

Enhancing 3D reconstruction with Android Sensor Fusion data



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Abstract

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To ...

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Acronyms

BA Bundle Adjustment. ix, 3

Base line The distance between the left and the right camera in a stereo pair.. ix

Epipolar lines TODO. ix

Essential Matrix TODO. ix

Extrasinc??? camera parameters TODO. ix

FoV Field of View. ix

Intersinc camera parameters TODO. ix

Pitch Rotation around the y axis.. ix

Pose Estimation TODO. ix

Quaternion TODO. ix

RANSAC Bundle Adjustment. ix

Roll Rotation around the x axis.. ix

Rotation Matrix TODO. ix

SIFT TODO. ix

SVD Singular Value Decomposition. ix

Yaw Rotation around the z axis.. ix

Chapter 1

Introduction

Mobile and wearable devices are becoming more and more popular. Modern smart-phones despite having extremely good camera's also use advanced sensor's, like Accelerometers, Gyroscope, Magnetometer, Barometer etc.. There is also a big need and growing market of Augmented Reality (AR) and Virtual Reality(VR). That's why image analysis and recognition, as well as 3-D reconstruction techniques are really hot topic. Unfortunately algorithms that support these techniques are very time and memory consuming, that's why it's really hard to run them on mobile devices, which have many limitations in terms of CPU speed and RAM memory capacity.

Today many devices are capable of 3D reconstruction. One of them is very popular Kinect(?). It has ability of performing real-time 3D cloud point generation, but it has very high accuracy of reconstruction, but in the same time it's very expansive and not exactly mobile.

1.1 Purpose of this thesis

Author of this document will present the reader with an overview of the idea of 3D reconstruction. This thesis also inculdes brief description of related research in this area. After short analysis of efficiency, accuracy and common problems of few chosen algorithms this thesis will propose their enhacement with data acquired with sensors, which can be found in smartphones. At the end author presents evaluation and discuss test results. TODO finish

1. INTRODUCTION

1.2 Scope

The author researched, how Accelerometer, Gyroscope and Magnetometer can be used in order to improve Fundamental, Essential matrix and also relative Pose Estimation. Unfortunately raw data sensors are really noisy and it's really hard to use them individually to enhance reconstruction. However there is a way to combine these data together in order to compensate error of each individual sensor. The term describing this process is called "Sensor Fusion". This data fusion allows to estimates in real time a relative or global(in term of earth magnetic field) rotation and translation of the device. TODO finish

1.3 Initial assumptions

The general process of 3-D reconstruction is quite broad, that's why the author of the thesis focus only on certain aspects of this topic. That's why author didn't write algorithms from the scratch, but built his algorithms on top of OpenCV library and "Relative Pose Esitmaton" Open-source project setuped by In terms of sensor fusion, currently state of art approach is used by most of big Mobile Operating Systems(Android, iOS, Windows Phone). That's why author used Sensor Fusion API from API and only wrote what's needed it terms of getting rotation and translation of the smartphone camera, when acquiring images for his research. TODO finish

1.4 Thesis Outline

In Chapter 2 something something and so on

In Chapter 3

In Chapter 4

In Chapter 5

In Chapter 6

In Chapter 7

In Chapter 8

Chapter 2

Fundamentals

This chapter explains the basic theory of 3D reconstruction and Structure from Motion. All information referred to herein can be found in (?). It also includes brief overview of sensor fusion made with the use of accelerometer, gyroscope and magnetometer data.

2.1 3-D reconstruction in general

There are many possibilities of performing reconstruction, starting from two-view reconstruction, multiple-view reconstruction and ending with the use of stereo calibrated cameras like the ones used in Kinect[reference]. Reconstruction can also be performed with a single hand-held camera either from a video or a sequence of images. As little as two pictures taken from different angles of a single object are sufficient to perform 3D model generation. Reconstruction process consists of the following steps:

1. **Image Acquisition**, where images are acquired
2. **Feature extraction and corresponding points matching**, where distinctive features are extracted from the images and compared
3. **Fundamental & Essential Matrices**, where matrices meeting the requirements of basic epipolar geometry are calculated
4. **Camera parameters estimation**, where external and internal camera parameters are estimated
5. **Triangulation**, where camera projection matrices are composed and used in order to calculate 3D cloud points

2. FUNDAMENTALS

2.1.1 Feature extraction and corresponding points matching

Usually, each image used in reconstruction has to be analysed in order for the distinctive features to be found. Afterwards all features in images are compared in order to find corresponding matches(2.1). There are multiple features detectors and extractors available for use http://en.wikipedia.org/wiki/Feature_detection_%28computer_vision%29. Some of them are more suitable for edge detection, while others are best used for corner or blob detection. One of the most popular and robust feature detection method is scale-invariant feature transform (SIFT) http://en.wikipedia.org/wiki/Scale-invariant_feature_transform. The use of these descriptors allows for detecting local features in images and describing them with metrics including scale, rotation and translation invariant.

2.1.2 Fundamental & Essential Matrix estimations

Once proper matches are found, it can be proven that there exists Fundamental matrix F for which the following equation is satisfied:

$$x'^T * F * x = 0 \quad (2.1)$$

where x and x' are uncalibrated notions of points correspondence (?) TODO chapter. It is known that solutions of this equation are highly sensitive to the occurrence of outliers. Usually, to make fundamental matrix estimations more accurate some outlier removing algorithms need to be used. One of the most robust approaches includes the use of of RANdom SAmple Consensus (Bundle Adjustment (RANSAC)) <http://en.wikipedia.org/wiki/RANSAC>. The example of sample fitting can be seen in 2.2 Its basic idea relies on choosing a random subset from among all matches, solving a problem of reduced dataset and establishing how many points from the original set satisfy the equation. The use of F matrix allows for calculating epipolar lines for each point (2.3). These lines cross exactly the same points in both images and can be used for dense feature matching since matches need to be searched for exclusively in the surroundings of these lines. When enough inliers are found, points that do not satisfy the equation can be removed from further processing. Once internal camera parameters K are known, the image points found can be calibrated and expressed in

2.1 3-D reconstruction in general



Figure 2.1

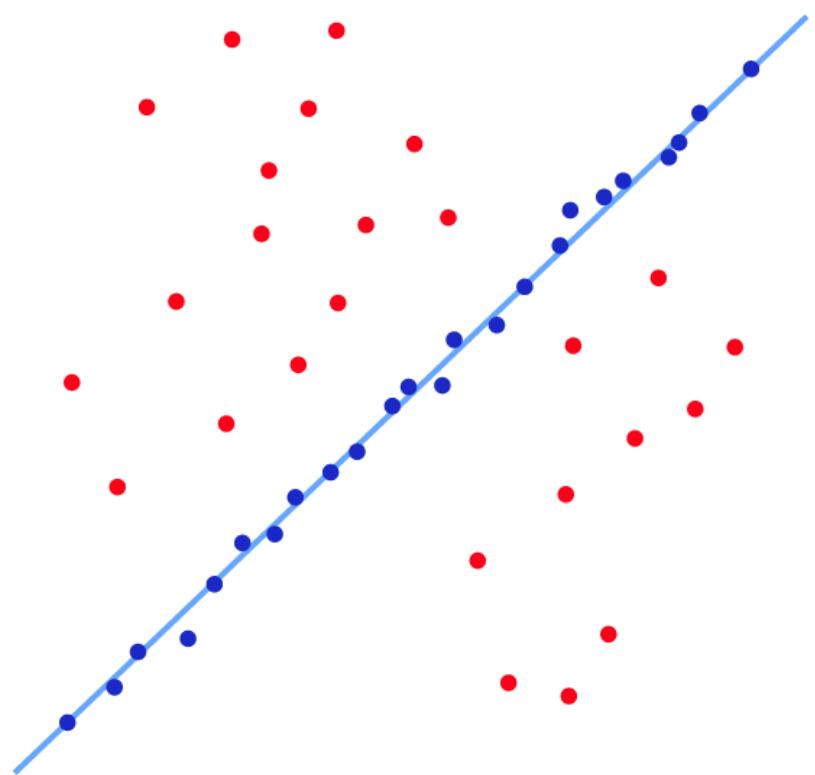


Figure 2.2: RANSAC fitting for 2D image TODO reference

2. FUNDAMENTALS

camera reference position system. Such calibrated points satisfy the following essential matrix E equation:

$$x_c'^T * E * x_c = 0 \quad (2.2)$$

which is very similar to fundamental equation 2.1. This results in:

$$E = K^T * F * K \quad (2.3)$$

with K being the internal camera parameters. This equation 2.3 is important in terms of decomposition of F matrix to relative rotation and translation.

2.1.3 Camera parameters estimations

Internal camera parameters are expressed by the following matrix:

$$\begin{bmatrix} \alpha_x & x_0 \\ \alpha_y & y_0 \\ 1 & \end{bmatrix} \quad (2.4)$$

where $x = fmx$ and $y = fmy$ represent the focal length of the camera expressed in pixel dimensions in the x and y direction respectively. Similarly, $x_0 = (x_0, y_0)$ is the principal point of pixel dimensions. These parameters need to be calculated only once for each camera model. Cameras can be calibrated with special reference boards of the known dimensions and characteristics. For the proper 3D reconstruction it is essential to properly estimate external camera parameters, such as rotation (orientation angles of the camera) and global position of the camera. It is often the case in 3D reconstruction that these parameters are not known. However, it is showed in Chapter 9 of Multiple View Geometry in Computer Vision ((?)), how essential matrix can be decomposed using Singular Value Decomposition Singular Value Decomposition (SVD) to relative camera positioning system of two projections:

$$P1 = K * [I | 0] \quad (2.5)$$

the second one is equal to

$$P2 = K * [RDifff | tDiff] \quad (2.6)$$

Unfortunately, there are four possible solutions for such a decomposition and it is not always possible to identify the correct one.

2.1.4 Points Triangulation

Once internal and external (global or relative) camera parameters are calculated, the triangulation can be performed in order to acquire an up-to-affine reconstruction model (??). The only elemnt that cannot be determined in such a relative case is the scale. This process is described in detail in [TODO hartley chapter 10].

2.2 Structure from Motion

The term "Structure from Motion(SfM)" refers to the reconstruction performed from the consecutive sequences of a moving camera. It is a popular research topic and the two main approaches, namely the Pose Estimation and Homography Estimation, can be used for the [urposes of reconstructing a 3D model of an object.

2.2.1 3D Pose Estimation

Assuming that some of the 3D cloud points are already known, the matches between 2D features in a new image and 3D point cloud positions can be established. Such 3D-2D matches can be used to estimate the camera position. This allows for reconstructing new 3D points and merging them smoothly into a functional model. Unfortunately, this process is also highly sensitive to the occurrence of outliers, therefore adequate measeures have to be undertaken to reduce their influence. One of the main advanteges of this method is its speed. On the other hand, its effectiveness relies strongly on the exising 3D cloud quality.

2.2.2 Homography estimation

A new image can be reconstructed with a previous one in a standard way in order to recive an up-to-scale 3D model. Afterwards, a newly acquired model can be merged into existing one using homography estimation between the coresponding 3D points. Such a strategy is slower than the previous one, but it is not influenced by the quality of the existing 3D model. Although it is highly sensitve to outliers as well, if used properly it can produce more new 3D points.

