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Nr. 9/2011

Arbeitsberichte aus dem Fachbereich Informatik

Arbeitsberichte des Fachbereichs Informatik

ISSN (Print): 1864-0346
ISSN (Online): 1864-0850

Herausgeber / Edited by:

Der Dekan:
Prof. Dr. Grimm

Kontaktdaten der Verfasser

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Combined Non-Linear Pose Estimation from Points and Lines

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Abstract

We present a non-linear camera pose estimator, which is able to handle a combined input of point and line feature correspondences. For three or more correspondences, the estimator works on any arbitrary number and choice of the feature type, which provides an estimation of the pose on a preferably small and flexible amount of 2D-3D correspondences. We also give an analysis of different minimization techniques, parametrizations of the pose data, and of error measurements between 2D and 3D data. These will be tested for the usage of point features, lines and the combination case. The result shows the most stable and fast working non-linear parameter set for pose estimation in model-based tracking.

Categories and Subject Descriptors (according to ACM CCS): I.4.8 [Image Processing and Computer Vision]: Scene Analysis—Tracking

1. Introduction

Tracking is the process of estimating the viewing position and orientation of a camera - the pose. This can be achieved by two opposing approaches. While marker tracking relies on the recognition of known artificial structures in the camera image, markerless tracking is based on natural features of existing objects in the scene. In the latter one, the environment to be tracked can be represented by 3D data available from a modeling process or created online. Tracking on CAD models was introduced by [CMC03], and respectable success in combination of edges with texture information could be demonstrated by [VLF04]. Current research is focused on SLAM (Simultaneous Localisation and Mapping) algorithms [KM07] [SRD06], where feature cloud maps are reconstructed from the visible surroundings.

In the presence of a model, it is possible to establish 2D-3D correspondences between features of the model and the camera image, which leads to more stable tracking without drift occurrence and an absolute initialization which would not be feasible without a reference model. Thus the pose estimation problem is to minimize the distance between projected 3D features and their 2D correspondences in the camera image. The pose of a camera can be estimated by two contrasting classes of algorithms: the linear and non-linear ones. The first linearize the problem and derive a direct solution without any additional knowledge besides the correspondences. The complexity is low, but noise and false correspondences may lead to inexact pose computation. The latter optimize an initial pose input by local linearization, which leads to a more exact approximation. This process is repeated iteratively until a pose of adequate accuracy is reached. Most of these pose algorithms originate from the domain of linear solutions and operate on point correspondences, some use line features. Combining both types is not a common task, especially when using non-linear optimization.

We construct a non-linear pose estimator that accepts point correspondences as well as line correspondences in arbitrary combination and number, assumed that at least three of them are given. First, we analyze several error measurements for the feature correspondences to be minimized by the optimization process. Then we take a look on the usability of common known optimization algorithms. Finally, we provide a discussion on possible parametrizations of the camera pose, including its constraints which must be taken into account during or after the optimization process. The complete analysis of optimization, error measurement and parametrization results in a combination of these components, most useful for practical applications concerning stability and real time capability.

Our resulting estimator will then be tested on ideal and noisy synthetic data. We investigate the behaviour on variable input types and numbers of correspondences, as well as the influence of noise and false correspondences on the robustness of the pose. The main benefit of this estimator is the ability to work on a flexible range of number and type of features.

2. Related Work

The problem of camera pose estimation with 2D-3D correspondences of points is known as perspective-n-point problem (PnP) [FB81]. Based on the theorem of Grunert (1841), a system of equations is built using the law of cosine. This system results in a polynom of forth degree with the known distances of at least three points in the world and their image points. It can be solved for the depth of the world points to the center of the camera which delivers the camera coordinates of the points, the coordinates of the camera center and the transformation between camera and world coordinate system.

There are several other approaches to the solution of P3P surveyed and compared for their numerical stability by [HLON94]. While these linear solutions work on a fixed number of three point correspondences, [LMNF09] introduce virtual control points to make possible a solution for arbitrary numbers of point correspondences (PnP) with linear complexity. Another popular linear solution is the POSIT algorithm [DD95] that begins with a paraperspective projection of world points and iteratively approximates the full perspective case. This approach has been extended to line correspondences by [CH99]. Another linear solution for any number of point or line correspondences is given by [AD03] but does not work on both types of features simultaneously.

Further, there are non-linear or indirect methods to estimate the camera pose. Most of them are based on classical iterative algorithms of optimization, like the Gauß-Newton or Levenberg-Marquardt-Method, which can be used in a broad context of problems, and particularly for the solution of sums of squared errors. Non-linear pose with line correspondences has been estimated by [KH94] who analyzed the influence of certain line representations on the optimization process. A solution using arbitrary line traits on an object is shown by [Low91]. Possible error measurements for point correspondences were analyzed by [LHM00], who also proposed a new possibility requiring less iterations.

