to see the detected match better.

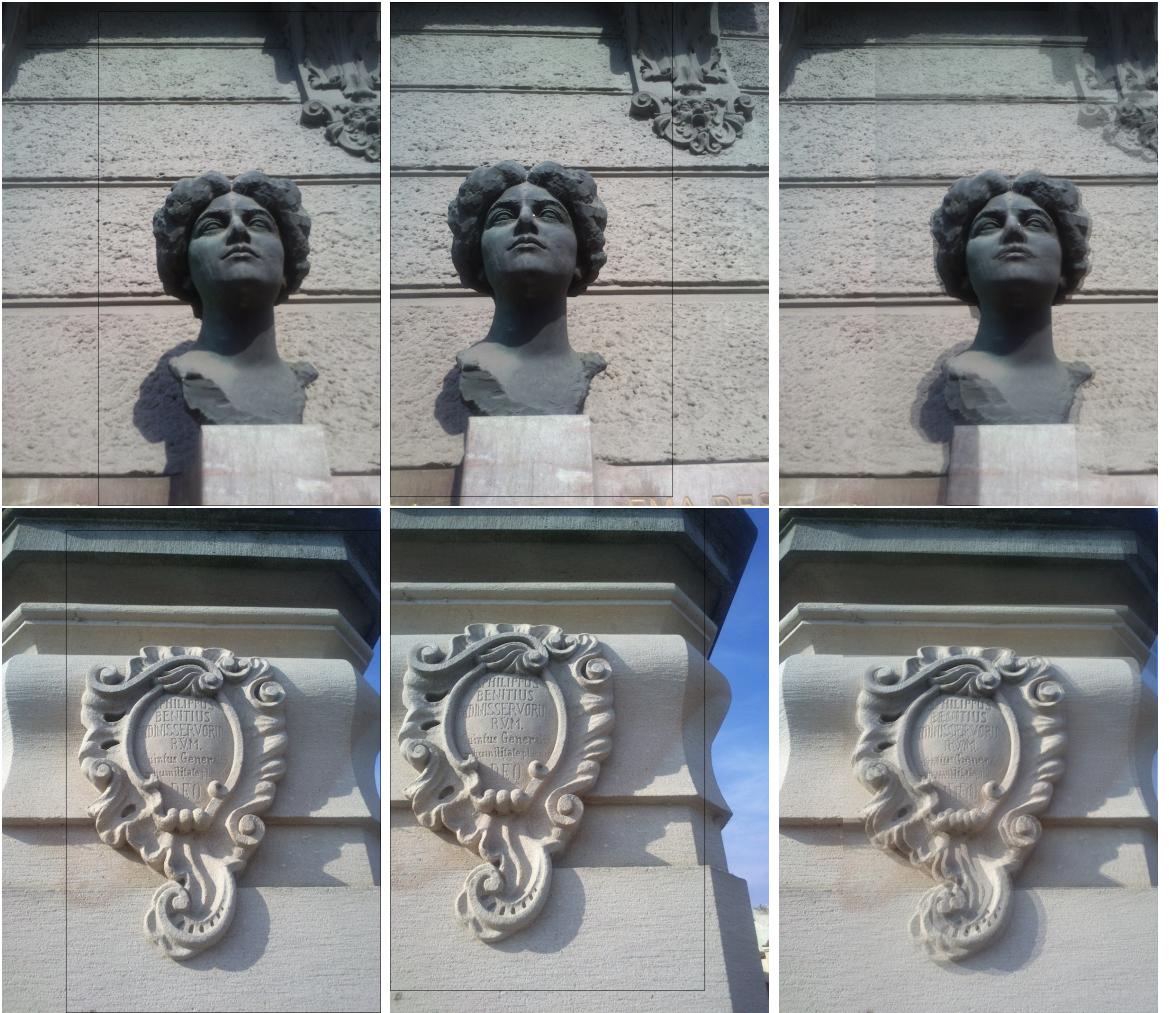


Figure 7.2: The result of the image registration. We can see the areas where was the overlap found in the first two images. In the third one the overlay is visualized.

For this highly textured input the SURF detector works properly. It detects sufficient amount of keypoints and after filtering there remain enough good matches to get the information about the depth of some parts of the input images. We can see the result in Figure 7.3.

In the Figure 7.4 we can see the final output of our application. For the pair of the images of a bust of Ema Destinová we get a 3D model shaping the head and a part of a wall in the background. The second mentioned pair of input images gives us a result as an inclined plane in the angle of the memorial in the picture. These results are comparable with the real appearance of the scenes.