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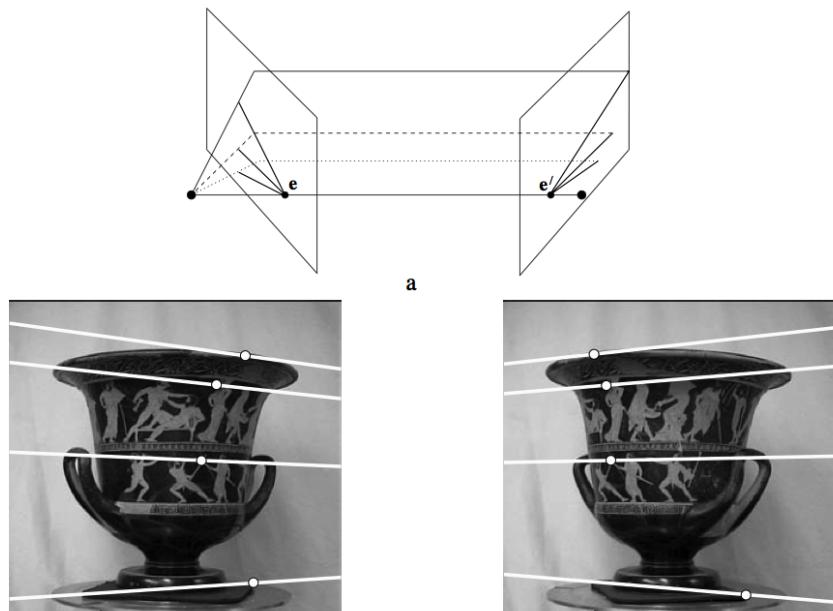


Figure 2.3: Epipolar lines found in an image of a vase TODO reference

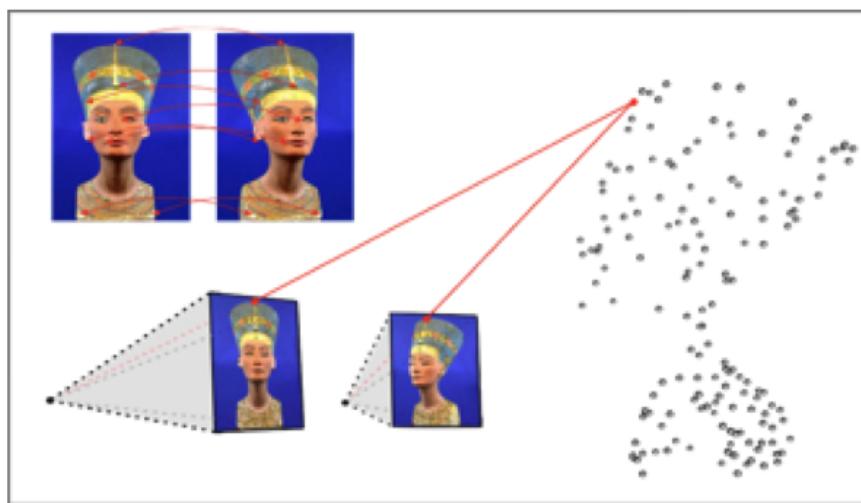


Figure 2.4

2.2.3 Structure Adjustment

Special refinement methods can be used to compensate for an error of mismatched points propagating through images. They include, among others, Bundle AdjustmentBundle Adjustment (BA) http://en.wikipedia.org/wiki/Bundle_adjustment. The algorithm, using the information concerning the corresponding matches between multiple sets of images, iteratively modifies either both the camera external parameters and 3D points positions or one of them. The main disadvantage of the method is its execution time. It is too time-consuming to use it in real-time applications. The basic idea of BA is expressed in figure 2.5.

2.3 Mobile Sensors overview

There are many sensors available in the nowadays smartphones, such as accelerometer, gyroscope, magnetometer, barometer, GPS, etc. All of them have their advantages and disadvantages, and thus the errors of some might be compensated for with the strengths of the others in order to, for example, accurately compute camera rotation angles.

2.3.1 Accelerometer

An accelerometer is a device that measures acceleration along 3 axes of the device [reference]. Generally, an accelerometer allows for measuring total acceleration by sensing what force is applied to its micro strings. An accelerometer, which lies on a flat surface perpendicular to the Earth's surface will indicate approximately 1G upwards. This gravitation vector can be used to calculate the relative camera rotation, but it is difficult to define to which direction the gravity vector points when the device is moving in not a linear manner. The gravity vector is obtained from the accelerometer data and tracked during unexpected movements with the use of gyroscope sensor.

2.3.2 Gyroscope

A gyroscope is a device for measuring or maintaining orientation, based on the principles of conservation of angular momentum [reference]. A standard gyroscope consists of a spinning wheel mounted on two gimbal rings, which allows it to rotate in all three axes. The spinning wheel will resist changes in orientation, due to an effect of the

2. FUNDAMENTALS

conservation of angular momentum. A conventional gyroscope measures orientation, in contrast to MEMS (Micro Electro-Mechanical System) types, which measure angular rate, and are therefore called rate-gyros [reference]. MEMS gyroscopes contain vibrating elements to measure the Coriolis effect. In the end the angular velocity can be calculated in each axis. It is important to note that whereas the accelerometer and the magnetometer measure acceleration and angle relative to the Earth, gyroscope measures angular velocity relative to the body.

2.3.3 Magnetometer

A magnetometer is an instrument used to measure the strength and/or direction of the magnetic field in the surrounding area of the instrument. Its main idea works in the same manner as the conventional compass'. With some magentometers magnetic field can be measured in 3 directions, relative to the spatial orientation of the device [reference]. Using magnetometers allows for estimating relative position in geomagnetic north position system.

2.3.4 Sensor Fusion

Sensor fusion is the process of combining sensory data derived from disparate sources in a way that the resulting information is to some extent more valuable than it would be possible should these sources be used individually. The term "more valuable" in this case may mean "more accurate", "more complete", or "more dependable", or refer to the result of an emerging view, such as stereoscopic vision (calculation of depth information by combining two-dimensional images from two cameras at slightly different viewpoints) [reference]. One of the strategies available is Kalman filtering(2.6) This approach is used in Sesnor Fusion available in Android API, where the gravity vector calculateion is enhanced with the accelerometer and gyroscope data. The gravity vector can be decomposed in order to estimate the camera's rotation angles. Magnetometer can be used optionally in order to acquire rotation angles referenced to the Earth's coordinate system. However, magnetometer is sensitive to changes in the electromagnetic fields, therefore its measurement can be noisy in confined spaces filled with electronic devices. Substracting gravity from the actual acceleration measurements allows for estimating linear acceleration. The use of linear acceleration makes it possible to measure the relative change of the device's translation. However, it requires a double integration

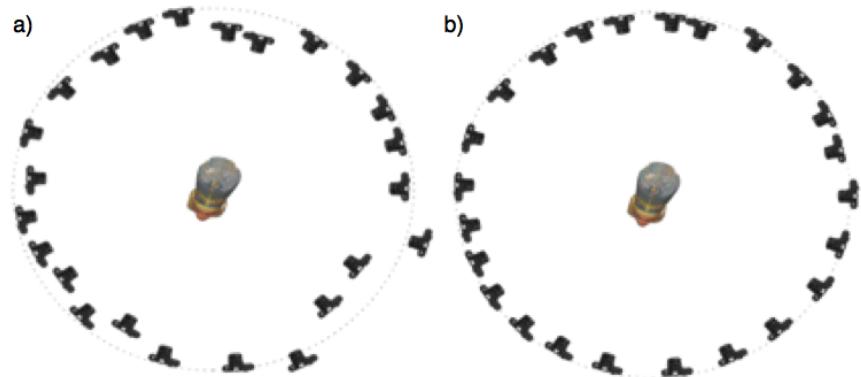


Figure 2.5: TODO reference

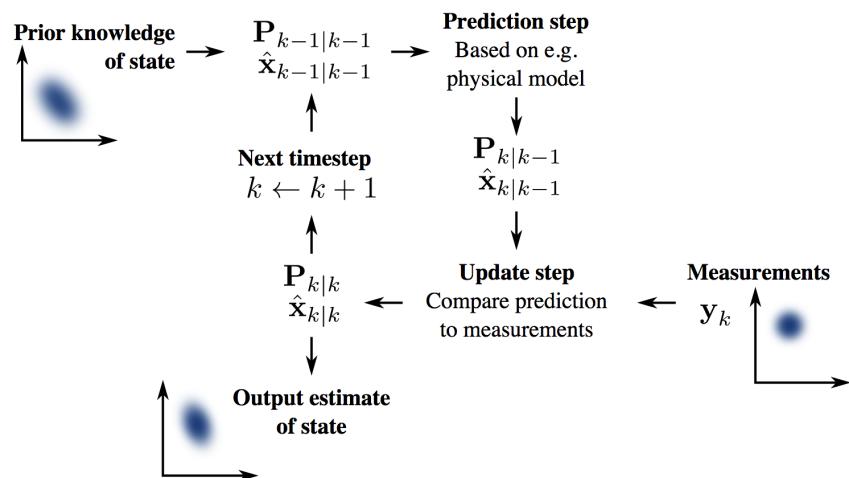


Figure 2.6

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over time, which results in increasing the translation's noise. It is important to note that calculating rotation is significantly more accurate than estimating the translation.

Chapter 3

Related Work

There are many approaches to the reconstruction problems, starting with the raw one-by-one pixel analysis for density matching, through high level abstraction of objects recognition and extraction and ending with the light and shadows-based reconstruction (?)(?). However this thesis does not focus on high-level abstraction reconstruction, but on refining relative poses estimation steps. As described in the theoretical part, in order to estimate the first two relative camera positions essential matrix must be decomposed. Since the basic epipolar geometry equation discovery, many scientist have introduced various ways to solve this linear problems, which differed primarily in terms of the accuracy and speed. One of the first was the 8-point algorithm (?), which can be used to compute a fundamental matrix. This can be done without any prior knowledge of the scene or camera external and internal parameters. Fundamental matrix has to be converted to essential matrix in order to find relative camera positions and that is why it is necessary to calculate internal camera parameters. Next, the 5-point algorithm approaches were introduced (?) (?), which used internal camera parameters for the proper essential matrix estimation. In his paper M. David Nister shows that the 5-point algorithm outperforms almost all similar algorithms in terms of accuracy and speed. Only the 8-point algorithm can be regarded as competitive, when it comes to forward image sequences. One of the state-of-art real-time and robust approaches is the iterative 5-point algorithm created by Vincent Lui and Tom Drummond(?).

Most of the algorithms are very sensitive to the occurrence of outliers. One of the most common approaches to use is RANSAC modelling(?).

3. RELATED WORK

A research group from Technische Universität Berlin made an interesting comparison and evaluation of methods, which were discovered by 2008 (?). It was discovered that estimation of camera rotation is much more stable than translation calculation. Furthermore, there are a lot of ambiguities regarding the choice of the correct solution of epipolar geometry equation.

In certain situations, where external camera parameters as rotation and translation can be measured, more accurate algorithms were proposed. In 2011 D. Scaramuzza from Zurich proposed a 1-point algorithm (?), which shows how to describe and use a model of a camera mounted on a car to enhance 3D reconstruction. The 4-point algorithm introduced in 2013, which uses information of rotation angle in certain axis from additional sensor, as shown in paper (?), can outperform even the 5-point algorithms. Lately the scientists have been creating more complex models to estimate relative stereometry, e.g. a team from Zurich proposed a way to enhance reconstruction with additional 6DOF sensor (?).

There are also non standard approaches like (?), where it is shown how to estimate the relative pose from 3 lines with two of the lines being parallel and orthogonal to the third one. Very accurate estimations can also be obtained for special camera model cases, when there is no rotation(?). All these references show that enhanced models often help to achieve more accurate or faster solutions to standard epipolar geometry problems.

Accuracy and speed constitute significant elements of the process of creating the systems capable of augmenting our reality. One of the first successful tracking and mapping reconstruction-based system was proposed by a research team from Oxford University (?). They showed how two simultaneously working threads can be used to both create a model of the environment being scanned and use this knowledge to apply graphical effects to objects presented on a video stream. Some of these concepts have already been applied to robotic vision. The authors showed efficiency of the proposed system for a robot walking in cluttered indoor workspaces(?). There were also approaches of porting reconstruction strategies to mobile devices(?)(?)(?)(?).

The major conclusions to be drawn include the fact that rotation estimation is more stable than translation estimation and that the reconstruction accuracy is improved by a better described model of camera movement. Some of the researches proposed many

scientific papers regarding rotation-improved solution space searching (?) (?). There are even some approaches involving the use of additional IMU accelerometer for the reconstruction process enhancement (?).

Chapter 4

Concept

As indicated in similar research it's very attractive to use additional data to enhance reconstruction and reduce ambiguity in finding correct solution of 3D reconstruction. Additional camera or model information help to implement faster, more stable and robust algorithms. This thesis will show how prior knowledge of rotation or translation acquired via mobile sensor fusion can be used to enhance process of 3D reconstruction from series images. When it comes to relaying on hand-held smartphones, collected sensor data are very noisy. This thesis, how even noisy informations can be used in structure reconstruction processes. Initially only camera rotation estimation was supposed to be used in the scope of this master thesis. However first trials of reconstruction proved to be not sufficient enough and additional rotation error matrix estimations were proposed. From analysis of theory and related works it seems that both epipolar equations and pose estimation techniques can be improved with additional rotation and translation information data. Author of this thesis proposes environment, where user can decide what type of stargy to use. In terms of initialization of 3D cloud point reconstruction can be made using:

4.1 Requirements

Proposed methodology needs as the input series of images with additional information about position of the camera - euclidian rotation and optionally translation. Usage of smartphone is actually not necessary. Any camera with SensorFusioned accelerometer and gyroscope(magnetometer is actually optional and as discussed in [TODO] has its

4.2 Enhancing epipolar geometry equations - rotation enhancements

advantages and disadvantages) capable of rotation and translation estimation can be used. Internal camera parameters need to be calculated before reconstruction process is started. Additional sensor data doesn't have to be very accurate. Noisy external camera parameters still can be successfully used in order to enhance reconstruction process.

