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# Two-view Matching with View Synthesis Revisited 

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#### Abstract

Wide-baseline matching focussing on problems with extreme viewpoint change is considered. We introduce the use of view synthesis with affine-covariant detectors to solve such problems and show that matching with the Hessian-Affine or MSER detectors outperforms the state-of-the-art ASIFT [18].

To minimise the loss of speed caused by view synthesis, we propose the Matching On Demand with view Synthesis algorithm (MODS) that uses progressively more synthesized images and more (timeconsuming) detectors until reliable estimation of geometry is possible. We show experimentally that the MODS algorithm solves problems beyond the state-of-the-art and yet is comparable in speed to standard wide-baseline matchers on simpler problems.

Minor contributions include an improved method for tentative correspondence selection, applicable both with and without view synthesis and a view synthesis setup greatly improving MSER robustness to blur and scale change that increase its running time by $10 \%$ only.


## 1 Introduction

The standard method for wide baseline matching involves detection of local features, calculation of descriptors, generation of tentative correspondences and their geometric verification using the homography or epipolar constraint.

It is well known [17, 8, 7] that performance of the pipeline decreases in the presence of viewpoint and scale changes, blur, compression artefacts, etc. Lepetit and Fua [12] showed that matching robustness is improved by synthesis of additional views given a single, fronto-parallel view of an object. Morel and Yu [18] combined viewpoint synthesis with the similarity-covariant Difference-of-Gaussians detector (DoG) and SIFT matching [14]. The resulting image matching method, called ASIFT, successfully matched challenging image pairs with significantly different viewing angles.

We develop the idea of view synthesis for wide baseline matching and propose a number of novelties that improve several stages of the matching pipeline. Some of the improvements are also applicable to two-view matching without synthesis. The proposed MODS wide-baseline matcher outperforms ASIFT in terms of speed, the number and percentage of correct matches generated as well as in the precision of the estimated geometry. Performance was tested mainly on image pairs with extreme viewpoint changes, but viewpoint synthesis also improves matching results in the presence of phenomena like blur, occlusion and scale change. The following contributions are made: first, we show that the seemingly counter-intuitive synthesis of affine views for "affine-covariant" detectors greatly improves their performance in wide baseline matching. With suitable detector-specific configurations of synthesized viewpoints, found through extensive experimentation, both the Hessian-Affine [16] and MSER [15] detectors clearly outperform DoG [14].

Second, we generalize the "first-to-second-closest SIFT distance ratio" criterion for the selection of tentative correspondences. Depending on the image, the new criterion gives $5-20 \%$ more true matches than the standard at no extra computation cost. The proposed criterion improves even matching performance without synthesis, especially in images with local symmetries.

Third, we propose an adaptive algorithm for matching very challenging image pairs which follows the "do only as much as needed" principle. The MODS algorithm (Matching On Demand with view Synthesis)

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Figure 1. Homography estimation with extreme viewpoint change. The proposed MODS algorithm produces 32 matches, 25 are correct. The state-of-the-art ASIFT [18] outputs 41 matches, 3 are correct. Blue dots: centers of detected regions. Green dots: reprojected centers of corresponding regions showing good alignment.
uses progressively more detector types and more synthesized images until enough correspondences for reliable estimation of two-view geometry are found. MODS is fast on easy image pairs without compromising performance on the hardest problems.

### 1.1 Related work

The use of view synthesis for image matching is a recent development and the literature is limited and includes mainly modifications of the ASIFT algorithm. Liu et al. [13] synthesised perspective warps rather than affine. Pang et al. [20] replaced SIFT by SURF [3] in the ASIFT algorithm to reduce the computation time. Sadek et al. [22] present a new affine covariant descriptor based on SIFT which can be used with or without view synthesis. Detection of the MSERs on the scale space pyramid was proposed by Forssén and Lowe [9].

The rest of the paper is organised in a top-down manner. In Section 2 , we introduce the adaptive MODS two-view matching algorithm. Section 3 studies view synthesis for affine-covariant detectors. Experiments are presented in Section 4 . Full experimental data is in Appendix.

## 2 Matching with On Demand View Synthesis

The iterative MODS algorithm (see Alg. 1] repeats a sequences of two-view matching procedures, until a required minimum number of geometrically verified correspondences is found. In each iteration, a different detector is used and a different set of views generated. The adopted sequence is an outcome of extensive experimentation with the objective of solving the most challenging problems while keeping speed comparable to standard single-detector wide-baseline matchers for simple problems. For instance, the first iteration of the MODS algorithm runs the MSER detector with only a very coarse scale space pyramid which is $10 \%$ slower than standard MSER. Subsequent iterations run complementary detectors with a higher number of synthesized views. Details on the chose configuration and the selection process are given in Section 3 . The rest of the section describes the steps employed in the iterations of the MODS algorithm.

```
Algorithm 1 MODS: Matching with On-Demand view Synthesis
Input: \(I_{1}, I_{2}\) - two images; \(\theta_{m}\) - minimum required number of matches; \(S_{\max }\) - maximum number of iterations.
Output: Fundamental of homography matrix F or H;
    list of corresponding points.
Variables: \(N_{\text {matches }}\) - detected correspondences, Iter - currect iteration.
while \(\left(N_{\text {matches }}<\theta_{m}\right)\) and (Iter \(\left.<S_{\text {max }}\right)\) do
for \(I_{1}\) and \(I_{2}\) separately do
            1 Generate synthetic views according to the
                scale-tilt-rotation-detector setup for the Iter.
            2 Detect and describe local features.
            3 Reproject local features to original image.
                Add described features to general list.
    end for
    4 Generate tentative correspondences
            using the first geom. inconsistent rule.
        5 Filter duplicate matches.
        6 Geometrically verify tentative correspondences
            while estimating F or H .
end while
```


### 2.1 Synthetic views generation

It is well known that a homography $H$ can be approximated by an affine transformation $A$ at a point using the first order Taylor expansion. Further, an affine transformation can be uniquely decomposed by SVD into a rotation, skew, scale and rotation around the optical axis [10]. Morel and Yu [18] proposed to decompose the affine transformation $A$ as

$$
\begin{align*}
A & =H_{\lambda} R_{1}(\psi) T_{t} R_{2}(\phi)= \\
& =\lambda\left(\begin{array}{cc}
\cos \psi & -\sin \psi \\
\sin \psi & \cos \psi
\end{array}\right)\left(\begin{array}{ll}
t & 0 \\
0 & 1
\end{array}\right)\left(\begin{array}{cc}
\cos \phi & -\sin \phi \\
\sin \phi & \cos \phi
\end{array}\right) \tag{1}
\end{align*}
$$

where $\lambda>0, R_{1}$ and $R_{2}$ are rotations, and $T_{t}$ is a diagonal matrix with $t>1$. Parameter $t$ is called the absolute tilt, $\phi \in\langle 0, \pi)$ is the optical axis longitude and $\psi \in\langle 0,2 \pi)$ is the rotation of the camera around the optical axis. Each synthesised view is parametrised by the tilt, longitude and optionally the scale and represents a sample of the view-sphere resp. view-volume around the original image.

The view synthesis proceeds in the following steps: at first, scale synthesis is performed by building a Gaussian scale-space with Gaussian $\sigma=\sigma_{\text {base }} \cdot S$ and downsampling factor $S(S<1)$. Second, each image in the scale-space is in-plane rotated by longitude $\phi$ with step $\Delta \phi=\Delta \phi_{\text {base }} / t$. In the third step, all rotated images are convolved with a Gaussian filter with $\sigma=\sigma_{\text {base }}$ along vertical direction and $\sigma=t \cdot \sigma_{\text {base }}$ along horizontal direction to eliminate aliasing in the final tilting step. The tilt is applied by shrinking the image along the horizontal direction by factor $t$. The parameters of the synthesis are: the set of scales $\{\mathrm{S}\}, \Delta \phi_{\text {base }}$ - the step of longitude samples at tilt $t=1$, and a set of simulated tilts $\{\mathrm{t}\}$.

### 2.2 Local feature detection and description

The goal of the view synthesis procedure is to provide detectors with a sufficiently similar subset of all artificial views on the view-sphere that allows matching. For affine-covariant detectors, unlike the similaritycovariant DoG of ASIFT, the number of necessary view samples is significantly decreased while the performance for the most difficult image pairs gets improved. Moreover, it is known that different detectors are suitable for different types of images [17] and that some detectors are complementary in the feature points they detect [1]. Our experiments show (c.f. Section 44) that combining detectors improves the overall robustness and speed of the matching procedure.

MODS uses the state-of-the-art affine covariant detectors MSER and Hessian-Affine. The normalised patches are described by the recent modification of SIFT [14] - the RootSIFT [2]. The local feature frames


Figure 2. Comparison of the proposed first to 1st inc. ratio matching strategy and the standard first to second closest ratio matching strategy. Red regions are the second closest descriptors, yellow regions correspond to the closest geometrically inconsistent descriptors, green are the true corresponding regions. Upper pair - rotationally symmetric DoG regions, lower pair - affine covariant MSER regions.
computed on the synthesised views are backprojected to the coordinate system of the original image by a known affine matrix $A$ and associated with the descriptor and the originating synthetic view.

### 2.3 Tentative correspondence generation

Different strategies for computation of the tentative correspondences in wide-baseline matching have been proposed. The standard method for matching SIFT(-like) descriptors is based on the distance ratio of the closest to the second closest descriptors in the other image [14]. Performance of this test in general very efficient method degrades when multiple observations of the same feature are present. In this case, the similar descriptors will lead to the first to second SIFT ratio to be close to 1 and the correspondences will "annihilate" each other, despite the fact they all represent the same geometric constraints and are therefore not mutually contradictory (see Figure 2). The problem of multiple detections is amplified in the matching by view synthesis since covariantly detected local features have often a response in multiple synthetic views. We propose to use, instead of comparing the first to the second closest descriptor distance, the distance of the first descriptor and the closest descriptor that is geometrically inconsistent with the first one (denoted 1st inc. in the following). We call descriptors in one image geometrically inconsistent if the Euclidean distance between centers of the regions is $\geq 10$ pixels. The difference of the first-to-second closest ratio strategy and the closest-to-1st inc. strategy is illustrated in Figure 2.

The kd-tree algorithm from FLANN library [19] effectively finds the N-closest descriptors in the other image. The distance ratio thresholds of the closest to 1 st inc. were experimentally selected based on the CDFs of matching and non-matching descriptors (see Appendix A). We recommend to use the same values for SIFT and RootSIFT descriptors, but different thresholds for the different local feature detectors: $R_{\mathrm{MSER}}=0.85, R_{\mathrm{DoG}}=0.85$ and $R_{\mathrm{HA}}=0.8$.

### 2.4 Duplicate filtering

The redetection of covariant features in synthetic views results in duplicates in tentative correspondences. The duplicate filtering is an optional step and prunes correspondences with close spatial distance of local features in both images. The number of pruned correspondences can be however used later for evaluating the quality (probability of being correct) in PROSAC-like [4] geometric verification.

### 2.5 Geometric verification

The LO-RANSAC [11] algorithm searches for the maximal set of geometrically consistent tentative correspondences. The model of the transformation is set either to homography or epipolar geometry, or automatically determined by a DegenSAC [5] procedure.

## 3 View synthesis for affine covariant detectors



Figure 3. Comparison of view synthesis configurations on the synthetic dataset. First row: the number of correct SIFT matches a robust minimum (value $4 \%$ quantile) over 100 random images from [21]). Second row: the ratio of the number of correct matches to the number of detected regions; the mean over 100 random images. Only selected configurations are shown, full version in Appendix.