While non-linear methods require an initial pose, an approximate linear solution can be given, which is then reiterated to gain a result more accurate. The image processing library OpenCV 2.1 delivers a function *solvePnP* for linear estimation of the camera pose by point correspondences. First, it is initialized by the Direct Linear Transform (DLT) [HZ04] and the result is refined by a Levenberg-Marquardt-Method.

Joint usage of point and line correspondences for a combined non-linear pose estimation together with a complete analysis of the parameters were not evident in the examined literature and will therefore be the aim of our work. Most authors analyze one parametrization and a single error measurement only, which is the reason for us to take a broader view and deeper comparison on these topics.

3. Definitions

The pose problem can be described as the estimation of the extrinsic camera parameters relative to a known reference coordiante system, i.e. the world coordinate system, from given correspondences between 2D features of a camera image and 3D features of a synthetic model. The coordinate system of a value is identified by a superscript w for world-, c for camera-, i for image- and p for pixel-coordinate-system. The camera pose is represented in combination as a tuple consisting of a rotation matrix $R \in \mathbb{R}^{3x3}$ and a translation vector $\vec{t^c} \in \mathbb{R}^3$ as

$$C : \left(R, t^c\right) \tag{1}$$

and represents the transformation between world- and camera-coordinate-system as $p^c = Rp^w + \vec{t^c}$. The image-coordinate-system includes the perspectively projected camera points on the image plane and the pixel-coordinate-system the pixel values of the camera image with origin in the upper left corner of the image plane. The camera model is assumed to be an ideal pinhole camera with known intrinsic camera matrix

$$K = \begin{pmatrix} f_x & 0 & h_x \\ 0 & f_y & h_y \\ 0 & 0 & 1 \end{pmatrix}. \tag{2}$$

Hence, given a world point $\vec{p^w}$, its pixel coordinates $\vec{p^p}$ are calculated by the perspective projection

$$\vec{p^p} = \begin{pmatrix} f_x \frac{p_x^w r_{11} + p_y^w r_{12} + p_z^w r_{13}}{p_x^w r_{31} + p_y^w r_{32} + p_z^w r_{33}} + h_x \\ h_y - f_y \frac{p_x^w r_{21} + p_y^w r_{22} + p_z^w r_{23}}{p_x^w r_{31} + p_y^w r_{32} + p_z^w r_{33}} \end{pmatrix}. \tag{3}$$

The connections between the different coordinate systems and their point vectors are shown in Fig. 1. The feature of the synthetical model in world coordinates is called synthetical feature and the feature of the camera image in pixel coordinates is called real feature; the vector in camera coordinates is also called sight vector. A point correspondence between the world point $\vec{p^w}$ as the synthetical feature and the pixel point $\vec{q^p}$ as the real feature is represented by a tuple $k : \left(\vec{p^w}, \vec{q^p}\right)$. The line features on the real camera images are defined as straight lines $l : (\phi^p, \rho^p)$ with infinite extent. ϕ^p represents the angle between the line normal and the y-axis of the accordant coordinate system and ρ^p is the orthogonal distance of the line from the origin (Fig. 2). Hence, for each point $p^p \in l$ it holds $\cos\phi^p p_x^p + \sin\phi^p p_y^p = \rho^p$. A straight line correspondence is represented by two world points $\vec{s^w}$ and $\vec{e^w}$ (typically start- and endpoint) of the model as the synthetical feature and an image line $l : (\phi^p, \rho^p)$ as the real feature by a tuple $k : \left((\vec{s^w}, \vec{e^w}), l\right)$.