4.2 Enhancing epipolar geometry equations - rotation enhancements

Initial pair reconstruction step is very important and needs to be accurate for other. Taking standard fundamental geometry equation and relative camera based system ($P = [I|0]$, $P' = [R|t]$) we can note that:

$$x_r^T * K^{-T} * [T]_x * R * K^{-1} * x = 0 \quad (4.1)$$

It is can be written that:

$$[T]_x = \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix} \text{ where } T = [t_x, t_y, t_z] \quad (4.2)$$

As we were discussing both rotation can be distorted with noise. This can be written as:

$$R = R_{error} * R_{init} \quad (4.3)$$

where R_{init} is rotation matrix from measured angles and R_{error} is rotation matrix of angles errors. Looking at this from different point of view 4.3 can be interpreted as multiplying two rotations matrix: One estimated, but close to local optimum initial rotation matrix and second one correcting noise error rotation matrix. Basic idea of algorithm proposed in this thesis is instead of R calculation, which as described in [reference] can be acquired from Essential matrix SVD decomposition, R_{error} will be estimated. In the end 4.1 can be rewritten in form:

$$x_r^T * K^{-T} * [T]_x * R_{error} * R_{init} * K^{-1} * x = 0 \quad (4.4)$$

Having:

$$\begin{aligned} h_r^T &= x_r^T * K^{-T} \\ h &= R_{init} * K^{-1} * x \\ G &= [T]_x * R_{error} \end{aligned} \quad (4.5)$$

4. CONCEPT

With such notation one can notice that

$$h'^T * G * h = 0 \quad (4.6)$$

quite resembles both standard fundamental and essential equation [reference]. Of course h' and h are both homogenous. From analysis it's known that G has 6DOF: 3 due to unknown translation and 3 due to unknown correction angles. From theory such matrix can be resolved for instance by both 5 and 8-point algorithms. So basicly standard fundamental and essential equation solvers can be used in order to retrieve both $[T]_x$ and R_{error} in order to resolve some common problems in retrieving correct solution and improve accuracy. In the end estimated R_{error} and calculated R_{init} can be multiplied to retrieve new rotation R (4.3). Also to reduce error estimation using Rodrigues parametrization, when the angles are small(and they indeed are because only small error is present in sensor data) we can note that R_{error} in fact is more or less equals to:

$$R_{error} \cong \begin{bmatrix} 1 & -w_z & w_y \\ w_z & 1 & -w_x \\ -w_y & w_x & 1 \end{bmatrix} \quad (4.7)$$

[Refernece to Hartley]. It can be used when decomposing G to ensure proper decomposition. What's more in normal situation in case of both these algorithms we have to decompose recovered matrix to both relative rotation and translation. However we normally have to deal with small ambiguity and check for instance by initial triangulation, which R and T use. Using this Rodriguez representation, we can reduce 4 solution test cases to 2 possibly solutions test-case.

4.2.1 Alternative 3-point algorithm for translation finding

Starting 4.6 it can be written that:

$$x'^T * K^{-T} * \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix} * R * K^{-1} * x = 0 \quad (4.8)$$

Having:

$$\begin{aligned} h'^T &= x'^T * K^{-T} \\ h &= K^{-1} * x \end{aligned} \quad (4.9)$$

$$[h'_1 \ h'_2 \ h'_3] * \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix} * \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix} = 0 \quad (4.10)$$

and multiplying it we will end up with

$$h_1 * h_{12} * t_z - h_1 * h_{13} * t_y - h_2 * h_{11} * t_z + h_2 * h_{13} * t_x + h_3 * h_{11} * t_y - h_3 * h_{12} * t_x = 0 \quad (4.11)$$

what can be grouped:

$$t_x * (h_2 * h_{13} - h_3 * h_{12}) + t_y * (h_3 * h_{11} - h_1 * h_{13}) + t_z * (h_1 * h_{12} - h_2 * h_{11}) = 0 \quad (4.12)$$

rewritten as:

$$\begin{bmatrix} t_x & t_y & t_z \end{bmatrix} * \begin{bmatrix} (h_2 * h_{13} - h_3 * h_{12}) \\ (h_3 * h_{11} - h_1 * h_{13}) \\ (h_1 * h_{12} - h_2 * h_{11}) \end{bmatrix} = 0 \quad (4.13)$$

and solved for instance with SVD with only 3 points. This is very attractive way of reconstructing images from only 3 points especially in terms of speed. Overall accuracy strictly relies on precise measurements of camera orientation.

4.3 Pose estimation

Different approaches to continuous multiview 3D reconstruction were discussed. This research main goal was to make it more accurate and faster. That is why it focuses on pose estimation instead of homographies merging. This is also good in terms of keeping scale in between next image analysis. For any point in image following condition is kept:

$$x = P * X \quad (4.14)$$

where x is homogenous image point ($x, y, 1$) and X homogenous 3D point ($X, Y, Z, 1$). Of course

$$P = K * [R | t] \quad (4.15)$$

4.3.1 Known rotations & translations

In situation where rotations and translations of cameras are known no additional calculations are needed. Both rotation and translation of the camera can be estimated from sensors. Such situation is interesting, because there is already everything needed for triangulation of points. To resolve inaccuracy of especially translation measurements standard Bundle Adjustment methods can be used in order to refine reconstruction results.

4. CONCEPT

4.3.2 Rotation enhancements

Using similar thinking as in previous section[ref] we can note that:

$$\begin{aligned} x &= K * [Rinit + dR | t] * X \\ x &= K * [Rinit | 0] * X + K * [dR | t] * X \\ x - K * [Rinit | 0] &= K * [dR | t] * X \end{aligned} \quad (4.16)$$

Substituting $x_m = x - K * [Rinit | 0]$ we get:

$$x_m = K * [dR | t] * X \quad (4.17)$$

This can be solved using normal PNP calculating algorithms. It's known that orientation estimation is more accurate than translation estimation using SensorFusion and this approach allows very accurate calculation of rotation error matrix dR and translation t , which keeps the scale of initially reconstructed points cloud.

4.3.3 Rotation & translation enhancements

Similar to 4.16:

$$\begin{aligned} x &= K * [Rinit + dR | Tinit + dt] * X \\ x &= K * [Rinit | Tinit] * X + K * [dR | dt] * X \\ x - K * [Rinit | Tinit] &= K * [dR | dt] * X \end{aligned} \quad (4.18)$$

end in the end by Substituting $x_n = x - K * [Rinit | Tinit]$ we get:

$$x_n = K * [dR | dt] * X \quad (4.19)$$

We can note that when initial solution is already known, the problems begins to focus on refining pose estimation instead of searching for it.

4.4 Reconstruction process strategy

Finally proposed reconstruction environment, where initial estimates of rotation

1. Known rotations and translations - relative poses are calculated from sensor data - euclidian reconstruction
2. Known rotations - Alternative 3-point algorithm for translation finding or enhanced fundamental/essential

4.4 Reconstruction process strategy

3. Noisy rotation - enhanced fundamental/essential for dR and translation
4. No known extrisinc parameters - standard fundamental/essential for R and Translation

Later one new images are analized in comparison to previous one to enrich initial cloud point with new points. It's only necessary to keep track of each 3D cloud point corresponding 2D positions in images. In terms of Pose Estimation following methodologies can be used:

1. Known rotatation and translations - no additional calculations, just triangulation - euclidian reconstruction
2. Known rotation - looking for relative translation by backProjection optimisations
3. Noisy rotation - looking for dR and translation by backProjection optimisations
4. No known extrisinc parameters - standard pose estimation

Of course in all of this steps it's really important to have as minimum outliers as possible. All of this methods are pretty good in terms of removing outliers, espiecially when connected with RANSAC algorithm.

Chapter 5

Implementation

In order to perform some tests with proposed methodology there was a need to prepare environment for it.

5.1 Choosing Environment

One thing was to prepare application, which would be capable of taking both pictures with additional SensorFusioned data. Currently Android has one of the best APIs which allows user to get both raw and fusioned sensor data. In order to avoid coding from scratch all sterometry algorithms there was need to choose library, which is fast and has most of discussed algorithms implemented. This is where OpenCV performs really good. However it's really hard to get it running on Android, due to long time compiling, problematic error debugging and speed performance. This is why author decided to separate process of acquiring images from processing them. In order to enrich images with sensor data Android app was created and standalone C++ desktop app to perform processing and evaluation.

5.2 Project Structure

Both applications source can be found on attached CD and under the Github webpage: <https://github.com/KrzysztofWrobel/MasterThesisSource.git>. In general project was separated to different subprojects: Android and Desktop. In addition some sample datasets were added to Dataset folder.

5.3 "Sensor Enhanced Images Camera" - Android Gradle based project

5.3 "Sensor Enhanced Images Camera" - Android Gradle based project

In order to capture images and associate them with Sensor data custom photo capture app called "... were created. User can track in real time parameters euclidian angles of smartphone in global earth coordinate system. When taking picture current roation data as well relative translation from last capture are stored in custom JSON file, which is later saved along taken picture in seperate folder. All of captured pictures and sensor data can be compressed and send though internet to the user. By default they are saved on internal SD card in folder, which is automaticly created timestamp folder.

5.3.1 Installation

Gradle based built system was used, which is currently recomended way to handle Android based projectsref. google. Currently this app supports devices with Android 4.0 and above. In order to compile this project it's recomended to install Android Studio. It already contains Android SDK and also has built-in Gradle support. More informations about configuration, compilation and install steps can be found in README.md in main catalog.

5.3.2 User Interface

ScreenShot. Apps allows to track camera angles in real time, so user can precisely decide angles of capture. Also heuristical movement and translation estimation can be seen. In order to capture photo, user only has to click in the screen center.

5.3.3 Important Implementation Aspects

Only master thesis specific code is described in detail.

5.3.3.1 Rotation calculation

Android SDK has already API, which can be used to access noth raw and "sensor fused" data. In particular for rotation estimation *Sensor.TYPE_ROTATION_VECTOR* was used. It returns 9DOF quaternion in reference to geomagnetic north. In order to decompose it to euler angles helper method were used:

5. IMPLEMENTATION

```
private float[] euclidianAnglesFromQuaternion(float[] quaternion) {
    ...
    //Converts quaternion to 4x4 rotation matrix
    SensorManager.getRotationMatrixFromVector(rotMat, quaternion);
    ...
    //Extracts euclidian Angles in radians
    SensorManager.getOrientation(rotMat, orientation);
    ...
    return orientation;
}
```

5.3.3.2 Custom heuristic for move estimation

Unfortunately using only accessible sensor data it's hard to estimate relative translation of the device. Accelerometer, even compensated Android *Sensor.TYPE_LINEAR_ACCELERATION*, measures only linear acceleration of the device. These measures, which are very noisy itself, not only due to for instance hands shaking, need to be double integrated in time in order to get move distance. As proposed system is supposed to be used for hand-held cameras on order to minimise noise influence following enhanced heuristic for people walk model was proposed:

1. When new linear acceleration sensor data is ready, first apply lowPass filtering in order to reduce some high frequency noise.
2. Change sensor datda vector from local camera coordinates to global reference system(multiply with inverted rotation matrix)
3. Decide depending on current state, if deviceMovmentState has changed:
 - (a) If device was previously IDLE and incoming Acceleration value is bigger than $0.5 \frac{m}{s^2}$ change device state to MOVING and reset current velocity to $0 \frac{m}{s}$
 - (b) If device was previously MOVING and incoming Acceleration value is smaller than $0.1 \frac{m}{s^2}$ change device state to IDLE
4. Only if device is currently moving:
 - (a) Update device velocity
 - (b) Check current speed with walk constraint(People walk with avarage speed $1.5 \frac{m}{s}$) and eventually scale it down to maximum value

5.3 "Sensor Enhanced Images Camera" - Android Gradle based project

(c) Update device position

Described algorithm implementation snippet can be found in listing 5.1. Human walking model was introduced in order to constraint the velocity. Without it integrating small noise over time, would eventually result in high unrealistic movements. Maximum walking speed can be adjusted but by default it should be around $1.5 \frac{m}{s}$ http://en.wikipedia.org/wiki/Preferred_walking_speed. In fact the most important factor of good position estimation is vector angle, fortunately noise equally influence each axes, so it should be statistically correct.

5.3.3.3 Custom Sensor Data File format

As mentioned each photo capture stores additional sensor information. These informations are:

- id - indicates order of photos
- relative path to image file
- Euler Angles - pitch, roll, azimuth
- Position coordinates in geomagnetic north system(relative to previous image)
- Android rotation quaternion

All of this information are stored in a list and when the user is done with taking pictures all informations are saved into JSON file named sensor.txt. Sample file can be found in attachments.