Configurations. The first two parameters of the view synthesis, tilt $\{\mathrm{t}\}$ sampling and latitude step $\Delta \phi_{\text {base }}$, were explored in the following synthetic experiment. For each of 100 random images from Oxford Building Datase $1^{2}$ [21], a set of simulated views with latitudes angles $\theta=(0,20,40,60,65,70,75,80,85)^{\circ}$, corresponding to tilt series $t=(1.00,1.06,1.30,2.00,2.36,2.92,3.86,5.75,11.47)^{3}$ was generated. The ground truth affine matrix $A$ was computed for each synthetic view using equation (1) and used in the final

[^1]

Figure 4. Estimation of the suitable scale synthesis configurations on the synthetic dataset. Ratio of the number of correct matches to the number of detected regions, mean over 100 random images from [21].

Table 1. View synthesis configurations based on the analysis of the algorithm on the synthetic dataset

|  | Configurations |  |
| :--- | :--- | :--- |
| Detector | SPARSE | DENSE |
| MSER | $\{S\}=\{1 ; 0.25 ; 0.125\},\{t\}=\{1 ; 5 ; 9\}$, <br> $\Delta \phi=360^{\circ} / t$ | $\{S\}=\{1 ; 0.25 ; 0.125\},\{t\}=\{1 ; 2 ; 4 ; 6 ; 8\}$, <br> $\Delta \phi=72^{\circ} / t$ |
| HessAff | $\{S\}=\{1\},\{t\}=\{1 ; \sqrt{2} ; 2 ; 2 \sqrt{2} ; 4 ; 4 \sqrt{2} ; 8\}$, <br> $\Delta \phi=360^{\circ} / t$ | $\{S\}=\{1\},\{t\}=\{1 ; 2 ; 4 ; 6 ; 8\}, \Delta \phi=72^{\circ} / t$ |
| DoG | $\{S\}=\{1\},\{t\}=\{1 ; 2 ; 4 ; 6 ; 8\}, \Delta \phi=120^{\circ} / t$ | $\{S\}=\{1\},\{t\}=\{1 ; \sqrt{2} ; 2 ; 2 \sqrt{2} ; 4 ; 4 \sqrt{2} ; 8\}$, <br> $\Delta \phi=72^{\circ} / t$ |

verification step of the MODS algorithm. The various configurations of the view synthesis were tested and results for the selected configurations are shown in Figure 3 . Note that the view synthesis significantly increases the matching performance, however after reaching some density of the view-sphere sampling additional views does not bring more correspondences. MSER and Hessian-Affine need sparser viewsphere sampling than DoG.

A similar experiment was performed to find the scale sampling set $\{\mathrm{S}\}$ of the view synthesis. Instead of tilting and rotating the images, a synthetic downsampling of the image by a factor $\lambda=1$ to 9 was employed (see Figure 4). It shows that MSER detector is prone to scale changes while the Hessian-Affine and DoG detectors perform well even without view synthesis with scale sampling. Consequently, the benefit of the scale sampling is higher for MSER than for Hessian-Affine and DoG detectors. Tilting and rotation parameters were not used in this experiment i.e. fixed to $\{\mathrm{t}\}=\{1\}$ and $\Delta \phi_{\text {base }}=180$.

Two configurations, SPARSE and DENSE, were chosen for each detector (see Table 1) using the following criteria: efficiency - the ratio of correct matches per detected region, matching performance - the number of unique (non-duplicated) matches on the synthetic image pairs with $85^{\circ}$ out of plane rotation. The SPARSE configuration is fast but still able to solve synthetic image pairs with up to $85^{\circ}$ out of plane rotation. The DENSE configuration generates sufficient number of correspondences for the most image pairs in the EVD dataset for each detector.

Image pre-smoothing. Parameter $\sigma_{\text {base }}$, the amount of image smoothing prior to view synthesis was set experimentally; it affects matching performance significantly. Values too small fail to prevent aliasing, values too high oversmooth the image reducing the number of detected regions. Unlike MSER, the scale-space based detectors like DoG, Hessian-Affine apply pre-smoothing as an initial step. This leads to different optimal values for different detectors. We set $\sigma_{\text {base }}=0.8,0.2$, and 0.4 for the MSER, Hessian-Affine and DoG detectors, respectively.


Figure 5. The ratio of the number of correct matches obtained by the 1 st inconsistent and 2 nd nearest method, without (left) and with (right) view synthesis. The black dashed line denotes the widely used distance ratio threshold $=0.8$.

## 4 Experiments

### 4.1 1st geometrically inconsistent vs. 2nd nearest neighbour correspondence selection strategy

The first to first geometrically inconsistent strategy was evaluated on 50 image pairs of the publicly available datasets [17] and [6]. The cumulative distributions of the number of correct tentative correspondences as functions of the descriptor distance ratio are used for comparison. The new matching strategy improves the performance by up to $5 \%$ for the matching without view synthesis and up to $30 \%$ (see Figure 5) for matching with view synthesis at almost no additional computational costs.

### 4.2 Results on the Extreme Viewpoint Dataset

We introduce a two-view matching evaluation datase $\left.\right|^{4}$ with extreme viewpoint changes, see Table 2 . The dataset includes image pairs from publicly available datasets: ADAM and MAG [18], GRAF [17] and THERE [6]. The ground truth homography matrices were estimated by LO-RANSAC using correspondences from all three detectors in view synthesis configuration $\{t\}=\{1 ; \sqrt{2} ; 2 ; 2 \sqrt{2} ; 4 ; 4 \sqrt{2} ; 8\}, \Delta \phi=72^{\circ} / t$. The number of inliers for each image pair was $\geq 50$ and the homographies were manually inspected. For the image pairs GRAF and THERE precise homographies are provided by Cordes et al. [6]. Transition tilts $\tau$ were computed using equation (1) with SVD decomposition of the linearised homography at center of the first image of the pair (see Table 2).

The configurations evaluated are specified in Table 1. For comparison, ASIFT ${ }^{5}$ results are added. Computations were performed on Intel i5 CPU @ 2.6 GHz with 4 Gb RAM; results for computation on one core are provided. Based on results of the different configuration, we have chosen the following configuration for MODS w.r.t increasing computation time and performance of the configurations - see Table 3. Please note that only views complementary to the previous iterations are synthesised.

The MODS algorithm allows to set the minimum desired number of inliers as a stopping criterion. The recommended value - 15 inliers to the homography, have a very low probability to be a random result, but are few enough to show the time gain from the algorithm. To maximize the number of inliers for each of the detectors, we recommend to use DENSE configuration as a single step. Figure 6 and Table 4 compare the different view synthesis configurations and the "affine-covariant" detectors - they generate more correct matches in a shorter time than the DoG detector. The DoG based matching and ASIFT matching cannot

[^2]Table 2. The Extreme View Dataset - EVD. Image sources: C - Cordes et al. [6], Ox - Mikolajczyk et al. [17], M Morel and Yu [18].


Table 3. Configurations for MODS steps

| Iter. | Setup |
| :---: | :--- |
| 1 | MSER, $\{S\}=\{1 ; 0.25 ; 0.125\},\{t\}=\{1\}, \Delta \phi=360^{\circ} / t$ |
| 2 | MSER, $\{S\}=\{1 ; 0.25 ; 0.125\},\{t\}=\{1 ; 5 ; 9\}, \Delta \phi=360^{\circ} / t$ |
| 3 | HessAff, $\{S\}=\{1\},\{t\}=\{1 ; \sqrt{2} ; 2 ; 2 \sqrt{2} ; 4 ; 4 \sqrt{2} ; 8\}, \Delta \phi=360^{\circ} / t$ |
| 4 | HessAff, $\{S\}=\{1\},\{t\}=\{1 ; 2 ; 4 ; 6 ; 8\}, \Delta \phi=72^{\circ} / t$ |

solve 3 resp. 9 out of the 15 image pairs. The ASIFT algorithm generates a lower number of correct inliers and works slower than our DoG DENSE configuration (which has the same tilt-rotation set). The main causes are elimination of "one-to-many", including correct, correspondences, the inferiority of the standard 2nd closest ratio and a simple bruteforce algorithm of matching used in ASIFT.

No single detector solved all image pairs. The Hessian-Affine with Dense configuration successfully solved 14 out of 15 image pairs and outperformed other detectors and configurations in the number of inliers, however, at the expense of the highest computational cost. MSER with no synthesis and in the SPARSE configuration is the fastest and could solve 10 out of 15 image pairs. The MODS algorithm solves all image pairs and saves computational time on processing of the easy pairs at the cost of a small matching overhead on the hard cases. Also, MODS is the fastest algorithm in 7 cases, and in another 2 cases it is just $\sim 10 \%$ slower than the fastest configuration. The difference results of MODS step 2 and MSER Sparse are caused by randomization in RANSAC and kd-tree building.

Fig. 7 shows the breakdown of the computational time. SIFT description with the dominant orientation estimation take $50 \%$ of the time. Note that the whole process is almost linear in the area of the synthesised views. The only super-linear part, matching, takes only $10 \%$ of the time.

### 4.3 MSER vs. blur and scale change

We have tested performance of recommended scale synthesis configuration for MSER on the image pairs most distorted by blur and scale change from the Oxford [17] dataset. To allow comparison with [17], the standard SIFT was used instead of RootSIFT in this experiment. Note that the results are not fully compatible as we use NN-distance ratio matching threshold $=0.8$ (In [17] no ratio threshold has been


Figure 6．Performance of the selected view synthesis configurations defined in Table 1．MODS set to find $\geq 15$ inliers． Left－the number of correct RANSAC inliers．The black dashed line marks the level of 10 correct inlier－a minimum for a reliable estimate of two－view geometry．Right－runtime（ 1 core）．


Figure 7．Percentage of time spent in the main stages of the matching with view synthesis process on a single core， DENSE configuration．SIFT description，i．e．the dominant gradient estimation and the descriptor computation is the most time－consuming part．

Table 4．A comparison of different view synthesis and detector configurations（with RootSIFT）．Best results are highlighted by a grey background．MODS set to find $\geq 15$ inliers．Results with less than 8 correct inliers are in red．