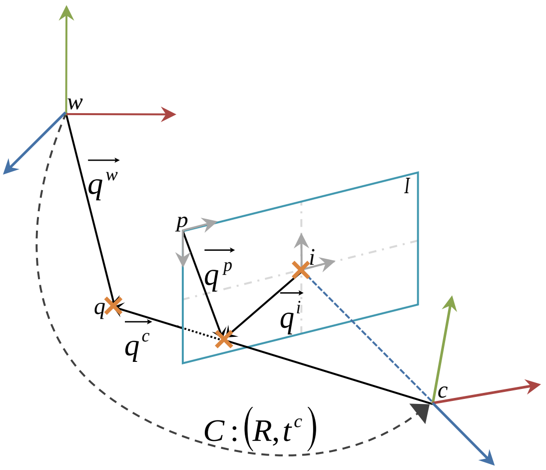


Figure 1: *The pose problem and its relevant coordinate systems.*

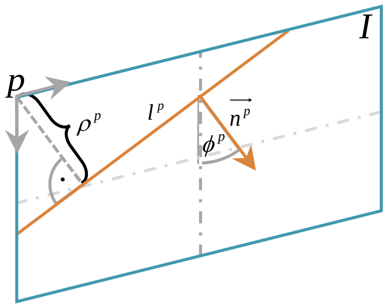


Figure 2: *Line parametrization*

4. Error Measurements for Points

Since the aim is to minimize the distance between the transformed synthetic and real feature, error measurements, i.e. residuals, for correspondences have to be defined. We investigated three different point residuals which measure the error in different coordinate-systems (Fig. 3).

4.1. Reprojection-Error

The well-known Reprojection-Error measures the distance between the real and the synthetical feature in pixel-coordinates. Hence, the residual for each correspondence becomes

$$\vec{r}^{RE} = \vec{p}^p - \vec{q}^p = \begin{pmatrix} p_x^p - q_x^p \\ p_y^p - q_y^p \end{pmatrix}. \qquad (4)$$

4.2. Object-Space-Error

The Object-Space-Error measures the distance in camera-coordinates and was introduced by [LHM00]. To recover the depth for the real feature, its normalized sight vector is projected onto the synthetical sight vector. The resulting scalar is used to scale the normalized real sight vector and both sight vectors are then compared based on their camera coordinates. The residual per correspondence becomes

$$\vec{r}^{OE} = \begin{pmatrix} p_x^p - \left\langle \vec{\hat{q}}^c, \vec{p}^c \right\rangle \hat{q}^p{}_x \\ p_y^p - \left\langle \vec{\hat{q}}^c, \vec{p}^c \right\rangle \hat{q}^p{}_y \end{pmatrix}. \qquad (5)$$

It has to be noted that points whose projections on the image plane are the same produce greater residuals for greater distances from the image plane, i.e. are not depth invariant.

4.3. Normal-Error

The Normal-Space-Error also measures the distance in the camera-coordinates. From the real feature $\vec{q}^i$ two orthogonal normals $\vec{n}_1^c$ and $\vec{n}_2^c$ can be created, describing the direction of the real sight vector in camera-coordinates. The dot product of these normals and the synthetical vector $\vec{p}^c$ provides a measurement between real and synthetical features and the residual per correspondence becomes

$$\vec{r}^{NE} = \begin{pmatrix} \left\langle \vec{n}_1^c, \vec{p}^c \right\rangle \\ \left\langle \vec{n}_2^c, \vec{p}^c \right\rangle \end{pmatrix}. \qquad (6)$$

The Normal-Space-Error is also not depth invariant.

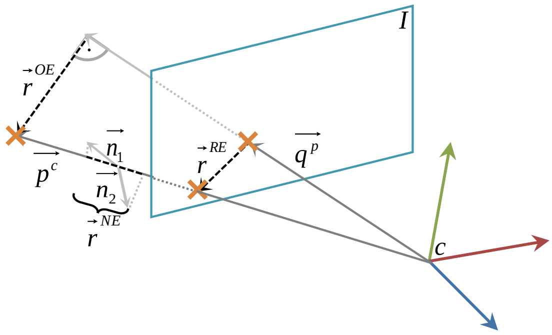


Figure 3: *Error measurements for points.*

5. Error Measurements for Lines

We investigated three different line residuals which measure the error in different coordinate-systems (Fig. 4).

5.1. Angle-/Distance-Error

The Angle-/Distance-Error measures the differences of the angles and the distances of the real and synthetical feature. The start- and endpoint of the synthetic feature are transformed into their pixel points and then the conjunctive line

$\ell : (\varphi^p, d^p)$ is computed. The residual per correspondence then compares the parameters of both lines

$$\vec{r}^{AE} = \begin{pmatrix} \varphi^p - \phi^p \\ d^p - \rho^p \end{pmatrix} = \begin{pmatrix} \arctan \frac{e_x^p - s_x^p}{s_y^p - e_y^p} - \phi^p \\ \cos\phi^p e_x^p + \sin\phi^p e_y^p - \rho^p \end{pmatrix}. \tag{7}$$

Noteable for this error measurement is that the dimensions of the angle and the distance are not equal.