On the other hand for images with noise or images which are not highly textured, the result is usually a bunch of mismatches so the 3D model does not correspond with the reality.

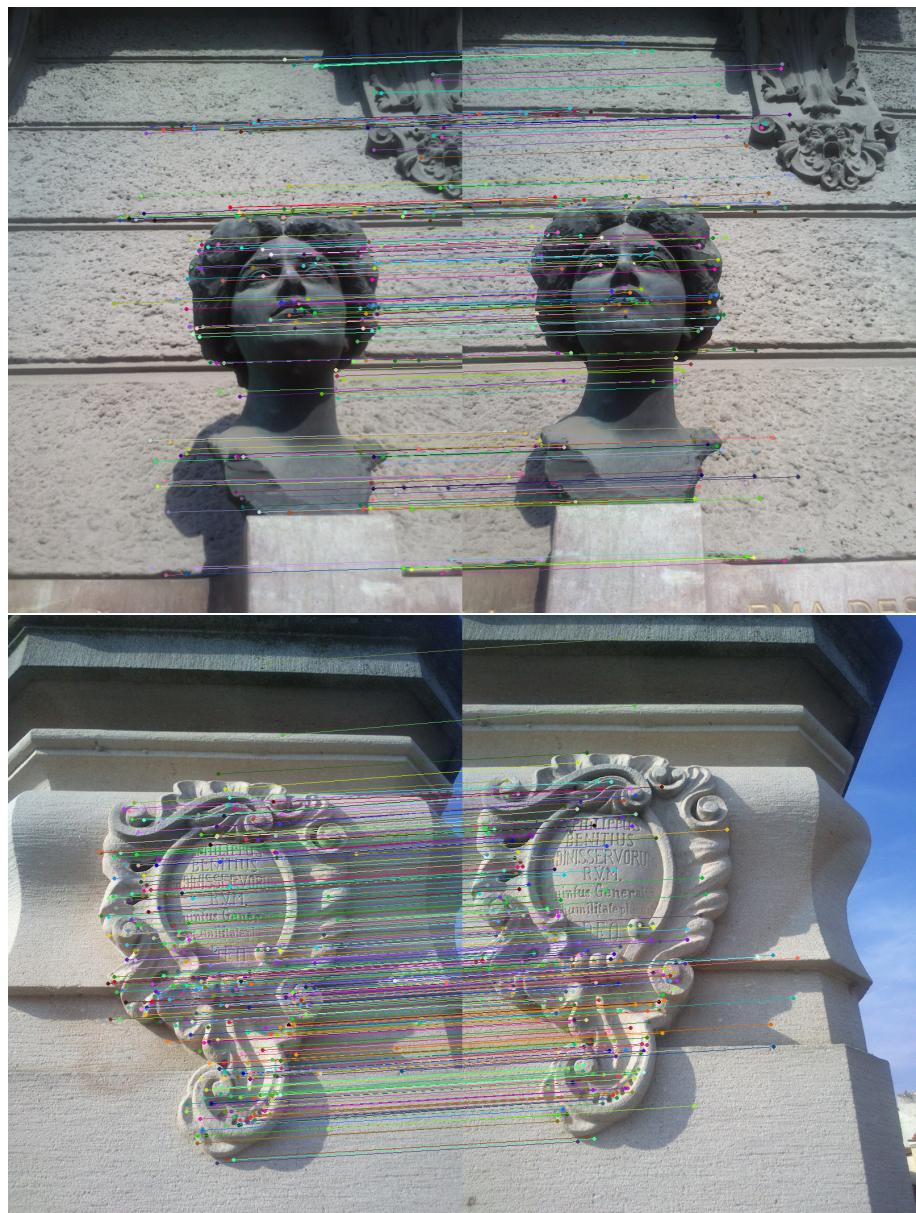


Figure 7.3: The result of SURF matching.



Figure 7.4: The output as a 3D model of disparity. The model of Ema Destinová sculpture (left) and of a memorial (right).