| Image | Correct inliers |  |  |  |  |  | Time， 1 core［ $s$ ］ |  |  |  |  |  | Correct inliers／sec |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\begin{aligned} & n \\ & 11 \\ & 0 \\ & 0 \\ & \hat{n} \\ & \hat{0} \\ & \sum \end{aligned}$ | 䨗 |  |  |  | $\begin{aligned} & \text { w } \\ & \sum_{1}^{2} \\ & \text { an } \\ & 0 \\ & 0 \\ & 0 \end{aligned}$ | $\begin{aligned} & n \\ & 11 \\ & 0 \\ & 0 \\ & \hat{n} \\ & \hat{0} \\ & \sum \end{aligned}$ | $\frac{\sqrt{4}}{\boxed{4}}$ |  |  |  |  | $\begin{aligned} & n \\ & 11 \\ & 0 \\ & 0 \\ & \hat{n} \\ & \hat{0} \\ & \sum \end{aligned}$ | $\begin{aligned} & \text { 㡙 } \\ & \text { 年 } \end{aligned}$ |  |  |  |  |
| graf | 82 | 322 | 165 | 375 | 1235 | 653 | 1.0 | 81.8 | 3.0 | 11.0 | 45.2 | 25.5 | 83.9 | 3.9 | 55 | 34.1 | 27.3 | 25.6 |
| index | 18 | 23 | 24 | 34 | 264 | 143 | 0.5 | 54.1 | 2.2 | 5.4 | 20.8 | 18.3 | 38.1 | 0.4 | 11.1 | 6.3 | 12.7 | 7.8 |
| shop | 29 | 17 | 73 | 133 | 311 | 130 | 0.8 | 79.5 | 2.5 | 10.1 | 36.2 | 24 | 35.2 | 0.2 | 28.7 | 13.2 | 8.6 | 5.4 |
| adam | 20 | 24 | 18 | 86 | 214 | 125 | 0.8 | 17.8 | 0.7 | 1.6 | 6.0 | 6.3 | 26.7 | 1.3 | 24.3 | 54.1 | 35.6 | 19.8 |
| there | 14 | 20 | 12 | 49 | 189 | 94 | 4.5 | 150.0 | 4.5 | 10.1 | 43.4 | 36.9 | 3.1 | 0.1 | 2.7 | 4.9 | 4.4 | 2.5 |
| mag | 31 | 11 | 28 | 54 | 72 | 59 | 0.8 | 16.1 | 0.8 | 1.6 | 5.3 | 5.4 | 37.3 | 0.7 | 34.4 | 33.5 | 13.5 | 10.9 |
| dum | 25 | 3 | 0 | 10 | 66 | 28 | 29.4 | 158.0 | 4.8 | 20.1 | 60.2 | 42.5 | 0.9 | 0.0 | 0.0 | 0.5 | 1.1 | 0.7 |
| grand | 14 | 0 | 9 | 0 | 42 | 28 | 21.9 | 131.0 | 4.2 | 14.8 | 50.8 | 34.6 | 0.6 | 0.0 | 2.1 | 0.0 | 0.8 | 0.8 |
| fox | 19 | 0 | 19 | 22 | 74 | 25 | 2.1 | 47.4 | 2.1 | 5.8 | 18.6 | 18.2 | 9.0 | 0.0 | 9.3 | 3.8 | 4 | 1.4 |
| cafe | 17 | 4 | 14 | 0 | 45 | 22 | 1.8 | 39.2 | 1.7 | 4.5 | 17.2 | 15.2 | 9.3 | 0.1 | 8.2 | 0.0 | 2.6 | 1.4 |
| girl | 34 | 0 | 0 | 14 | 59 | 18 | 13.1 | 110.0 | 2.7 | 10.0 | 36.7 | 27.5 | 2.6 | 0.0 | 0.0 | 1.4 | 1.6 | 0.7 |
| pkk | 27 | 0 | 6 | 12 | 41 | 10 | 9.5 | 75.9 | 2.4 | 6.8 | 24.1 | 25.5 | 2.8 | 0.0 | 2.5 | 1.8 | 1.7 | 0.4 |
| cat | 25 | 3 | 0 | 21 | 18 | 6 | 3.9 | 36.2 | 1.4 | 2.2 | 7.8 | 11.7 | 6.3 | 0.1 | 0.0 | 9.6 | 2.3 | 0.5 |
| face | 39 | 0 | 9 | 17 | 24 | 0 | 15.6 | 138.0 | 3.4 | 11.3 | 38.8 | 32.0 | 2.5 | 0.0 | 2.7 | 1.5 | 0.6 | 0.0 |
| vin | 19 | 0 | 0 | 0 | 6 | 0 | 30.3 | 66.9 | 2.3 | 6.3 | 22.8 | 21.7 | 0.6 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 |

used，so the absolute number of the matches differs a lot．But relative ratio between detectors performance remains the same）．We have also performed the duplicate filtering procedure，which reduces the number of correspondences（c．f．Section 2）．

Figure 8 shows that scale synthesis with 1 st geom．inconsistent rule improves MSER performance by $60 \%$ to $1000 \%$ ，solving the most common MSER problems－sensitivity to blur and scale change． The quality of tentative correspondences also increases with the proposed scale synthesis configuration （Figure 8，right）．Table 6shows the computation time．

Table 5. MODS $\left(\theta_{m}=15\right)$ performance on the EVD dataset. The k-th iteration includes regions from all previous steps.

| Image | MODS (SIFT) 4 steps. <br> 1. MSER Scale only. 2. MSER Sparse. <br> 3. HessAff Sparse. 4. HessAff Max |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Time | RANSAC | Tentatives quality | Regions |
|  | $\begin{array}{ccc} \approx & \infty & \infty \\ 0 & \infty & 0 \\ 0 & 0 & 0 \\ 0 & 0 \\ 0 & 0 & 0 \\ -0 & N & \ddots \end{array}$ |  |  | $\begin{array}{ll} \overline{0} & \text { N } \\ \text { on } & 0 \\ \tilde{\Xi} & \tilde{\Xi} \end{array}$ |
| graf | $\begin{array}{llll}1 & 1 & 0.8 & 0.8\end{array}$ | 8185 | $82 \quad 16051.2$ | 10181674 |
| index | $\begin{array}{lllll}1 & 0.5 & 0.4 & 0.4\end{array}$ | $19 \quad 20$ | $19 \quad 5633.9$ | 411246 |
| shop | $\begin{array}{lllll}1 & 0.8 & 0.7 & 0.7\end{array}$ | $28 \quad 30$ | $28 \quad 8433.3$ | 1321711 |
| adam | $\begin{array}{lllll}2 & 0.8 & 0.5 & 0.3\end{array}$ | 1922 | $21 \quad 4843.8$ | 357164 |
| there | $\begin{array}{llll}2 & 4.5 & 2.8 & 2\end{array}$ | $10 \quad 18$ | $15 \quad 6622.7$ | 5712833 |
| mag | $\begin{array}{lllll}2 & 0.8 & 0.5 & 0.4\end{array}$ | $30 \quad 31$ | $30 \quad 5257.7$ | 393509 |
| dum | 329.418 .915 .5 | $24 \quad 29$ | 3011362.6 | 3334223711 |
| grand | 321.913 .711 .3 | $17 \quad 25$ | $\begin{array}{llll}21 & 754 & 2.8\end{array}$ | 2473120297 |
| fox | $\begin{array}{llll}2 & 2.1 & 1.4 & 1.1\end{array}$ | $16 \quad 19$ | $19 \quad 7625$ | 17171011 |
| cafe | $\begin{array}{llll}2 & 1.8 & 1.2 & 0.9\end{array}$ | $18 \quad 20$ | $18 \quad 142 \quad 12.7$ | 14021319 |
| girl | $\begin{array}{lllll}3 & 13.1 & 7.4 & 5.3\end{array}$ | $35 \quad 46$ | $38 \quad 549 \quad 6.9$ | 1046016105 |
| pkk | $\begin{array}{lllll}2 & 2.5 & 1.6 & 1.3\end{array}$ | $7 \quad 15$ | $10 \quad 8112.3$ | 12291267 |
| cat | $\begin{array}{lllll}3 & 3.9 & 2 & 1.4\end{array}$ | $35 \quad 38$ | $35 \quad 14324.5$ | 12623279 |
| face | $\begin{array}{llll}2 & 3.6 & 2.4 & 2\end{array}$ | $9 \quad 15$ | 111118 | 34112371 |
| vin | 430.317 .812 .5 | $18 \quad 38$ | $22 \quad 657 \quad 3.4$ | 1895631984 |


| Image | MODS (RootSIFT), 4 steps. <br> 1. MSER Scale only. 2. MSER Sparse. <br> 3. HessAff Sparse. 4. HessAff Max |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Time | RANSAC | Tentatives quality | Regions |
|  | $\begin{array}{ccc} \pi & \infty & \infty \\ 0 & \infty & 0 \\ 0 & 0 & 0 \\ 0 & 0 \\ 0 & 0 & 0 \\ -i & N & \ddots \end{array}$ |  |  |  |
| graf | $\begin{array}{lllll}1 & 1 & 0.8 & 0.8\end{array}$ | $82 \quad 87$ | 8315453.9 | 10181674 |
| index | $\begin{array}{lllll}1 & 0.5 & 0.4 & 0.4\end{array}$ | $18 \quad 20$ | $18 \quad 4242.9$ | 411246 |
| shop | $\begin{array}{lllll}1 & 0.8 & 0.7 & 0.7\end{array}$ | $29 \quad 31$ | 296147.5 | $1321 \quad 711$ |
| adam | $\begin{array}{lllll}2 & 0.8 & 0.5 & 0.4\end{array}$ | $20 \quad 23$ | $22 \quad 4746.8$ | 357164 |
| there | $\begin{array}{lllll}2 & 4.5 & 2.8 & 2\end{array}$ | $14 \quad 17$ | $16 \quad 6026.7$ | 5712833 |
| mag | $\begin{array}{lllll}2 & 0.9 & 0.5 & 0.4\end{array}$ | $31 \quad 31$ | 314470.5 | 393509 |
| dum | 327.216 .913 .5 | $25 \quad 32$ | 298503.4 | 3334223711 |
| grand | 320.912 .510 | $14 \quad 24$ | 194684.1 | 2473120297 |
| fox | $\begin{array}{llll}2 & 2.1 & 1.4 & 1.1\end{array}$ | 1920 | $20 \quad 6232.3$ | 17171011 |
| cafe | $\begin{array}{llll}2 & 1.8 & 1.2 & 0.9\end{array}$ | $17 \quad 21$ | 1811715.4 | 14021319 |
| girl | $\begin{array}{llllll}3 & 13.1 & 7.3 & 5.2\end{array}$ | $34 \quad 44$ | 384368.7 | 1046016105 |
| pkk | $\begin{array}{lllll}3 & 9.5 & 5.3 & 4\end{array}$ | $27 \quad 37$ | 333449.6 | 106867085 |
| cat | $\begin{array}{lllll}3 & 3.6 & 2.1 & 1.5\end{array}$ | $25 \quad 34$ | 3014920.1 | 12623279 |
| face | $\begin{array}{llllllllllll}3 & 15.6 & 8.9 & 7.1\end{array}$ | $39 \quad 44$ | 425347.9 | 1885713271 |
| vin | 429.717 .111 .8 | 1932 | 214554.6 | 1895631984 |



Figure 8. MSER performance with and w/o scale synthesis on the most distorted pairs (1-6) with scale change and blur from [17]. Left - the number of correct SIFT matches. Right - the proportion of correct matches within tentative correspondences. The best detectors from [17]: BARK, BOAT, TREES - Hessian-Affine, BIKES - IBR are shown for comparison.

## 5 Conclusions

We have introduced view synthesis to two-view wide-baseline matching with affine-covariant detectors and shown that matching with the Hessian-Affine or MSER detectors outperforms the state-of-the-art ASIFT.

Table 6. MSER matcher runtime on Oxford [17] dataset

| scale synthesis setup | time $[\mathrm{s}]$ |
| :--- | :--- |
| $\{S\}=\{1\}$ | 56.6 |
| $\{S\}=\{1 ; 0.25 ; 0.125\}$ | 61.5 |

To address the robustness vs. speed trade-off, we have proposed the Matching On Demand with view Synthesis algorithm (MODS) that uses progressively more synthesized images and more (time-consuming) detectors until a reliable estimate of geometry is obtained. We show experimentally that the MODS algorithm solves matching problems beyond the state-of-the-art and yet is comparable in speed to standard wide-baseline matchers on simpler problems.

Minor contributions include an improved method for tentative correspondence selection, applicable both with and without view synthesis. A modification of the standard first to second nearest SIFT distance rule increases the number of correct matches by $5-20 \%$ at no additional computational cost. Finally, we found a simple view synthesis set up costing less than $10 \%$ of time that greatly improves MSER robustness to blur and scale change.

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## Appendix

## A Tuning view synthesis parameters

Estimating threshold on the distance ratio. The well known [14] matching strategy for SIFT descriptors is based on the distance ratio of the first to the second closest descriptor. The aim of this experiment is to set the threshold of the proposed modification - first to first geometrically inconsistent matching strategy.

To estimate the threshold we used 50 image pairs of the publicly available datasets [17] and [6], all pairs are provided with known homography transformation. The detectors - MSER, Hessian-Affine, DoG - were run on all pairs of images and distances between all descriptors in each pair computed. Then the closest, second closest and closest geometrically inconsistent descriptors were identified. The cumulative distributions of the number of correct and incorrect tentative correspondences as a function of the distance ratio were computed for both strategies using the ground truth homographies.