5. IMPLEMENTATION

```
1  public void onSensorChanged(SensorEvent event) {
2      ...
3      } else if (event.sensor == mLinearAcceleration) {
4          ...
5              //Filtering out some noise
6              newGlobalAcceleration = lowPass(newGlobalAcceleration,
7                  currentGlobalAcceleration);
8              //Switch linear acceleration from phone local coordinates to
9                  global coordinates
10             Matrix.multiplyMV(newGlobalAcceleration, 0,
11                 invertedRotationMatrix.clone(), 0, newGlobalAcceleration,
12                 0);
13
14             double distance = getLength(currentGlobalAcceleration);
15             long currentTimeMillis = System.currentTimeMillis();
16             //Decide state of the device. Distance is in m/s^2
17             if (distance > 0.5 && deviceState == State.IDLE) {
18                 if (currentTimeMillis - movingEndTime > 300) {
19                     deviceState = State.MOVING;
20                     currentGlobalVelocity = {0,0,0};
21                 }
22             }
23
24             if (deviceState == State.MOVING) {
25                 //Update current device velocity
26                 currentGlobalVelocity += currentGlobalAcceleration * dT;
27
28                 double velocity = getLength(currentGlobalVelocity);
29                 //Check and adjust current velocity. People walk with
30                     avarage speed 1.5\frac{m}{s}
31                 if (velocity > WALKING_MAX_VELOCITY) {
32                     currentGlobalVelocity /= velocity /
33                         WALKING_MAX_VELOCITY;
34                 }
35
36                 //Update device relative position, s = v0 * t + a * t
37                     ^2/2;
38                 currentRelativePosition += currentGlobalVelocity * dT +
39                     currentGlobalAcceleration * dT * dT / 2;
40             }
41             ...
42 }
```

Listing 5.1: Snippet from Android source code position estimation heuristic

5.4 "Enhanced 3D Reconstructor" - OSX CMake based project

In order to evaluate algorithms there was need to prepare project environment suitable for this task. Discussion of choosing motivations, where done in 5.2. Author choosed CMake in order to make simpler build and compilation process. Whole project, where developed and tested on OSX 10.9 Mavericks. In order to compile this project following things need to be installed first:

- CMake 2.8
- OpenCV 2.4.10
- Point Cloud Library (PCL) 1.7
- Boost 1.55
- cvsba (<http://www.uco.es/investiga/grupos/ava/node/39>)

5.4.1 User Interface

There two targets defined in CMake file:

1. Test efficiency - used to evaluate pair reconstruction methods, draw epipolar lines in images and calculate samson error distances
2. Test reconstruction - used to evaluate proposed initialization reconstruction with different pose estimation methods

5.4.1.1 Test Efficiency

There is no graphical interface for reconstruction parameters configuration. However at the beginning there are few command-line inputs required to continue reconstruction. User needs to configure:

1. Enhanced Photo Data folder path
2. SIFT features number

Calculated parameters are printed to Console Window. TODO What can be seen there? Screenshot from console output.

5. IMPLEMENTATION

5.4.1.2 Test reconstruction

There is no graphical interface for reconstruction parameters configuration. However at the beginning there are few command-line inputs required to continue reconstruction. User needs to configure:

1. Enhanced Photo Data folder path
2. SIFT features number
3. Init pair reconstruct method:
 - Standard Fundamental equation based
 - Enhanced Fundamental equation based
 - Standard essential equation based
 - Enhanced essential equation based
 - 3-point Translation estimation
 - None - use existing rotations and translations
4. Pose estimation method:
 - Standard 3d-2d perspective estimation
 - Enhanced 3d-2d perspective estimation with noisy rotation
 - Enhanced 3d-2d perspective estimation with noisy rotation and translation
 - None - use existing rotations and translations
5. Whether drop outliers or not
6. Whether use Bundla Adjustment or not

As output user gets reconstructed *.asc files with suffix depending on used methods and choosed features. TODO write more about it

5.4.2 Important Implementation Aspects

Write about how you modified different libraries and how you tricked OpenCV to do what you need to get

5.4.2.1 Rotation matrix generation

To parse Android generated Sensor data file Boost JsonParser was used. As mentioned earlier Android saves decomposed Euler Angles. In order to properly multiply this

5.4 "Enhanced 3D Reconstructor" - OSX CMake based project

angles to acquire proper rotation matrix following code inspired on MathWorld Wolfram
<http://mathworld.wolfram.com/EulerAngles.html>

```
Mat getRotation3DMatrix(double pitch, double azimuth, double roll) {
    Mat D = (Mat_<T>(3, 3) <<
        cos(roll), -sin(roll), 0,
        sin(roll), cos(roll), 0,
        0, 0, 1);

    Mat C = (Mat_<T>(3, 3) <<
        cos(azimuth), 0, -sin(azimuth),
        0, 1, 0,
        sin(azimuth), 0, cos(azimuth));
    Mat B = (Mat_<T>(3, 3) <<
        1, 0, 0,
        0, cos(pitch), -sin(pitch),
        0, sin(pitch), cos(pitch));
    //Important
    return B * C * D;
}
```

5.4.2.2 Enhancing epipolar equations

As we could observe in ?? in order to enhance initial pair reconstruction we can use the same algorithms as standard ones, for example 8-point and 5-point algorithms. The only thing to do is to change input data from local image coordinates into camera coordinates. In OpenCV it can be done with:

```
...
undistortPoints(points1Exp, points1Exp, K, distCoeffs, rotDiffGlobal
);
undistortPoints(points2Exp, points2Exp, K, distCoeffs);
...
```

where `rotDiffGlobal` is rotation between 2 cameras. These lines automatically allow us to calculate h and h' from 4.4. In order to choose proper matrix decomposition we can do as follows:

```
void chooseProperMatrixFromEnhanced(Mat &dRx, Mat &dR1x, Mat &TdRExp,
    Mat &dR, Mat &T) {
    dR = dRx;
    if (decideProperMatrix(dRx, 0.05)) {
        dR = constraintMatrix(dRx);
```

5. IMPLEMENTATION

```
    } else if (decideProperMatrix(dR1x, 0.05)) {
        dR = constraintMatrix(dR1x);
    } else if (decideProperMatrix(-dRx, 0.05)) {
        dR = constraintMatrix(-dRx);
    } else if (decideProperMatrix(-dR1x, 0.05)) {
        dR = constraintMatrix(-dR1x);
    }

    Mat skewT = TdRExp * dR.inv();
    cout << "skewT" << skewT << endl;

    Mat tdecx = Mat(3,1, CV_64FC1);
    tdecx.at<double>(0) = (skewT.at<double>(2,1) - skewT.at<double>(1,2)
        )/2;
    tdecx.at<double>(1) = (skewT.at<double>(0,2) - skewT.at<double>(2,0)
        )/2;
    tdecx.at<double>(2) = (skewT.at<double>(1,0) - skewT.at<double>(0,1)
        )/2;
    T = tdecx;

}

bool decideProperMatrix(Mat dRot, double tolerance){
    double a00 = abs(dRot.at<double>(0,0) - 1);
    double a11 = abs(dRot.at<double>(1,1) - 1);
    double a22 = abs(dRot.at<double>(2,2) - 1);
    if((a00 + a11 + a22)/3 < tolerance) {
        return true;
    }else {
        return false;
    }
}
```

5.4.2.3 3-point translation estimation, between cameras

When we do have rotation data, which are more or less accurate, we can focus on estimating only translation between images. Proposed in 4.11 and 4.13 were implemented. As similar to other Epipolar estimations methods implemented in OpenCV, this one also has ability to filter out outliers with RANSAC schema.

```
...
for (iterationNumber = 0; iterationNumber < niters; iterationNumber
    ++){
```

5.4 "Enhanced 3D Reconstructor" - OSX CMake based project

```
getSubsety(prev_points_raw, next_points_raw, point1s, point2s,
           300, modelPoints);
Mat t = findTranslation(point1s, point2s, rotDiffGlobal, Kinv);
Mat F1 = constructFundamentalMatrix(rotDiffGlobal, t, Kinv);

int goodCount = findInliersy(prev_points_raw, next_points_raw,
                               F1, errors, statuses, reprojThreshold);
if (goodCount > maxGoodCount) {
    swap(statuses, goodStatuses);
    FEnhanced = F1;
    tEnhanced = t / t.at<double>(2);
    maxGoodCount = goodCount;
    niters = cvRANSACUpdateNumIters(confidence,
                                      (double) (count - maxGoodCount) / count, modelPoints
                                      , niters);
}

}

...
.

Mat findTranslation(std::vector<cv::Point2d> &points1, std::vector<
cv::Point2d> &points2, Mat &rotDiff, Mat &Kinv) {

Mat hg1 = Mat::zeros(points1.size(), 3, CV_64FC1);
Mat hg2 = Mat::zeros(points2.size(), 3, CV_64FC1);
for (int i = 0; i < points1.size(); i++) {
    hg1.at<double>(i, 0) = points1[i].x;
    hg1.at<double>(i, 1) = points1[i].y;
    hg1.at<double>(i, 2) = 1;
    hg2.at<double>(i, 0) = points2[i].x;
    hg2.at<double>(i, 1) = points2[i].y;
    hg2.at<double>(i, 2) = 1;
}

hg1 = hg1 * (rotDiff * Kinv).t();
hg2 = hg2 * (Kinv).t();

Mat A = Mat::zeros(hg1.rows, 3, CV_64FC1);
for (int i = 0; i < hg1.rows; i++) {
    A.at<double>(i, 0) = (hg2.at<double>(i, 2) * hg1.at<double>(i,
        1) - hg2.at<double>(i, 1) * hg1.at<double>(i, 2));
    A.at<double>(i, 1) = (hg2.at<double>(i, 0) * hg1.at<double>(i,
        2) - hg2.at<double>(i, 2) * hg1.at<double>(i, 0));
```

5. IMPLEMENTATION

```
A.at<double>(i, 2) = (hg2.at<double>(i, 1) * hg1.at<double>(i,
    0) - hg2.at<double>(i, 0) * hg1.at<double>(i, 1));
}

SVD svd1(A);
Mat tCalc = svd1.vt.row(2);

//Translation between cameras estimated and Fundamental Matrix from
//that as well
Mat T = (tCalc.t());

return T;
```

5.4.2.4 Enhancing pose estimation

There was nothing special to implement regarding enhanced pose estimation. OpenCv has option to use initially estimated rotation and translation values(reference)

Chapter 6

Evaluation

All implemented algorithms were tested in terms of speed, accuracy and effectiveness. As regards the speed test, it included the measurement of the reconstruction execution time. In the accuracy testing Sampson Error measurement was used (this variable measures the distance between all points and their corresponding epipolar lines in an image). Effectiveness was tested using visual comparison of reconstructed 3D cloud points.

6.1 Acquiring datasets

For the purpose of analysis the following datasets were captured with implemented "Sensor Enhanced Images Camera" and Nexus 5 camera:

1. Warsaw University of technology main building(4 images 1024x768pixels)
2. Advertisement Pole ???
3. Warsaw Business School Gate and Entrance ??
4. Warsaw Shopping Center Back???
5. Warsaw Shopping Center Front???

Since most of the algorithms proposed in the (TODOreference to Concept) Concept section require internal camera parameters to be known, the camera used in the course of conducting this study was calibrated and its parameters were stored in "*out_camera_data.yml*" file. All of these datasets can be found in attached CD or Github repository.

6. EVALUATION

6.2 Test Environment

All tests were performed on MacBook Air with 1.7GHz dual-core Intel Core i7 processor and 8GB 1600MHz DDR3 RAM using "Enhanced 3D Reconstructor" implemented as described in Implementation section. Numerical tests which allowed for measuring total errors and execution time were run on "Warsaw University of Technology" dataset. Initial pair reconstruction ability of each method proposed was measured as well as various reconstruction strategies. Finally, for each dataset the most effective methods were used to reconstruct sparse models.