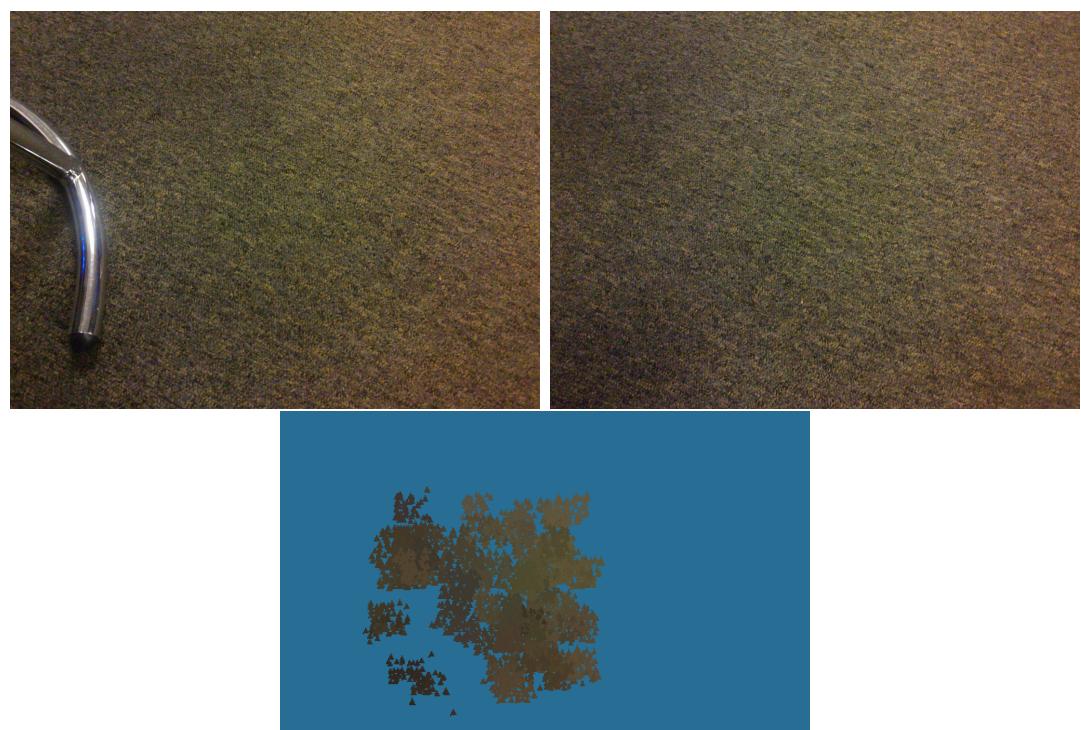


Figure 7.5: An example of an input and output of a scene that does not give a good result.

## 8. User manual

A camera interface is shown immediately after starting the application:

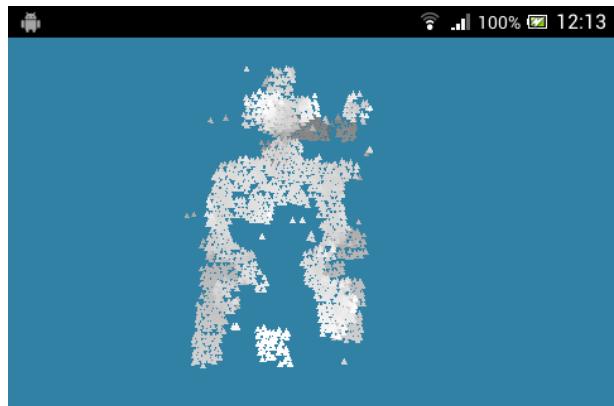


The user can then take one or more photos which are automatically saved in the application's gallery. Also, the user is free to rotate the phone in the portrait or landscape orientation and the interface adjusts accordingly. The list of photos taken by the user using the application can be accessed by tapping the "menu button" (typically the right-most button located below the phone's screen) and then selecting "Gallery". This reveals a persistent list of all user's photographs:



For the purposes of evaluating this work, there is also a second button besides "Gallery" labelled as "Sample Data". This displays a list of testing photos using the same interface as the main gallery.

The user can then select a pair of photos by tapping on each of them. The selected photos are highlighted. The 3D reconstruction process is started by tapping the device's "menu button" again and pressing the "3D View" option in the menu that subsequently appears. A visualization of the reconstruction is then displayed:



Note that the reconstruction algorithm runs in parallel with the visualization. Therefore, more and more features and details are gradually added to the 3D visualization. The user can rotate the 3D model using swiping from left to right and vice versa. A landscape mode is enforced for this part of the UI.

Besides “3D View”, there is also a “2D View” option that displays the reconstruction as a set of points in a grayscale image with the brightness of each point depicting the reconstructed depth.

The “back” button (typically the left-most button on most Android phones) can be used to go back to the gallery. Tapping this button again gets us back to the camera mode.

# Conclusion

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