The results for both SIFT and RootSIFT descriptors are shown in Figure 9 . We see that the DoG and MSER features are slightly less discriminative than Hessian-Affine. It is also clear from comparing the left and right columns in Figure 9 , that the features detected using view synthesis are less distinctive. However, the distribution of incorrect matches does not change significantly, thus the thresholds for the new strategy with view synthesis can be kept on the value similar to the threshold without view synthesis. The results for the SIFT and RootSIFT descriptors are also very similar. Therefore, we propose to set the threshold of the first to first geometrically inconsistent distance ratio $R$ for the local feature detectors as follows: $R_{\mathrm{MSER}}=0.85, R_{\mathrm{DoG}}=0.85$ and $R_{\mathrm{HA}}=0.8$.
Tilt set and latitude sampling step. The first two parameters of the view synthesis, tilt $\{\mathrm{t}\}$ sampling and latitude step $\Delta \phi_{\text {base }}$, were explored in the following synthetic experiment. For each of 100 random images from Oxford Building Dataset ${ }^{6}$ [21], a set of simulated views with latitudes angles $\theta=(0,20,40$, $60,65,70,75,80,85)^{\circ}$, corresponding to tilt series $t=(1.00,1.06,1.30,2.00,2.36,2.92,3.86,5.75$, $11.47)^{7}$ was generated. The reference image have been convolved with a Gaussian filter with $\sigma_{H}=0.8$ along horizontal direction and $\sigma_{V}=0.8 t$ along vertical direction and finally shrunk in vertical direction by $t$. The ground truth affine matrix $A$ was computed for each synthetic view using equation (1) and used in the final verification step of the MODS algorithm. The various configurations of the view synthesis were tested and results for the selected configurations are shown in Figures 10-12. Note that the view synthesis significantly increases the matching performance, however after reaching some density of the view-sphere sampling additional views does not bring more correspondences. MSER and Hessian-Affine need sparser view-sphere sampling than DoG.

Two configurations, Sparse and Dense, were chosen for each detector (see Table 1) using the following criteria: efficiency - the ratio of correct matches per detected region, matching performance - the number of unique (non-duplicated) matches on the synthetic image pairs with $85^{\circ}$ out of plane rotation. The SpARSE configuration is fast but still able to solve synthetic image pairs with up to $85^{\circ}$ out of plane rotation. The DENSE configuration generates sufficient number of correspondences for the most image pairs in the EVD dataset for each detector.
Image pre-smoothing. The early experiments with view synthesis, have shown that the amount of image smoothing $\sigma_{\text {base }}$ prior to view synthesis affects matching performance significantly. Values too small fail to prevent aliasing, values too high oversmooth the image reducing the number of detected regions. Unlike MSER, the scale-space based detectors - DoG, Hessian-Affine apply pre-smoothing as the initial step of the scale-space pyramid.

This experiment measures the effect of the pre-smoothing parameter $\sigma_{\text {base }}$ on the matching performance of different detectors. The range of values of the $\sigma_{\text {base }}$ were used in matching of 35 image pairs of the publicly available datasets [17] and [6]. We have divided all pairs into two sets "Structured images" - scenes GRAF, GRACE, POSTERS, THERE, UNDERGROUND (25 image pairs in total) from [6] and "Images with repeated textures" - scenes wall, colors (10 image pairs in total) [6], [17]. The DEnSE configurations

[^3]

Figure 9. CDF. Columns: left - no view synthesis, right - with view synthesis. Rows: upper - SIFT, lower - RootSIFT. Average over 50 image pairs from Mikolajczyk et al. [17] and Cordes et al. [6] datasets. Black dashed line displays standard threshold $=0.8$.
of the view synthesis were chosen for each of the detectors (see Table 1). Based on this experiment (see Figure (13), we have set following parameters for image pre-smoothing in the MODS algorithm: $\sigma_{\text {base }}=$ $0.8,0.2$, and 0.4 for the MSER, Hessian-Affine and DoG detectors, respectively.

## B Full version of the experiments on the EVD dataset

The full version of experimental evaluation of the matching with view synthesis algorithm on EVD dataset is presented in this section. For this very challenging dataset it is hard to obtain ground truth homographies from the manually selected correspondences. Therefore, the ground truth homography matrices were estimated by running LO-RANSAC on correspondences of all three detectors with the view synthesis con-
figuration $\{t\}=\{1 ; \sqrt{2} ; 2 ; 2 \sqrt{2} ; 4 ; 4 \sqrt{2} ; 8\}, \Delta \phi=72^{\circ} / t$. The number of inliers for each image pair was $\geq$ 50 and the homographies were manually inspected. For the image pairs GRAF and THERE precise homographies were provided by Cordes et al. [6]. The transition tilts were computed using equation (1) with SVD decomposition of the linearised homography at the center of the first image of the pair. The configurations of detectors evaluated are listed in Table 1, additionally, the performance of the MODS and MSER detector with scale synthesis were compared. The configuration for MODS algorithm is shown in Table 3. The MODS algorithm allows to set the minimum desired number of inliers as a stopping criterion. We set the threshold to 15 inliers, since fifteen inliers to a homography (with duplicate matches removed) have very low probability of being accidental and yet allow to demonstrate the speed gain of the algorithm.

The results for all configurations for all detectors are shown in Tables $7-19$. For comparison, ASIFT ${ }^{8}$ results were added. The timing measurements are reported for single, two and four cores of the Intel i5 CPU @ 2.6 GHz processor with 4GB RAM.

[^4]

Figure 10. Comparison of MSER view synthesis configurations on the synthetic dataset. Upper graph - the number of correct SIFT matches a robust minimum (value $4 \%$ quantile) over 100 random images from [21]. Lower graph the ratio of the number of correct matches to the number of detected regions; the mean over 100 random images.


Figure 11. Comparison of Hessian-Affine view synthesis configurations on the synthetic dataset. Upper graph - the number of correct SIFT matches a robust minimum (value $4 \%$ quantile) over 100 random images from [21]. Lower graph - the ratio of the number of correct matches to the number of detected regions; the mean over 100 random images.


Figure 12. Comparison of DoG view synthesis configurations on the synthetic dataset. Upper graph - the number of correct SIFT matches a robust minimum (value $4 \%$ quantile) over 100 random images from [21]. Lower graph - the ratio of the number of correct matches to the number of detected regions; the mean over 100 random images.


Figure 13. Matching with view synthesis (DENSE configuration) using different image pre-smoothing factor $\sigma_{\text {base }}$. Rows: upper - ratio of correct SIFT matches to number of detected regions, lower - number of correct SIFT matches - robust minimum (value $4 \%$ quantile). Columns: left - structured images, right - images with repeated patterns.


Figure 14. Running time of the different view synthesis configurations (Table 1). Left - 1 core, right - 4 cores.

Table 7. Performance on the EVD dataset. MSER, no view synthesis. Results with less than 8 correct inliers are in red.

| Image | MSER, no synths. |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Time | LO-RA | NSAC | Tentat | quality | Regions |
|  | 0 0 0 0 0 | $\infty$ $\infty$ <br> $\infty$ $\infty$ <br> 0 0 <br> 0 0 <br> $\sim$ $\ddots$ |  |  |  |  | $\begin{array}{ll} \overline{0} & \text { N } \\ 0 & 0 \\ \ddot{0} & 0 \\ \Xi & \tilde{\Xi} \end{array}$ |
| f | 0.8 | 0.8 0.8 | 656895.6 | 6770 | $65 \quad 12153.7$ | $\begin{array}{llll}67 & 110 & 60.9\end{array}$ | 8041432 |
| index | 0.4 | $0.4 \begin{array}{ll}0.4\end{array}$ | $\begin{array}{llll}18 & 19 & 94.7\end{array}$ | 17 1818 | $\begin{array}{llll}18 & 44 & 40.9\end{array}$ | $17 \quad 3647.2$ | 291172 |
| shop | 0.7 | 0.70 .7 | $\begin{array}{llll}18 & 19 & 94.7\end{array}$ | $\begin{array}{llll}18 & 18 & 100\end{array}$ | $\begin{array}{llll}18 & 65 & 27.7\end{array}$ | $18 \quad 4045$ | 1131646 |
| adam | 0.1 | 0.10 .1 | 0 0 0 | $\begin{array}{lll}0 & 0 & 0\end{array}$ | $6 \quad 1540$ | $\begin{array}{llll}7 & 16 & 43.8\end{array}$ | 11848 |
| there | 0.7 | 0.70 .8 | $\begin{array}{lll}0 & 0 & 0\end{array}$ | $\begin{array}{lll}0 & 0 & 0\end{array}$ | $3 \begin{array}{lll}3 & 11 & 27.3\end{array}$ | $3 \quad 1030$ | 97689 |
| mag | 0.2 | 0.20 .2 | $\begin{array}{llll}11 & 11 & 100\end{array}$ | 11111100 | $11 \quad 2055$ | $11 \quad 20 \quad 55$ | 203306 |
| dum | 1.9 | 1.81 .8 | 00 | $\begin{array}{lll}0 & 0 & 0\end{array}$ | $\begin{array}{llll}8 & 121 & 6.6\end{array}$ | $\begin{array}{lll}7 & 110 & 6.4\end{array}$ | 31081970 |
| grand | 1.6 | 1.51 .5 | 0 0 0 | 0 0 0 | $\begin{array}{llll}4 & 51 & 7.8\end{array}$ | $\begin{array}{llll}5 & 36 & 13.9\end{array}$ | 20992598 |
| fox | 0.6 | $0.6 \quad 0.6$ | 0 0 0 | $00^{0} 0$ | $\begin{array}{llll}2 & 15 & 13.3\end{array}$ | $2 \begin{array}{llll}2 & 17 & 11.8\end{array}$ | 893558 |
| cafe | 0.5 | $0.4 \quad 0.5$ | $7 \quad 10 \quad 70$ | $\begin{array}{lll}7 & 9 & 77.8\end{array}$ | $8 \quad 6312.7$ | $8 \quad 4318.6$ | 621472 |
| girl | 0.6 | $0.6 \quad 0.6$ | 000 | 000 | $3 \begin{array}{llll}3 & 21 & 14.3\end{array}$ | $\begin{array}{lll}2 & 22 & 9.1\end{array}$ | 566816 |
| pkk | 0.6 | 0.60 .6 | 0 0 0 | 0 0 0 | $36 \quad 2.8$ | $1 \quad 254$ | 661343 |
| cat | 0.2 | 0.20 .2 | 000 | 00 | 425 | $1 \quad 616.7$ | 4893 |
| face | 1.3 | 1.21 .2 | 000 | 000 | 056 | $0 \quad 410$ | $2323 \quad 747$ |
| vin | 0.6 | $0.6 \quad 0.6$ | 0 0 0 | 0 | $0 \quad 11 \quad 0$ | $0 \quad 8 \quad 0$ | 597899 |

Table 8. Performance on the EVD dataset. MSER, scale view synthesis only. Results with less than 8 correct inliers are in red.