5.2. Line-Error

The Line-Error measures the distances of the start- and end-point to the real line and is used, among others, by Lowe [Low91]. Both distances are computed in pixel-coordinates and hence have an equal dimension. The residual for each correspondence becomes

$$\vec{r}^{LE} = \begin{pmatrix} \cos\phi^p s_x^p + \sin\phi^p s_y^p - \rho^p \\ \cos\phi^p e_x^p + \sin\phi^p e_y^p - \rho^p \end{pmatrix}. \tag{8}$$

5.3. Plane-Error

The Plane-Error can be regarded as the Object-Space-Error extension for straight lines, i.e. the depth recovery of the real feature, and is used e.g. by [KH94]. The optical center and the image line define a plane E^c in camera coordinates with normal $\vec{n^c} = \begin{pmatrix} \cos\phi^i & \sin\phi^i & -\rho^i \end{pmatrix}^T$. The residual for each correspondence becomes:

$$\vec{r}^{PE} = \frac{1}{\left|\vec{n^c}\right|} \begin{pmatrix} \left\langle \vec{n^c}, \vec{s^c} \right\rangle \\ \left\langle \vec{n^c}, \vec{e^c} \right\rangle \end{pmatrix}. \tag{9}$$

Similar to the Object-Space-Error, the Plane-Error is not depth invariant.

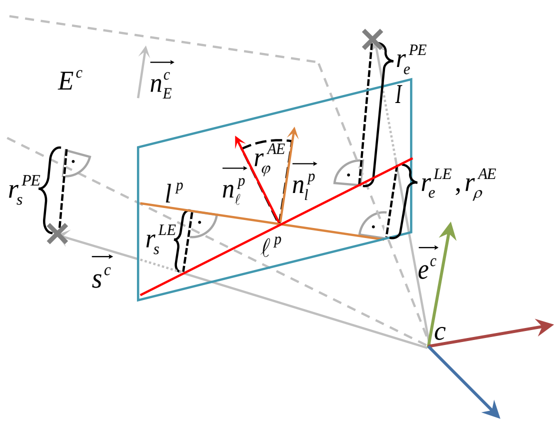


Figure 4: *Error measurements for lines.*

6. Optimization

The residuals of all correspondences are joined in one combined residual $\vec{r}$. The pose parameters for translation $\vec{a^t}$ and rotation $\vec{a^R}$ are combined in the parameter vector $\vec{a}$. The objective is to minimize the sum of the squared entries of this combined residual in terms of the pose parameters $\vec{a}$.

$$\operatorname*{argmin}_{\vec{a}} \sum_{j=0}^{2m} r_j^2 \tag{10}$$

To solve this problem we used standard optimization techniques so that the parameter vector is turned into the sequence $\langle \vec{a_i} \rangle$. Since the Gauß-Newton optimization is comparatively fast but does not guarantee convergence and Gradient-Descent optimization is slow but guarantees convergence, we used the Levenberg-Marquardt optimization as described in [PTVF92] as a technique which guarantees convergence but is still comparatively fast. The iteration rule is $\vec{a_{i+1}} = \vec{a_i} + \vec{\delta}$ with

$$\vec{\delta} = \left(J_{\vec{r}}(\vec{a_i})^T J_{\vec{r}}(\vec{a_i}) + \lambda D \right)^{-1} J_{\vec{r}}(\vec{a_i}) \vec{r}(\vec{a_i}), \tag{11}$$

$D = \operatorname{diag}\left(J_{\vec{r}}(\vec{a_i})^T J_{\vec{r}}(\vec{a_i}) \right)$ and $J_{\vec{r}}$ the Jacobian matrix of $\vec{r}$. We found the initial value of $\lambda = 10^{-3}$ and an alteration rule of $\lambda_i = \lambda_{i-1}/10$ for a residual decrease and $\lambda_i = \lambda_{i-1} * 10^w$ with $w \in \mathbb{N}$ for a residual increase of the last step to work best.

7. Parametrization

We also investigated the influence and conditions of different parametrizations of the pose as described in Eq. 1. Different parametrizations of the translation vector $\vec{t^c}$ do not hold any major differences and it is therefore represented by three scalars t_x^c, t_y^c and t_z^c, describing the translation in camera coordinates; the translation parameter vector is $\vec{a_{t^c}} = \vec{t^c}$.

For rotation parametrization we investgated four different choices. All rotations are described by their corresponding rotation matrices R and have to fulfill certain properties since $R \in SO(\mathbb{R}, 3)$, i.e. the special orthogonal group properties (SOP). In general, these properties can be assured at various stages of the optimization process:

I. *prior to optimization*
By choosing an appropriate rotation parametrization the SOP can be assured partly or completely prior to the optimization process.

II. *during optimzation*
By adding the SOP as additional elements to the residual vector, these properties are optimized with the other residuals. A drawback of this alternative is that with the presence of imperfect or false correspondences the properties are not enforced but only minimized according to the least squares approach of the optimization.