6.3 Testing initial pair reconstruction methods

The key question to be answered at this point was whether the proposed sensor enhancement gave better results than standard algorithms. The following methods were tested: TODO methods should be already described in Concept and implementation

1. **Standard 8-point** - based on [] Fundamental matrix decomposition, implemented in OpenCV
2. **Enhanced 8-point** - proposed camera rotation enhanced version of above 8-point algorithm
3. **Alternative 3-point** - proposed 3-point algorithm to translation estimation.
4. **Known rotations and translations** - calculation from known cameras rotations and translations
5. **Standard essential 5-point** - based on [] Essential matrix decomposition, implemented in []
6. **Enhanced essential 5-point** - similar to 2. improvements rotation enhanced version of above 5-point algorithm

6.3.1 Accuracy - Epipolar lines correspondence

In the case of initial pair images one of the most important factors include the epipolar constraint. Using a properly estimated fundamental matrix drawing corresponding epipolar lines in both images is possible. Furthermore, points lying on two matching epipolars lines in different images can be easily matched. In other words, epipolar lines cross exactly the same points in both images. The more accurate they are the

6.3 Testing initial pair reconstruction methods

more corresponding pairs can be found, e.g. for the purposes of performing dense reconstruction. Sampson Error is one of metrics that can be used in order to estimate the accuracy of epipolars lines; the smaller the error's value the more accurate the lines. Its primary function is to measure the sum of distance between all points and their corresponding epipolar lines. However, each of proposed methods has different outliers removal capabilities, therefore in order to compare their efficiency the average

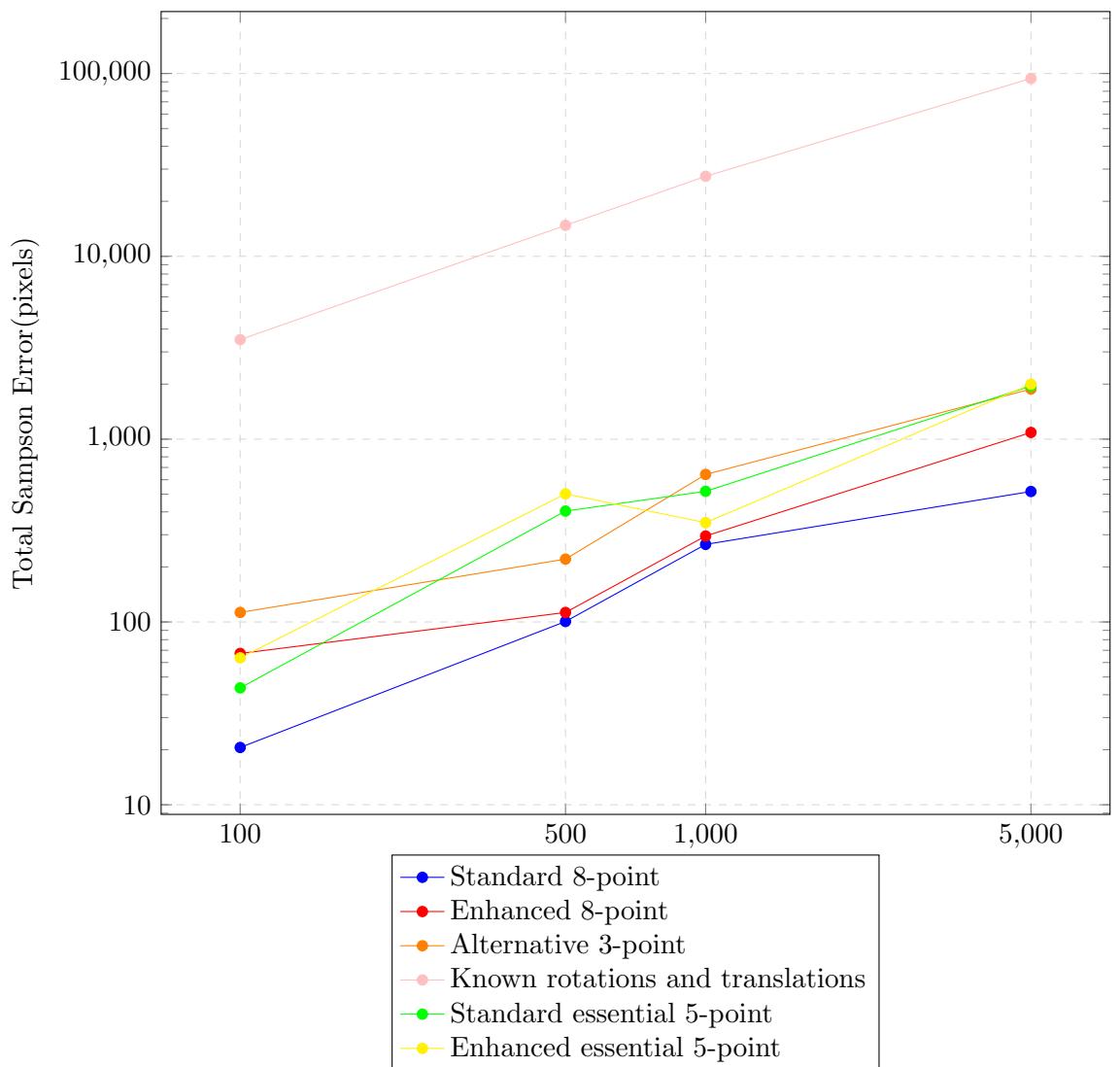


Figure 6.1: Chart showing the sum of Sampson Errors in a picture(1024x768pixels) per various initial Sift features sets sizes

6. EVALUATION

of Samson Error per a corresponding pair was calculated. The following chart 6.1 shows the total Sampson Errors for different sets of initial SIFT features. The major observation made based on these results is that most of the algorithms remove outliers properly. As could have been expected the only one that is not efficient in this regard is the method involving drawing epipolar lines from heuristically estimated movement and noisy rotation, which produces significantly larger error than the other algorithms. Analysing the Per Pair Sampson Error results 6.2 it can be noted that the proposed sensor enhanced methods did not improve either the 8-point or 5-point algorithms, but the 3-point algorithm developed for the purposes of this thesis proved to be much faster than the 8-point algorithm and also quite accurate. To present the discussed errors, estimated epipolar lines for 300 initial SIFT features set were drawn on the figures 6.3 - 6.4. It can be seen that both standard 8-point algorithm and the proposed rotation enhanced version return very good results in terms of epipolar lines accuracy. The alternative 3-point algorithm gives slightly worse results due to uncompensated mobile sensors noise. In this particular dataset the essential 5-point method was inefficient in producing proper essential matrix estimation, contrary to the proposed sensor enhanced 5-point algorithm, which found satisfactory correspondency in epipolar lines.

To verify whether the epipolar lines calculation is influenced by the number of SIFT features, the same process was applied to 1000 SIFT features set(6.5 - 6.6). In general, the proposed enhanced algorithms are not better than standard versions in terms of accuracy of epipolar lines estimation. It is mostly because during calculation some of the noise in sensor data is propagated on Epipolar geometry estimation. However, enhanced versions are always close to optimal solutions, while the standard versions can often fail in terms of fundamental matrix estimation.

6.3 Testing initial pair reconstruction methods

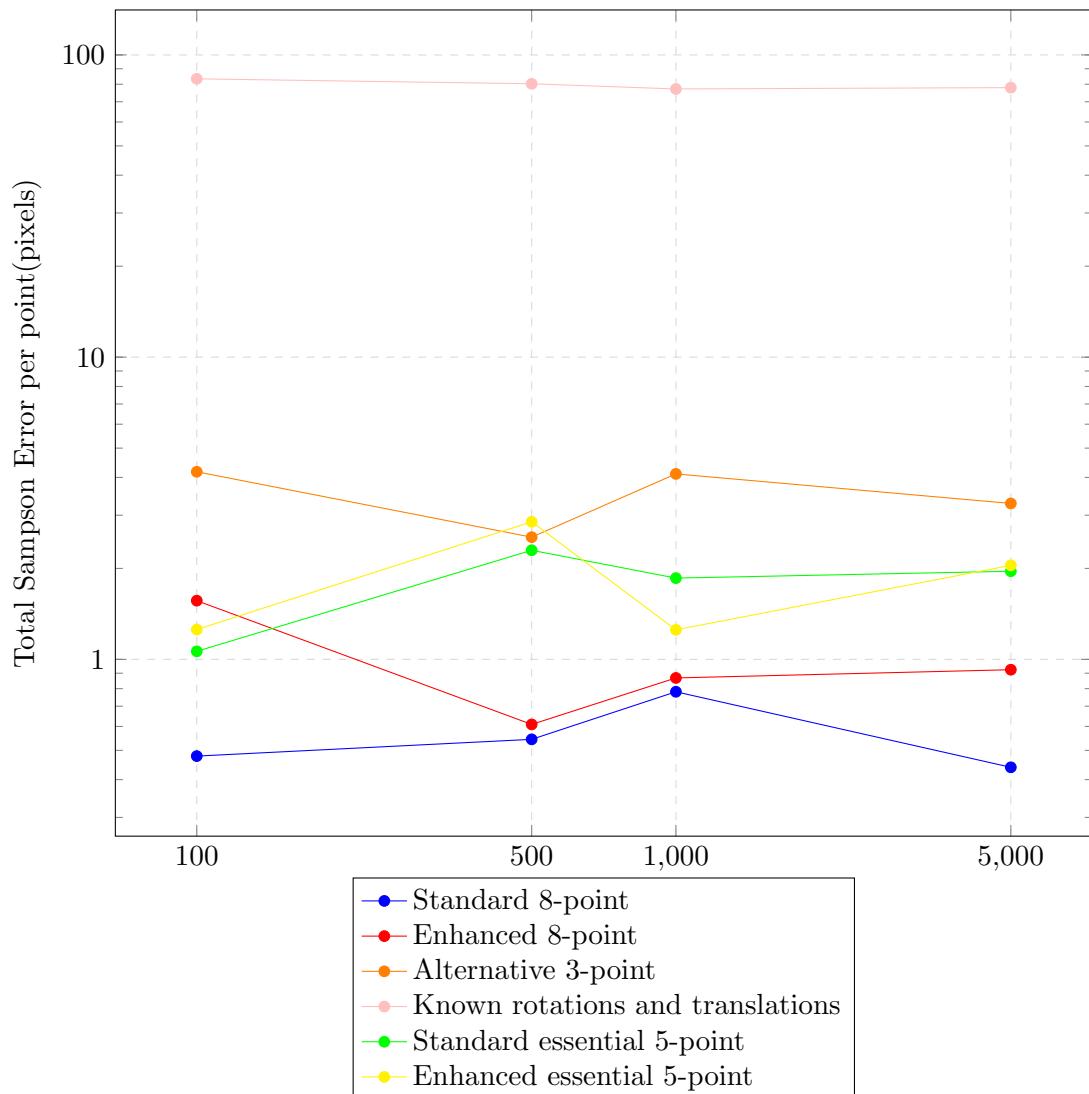


Figure 6.2: Chart showing per point Sampson Error in a picture(1024x768pixels) per various initial Sift features sets sizes

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Figure 6.3: The results of drawing estimated epipolar lines on Warsaw University Dataset with 300 Sift points. 1) Standard Fundamental 8-point algorithm (upper pair), 2) Rotation Enhanced Fundamental 8-point algorithm (middle pair), 3) Alternative 3-point algorithm (bottom pair)

6.3 Testing initial pair reconstruction methods



Figure 6.4: The results of drawing estimated epipolar lines on Warsaw University Dataset with 300 Sift points. 1) Fundamental matrix created from rotation and translation (upper pair), 2) Standard Essential matrix 5-point algorithm (middle pair), 3) Rotation Enhanced Essential 5-point algorithm (bottom pair)

6. EVALUATION



Figure 6.5: The results of drawing estimated epipolar lines on Warsaw University Dataset with 1000 Sift points. 1) Standard Fundamental 8-point algorithm (upper pair), 2) Rotation Enhanced Fundamental 8-point algorithm (middle pair), 3) Alternative 3-point algorithm (bottom pair)

6.3 Testing initial pair reconstruction methods



Figure 6.6: The results of drawing estimated epipolar lines on Warsaw University Dataset with 1000 Sift points. 1) Fundamental matrix created from rotation and translation (upper pair), 2) Standard Essential matrix 5-point algorithm (middle pair), 3) Rotation Enhanced Essential 5-point algorithm (bottom pair)

6. EVALUATION

6.3.2 Time comparison

The chart 6.7 shows the avaraged execution time for 100 estimation attempts. Execution