| Image | MSER, 2 scale synths. Total image area $A_{\text {total }}=1.08 A_{\text {orig }}$ |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Time | LO-RA | ANSAC | Tentative | es quality | Regions |
|  | $\infty$ 0 0 0 0 | $\begin{array}{cc} \infty & \infty \\ \ddot{\sim} & \ddot{0} \\ 0 & 0 \\ \sim & \ddots \\ \sim & \square \end{array}$ |  |  |  |  |  |
| graf | 1 | 0.8 0.8 | $\begin{array}{lll}81 & 85 & 95.3\end{array}$ | $\begin{array}{llll}82 & 87 & 94.3\end{array}$ | $82 \quad 16051.2$ | $83 \quad 154 \quad 53.9$ | 10181674 |
| index | 0.5 | 0.410 .4 | $19 \quad 2095$ | $18 \quad 20 \quad 90$ | $\begin{array}{llll}19 & 56 & 33.9\end{array}$ | $\begin{array}{llll}18 & 42 & 42.9\end{array}$ | 411246 |
| shop | 0.8 | 0.710 .7 | $28 \quad 30$ | 293193.5 | $28 \quad 8433.3$ | $29 \quad 6147.5$ | 1321711 |
| adam | 0.2 | 0.10 .1 | $\begin{array}{lll}0 & 0 & 0\end{array}$ | $8 \quad 8100$ | $\begin{array}{llll}8 & 18 & 44.4\end{array}$ | $9 \quad 1947.4$ | 13562 |
| there | 0.9 | 0.70 .8 | $\begin{array}{lll}0 & 0 & 0\end{array}$ | 0 0 0 | $\begin{array}{llll}6 & 19 & 31.6\end{array}$ | $\begin{array}{llll}6 & 17 & 35.3\end{array}$ | 160947 |
| mag | 0.2 | 0.20 .2 | $\begin{array}{llll}13 & 13 & 100\end{array}$ | 1212100 | $13 \quad 2259.1$ | $12 \quad 18 \quad 66.7$ | 223330 |
| dum | 2.1 | 1.91 .9 | 0 0 0 | 000 | 81346 | $\begin{array}{llll}9 & 129 & 7\end{array}$ | 33672247 |
| grand | 1.9 | 1.71 .7 | 000 | 0 0 0 | $\begin{array}{lll}4 & 70 & 5.7\end{array}$ | $\begin{array}{lll}4 & 46 & 8.7\end{array}$ | 23622763 |
| fox | 0.7 | $0.6 \quad 0.6$ | 000 | 0 0 0 | $2 \quad 1910.5$ | $2 \begin{array}{llll}2 & 12 & 16.7\end{array}$ | 967605 |
| cafe | 0.6 | 0.50 .5 | 000 | $8 \quad 8100$ | $\begin{array}{llll}8 & 65 & 12.3\end{array}$ | $\begin{array}{llll}8 & 54 & 14.8\end{array}$ | 715561 |
| girl | 0.8 | $\begin{array}{ll}0.6 & 0.7\end{array}$ | 0 0 0 | 0 0 0 | $\begin{array}{llll}6 & 32 & 18.8\end{array}$ | $5 \quad 24 \quad 20.8$ | 675949 |
| pkk | 0.7 | $0.6 \quad 0.6$ | 000 | 000 | $2 \begin{array}{lll}2 & 44 & 4.6\end{array}$ | $4 \quad 2913.8$ | 729437 |
| cat | 0.3 | $0.2 \quad 0.2$ | 000 | $0 \quad 0 \quad 0$ | 1520 | $1 \begin{array}{lll}1 & 6 & 16.7\end{array}$ | 59138 |
| face | 1.4 | $1.2 \quad 1.2$ | 000 | 000 | $\begin{array}{lll}2 & 57 & 3.5\end{array}$ | $2 \begin{array}{lll}2 & 43 & 4.7\end{array}$ | 2442911 |
| vin | 0.7 | $0.6 \quad 0.6$ | $0 \quad 0$ | $0 \quad 0 \quad 0$ | $\begin{array}{llll}0 & 12 & 0\end{array}$ | $\begin{array}{lll}0 & 12 & 0\end{array}$ | 6421012 |

Table 9. Performance on the EVD dataset.Hessian-Affine, no view synthesis. Results with less than 8 correct inliers are in red.

| Image | HessAff, no synths. |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time |  |  | LO-RANSAC |  |  |  |  | Tentatives quality |  |  |  |  |  | Regions |  |
|  | $\infty$ 0 0 0 0 | $\begin{aligned} & \infty \\ & \stackrel{\pi}{0} \\ & 0 \\ & 0 \\ & \sim \end{aligned}$ | $\begin{aligned} & \infty \\ & \substack{0 \\ 0 \\ 0 \\ \dot{U} \\ \hline} \end{aligned}$ |  |  | R 0 0 $\vdots$ $\vdots$ 0 0 0 0 | ootSI $\frac{\tilde{U}}{\Xi}$ |  |  | SIF <br>  |  |  | ootS |  |  | $\begin{aligned} & \text { N } \\ & \text { O. } \\ & \text { Ï } \\ & \text { In } \end{aligned}$ |
| graf | 3.4 | 3.3 | 3.3 | 14 | 1782.4 | 16 | 19 | 84.2 | 15 | 141 | 10.6 | 19 | 97 | 19.6 | 3630 | 4614 |
| index | 1.6 | 1.6 | 1.6 | 0 | $0 \quad 0$ | 0 | 0 | 0 | 0 | 114 | 0 |  | 79 | 1.3 | 2188 | 874 |
| shop | 3.7 | 3.6 | 3.5 | 0 | $0 \quad 0$ | 0 | 0 | 0 | 0 | 78 | 0 |  | 39 | 0 | 5675 | 2657 |
| adam | 0.5 | 0.6 | 0.5 | 0 | 00 | 0 | 0 | 0 | 2 | 24 | 8.3 |  | 19 | 10.5 | 812 | 208 |
| there | 2.7 | 2.7 | 2.7 | 0 | 00 | 0 | 0 | 0 | 0 | 8 | 0 |  | 9 | 0 | 467 | 3659 |
| mag | 0.5 | 0.5 | 0.5 | 0 | $0 \quad 0$ | 0 | 0 | 0 | 0 | 12 | 0 |  | 7 | 0 | 502 | 784 |
| dum | 6.6 | 6.5 | 6.3 | 0 | 00 | 0 | 8 | 0 | 6 | 147 | 4.1 |  | 76 | 4 | 9248 | 6666 |
| grand | 5 | 4.8 | 4.8 | 0 | $0 \quad 0$ | 0 | 0 | 0 | 3 | 62 | 4.8 | 3 | 34 | 8.8 | 6364 | 6555 |
| fox | 2 | 1.9 | 1.9 | 0 | $0 \quad 0$ | 0 | 0 | 0 | 0 | 17 | 0 |  | 8 | 0 | 3324 | 1393 |
| cafe | 1.2 | 1.2 | 1.2 |  | $10 \quad 0$ | 0 | 11 | 0 | 2 | 58 | 3.5 |  | 42 | 2.4 | 1510 | 1184 |
| girl | 3.1 | 3.1 | 3 | 0 | 00 | 0 | 0 | 0 | 0 | 29 | 0 |  | 20 | 0 | 2808 | 4306 |
| pkk | 2.5 | 2.4 | 2.4 | 0 | $0 \quad 0$ | 0 | 0 | 0 | 0 | 39 | 0 |  | 16 | 0 | 3832 | 1568 |
| cat | 0.7 | 0.7 | 0.7 |  | $0 \quad 0$ | 0 | 0 | 0 | 1 | 18 | 5.6 |  | 13 | 0 | 388 | 581 |
| face | 4.2 | 4 | 4 |  | $0 \quad 0$ | 0 | 0 | 0 | 0 | 21 | 0 |  | 21 | 0 | 6283 | 3638 |
| vin | 2 | 1.9 | 2 | 0 | $0 \quad 0$ | 0 | 0 | 0 | 0 | 25 | 0 |  | 20 | 0 | 1759 | 2913 |

Table 10. Performance on the EVD dataset. DoG, no view synthesis. Results with less than 8 correct inliers are in red.

| Image | DoG, no synths. |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Time | LO-R | NSAC |  | Tentativ | quality | Regions |
|  | $\infty$ 0 0.0 0 0 | $\begin{array}{cc} \infty & \infty \\ 0 & \ddot{0} \\ 0 & 0 \\ 0 & 0 \\ \sim & \ddots \end{array}$ |  |  |  |  |  | $\begin{array}{ll} \overline{0} & \text { N } \\ \text { En } & 0 \\ \text { En } & \stackrel{0}{\Xi} \end{array}$ |
| graf | 2.5 | $2.5 \quad 2.5$ | $0 \begin{array}{lll}0 & 0\end{array}$ | 000 | 3 | $120 \quad 2.5$ | 4834.8 | 16822419 |
| index | 0.9 | 0.900 .9 | $0 \quad 0 \quad 0$ | 000 | 0 | 1060 | 080 | 1171516 |
| shop | 1.6 | 1.61 .6 | $0 \quad 0 \quad 0$ | 0 0 0 | 0 | 930 | 0830 | 25701238 |
| adam | 0.3 | 0.30 .3 | $0 \quad 0 \quad 0$ | 0 0 0 | 0 | 310 | 0290 | 495132 |
| there | 1.8 | 1.91 .8 | $0 \quad 0 \quad 0$ | 000 | 0 | 490 | 030 | 5412476 |
| mag | 0.3 | 0.30 .3 | $0 \quad 0 \quad 0$ | 000 | 0 | 17 0 | 0150 | 252370 |
| dum | 3.6 | $3.5 \quad 3.5$ | 0 | 000 | 0 | 1440 | 0890 | 42422791 |
| grand | 2 | 2 | 0 | 000 | 0 | 660 | 1472.1 | 27542956 |
| fo | 1.1 | 1.11 | $0 \quad 0 \quad 0$ | 000 | 0 | 420 | 0220 | 1764817 |
| cafe | 0.7 | 0.70 .7 | 010 | 080 | 1 | $60 \quad 1.7$ | 0460 | 847813 |
| girl | 1.5 | 1.51 .5 | 0 | 000 | 0 | $60 \quad 0$ | 0390 | 12172190 |
| pkk | 1.5 | 1.51 .5 | 0 | 000 | 0 | 40 0 | 0260 | 20911487 |
| cat | 0.5 | 0.50 .6 | 0 | 000 | 0 | 300 | 0190 | 262519 |
| face | 1.8 | 1.81 .7 | 0 | 0 0 0 | 0 | 340 | 0390 | 24062457 |
| vin | 1.1 | 1.21 .1 | $\begin{array}{llll}0 & 0 & 0\end{array}$ | $0 \quad 0 \quad 0$ | 0 | 480 | 0320 | 8761661 |

Table 11. Performance on the EVD dataset.MSER, SPARSE configuration. Results with less than 8 correct inliers are in red.