III. *after optimization*
By employing the singular value decomposition as described in [CM06], a rotation matrix $\tilde{R}$ can be computed from the estimated rotation matrix R that assures the SOP and is similar to R.

These three possibilities are not exclusionary; alternative II. always has to be combined with alternative III. for the SOP to be fulfilled.

7.1. Matrix-Parametrization

The parameter vector of the Matrix-Parametrization is $\vec{a}^R = \begin{pmatrix} i_x & i_y & i_z & j_x & j_y & j_z & k_x & k_y & k_z \end{pmatrix}^T$. The rotation matrix is composed of three vectors $\vec{i}, \vec{j}, \vec{k} \in \mathbb{R}^3$:

$$R^M = \begin{pmatrix} i_x & i_y & i_z \\ j_x & j_y & j_z \\ k_x & k_y & k_z \end{pmatrix} \tag{12}$$

Advantageous is that the rotation matrix and its derivatives can easily be computed. However, the SOP are not enforced and alternatives II. and III. have to be used. Matrix R should form an orthonormal basis and have determinant $+1$. Both constraints are added to the residual to meet the SOP.

7.2. Euler-Angles-Parametrization

The parameter vector of the Euler-Angles-Parametrization is $\vec{a}^R = \begin{pmatrix} \phi_x & \phi_y & \phi_z \end{pmatrix}^T$. The rotation matrix is composed of three consecutive rotations around the coordinate axis:

$$R^E = R_{\phi_z} R_{\phi_x} R_{\phi_y} = \begin{pmatrix} c_y c_z - s_x s_y s_z & -c_x s_z & c_z s_y + c_y s_x s_z \\ c_y s_z + c_z s_x s_y & c_x c_z & s_y s_z + c_y c_z s_x \\ -c_x s_y & s_x & c_x c_y \end{pmatrix} \tag{13}$$

with $c_x = \cos\phi_x$, $c_y = \cos\phi_y$, $c_z = \cos\phi_z$, $s_x = \sin\phi_x$, $s_y = \sin\phi_y$ and $s_z = \sin\phi_z$. The SOP are therefore enforced prior to optimization. Disadvantageous is the well-known gimbal lock and the extensive usage of trigonometric functions.

7.3. Quaternion-Parametrization

The parameter vector of the Quaternion-Parametrization is $\vec{a}^R = \begin{pmatrix} w & x & y & z \end{pmatrix}^T$. The rotation matrix is composed by using a unit quaternion $q : (w,x,y,z) \in \mathbb{H}$ with rotation axis $v = (x,y,z)^T$ and rotation angle $\phi = 2\arccos w$:

$$R^Q = \begin{pmatrix} w^2 + x^2 - y^2 - z^2 & 2(xy - wz) & 2(xz + wy) \\ 2(xy + wz) & w^2 - x^2 + y^2 - z^2 & 2(yz - wx) \\ 2(xz - wy) & 2(yz + wx) & w^2 - x^2 - y^2 + z^2 \end{pmatrix} \tag{14}$$

Since q has to be a unit quaternion, the SOP are not completely enforced and alternative II. and III. have to be employed with $|q| = 1$ added to the residual. It is cogitable to substitute e.g. w in terms of x, y and z as $w = \sqrt{1 - x^2 - y^2 - z^2}$. Disadvantageous with quaternions is that there exist complex solutions for w.

7.4. Rodrigues'-Formula-Parametrization

The parameter vector of the Rodrigues'-Formula-Parametrization is $\vec{a}^R = \begin{pmatrix} x & y & z \end{pmatrix}^T$. The rotation matrix is composed by a rotation axis $\vec{v} = (x,y,z)^T$ and a rotation angle $\phi = |\vec{v}|$:

$$R^R = \begin{pmatrix} \cos\phi + x^2 c_\phi & xyc_\phi - zs_\phi & ys_\phi - xzc_\phi \\ zs_\phi + xyc_\phi & \cos\phi + y^2 c_\phi & yzc_\phi - xs_\phi \\ xzc_\phi - ys_\phi & xs_\phi + yzc_\phi & \cos\phi + z^2 c_\phi \end{pmatrix} \tag{15}$$

with $c_\phi = \frac{1-\cos\phi}{\phi^2}$, $s_\phi = \frac{\sin\phi}{\phi}$ and $\phi = \sqrt{x^2 + y^2 + z^2}$, or in case of $\phi = 0$ it holds $R_R = I_3$. The SOP are guaranteed by this parametrization.