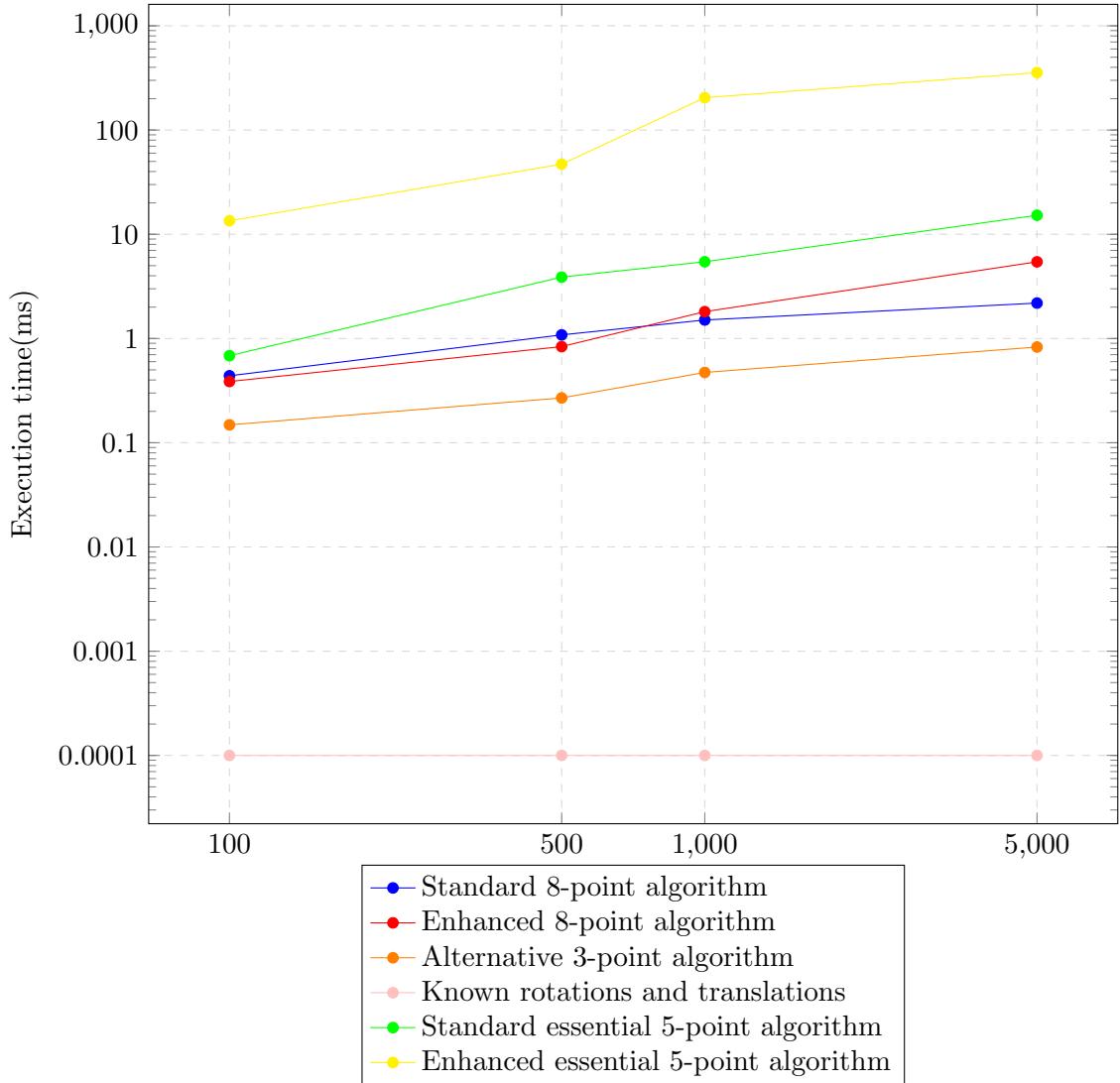


Figure 6.7: Execution time of the proposed algorithms(1024x768pixels) per initial SIFT feature set size

time of 8-point versions are very similar, which is understandable, since their implementation is nearly identical and they differ only in the characteristics of analysed dataset. It can be seen, however, that execution time of 5-point epipolar estimations differs much depending on the version. In this situation either finding optimal solution

6.4 Testing reconstruction strategies

with initial rotation is much harder or implementation of these methods is significantly different in terms of memory allocation. Execution time of 3-points algorithm is few times faster than the one of 8-point algorithms. Reconstruction with the sole use of known rotations and translations has a hundred times lower execution time than the standard algorithms, but at the same time it does not produce properly correlated epipolar lines.

6.4 Testing reconstruction strategies

As was shown in 6.3 not every initial reconstruction methods gives good results. Only the most effective techniques were used to prepare a number of completely different strategies:

1. Standard 8-point + OpenCV Pose Estimation
2. Enhanced 8-point + OpenCV Pose Estimation
3. Enhanced 8-point + Initial Rotation and Translation OpenCV Pose Estimation
4. Alternative 3-point + OpenCV Pose Estimation
5. Alternative 3-point + Initial Rotation and Translation OpenCV Pose Estimation

The first method gives the basic reference to standard 3D reconstruction strategy. The second one was chosen for its consistency in 3D reconstruction. It has never failed to produce solution close to optimal. The third one was prepared in order to check how the enhanced pose estimation influences the final reconstruction outcomes. The strategies number four and five were used to see if the models can be produced faster without impacting final accuracy too heavily. Finally, the sixth one was proposed in order to check whether the entire reconstruction process can be performed using solely sensor data.

6.4.1 Accuracy

Accuracy of 3D reconstruction was measured using Bundle Adjustment algorithm from SBA library[ref]. It allows to calculate error based on projective constraint both before and after Bundle Adjustment. The tests performed with different strategies for the "Warsaw University" dataset are presented on 6.8. The significant differences in initial error can be explained by different numbers of reconstructed points after initial phase

6. EVALUATION

and inconsistent and unknown scale of the finally reconstructed models. Enhanced initial pair reconstruction and pose estimation methods have bigger impact on Bundle Adjustment error reduction.

6.4 Testing reconstruction strategies

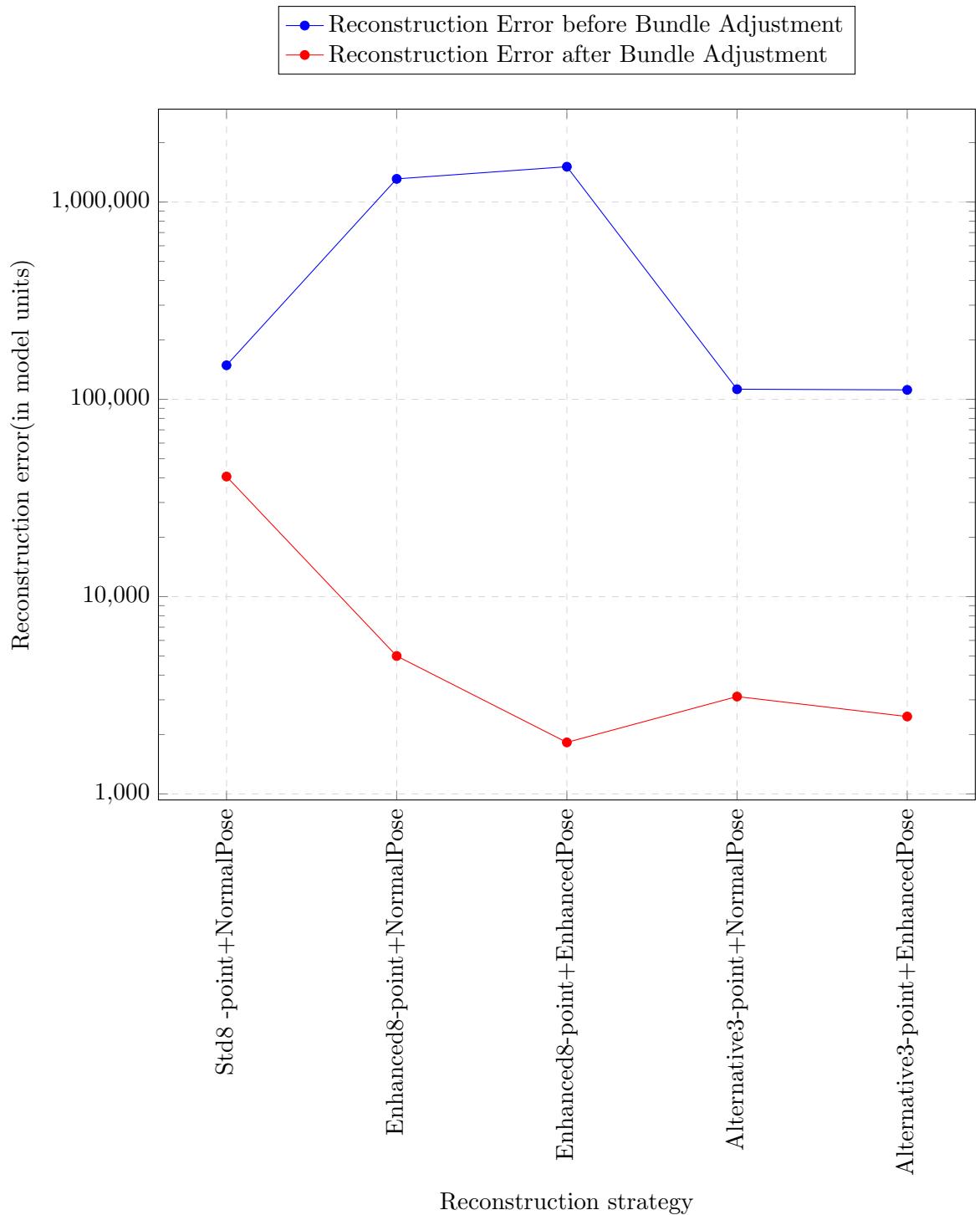


Figure 6.8: Influence of Bundle Adjustment on the models produced with different reconstruction strategies

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In general, Bundle Adjustmet process allows to rearrange and modify 3D points positions and change external parameters of estimated cameras. However, in the case of enhanced algorithms estimated camera positions are already very close to their optimal orientations. This allows Bundle Adjustment method to focus mainly on 3D points modifications. It can be observed that enhanced Pose Estimation results in further reduction of BA error when compared to standard the standard strategy.

6.4.2 Execution time

The chart 6.10 presentes the execution time without Bundle Adjustment. Comparing it to execution times in 6.7 one can see that most of the time is allocated for SIFT correspondences matching, which constitutes a bottleneck in the proposed reconstruction methodology [reference to concept pose esitmation choosing]. Furthermore, the reconstruction time was also measured with Bundle Adjustment process at the end(6.11). It was found that Bundle Adjustment works significantly better with enhanced initial pair reconstruction and pose estimation. Cloud points in that case are better organised than the standard reconstructed ones, which results in faster convergence of BA. Sample difference between cloud points before and after BA can be seen in 6.9

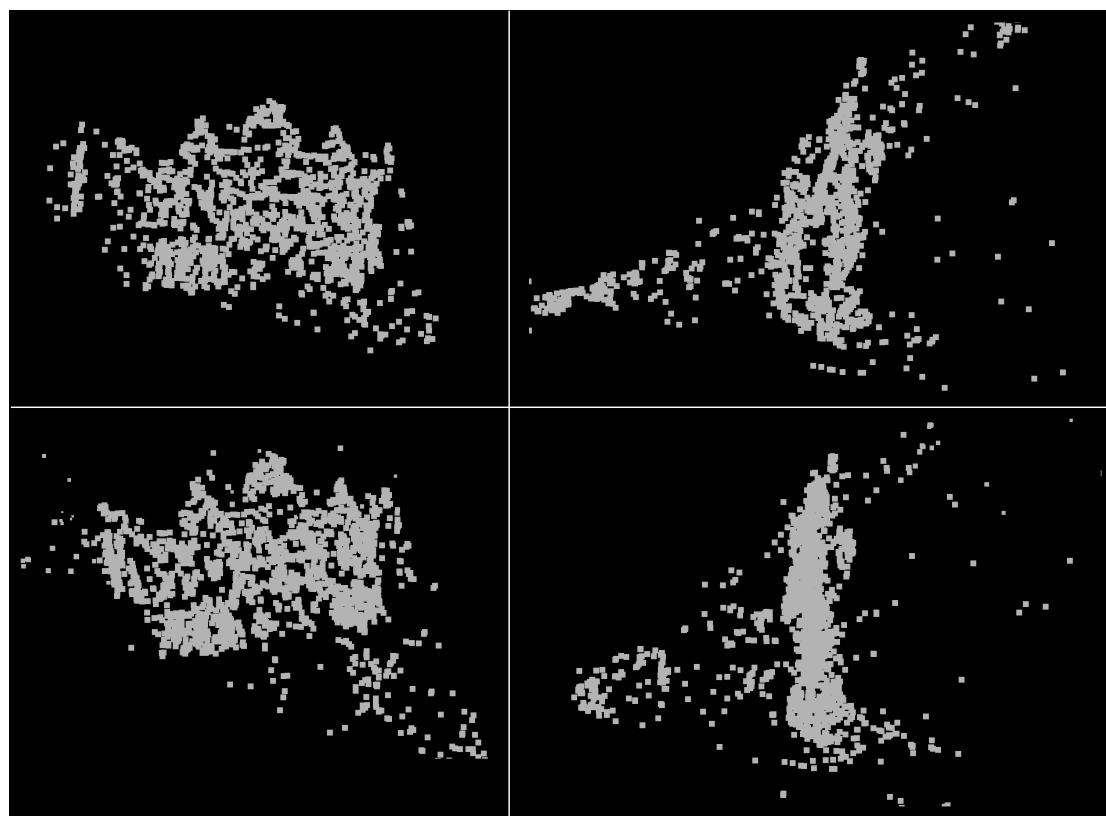


Figure 6.9: 3D point clouds before Bundle Adjustment (upper) and after (bottom) for enhanced 8-point with enhanced pose estimation. Warsaw University of Technology dataset with 1000 SIFT corresponding features (left - front, right - side)