| Image | MSER, 6 tilt synths x ( $1+2$ scale synth). $\Delta \phi=360^{\circ} / t$, $\mathrm{t}=\{1 ; 5 ; 9\}$. Total image area $A_{\text {total }}=2.8 A_{\text {orig }}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time | LO-R | ANSAC | Tentative | es quality | Regions |
|  | $\left\lvert\, \begin{array}{ccc} \infty & \infty & \infty \\ \hdashline & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \sim & N & \ddots \end{array}\right.$ |  |  |  |  |  |
| graf | 3101.61 .1 | $167 \quad 17396.5$ | $165169 \quad 97.6$ | 17534051.5 | 17033950.1 | 27803782 |
| index | $\begin{array}{lll}2.2 & 1.2 & 0.8\end{array}$ | $23 \quad 3271.9$ | $\begin{array}{llll}24 & 35 & 68.6\end{array}$ | 2510623.6 | $\begin{array}{lllll}27 & 103 & 26.2\end{array}$ | 1204736 |
| shop | $\begin{array}{lll}2.5 & 1.4 & 0.9\end{array}$ | $\begin{array}{llll}67 & 69 & 97.1\end{array}$ | $\begin{array}{lll}73 & 74 & 98.6\end{array}$ | $\begin{array}{llll}67 & 172 & 39\end{array}$ | $\begin{array}{lllll}73 & 163 & 44.8\end{array}$ | 28991474 |
| adam | $\begin{array}{lll}0.7 & 0.4 & 0.3\end{array}$ | $18 \quad 2090$ | $\begin{array}{lll}18 & 21 & 85.7\end{array}$ | $\begin{array}{lll}20 & 48 & 41.7\end{array}$ | $20 \quad 4247.6$ | 357164 |
| there | $\begin{array}{lll}4.5 & 2.5 & 1.6\end{array}$ | $12 \quad 1963.2$ | $\begin{array}{lll}12 & 18 & 66.7\end{array}$ | $\begin{array}{llll}15 & 65 & 23.1\end{array}$ | $\begin{array}{llll}17 & 61 & 27.9\end{array}$ | 5712833 |
| mag | $\begin{array}{lll}0.8 & 0.5 & 0.3\end{array}$ | $25 \quad 2792.6$ | $28 \quad 28100$ | $\begin{array}{llll}26 & 47 & 55.3\end{array}$ | $28 \quad 4070$ | 393509 |
| dum | $\begin{array}{lll}4.8 & 2.7 & 2.1\end{array}$ | 000 | $0 \quad 00$ | $\begin{array}{lll}12 & 229 & 5.2\end{array}$ | 141738.1 | 62764579 |
| grand | $\begin{array}{lll}4.2 & 2.4 & 1.9\end{array}$ | $0 \quad 0$ | $\begin{array}{lll}9 & 14 & 64.3\end{array}$ | $\begin{array}{llll}10 & 163 & 6.1\end{array}$ | 91058.6 | 48404346 |
| fox | $\begin{array}{lll}2.1 & 1.1 & 0.7\end{array}$ | $\begin{array}{lll}12 & 17 & 70.6\end{array}$ | $\begin{array}{lll}19 & 20 & 95\end{array}$ | $16 \quad 68 \quad 23.5$ | $20 \quad 6132.8$ | 17171011 |
| cafe | $\begin{array}{lll}1.7 & 1 & 0.6\end{array}$ | $13 \quad 2065$ | $14 \quad 20 \quad 70$ | $\begin{array}{llll}15 & 117 & 12.8\end{array}$ | 1610415.4 | 14021319 |
| girl | $\begin{array}{lll}2.7 & 1.5 & 1\end{array}$ | $\begin{array}{llll}10 & 15 & 66.7\end{array}$ | $0 \quad 0 \quad 0$ | $\begin{array}{llll}11 & 82 & 13.4\end{array}$ | $\begin{array}{llll}10 & 61 & 16.4\end{array}$ | 14792208 |
| pkk | $\begin{array}{lll}2.4 & 1.3 & 0.9\end{array}$ | $4 \quad 14 \quad 28.6$ | $6 \quad 10 \quad 60$ | $\begin{array}{llll}7 & 68 & 10.3\end{array}$ | $8 \quad 4517.8$ | 12291267 |
| cat | $\begin{array}{lll}1.4 & 0.8 & 0.5\end{array}$ | 000 | $0 \quad 0 \quad 0$ | $2 \begin{array}{lll}2 & 13 & 15.4\end{array}$ | $2 \begin{array}{llll}2 & 13 & 15.4\end{array}$ | 144440 |
| face | $\begin{array}{lll}3.4 & 1.9 & 1.4\end{array}$ | 000 | $\begin{array}{lll}9 & 14 & 64.3\end{array}$ | 1119311.8 | $10 \quad 8611.6$ | 34112371 |
| vin | $\begin{array}{lll}2.3 & 1.3 & 0.8\end{array}$ | $0 \quad 0$ | $0 \quad 0$ | $\begin{array}{llll}4 & 24 & 16.7\end{array}$ | $\begin{array}{lll}4 & 21 & 19\end{array}$ | 11061881 |

Table 12. Performance on the EVD dataset.Hessian-Affine, SPARSE configuration. Results with less than 8 correct inliers are in red.

| Image | HessAff, 10 synths. $\Delta \phi=360^{\circ} / t$, $\mathrm{t}=\{1 ; \sqrt{2} ; 2 ; 2 \sqrt{2} ; 4 ; 4 \sqrt{2} ; 8\}$. Total image area $A_{\text {total }}=4 A_{\text {orig }}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time | LO-RANSAC |  | Tentatives quality |  | Regions |
|  | $\begin{array}{ccc} \infty & \infty & \infty \\ \hdashline & 0 & \pi \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ - & N & \tau \end{array}$ |  |  |  |  |  |
|  | $\begin{array}{lll}11 & 5.9 & 3.9\end{array}$ | 37137997.9 | $\begin{array}{llll}375 & 383 & 97.9\end{array}$ | 37579946.9 | $384765 \quad 50.2$ | 1251914144 |
| index | $\begin{array}{lll}5.4 & 3 & 2\end{array}$ | $23 \quad 4057.5$ | $\begin{array}{llll}34 & 52 & 65.4\end{array}$ | $\begin{array}{llll}34 & 412 & 8.3\end{array}$ | $44 \quad 28415.5$ | 79673139 |
| shop | 10.1 5.4 3.9 | 134143193.7 | $1 \begin{array}{llll}133 & 141 & 94.3\end{array}$ | 13834140.5 | $135 \quad 25752.5$ | 163268549 |
| adam | $\begin{array}{lll}1.6 & 0.8 & 0.6\end{array}$ | $86 \quad 9392.5$ | 86 | $\begin{array}{llll}88 & 157 & 56.1\end{array}$ | $\begin{array}{llll}88 & 151 & 58.3\end{array}$ | 2486635 |
| there | $\begin{array}{llll}10.1 & 5.3 & 3.3\end{array}$ | $\begin{array}{llll}58 & 66 & 87.9\end{array}$ | $49 \quad 5687.5$ | $\begin{array}{llll}64 & 223 & 28.7\end{array}$ | $\begin{array}{llll}52 & 163 & 31.9\end{array}$ | 270215991 |
| mag | $\begin{array}{lll}1.6 & 0.9 & 0.6\end{array}$ | $55 \quad 6091.7$ | $54 \quad 5991.5$ | $\begin{array}{lll}57 & 95 & 60\end{array}$ | $\begin{array}{llll}57 & 93 & 61.3\end{array}$ | 16642162 |
| dum | $\begin{array}{lll}20.1 & 11.7 & 9.1\end{array}$ | 00 | $\begin{array}{llll}10 & 12 & 83.3\end{array}$ | $\begin{array}{lll}10 & 254 & 3.9\end{array}$ | $\begin{array}{llll}11 & 150 & 7.3\end{array}$ | 2706619132 |
| grand | 14.8 8.1 6.2 | 0 0 | 000 | $\begin{array}{llll}8 & 152 & 5.3\end{array}$ | $65 \quad 7.7$ | 1989115951 |
| fox | $\begin{array}{lll}5.8 & 3.1 & 2.2\end{array}$ | $27 \quad 34 \quad 79.4$ | $22 \quad 3268.8$ | $30 \quad 9930.3$ | $27 \quad 72 \quad 37.5$ | 102273798 |
| cafe | $\begin{array}{lll}4.5 & 2.4 & 1.6\end{array}$ | $0 \quad 14$ | $\begin{array}{lll}0 & 14 & 0\end{array}$ | $\begin{array}{llll}9 & 135 & 6.7\end{array}$ | $\begin{array}{lll}7 & 112 & 6.3\end{array}$ | 46425349 |
| girl | $\begin{array}{lll}10 & 5.3 & 3.7\end{array}$ | $16 \quad 2564$ | $\begin{array}{llll}14 & 23 & 60.9\end{array}$ | 1817010.6 | $\begin{array}{llll}17 & 120 & 14.2\end{array}$ | 898113897 |
| pkk | $\begin{array}{lll}6.8 & 3.7 & 2.7\end{array}$ | $21 \quad 2584$ | $12 \quad 1963.2$ | $\begin{array}{llll}25 & 105 & 23.8\end{array}$ | $17 \begin{array}{lll}17 & 84 & 20.2\end{array}$ | 94575818 |
| cat | $\begin{array}{lll}2.2 & 1.2 & 0.8\end{array}$ | $24 \quad 2692.3$ | $\begin{array}{llll}21 & 29 & 72.4\end{array}$ | $\begin{array}{llll}24 & 75 & 32\end{array}$ | $23 \quad 6734.3$ | 11182839 |
| face | $\begin{array}{ccc}11.3 & 6 & 4.6\end{array}$ | $\begin{array}{llll}35 & 39 & 89.7\end{array}$ | $17 \quad 2085$ | $\begin{array}{llll}38 & 139 & 27.3\end{array}$ | $\begin{array}{llll}18 & 93 & 19.4\end{array}$ | 1544610900 |
| vin | $\begin{array}{llll}6.3 & 3.4 & 2.4\end{array}$ | $0 \quad 0$ | $0 \quad 0$ | $0 \quad 460$ | $0 \quad 310$ | 56568401 |

Table 13. Performance on the EVD dataset.DoG, Sparse configuration. Results with less than 8 correct inliers are in red.


Table 14. Performance on the EVD dataset. MSER,DENSE configuration. Results with less than 8 correct inliers are in red.

| Image | MSER, 14 tilt synths $x\left(1+2\right.$ scale synth). $\Delta \phi=180^{\circ} / t$, $\mathrm{t}=\{1 ; 5 ; 9\}$. Total image area $A_{\text {total }}=4.2 A_{\text {orig }}$ |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time | LO-RA | ANSAC |  | Tentativ | qua |  |  | ons |
|  | $\begin{array}{ccc} \infty & \infty & \infty \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ - & \sim & \ddots \end{array}$ |  |  | $\begin{aligned} & \text { U } \\ & \text { U } \\ & \text { U } \\ & \ddot{\Xi} \\ & 0 \\ & 0 \\ & 0 \\ & 0 \end{aligned}$ |  |  |  |  | $\begin{aligned} & \text { N } \\ & \text { 品 } \\ & \text { Ï } \\ & \equiv \end{aligned}$ |
|  | $\begin{array}{llll}22.2 & 11.7 & 6.9\end{array}$ | 33036191.4 | 33235394.1 | 339 | 106132 | 342 | 101433.7 | 2045 | 26177 |
| index | $\begin{array}{llll}16.6 & 8.8 & 5.1\end{array}$ | $\begin{array}{llll}51 & 65 & 78.5\end{array}$ | $\begin{array}{llll}56 & 76 & 73.7\end{array}$ | 60 | 39015.4 | 66 | 39116.9 | 9087 | 5733 |
| shop | $\begin{array}{lll}18.5 & 9.7 & 5.7\end{array}$ | 13915291.4 | 14716191.3 | 145 | 53027.4 | 150 | 44633.6 | 1956 | 9905 |
| adam | $\begin{array}{lll}5.4 & 2.8 & 1.7\end{array}$ | $\begin{array}{llll}36 & 41 & 87.8\end{array}$ | $\begin{array}{llll}26 & 38 & 68.4\end{array}$ | 38 | 11433.3 | 34 | 10432.7 | 2161 | 1201 |
| there | $\begin{array}{llll}34.1 & 18 & 10.4\end{array}$ | $43 \quad 68 \quad 63.2$ | 46 | 59 | 24324.3 | 61 | 24724.7 | 4405 | 20824 |
| mag | $\begin{array}{llll}5.7 & 3 & 1.8\end{array}$ | 30 | $\begin{array}{llll}32 & 39 & 82.1\end{array}$ | 35 | 11430.7 | 35 | 10533.3 | 2123 | 2836 |
| dum | $\begin{array}{lllll}33.9 & 18.7 & 11.8\end{array}$ | $42 \quad 4789.4$ | $34 \quad 3987.2$ | 43 | 8675 | 38 | 6535.8 | 38881 | 29687 |
| grand | $\begin{array}{lllll}29.1 & 16.5 & 10.6\end{array}$ | 000 | $0 \quad 0$ | 15 | $540 \quad 2.8$ | 12 | $349 \quad 3.4$ | 29894 | 23431 |
| fox | $\begin{array}{llll}14.6 & 7.6 & 4.5\end{array}$ | $37 \quad 4190.2$ | $\begin{array}{llll}39 & 43 & 90.7\end{array}$ | 42 | 24117.4 | 41 | 20919.6 | 10731 | 5960 |
| cafe | $\begin{array}{lll}12.3 & 6.5 & 3.9\end{array}$ | $17 \quad 3056.7$ | $\begin{array}{llll}19 & 32 & 59.4\end{array}$ | 20 | 287 | 22 | 2638.4 | 8932 | 8805 |
| girl | $\begin{array}{llll}19.6 & 10.4 & 6.1\end{array}$ | $\begin{array}{llll}9 & 25 & 36\end{array}$ | $\begin{array}{llll}11 & 21 & 52.4\end{array}$ | 23 | $237 \quad 9.7$ | 16 | 1928.3 | 9313 | 15567 |
| pkk | $\begin{array}{lll}17.1 & 9.1 & 5.3\end{array}$ | $2 \quad 258$ | $7 \quad 2924.1$ | 12 | 1826.6 | 18 | 1949.3 | 6922 | 9210 |
| cat | $\begin{array}{llll}11.1 & 5.9 & 3.4\end{array}$ | 000 | $0 \quad 0$ | 4 | 3112.9 | 3 | 417.3 | 1084 | 3333 |
| face | $\begin{array}{llll}21.5 & 11.3 & 6.6\end{array}$ | $\begin{array}{llll}52 & 68 & 76.5\end{array}$ | $\begin{array}{llll}55 & 70 & 78.6\end{array}$ | 56 | 43812.8 | 64 | 35817.9 | 13733 | 17135 |
| vin | $\begin{array}{llll}16.3 & 8.6 & 5.1\end{array}$ | $\begin{array}{llll}10 & 15 & 66.7\end{array}$ | $11 \quad 17 \quad 64.7$ | 10 | 125 | 11 | 10110.9 | 6423 | 10539 |