8. Scaling and Combination

Multiple different error measurements for each correspondence can be used for the combined residual vector. While generally each error measurement can be included without further consideration, regarding accuracy it is important to take a closer look on the influence of each correspondence on the estimated pose. In general, due to discretization and erroneous matching we cannot rely on perfect correspondences. Therefore, the weight of each correspondence becomes crucial for the estimated result as unequal weights shift the minima of the squared sum (Eq. 10) to different positions. In order to find the optimal least-squares value for all given correspondences, the dimensions of all entries of the residual have to be equal. Except for the Angle-/Distance-Error, all error measurements and SOP have a dimension of either pixel or camera points, and scaling factors for the respectively other dimension can easily be derived using the given camera matrix (Eq. 2).

Most notably, it is possible to join error measurements for points and lines in the combined residual and therefore estimate the pose using both types of correspondences. Hence, in absence of sufficient correspondences of one type of correspondences, the described approach is capable of estimating the pose using both feature types. Moreover, the approach enables the matching process to be more flexible as it can match points and lines (and by extension possibly other feature types) and be more restrictive regarding the quality of the matched correspondences; consequently the total number of correspondences of one type required to estimate the pose can be lowered.

9. Results

In order to find the best combination of error measurement and parametrization we tested them for point and line correspondences in a standard scenario. Because the problem of matching correspondences was beyond the scope of this paper, we used ideal correspondences between 3D model features and their projections to the image plane and added several levels of noise error in means of pixel displacement. We used an image resolution of 640 x 480 pixel. To obtain a minimal set of correspondences as input features to the estimator, we selected model lines of maximal length and distance and model points of maximal distance. The object was then rotated and translated for fixed angle and distance from the initial pose 100.000 times and we listed mean error as well as standard derivation for translation, rotation and number of iterations. Rotation error is specified as frobenius norm of the difference matrix between real and estimated rotation, translation error is specified as euclidean norm of the translational difference vector.

First, we tested the influence of chosen error measurement and parametrization on the optimization stability for points (Fig. 5) and lines (Fig. 6). The estimator requires a minimum of three correspondences. However, we decided to use six correspondences for testing, as they are proven to deliver an unambiguous result always [GT06]. The error level was ten. On points the comparison of error measurements shows that the image based reprojection-error performs more accurate than the object-space-error and normal-error for all possible pose parametrizations. This can be explained by a potentionally higher weighting of points in the object space when they are more distant form the camera center. The number of iterations are comparable while the object-space-error is slightly faster, except for Euler parametrization. The influence of the parametrization on the pose is neglectible, while Quaternions perform somewhat better and lead to less accurate translation estimation. For line correspondences, the angle-distance-error causes bad pose results and results in higher computation time. Line- and plane-error are comparable for all parametrizations. Again. the plane-error in object space is slightly faster, except for Euler parametrization. Quaternions are also faster for lines as it is the case for points.

The results lead to the decision for one error measurement, we use for further testing. The reprojection-error for points and the line-error for lines show the smallest pose error with all parametrizations and good computational speed. But the advantage of using pixel space error is, that scaling is not neccessary to compensate depth differences between the correspondences. The Rodrigues formula proves as the best parametrization. All parametrizations may be comparable concerning accuracy, but Rodrigues is gimbal-lock free and it complies with the constraints of a rotation matrix by definition. Thus, there is neither need for additional entries in the residual vector to be optimized nor for a singular value decomposition to correct the result afterwards. Therefore, we use Rodrigues parametrization with reprojection- and line-error for the following tests on combined pose estimation.

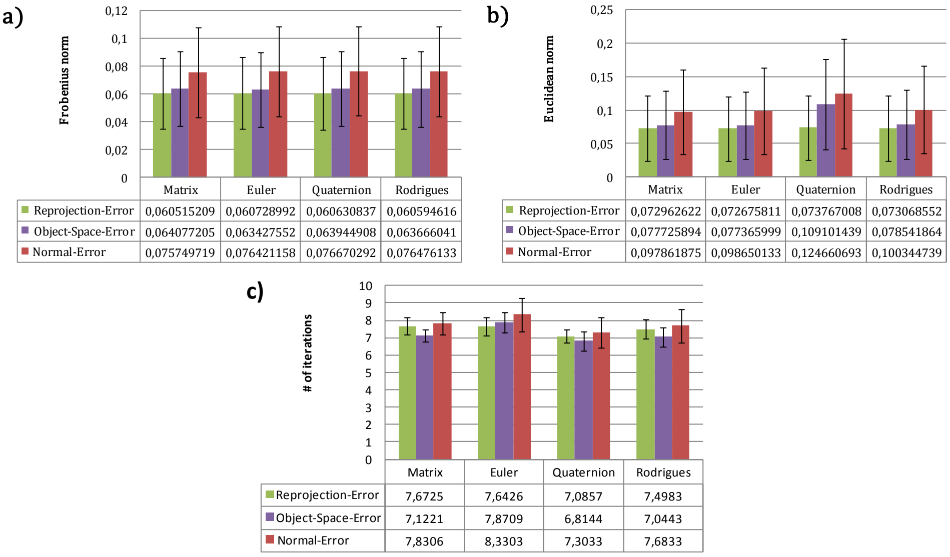
We compared our combined pose estimator to state of the art algorithms: The method *solvePnP* of the OpenCV library, which also implements a Levenberg-Marquardt variant, and *ePnP* that solves for the pose with linear estimation first, followed by a Gauß-Newton refinement [LMNF09]. Both accept point correspondences as input only. The error level of the correspondences was increased step by step up to 20 pixel. As expected, the *ePnP* delivered bad results with growing error level. Our combined estimator showed the same performance on noisy correspondences as *solvePnP*. The pose error grows linearly with increasing error level in the correspondences. Another result is, that the required number of iterations depends on the error level of the correspondences, while it is hardly influenced by the total number of correspondences.