6. EVALUATION

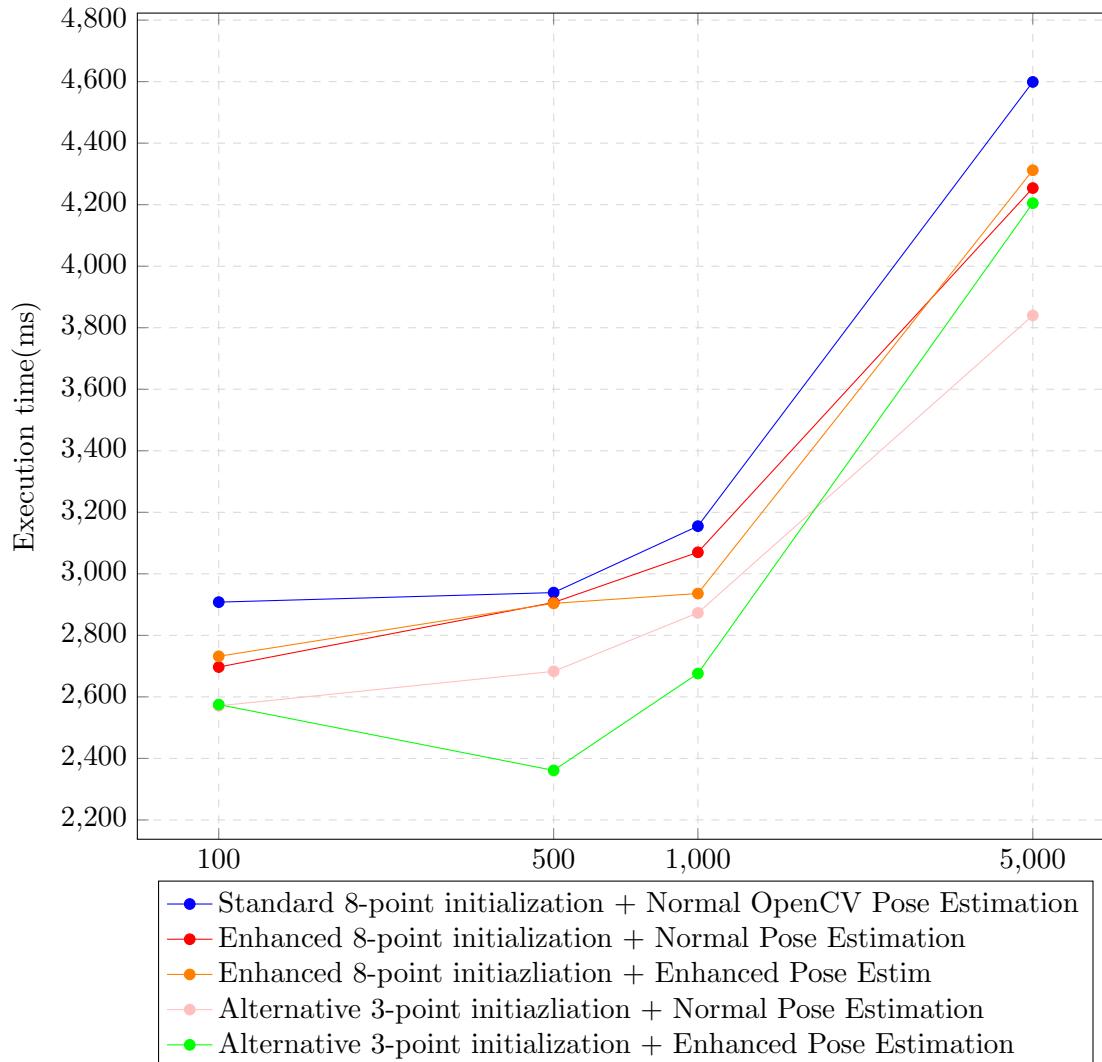


Figure 6.10: Total reconstruction execution time (4 images with resolution 1024x768pixels) per SIFT features set size

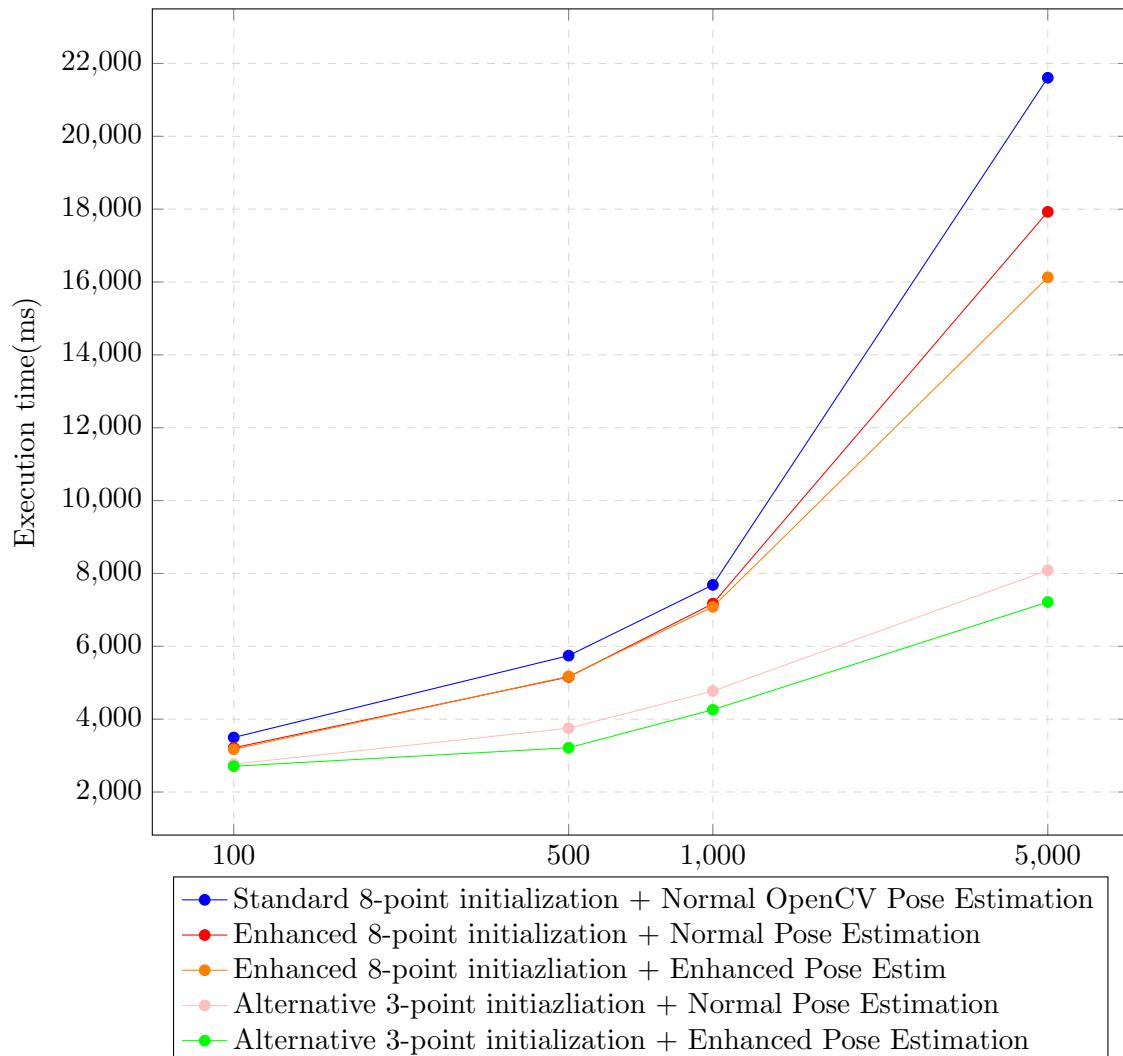


Figure 6.11: Total execution time of reconstruction with Bundle Adjustment (4 images with resolution 1024x768pixels) per SIFT features set size

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6.5 Effectivness

The numerical measuerments used do not always correspond to proper 3D model reconstructions. The following four pages present the reconstruction effects of the proposed strategies. Figure 6.12 shows reconstructed effects for different initialization pair methods and 4000 SIFT features set. It can be observed that both standard and enhaced 8-point methods produces very good results, which differ only in terms of final reconstruction scale. Alternative 3-point algorithm produces slighlty worse and distorted models due to uncompenstaed noise in the rotations of the camera used. A model reconstructed from the known rotations and translations is very distorted, but nonetheless stil recognizable. It could prove usefull should a very fast reconstruction be needed. The matter is slightly different when 400 SIFT feature points are used. [reference] In the first case all algorithms were able to find solutions close to optimal. However, in the second attempt the traingulation test, which is used to identify proper deconmposition in standard 8-point approach, failed and produced an unrecognizable model (6.14). It can be seen that pose estimations enhancments result primarily in the reduction of outliers (6.15).

Figure 6.16 shows that reconstruction from known rotations and translations produces many outliers.

More reconstructed models can be found in [TODO Materials]

6.5 Effectivness

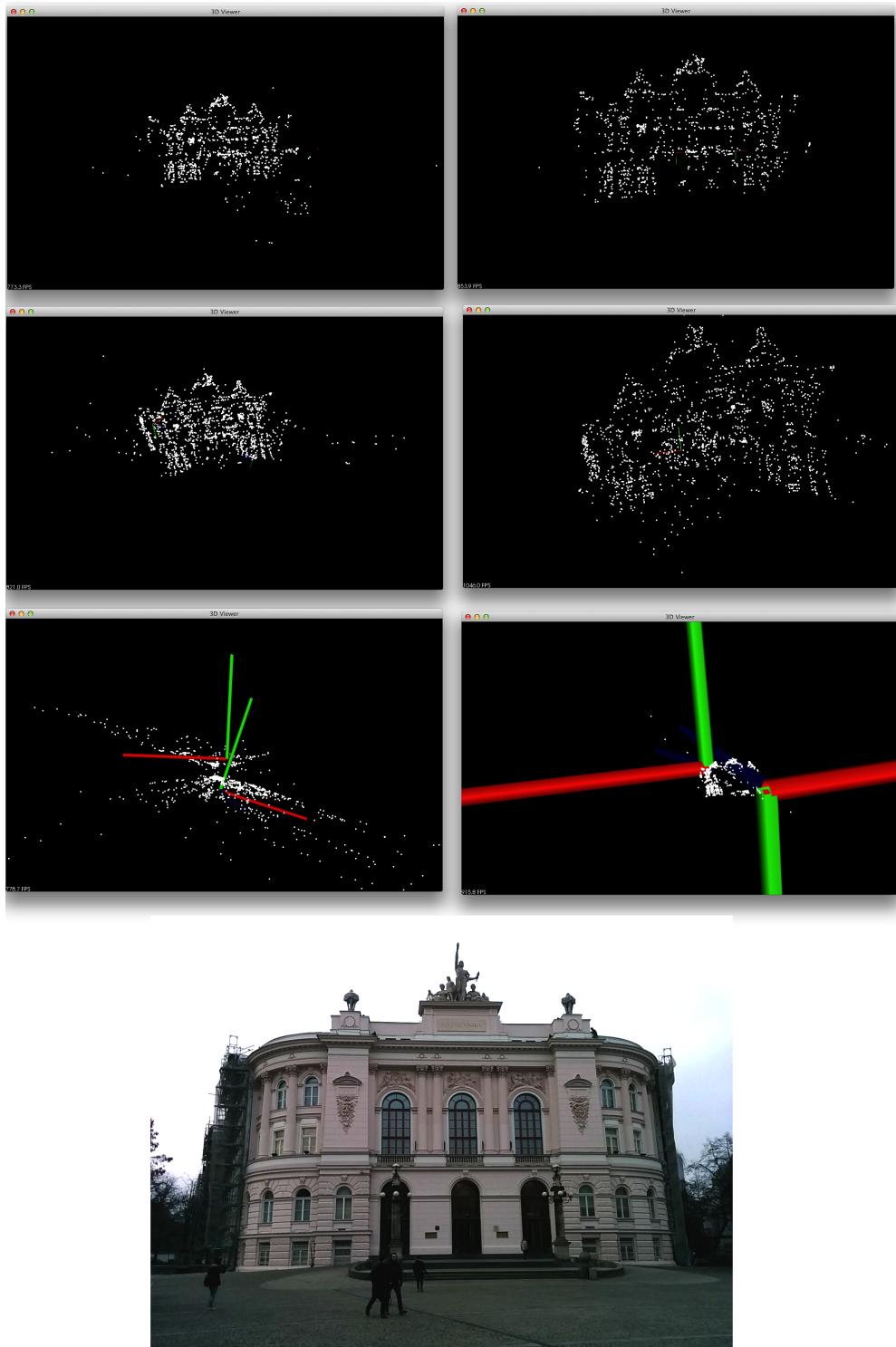


Figure 6.12: Reconstructed models for the proposed initial reconstruction methods and 4000 SIFT features. From upper left to bottom right: 1) standard 8-point, 2) enhanced 8-point, 3) alternative 3-point, 4) known rotations and translations, 5) standard 5-point, 6) enhanced 5-point