Table 15. Performance on the EVD dataset. Hessian-Affine, DENSE configuration. Results with less than 8 correct inliers are in red.

| Image | HessAff, 50 synths. $\Delta \phi=72^{\circ} / t$, $\mathrm{t}=\{1 ; 2 ; 4 ; 6 ; 8\}$. Total image area $A_{\text {total }}=11 A_{\text {orig }}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time | LO-RA | NSAC | Tentative | quality | Regions |
|  | $\left\lvert\, \begin{array}{ccc} \infty & \infty & \infty \\ \hdashline & \infty & \infty \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ - & N & \ddots \end{array}\right.$ |  |  |  |  |  |
| gra | $\begin{array}{llll}45.2 & 23.8 & 14.2\end{array}$ | 1214126096.3 | $12351274 \quad 96.9$ | 1249295842.2 | 1267288743.9 | 4699758020 |
| index | $\begin{array}{llll}20.8 & 10.9 & 6.5\end{array}$ | $270 \quad 29790.9$ | $\begin{array}{llll}264 & 302 & 87.4\end{array}$ | $\begin{array}{llll}312 & 1698 & 18.4\end{array}$ | $\begin{array}{lllllllllllllll}326 & 1297 & 25.1\end{array}$ | 2791011497 |
| shop | $\begin{array}{llll}36.2 & 19.2 & 11.3\end{array}$ | $303 \quad 31596.2$ | $\begin{array}{llll}311 & 322 & 96.6\end{array}$ | $\begin{array}{llll}311 & 847 & 36.7\end{array}$ | $\begin{array}{llllllllllllll}326 & 676\end{array}$ | 5550825538 |
| adam | 3.11 .9 | $205 \quad 23985.8$ | $214 \quad 23192.6$ | $242 \quad 525 \quad 46.1$ | 23949748.1 | 76162310 |
| there | $\begin{array}{llll}43.4 & 23 & 13.6\end{array}$ | $\begin{array}{lll}211 & 274 & 77\end{array}$ | $\begin{array}{llll}189 & 234 & 80.8\end{array}$ | $\begin{array}{llll}240 & 905 & 26.5\end{array}$ | $\begin{array}{lllll}212 & 680 & 31.2\end{array}$ | 1178461930 |
| mag | $\begin{array}{lll}5.3 & 2.8 & 1.7\end{array}$ | $\begin{array}{llll}71 & 79 & 89.9\end{array}$ | $72 \quad 7694.7$ | $\begin{array}{llll}74 & 184 & 40.2\end{array}$ | $\begin{array}{llll}73 & 151 & 48.3\end{array}$ | 43626296 |
| dum | $\begin{array}{llll}60.2 & 31.6 & 18.7\end{array}$ | $\begin{array}{llll}61 & 68 & 89.7\end{array}$ | $66 \quad 7489.2$ | $\begin{array}{llll}63 & 617 & 10.2\end{array}$ | $\begin{array}{llll}68 & 419 & 16.2\end{array}$ | 7949964321 |
| grand | $\begin{array}{lllllllllll}50.8 & 26.6 & 15.8\end{array}$ | $\begin{array}{llll}54 & 61 & 88.5\end{array}$ | $42 \quad 5477.8$ | $\begin{array}{llll}56 & 525 & 10.7\end{array}$ | $46 \quad 27616.7$ | 6396252899 |
| fox | $\begin{array}{lll}18.6 & 9.7 & 5.8\end{array}$ | $\begin{array}{llll}75 & 86 & 87.2\end{array}$ | $74 \quad 8488.1$ | $79 \quad 25830.6$ | $76 \quad 20537.1$ | 2694612327 |
| cafe | $\begin{array}{lll}17.2 & 9.2 & 5.4\end{array}$ | $34 \quad 4575.6$ | $45 \quad 5384.9$ | $\begin{array}{lll}39 & 437 & 8.9\end{array}$ | $48 \quad 40911.7$ | 1653818329 |
| girl | $\begin{array}{llll}36.7 & 19.3 & 11.4\end{array}$ | $55 \quad 6584.6$ | $59 \quad 6985.5$ | $\begin{array}{llll}64 & 452 & 14.2\end{array}$ | $65 \quad 291 \quad 22.3$ | 2677649353 |
| pkk | $\begin{array}{llll}24.1 & 12.7 & 7.5\end{array}$ | $40 \quad 73 \quad 54.8$ | $41 \quad 7356.2$ | $\begin{array}{llll}52 & 349 & 14.9\end{array}$ | $52 \quad 24721.1$ | 2526622414 |
| cat | $\begin{array}{lll}7.8 & 4.2 & 2.5\end{array}$ | $21 \quad 3855.3$ | $18 \quad 34 \quad 52.9$ | $37 \quad 147 \quad 25.2$ | $\begin{array}{llll}29 & 115 & 25.2\end{array}$ | 36457267 |
| face | $\begin{array}{llll}38.8 & 20.5 & 12\end{array}$ | $52 \quad 5594.5$ | $24 \quad 2596$ | $\begin{array}{llll}56 & 417 & 13.4\end{array}$ | $26 \quad 277 \quad 9.4$ | 4268938507 |
| vin | $\begin{array}{llll}22.8 & 12.2 & 7.2\end{array}$ | $8 \quad 1650$ | $6 \quad 12 \quad 50$ | $\begin{array}{lll}10 & 147 & 6.8\end{array}$ | $7 \quad 94$ | 1660828275 |

Table 16. Performance on the EVD dataset. DoG,DENSE configuration. Results with less than 8 correct inliers are in red.

| Image | DoG, 59 synths. $\Delta \phi=72^{\circ} / t$, $\mathrm{t}=\{1 ; \sqrt{2} ; 2 ; 2 \sqrt{2} ; 4 ; 4 \sqrt{2} ; 8\}$. Total image area $A_{\text {total }}=16 A_{\text {orig }}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time | LO-RA | NSAC | Tentative | es quality | Regions |
|  | $\left\lvert\, \begin{array}{ccc} \infty & \infty & \infty \\ \hdashline & \infty & \infty \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \sim & N & \ddots \end{array}\right.$ |  |  |  |  | $\begin{array}{ll} \overrightarrow{0} & \text { N } \\ \text { on } & \text { ® } \\ \ddot{\Xi} & \Xi \end{array}$ |
|  | $\begin{array}{llll}25.5 & 13.9 & 8.1\end{array}$ | 63765996.7 | 65367596.7 | 665228429.1 | 675204133.1 | 2883638361 |
| index | 18.3 9.9 6.1 | $\begin{array}{lllll}138 & 167 & 82.6\end{array}$ | 14316487.2 | $\begin{array}{llll}161 & 1901 & 8.5\end{array}$ | 157138511.3 | 1847710549 |
| shop | 24 12.8 7.7 | $\begin{array}{lllll}118 & 122 & 96.7\end{array}$ | $\begin{array}{llll}130 & 134 & 97\end{array}$ | $\begin{array}{llll}124 & 1238 & 10\end{array}$ | $\begin{array}{llll}132 & 845 & 15.6\end{array}$ | 3720518541 |
| adam | $\begin{array}{lll}6.3 & 3.3 & 1.9\end{array}$ | 12913595.6 | $\begin{array}{lllll}125 & 138 & 90.6\end{array}$ | $136 \quad 54924.8$ | 145434333.4 | 74622062 |
| there | 36.919 .611 .6 | $\begin{array}{llll}98 & 125 & 78.4\end{array}$ | $\begin{array}{llll}94 & 112 & 83.9\end{array}$ | 119112910.5 | $\begin{array}{llll}108 & 817 & 13.2\end{array}$ | 1204147887 |
| mag | $\begin{array}{lll}5.4 & 2.8 & 1.7\end{array}$ | $\begin{array}{lllll}52 & 57 & 91.2\end{array}$ | $\begin{array}{llll}59 & 62 & 95.2\end{array}$ | $\begin{array}{llll}54 & 209 & 25.8\end{array}$ | $\begin{array}{llll}59 & 178 & 33.1\end{array}$ | 35223952 |
| dum | $\begin{array}{llll}42.5 & 24.9 & 16.9\end{array}$ | 3136686.1 | $\begin{array}{llll}28 & 35 & 80\end{array}$ | $\begin{array}{lll}36 & 1440 & 2.5\end{array}$ | $\begin{array}{lll}31 & 966 & 3.2\end{array}$ | 5470043809 |
| grand | $\begin{array}{lll}34.6 & 20 & 13.3\end{array}$ | $\begin{array}{llll}26 & 34 & 76.5\end{array}$ | $28 \quad 3873.7$ | 309433 | $\begin{array}{lll}32 & 595 & 5.4\end{array}$ | 4203235904 |
| fox | $18.210 \quad 6.1$ | $27 \quad 4067.5$ | $25 \quad 3964.1$ | $\begin{array}{lll}33 & 614 & 5.4\end{array}$ | $\begin{array}{lll}28 & 370 & 7.6\end{array}$ | 2403911336 |
| cafe | $\begin{array}{lll}15.2 & 9 & 6.1\end{array}$ |  | $22 \quad 28 \quad 78.6$ | $25 \quad 558$ | $\begin{array}{llll}23 & 415 & 5.5\end{array}$ | 1231014829 |
| girl | $\begin{array}{llll}27.5 & 16 & 10.9\end{array}$ | $11 \quad 20 \quad 55$ | $18 \quad 24 \quad 75$ | $\begin{array}{lll}18 & 759 & 2.4\end{array}$ | 214964.2 | 1786733840 |
| pkk | $\begin{array}{llll}25.5 & 14.8 & 9.5\end{array}$ | $13 \quad 4131.7$ | $\begin{array}{llll}10 & 28 & 35.7\end{array}$ | $23 \quad 763$ | $\begin{array}{lll}22 & 473 & 4.7\end{array}$ | 2347024826 |
| cat | $\begin{array}{lll}11.7 & 6.5 & 4.1\end{array}$ | 000 | $\begin{array}{llll}6 & 16 & 37.5\end{array}$ | $\begin{array}{llll}5 & 215 & 2.3\end{array}$ | $\begin{array}{lll}11 & 153 & 7.2\end{array}$ | 42668714 |
| face | $\begin{array}{llll}32 & 17.8 & 11.3\end{array}$ | 000 | 000 | $\begin{array}{lll}33 & 1205 & 2.7\end{array}$ | $\begin{array}{llll}6 & 980 & 0.6\end{array}$ | 3833432892 |
| vin | $21.7 \quad 12.618 .4$ | $0 \quad 0$ | $0 \quad 0$ | 7491 | $5 \quad 270 \quad 1.9$ | 1422323069 |