Finally, figure 7 shows the result of pose estimation on combined points and lines. We combined six correspondences of one feature type with zero to six of the other one. The error level was ten pixel. Obviously, adding line correspondences to a pose estimated by points declines the error in rotation and translation, while in the opposing case additional point correspondences show hardly a positive impact on pose exactness when the line estimate is already good. This is due to a generally higher stability of line features concerning displacement error. Point features will be affected stronger by growing correspondence errors than lines. We can state that a combination of point and line features is useful in practical application to stabilize the estimated pose, especially when there is only a minimal set of correspondences available. The combination of both feature types did not reduce computational speed, thus real time application is ensured.

10. Conclusion

We presented a non-linear pose estimator that allows for combined input of point and line correspondences. It works on any arbitrary number and choice of the feature type greater three. While using a high number of correspondences is generally common for the reduction of the pose error, our estimator will improve the pose with as little correspondences as possible. Test results show that the error measurement in pixel coordinates is superior to the object-space-error for points as well as for lines. Further, we proved that the influence of the underlying pose parametrization on the optimization process is neglectible. Thus, a parametrization may be chosen which shows the best compliance with the constraints of a rotation matrix without additional computational load. This is the case for Rodrigues parametrization.

Our future focus will be on feature selection and matching. The presence of a 3D-model delivers information which can be used to predict features with high quality for every frame. The idea is a feature manager that will select and priorize features upon criteria of geometry, projection, global simulation and success feedback from matching. This ensures a dynamic ranking of a few, but the best features as input to our pose estimator, e.g. when there is not a sufficient number of point correspondences for stable pose estimation, try to take additional line features or use only those, which fulfill certain predefined criteria. Selecting a minimal



a)

	Matrix	Euler	Quaternion	Rodrigues
Reprojection-Error	0,060515209	0,060728992	0,060630837	0,060594616
Object-Space-Error	0,064077205	0,063427552	0,063944908	0,063666041
Normal-Error	0,075749719	0,076421158	0,076670292	0,076476133

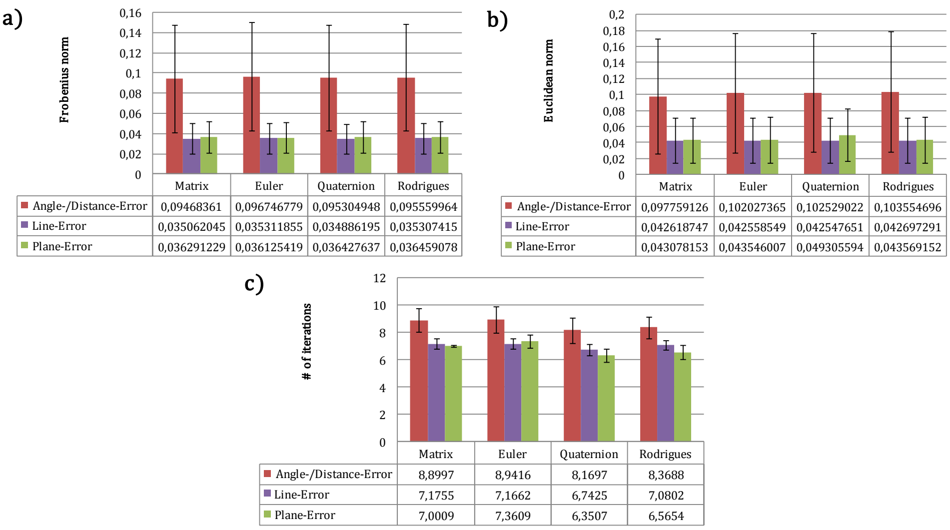
b)