6. EVALUATION

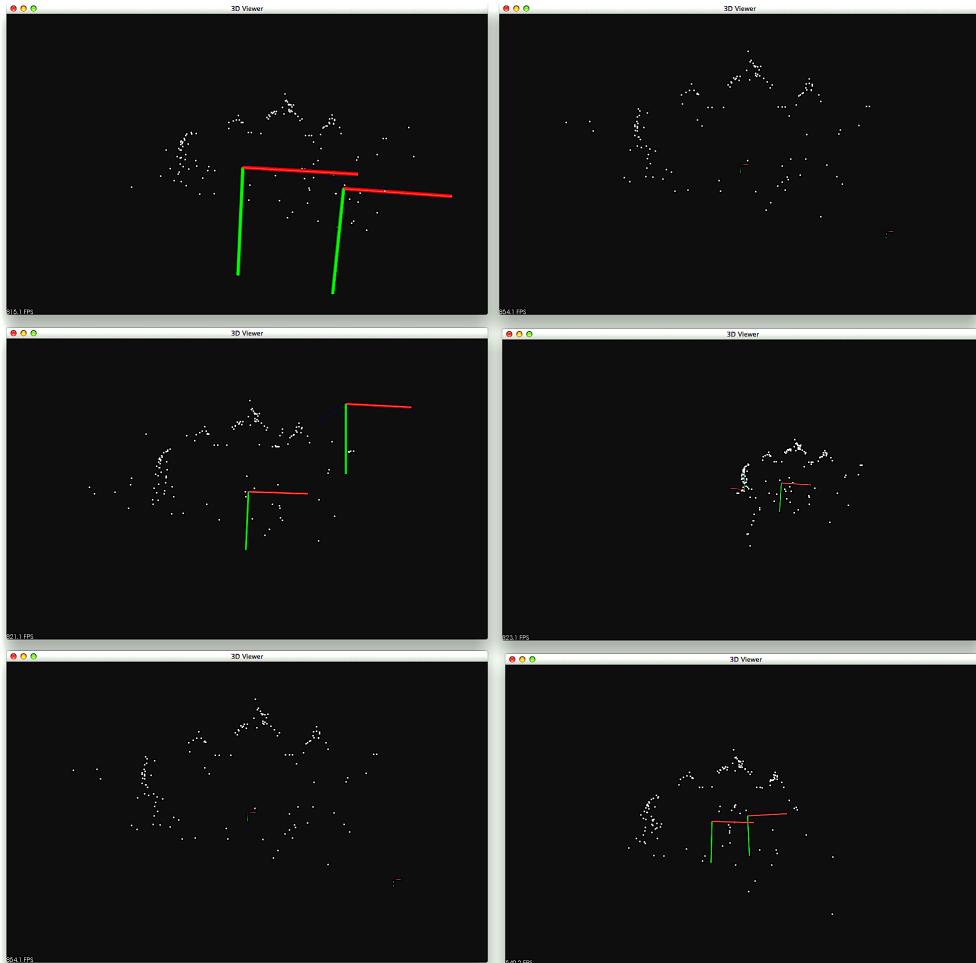


Figure 6.13: Reconstructed models for the proposed initial reconstruction methods and 400 SIFT features. From upper left to bottom right: 1) standard 8-point, 2) enhanced 8-point, 3) alternative 3-point, 4) known rotations and translations, 5) standard 5-point, 6) enhanced 5-point

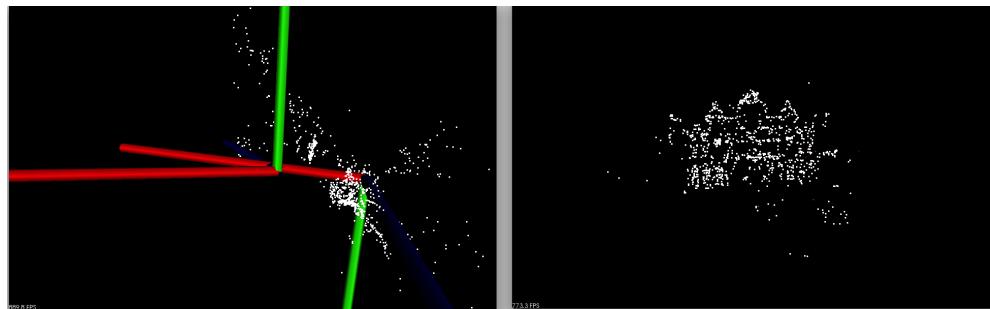


Figure 6.14: Fail test case of Standard 8-point triangulation(left) in comparison to fortunate reconstruction(right)

6.5 Effectivness



Figure 6.15: Pose estimation methods comparison (Views from front and side). Left:
Normal Pose Estimation, right: Enhanced Rotation and Translation Pose Estimation
. Less outliers appear in the reconstruction if enhancment is applied.

6. EVALUATION



Figure 6.16: Reconstruction results from known translations and rotations from different angles. The upper one shows the front face of building, the others present views from side angles. In the reconstructed model many outliers are present.

Chapter 7

Conclusion

This chapter describes the work performed in the course of investigating the master thesis subject, discusses the problems encountered and proposes ideas for future development.

7.1 Summary

The idea of enhancing standard 3D reconstruction algorithms with Android sensor fusion data was conceptualised, implemented and verified in a few different versions. At the beginning, only the alternative 3-point version was planned to be implemented for the purposes of this thesis. However, it did not produce results of enough accuracy. After few iterations of implementation and testing of the 3-point algorithm it was concluded that it is not enough to base the reconstruction solely on the data of the rotation from Android sensor fusion. That was when the enhanced 8-point and 5-point versions were designed. In addition, the author proposed different reconstruction strategies, which can be used depending on accuracy and speed trade-offs preferred. They were built on personal observations of the reconstructions performed and inspired by related works in the field. In order to acquire datasets for algorithm, an evaluation Android application named "Sensor Enhanced Images Camera" was developed. Upon capturing the picture it automatically stores the current device's rotation information and proposed heuristically estimated translation. To evaluate the proposed methods and collected datasets a desktop application named "Enhanced 3D reconstructor" was implemented. It can be used in two different modes: 1) Efficiency testing - for comparing Samson

7. CONCLUSION

Error and visual estimation of calculated epipolar lines. The proposed enhancements to the standard 8-point algorithm allow to unambiguously calculate the proper rotation and translation. Application of the enhanced 5-point algorithm resulted in better accuracy than in the case of the standard 5-point algorithm in terms of Sampson Error. Execution time of the enhanced reconstruction methods is generally longer than the standard ones'. The use of initial rotation and translation estimation in pose estimation results in a greater reconstruction accuracy, particularly in terms of outliers removal and Bundle Adjustment convergence speed. In general, applying Bundle Adjustment of sensor enhanced reconstruction results in greater error reduction and shorter execution time in comparison to the refining standard ones. The major problem, a bottleneck of some sort, of the proposed reconstruction process was the time needed for matching corresponding items. The study showed that using the sensor data only is not enough to create accurate 3D models. However, it is possible to find recognizable model among the reconstructed 3D cloud of points. The only problem is how to distinguish a recognizable model from the one reconstructed from uncorrect 3D points. It turned out that estimating rotation error matrix (R_{error}) is quite accurate and useful for that purpose and the proposed Rodrigues decomposition and its rounding, such as diagonal of R_{error} consisting of a diagonal identity matrix, returns better accuracy of 3D reconstruction and unambiguously defines the proper camera decomposition. Heuristical movement estimation is not entirely accurate and does not have significant impact on the reconstruction process. Finally, the proposed 3-point algorithm for translation estimation allows for faster and quite accurate recreation of the structure.

7.2 Dissemination

So far no one has used the implemented applications. Nonetheless an Android app can be useful for further 3D reconstruction research and it is planned to be published to Google Play Store once most needed improvements are made and properly tested. "Enhanced 3D reconstructor" has been already published to GitHub as open-source project distributed on LGPL license [reference].

7.3 Problems Encountered

The majority of the problems were related to bugs which appeared during implementation of the proposed algorithms and adaptation of the third party libraries. Android API allows a user to get rotation quaternion and a way to decompose it, but it does not explain how it is calculated. Decomposition of rotation matrix to euclidian angles and their composition needs to be done in the same order. Some tests were conducted in order to establish its proper rotation matrix composition. All of these problems were successfully resolved. It turned out that using the pose estimation instead of homography merging was not the optimal solution. Relaying on the pose estimation produced very small amount of points and sometimes reconstruction stopped only after analysing merely a few images.

7.4 Future work

Firstly, it would be useful to establish how the homography merging approach would influence an accuracy of 3D reconstruction. Secondly, other correspondence matching approaches should be tested. An optical flow estimation using video sequences could constitute one example thereof. This would both allow for a very quick relative pose estimation and could be used for dense model reconstruction afterwards. All of the libraries used are available or can be ported to Android, therefore it might be valuable to determine whether it is possible to achieve a real-time tracking and mapping (similar to (?)).

Chapter 8

Materials & methods

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24 }  
25 . . .  
26 ]
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8. MATERIALS & METHODS

100 SIFT Features	Total Sampson Error	Sampson Error per Point	Points left	Execution time(ms)
8-point OpenCV	20.5793	0.478588	43	0.4387
Alternative 3-point	112.749	4.17588	27	0.1484
8-point enhanced	67.2559	1.56409	43	0.3867
Known rot and trans	3501.23	83.3625	42	0.0001
Essential 5-point	43.5866	1.06309	41	0.684
5-point enhanced	1863.66	45.4552	41	13.4643

Table 8.1: Efficiency table of proposed methods for 100 SIFT features in Warsaw University of technology dataset. Columns: Total Sampson Error, Average Sampson error per point, Amount of points left after outliers removal, Execution time

500 SIFT features	Total Sampson Error	Sampson Error per Point	Points left & Execution time(ms)
8-point OpenCV	100.584	0.543697	185 1.0833
Alternative 3-point	220.722	2.53704	87 0.2692
8-point enhanced	112.7	0.609189	185 0.8362
Known rot and trans	14770.7	80.2756	184 0.0001
Essential 5-point	404.098	2.29601	176 3.8827
5-point enhanced	501.987	2.8522	176 47.0683

Table 8.2: Efficiency table of proposed methods for 500 SIFT features in Warsaw University of technology dataset. Columns: Total Sampson Error, Average Sampson error per point, Amount of points left after outliers removal, Execution time

1000 SIFT features	Total Sampson Error	Sampson Error per Point	Points left	Execution time(ms)
8-point OpenCV	265.637	0.781287	340	1.5055
Alternative 3-point	640.895	4.1083	156	0.4725
8-point enhanced	295.152	0.868093	340	1.8099
Known rot and trans	27394.4	77.1673	355	0.0001
Essential 5-point	518.293	1.85768	279	5.4482
5-point enhanced	349.393	1.2523	279	204.2998

Table 8.3: Efficiency table of proposed methods for 1000 SIFT features in Warsaw University of technology dataset. Columns: Total Sampson Error, Average Sampson error per point, Amount of points left after outliers removal, Execution time

5000 SIFT features	Total Sampson Error	Sampson Error per Point	Points left	Execution time(ms)
8-point OpenCV	517.189	0.439413	1177	2.187
Alternative 3-point	1879.98	3.28094	573	0.8286
8-point enhanced	1087.78	0.924199	1177	5.4395
Known rot and trans	93951.1	77.9677	1205	0.0001
Essential 5-point	1949.53	1.95736	996	15.2223
5-point enhanced	19966.6	20.0468	996	355.464

Table 8.4: Efficiency table of proposed methods for 5000 SIFT features in Warsaw University of technology dataset. Columns: Total Sampson Error, Average Sampson error per point, Amount of points left after outliers removal, Execution time

References

Declaration

I herewith declare that I have produced this paper without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This paper has not previously been presented in identical or similar form to any other German or foreign examination board. The thesis work was conducted from XXX to YYY under the supervision of PI at ZZZ.

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