Table 17. Performance on the EVD dataset.ASIFT. Results with less than 8 correct inliers are in red.

| Image | ASIFT, 59 synths. $\Delta \phi=72^{\circ} / t$, $\mathrm{t}=\{1 ; \sqrt{2} ; 2 ; 2 \sqrt{2} ; 4 ; 4 \sqrt{2} ; 8\}$. Total image area $A_{\text {total }}=16 A_{\text {orig }}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time | ORSA | Tentatives quality |  | Regions |  |
|  | $\begin{array}{ccc} \infty & \infty & \infty \\ \hdashline & \mathscr{\infty} & \ddot{0} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \sim & N & \ddots \end{array}$ |  |  |  |  | $\begin{aligned} & \text { N } \\ & 0 \\ & \text { O} \\ & \text { B } \end{aligned}$ |
|  | $81.8 \quad 26.514 .8$ | $322531 \quad 60.6$ | 325582 | 55.8 | 31 | 38677 |
| index | $\begin{array}{lllll}54.1 & 18.3 & 10.9\end{array}$ | $23 \quad 94 \begin{array}{lll}24.5\end{array}$ | 23178 | 12.9 | 20349 | 10115 |
| shop | $\begin{array}{llll}79.5 & 25 & 14.1\end{array}$ | $17 \quad 3450$ | 1876 | 23.6 | 41984 | 25270 |
| adam | $\begin{array}{lll}17.8 & 6 & 4.3\end{array}$ | $\begin{array}{llll}24 & 63 & 38.1\end{array}$ | 2592 | 27.1 | 7572 | 3295 |
| there | $150 \quad 48.4 \quad 27.8$ | $\begin{array}{llll}20 & 72 & 27.8\end{array}$ | 21365 | 5.8 | 26901 | 52334 |
| mag | $\begin{array}{lll}16.1 & 5.5 & 3.8\end{array}$ | $11 \quad 2544$ | 1254 | 22.2 | 4204 | 6399 |
| dum | $158 \quad 50.8 \quad 48.3$ | $\begin{array}{lll}3 & 39 & 7.7\end{array}$ | 364 | 4.7 | 66380 | 48622 |
| grand | 13141.840 .4 | 00 | 81 | 1.2 | 54350 | 43713 |
| fox | $\begin{array}{llll}47.4 & 15.7 & 9.5\end{array}$ | 00 | 432 | 12.5 | 22300 | 13502 |
| cafe | $\begin{array}{llll}39.2 & 12.9 & 8\end{array}$ | $\begin{array}{lll}4 & 74 & 5.4\end{array}$ | 4109 | 3.6 | 16088 | 16245 |
| girl | $110 \quad 35.6 \quad 20.8$ | 000 | 12199 | 6 | 35834 | 46892 |
| pkk | $\begin{array}{llll}75.9 & 25.1 & 14.9\end{array}$ | $0 \quad 0 \quad 0$ | 6107 | 5.6 | 33229 | 22352 |
| cat | $\begin{array}{llll}36.2 & 12.6 & 7.8\end{array}$ | $37 \quad 8.1$ | 642 | 14.3 | 4979 | 10142 |
| face | $138 \quad 44.1 \quad 25.4$ | 000 | 6136 | 4.4 | 59278 | 41859 |
| vin | $66.9 \quad 21.3 \quad 20.6$ | $0 \quad 0$ | $0 \quad 49$ | 0 | 17127 | 31329 |

Table 18. Performance on the EVD dataset. MODS $\left(\theta_{m}=15\right)$, SIFT. Results with less than 8 correct inliers are in red.

| Image | MODS, 4 steps. <br> 1. MSER Scale only. 2. MSER Sparse. <br> 3. HessAff Sparse. 4. HessAff Dense |  |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time |  |  |  | LO-RANSAC |  |  | Tentatives quality |  |  | Regions |  |
|  |  | $\infty$ 0 0 0 0 0 | $\begin{aligned} & \infty \\ & 0 \\ & 0 \\ & 0 \\ & 0 \\ & N \end{aligned}$ | $\begin{aligned} & \infty \\ & 0 \\ & 0 \\ & 0 \\ & 0 \\ & \dot{0} \end{aligned}$ | $\begin{aligned} & : \ddot{0} \\ & . \Xi \\ & . \ddot{0} \\ & 0.0 \\ & 0 \end{aligned}$ | SIF $\frac{0}{E}$ |  |  | $$ |  | $\begin{aligned} & \overline{0} \\ & \text { ت口 } \\ & \text { In } \end{aligned}$ | $\begin{aligned} & \text { N } \\ & \text { 品 } \\ & \text { E } \end{aligned}$ |
|  | 1 | 1 | 0.8 | 0.8 | 81 | 85 | 95.3 | 82 | 160 | 51.2 | 1018 | 1674 |
| index | 1 | 0.5 | 0.4 | 0.4 | 19 | 20 | 95 | 19 | 56 | 33.9 | 411 | 246 |
| shop | 1 | 0.8 | 0.7 | 0.7 | 28 | 30 | 93.3 | 28 | 84 | 33.3 | 1321 | 711 |
| adam | 2 | 0.8 | 0.5 | 0.3 | 19 | 22 | 86.4 | 21 | 48 | 43.8 | 357 | 164 |
| there | 2 | 4.5 | 2.8 | 2 | 10 | 18 | 55.6 | 15 | 66 | 22.7 | 571 | 2833 |
| mag | 2 | 0.8 | 0.5 | 0.4 | 30 | 31 | 96.8 | 30 | 52 | 57.7 | 393 | 509 |
| dum | 3 | 29.4 | 18.9 | 15.5 |  | 29 | 82.8 | 30 | 1136 | 2.6 | 33342 | 23711 |
| grand | 3 | 21.9 | 13.7 | 11.3 | 17 | 25 | 68 | 21 | 754 | 2.8 | 24731 | 20297 |
| fox | 2 | 2.1 | 1.4 | 1.1 | 16 | 19 | 84.2 | 19 | 76 | 25 | 1717 | 1011 |
| cafe | 2 | 1.8 | 1.2 | 0.9 | 18 | 20 | 90 | 18 | 142 | 12.7 | 1402 | 1319 |
| girl | 3 | 13.1 | 7.4 | 5.3 | 35 | 46 | 76.1 | 38 | 549 | 6.9 | 10460 | 16105 |
| pkk | 2 | 2.5 | 1.6 | 1.3 | 7 | 15 | 46.7 | 10 | 81 | 12.3 | 1229 | 1267 |
| cat | 3 | 3.9 | 2 | 1.4 | 35 | 38 | 92.1 | 35 | 143 | 24.5 | 1262 | 3279 |
| face | 2 | 3.6 | 2.4 | 2 |  | 15 | 60 | 11 | 118 | 9.3 | 3411 | 2371 |
| vin | 4 | 30.3 | 17.8 | 12.5 | 18 | 38 | 47.4 | 22 | 657 | 3.4 | 18956 | 31984 |

Table 19. Performance on the EVD dataset.MODS $\left(\theta_{m}=15\right)$, RootSIFT. Results with less than 8 correct inliers are in red.

| Image | MODS, 4 steps. <br> 1. MSER Scale only. 2. MSER Sparse. <br> 3. HessAff Sparse. 4. HessAff Dense |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Time | LO-RAI | NSAC | Tentativ | uality |  | ons |
|  | $\begin{array}{ccc}  & \infty & \infty \\ & \infty & \infty \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \dot{0} & - & 0 \\ 0 & \ddots \end{array}$ |  |  |  | $\begin{aligned} & \overline{0} \\ & \bar{\sigma} \\ & \overline{0} \\ & 0 \\ & 0 \\ & 0 \end{aligned}$ | $\begin{aligned} & \overline{0} \\ & \text { © } \\ & \text { ت̈ } \end{aligned}$ |  |
| gr | 0.8 0.8 | 8287 | 94.3 | 83154 | 53.9 | 101 | 1674 |
| index | $\begin{array}{llll}1 & 0.5 & 0.4 & 0.4\end{array}$ | $18 \quad 20$ | 90 | $18 \quad 42$ | 42.9 | 411 | 246 |
| shop | $\begin{array}{llll}1 & 0.8 & 0.7 & 0.7\end{array}$ | 2931 | 93.5 | $29 \quad 61$ | 47.5 | 1321 | 711 |
| adam | $\begin{array}{llll}2 & 0.8 & 0.5 & 0.4\end{array}$ | 2023 | 87 | 2247 | 46.8 | 357 | 164 |
| there | $\begin{array}{llll}2 & 4.5 & 2.8 & 2\end{array}$ | 1417 | 82.4 | $16 \quad 60$ | 26.7 | 571 | 2833 |
| mag | $\begin{array}{llll}2 & 0.9 & 0.5 & 0.4\end{array}$ | 3131 | 100 | 3144 | 70.5 | 393 | 509 |
| dum | $\begin{array}{llllllllll}3 & 27.2 & 16.9 & 13.5\end{array}$ | 2532 | 78.1 | 29850 | 3.4 | 33342 | 23711 |
| grand | $\begin{array}{lllll}3 & 20.9 & 12.5 & 10\end{array}$ | 1424 | 58.3 | 19468 | 4.1 | 24731 | 20297 |
| fox | $\begin{array}{llll}2 & 2.1 & 1.4 & 1.1\end{array}$ | 1920 | 95 | $20 \quad 62$ | 32.3 | 1717 | 1011 |
| cafe | $\begin{array}{llll}2 & 1.8 & 1.2 & 0.9\end{array}$ | 1721 | 81 | 18117 | 15.4 | 1402 | 1319 |
| girl | $\begin{array}{lllll}3 & 13.1 & 7.3 & 5.2\end{array}$ | 3444 | 77.3 | 38436 | 8.7 | 10460 | 16105 |
| pkk | $\begin{array}{lll}3 & 9.5 & 5.3\end{array}$ | 2737 | 73 | 33344 | 9.6 | 10686 | 7085 |
| cat | $\begin{array}{llll}3 & 3.6 & 2.1 & 1.5\end{array}$ | 2534 | 73.5 | 30149 | 20.1 | 1262 | 3279 |
| face | $\begin{array}{lllll}3 & 15.6 & 8.9 & 7.1\end{array}$ | 3944 | 88.6 | 42534 | 7.9 | 18857 | 13271 |
| vin | $4 \begin{array}{lllll}4 & 29.7 & 17.1 & 11.8\end{array}$ | 1932 | 59.4 | 21455 | 4.6 | 18956 | 31984 |


[^0]:    ${ }^{1}$ Available at http://cmp.felk.cvut.cz/wbs/index.html

[^1]:    ${ }^{2}$ available at http://www.robots.ox.ac.uk/~vgg/data/oxbuildings/
    ${ }^{3}$ assuming that the original image is in the fronto-parallel view

[^2]:    ${ }^{4}$ Available at http://cmp.felk.cvut.cz/wbs/index.html
    ${ }^{5}$ Reference code from http://demo.ipol.im/demo/my_affine_sift

[^3]:    ${ }^{6}$ available at http://www.robots.ox.ac.uk/ $\sim v g g /$ data/oxbuildings/
    ${ }^{7}$ assuming that the original image is in the fronto-parallel view

[^4]:    ${ }^{8}$ Reference code from http://demo.ipol.im/demo/my_affine_sift