	Matrix	Euler	Quaternion	Rodrigues
Reprojection-Error	0,072962622	0,072675811	0,073767008	0,073068552
Object-Space-Error	0,077725894	0,077365999	0,109101439	0,078541864
Normal-Error	0,097861875	0,098650133	0,124660693	0,100344739

c)

	Matrix	Euler	Quaternion	Rodrigues
Reprojection-Error	7,6725	7,6426	7,0857	7,4983
Object-Space-Error	7,1221	7,8709	6,8144	7,0443
Normal-Error	7,8306	8,3303	7,3033	7,6833

Figure 5: *Points: Error measurement and parametrization; rotation error in a), translation error in b) and number of iterations in c); standard deviation shown as positive and negative error indicator*



a)

	Matrix	Euler	Quaternion	Rodrigues
Angle-/Distance-Error	0,09468361	0,096746779	0,095304948	0,095559964
Line-Error	0,035062045	0,035311855	0,034886195	0,035307415
Plane-Error	0,036291229	0,036125419	0,036427637	0,036459078

b)

	Matrix	Euler	Quaternion	Rodrigues
Angle-/Distance-Error	0,097759126	0,102027365	0,102529022	0,103554696
Line-Error	0,042618747	0,042558549	0,042547651	0,042697291
Plane-Error	0,043078153	0,043546007	0,049305594	0,043569152

c)

	Matrix	Euler	Quaternion	Rodrigues
Angle-/Distance-Error	8,8997	8,9416	8,1697	8,3688
Line-Error	7,1755	7,1662	6,7425	7,0802
Plane-Error	7,0009	7,3609	6,3507	6,5654

Figure 6: *Lines: Error measurement and parametrization; rotation error in a), translation error in b) and number of iterations in c); standard deviation shown as positive and negative error indicator*

but qualitative set of features for tracking can reduce computation time significantly, which is desirable especially on mobile devices.

Acknowledgements

This work was supported by grant no. MU 2783/3-1 of the German Research Foundation (DFG).

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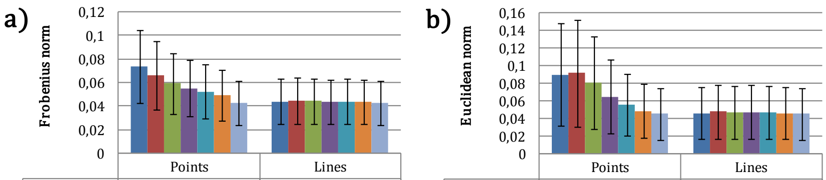

a)

	Points	Lines
0 additional	0,073585423	0,043728671
1 additional	0,066206981	0,044546786
2 additional	0,059139783	0,04414166
3 additional	0,055122703	0,043747758
4 additional	0,052164676	0,043929681
5 additional	0,049424468	0,043525561
6 additional	0,042585884	0,042585884

b)

	Points	Lines
0 additional	0,089844951	0,046075405
1 additional	0,091286738	0,047450707
2 additional	0,080657104	0,047064991
3 additional	0,064888562	0,047084968
4 additional	0,055519589	0,04639309
5 additional	0,048644953	0,045911735
6 additional	0,045365612	0,045365612

Figure 7: *Combination of points and lines; rotation error in a), translation error in b); standard deviation shown as positive and negative error indicator*

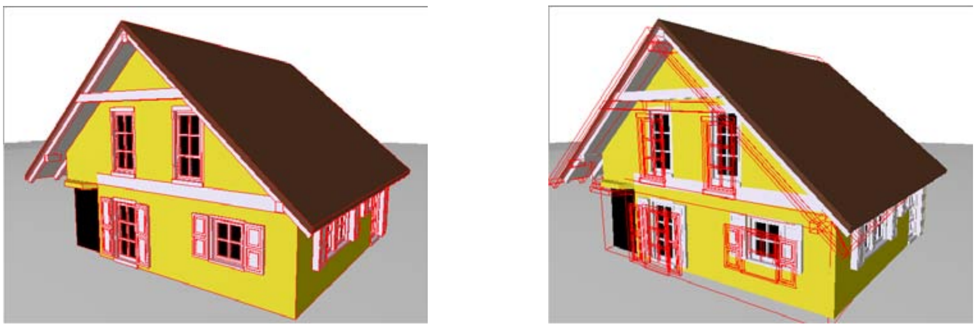

Figure 8: *Pose estimation (left: ideal, right: 10 pixel error)*

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