

TILDE: A Temporally Invariant Learned DETector

Yannick Verdie^{1,*} Kwang Moo Yi^{1,*} Pascal Fua¹ Vincent Lepetit²
¹Computer Vision Laboratory, École Polytechnique Fédérale de Lausanne (EPFL)
²Institute for Computer Graphics and Vision, Graz University of Technology
 {yannick.verdie, kwang.yi, pascal.fua}@epfl.ch, lepetit@icg.tugraz.at

Abstract

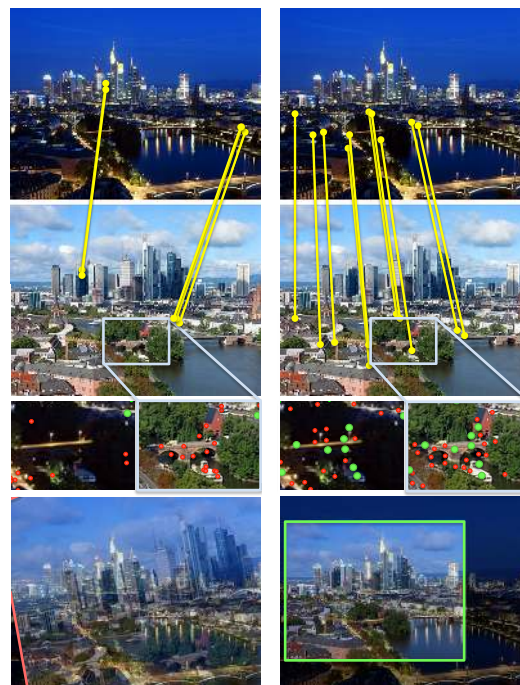
We introduce a learning-based approach to detect repeatable keypoints under drastic imaging changes of weather and lighting conditions to which state-of-the-art keypoint detectors are surprisingly sensitive. We first identify good keypoint candidates in multiple training images taken from the same viewpoint. We then train a regressor to predict a score map whose maxima are those points so that they can be found by simple non-maximum suppression.

As there are no standard datasets to test the influence of these kinds of changes, we created our own, which we will make publicly available. We will show that our method significantly outperforms the state-of-the-art methods in such challenging conditions, while still achieving state-of-the-art performance on untrained standard datasets.

1. Introduction

Keypoint detection and matching is an essential tool to address many Computer Vision problems such as image retrieval, object tracking, and image registration. Since the introduction of the Moravec, Förstner, and Harris corner detectors [27, 11, 15] in the 1980s, many others have been proposed [41, 10, 31]. Some exhibit excellent repeatability when the scale and viewpoint change or the images are blurred [26]. However, their reliability degrades significantly when the images are acquired outdoors at different times of day and in different weathers or seasons, as shown in Fig. 1. This is a severe handicap when attempting to match images taken in fair and foul weather, in the morning and evening, in winter and summer, even with illumination invariant descriptors [13, 39, 14, 43].

In this paper, we propose an approach to learn a keypoint detector that extracts keypoints which are stable under such challenging conditions and allow matching in situations as difficult as the one depicted by Fig. 1. To this end, we first



(a) With SURF [3] keypoints (b) With our keypoints

Figure 1: Image matching example using Speeded-Up Robust Features (SURF) [3] and our method. *Same number of keypoints and descriptor [23] was used for both keypoint detectors.* Detected keypoints are shown in the third row, with the repeated ones in green. For SURF, only one keypoint detected in the daytime image was detected in the nighttime image. Our method on the other hand returns many common keypoints regardless of the drastic lighting change. ¹

introduce a simple but effective method to identify potentially stable points in training images. We then use them to train a regressor that produces a score map whose values are local maxima at these locations. By running it on new images, we can extract keypoints with simple non-maximum suppression. Our approach is inspired by a recently proposed algorithm [34] that relies on regression to extract cen-

*First two authors contributed equally

¹Figures are best viewed in color.

terlines from images of linear structures. Using this idea for our purposes has required us to develop a new kind of regressor that is robust to complex appearance variation so that it can efficiently and reliably process the input images.

As in the successful application of Machine Learning to descriptors [5, 40] and edge detection [8], learning methods have also been used before in the context of keypoint detection [30, 37] to reduce the number of operations required when finding the *same* keypoints as handcrafted methods. However, in spite of an extensive literature search, we have only found one method [38] that attempts to improve the repeatability of keypoints by learning. This method focuses on learning a classifier to filter out initially detected keypoints but achieved limited improvement. This may be because their method was based on pure classification and also because it is non-trivial to find good keypoints to be learned by a classifier in the first place.

Probably as a consequence, there is currently no standard benchmark dataset designed to test the robustness of keypoint detectors to these kinds of temporal changes. We therefore created our own from images from the Archive of Many Outdoor Scenes (AMOS) [18] and our own panoramic images to validate our approach. We will use our dataset in addition to the standard *Oxford* [26] and *EF* [44] datasets to demonstrate that our approach significantly outperforms state-of-the-art methods in terms of repeatability. In the hope of spurring further research on this important topic, we will make it publicly available along with our code.

In summary, our contribution is threefold:

- We introduce a “Temporally Invariant Learned DEtector” (TILDE), a new regression-based approach to extracting feature points that are repeatable under drastic illumination changes caused by changes in weather, season, and time of day.
- We propose an effective method to generate the required training set of “good keypoints to learn.”
- We created a new benchmark dataset for evaluation of feature point detectors on outdoor images captured at different times and seasons.

In the remainder of this paper, we first discuss related work, give an overview of our approach, and then detail our regression-based approach. We finally present the comparison of our approach to state-of-the-art keypoint detectors.

2. Related Work

Handcrafted Keypoint Detectors An extraordinary large amount of work has been dedicated to developing ever more effective feature point detectors. Even though the methods that appeared in the 1980s [27, 11, 15] are still in wide use, many new ones have been developed since.

[10] proposed the SFOP detector to use junctions as well as blobs, based on a general spiral model. [17] and the WADE detector of [33] use symmetries to obtain reliable keypoints. With SIFER and D-SIFER, [25, 24] used Cosine Modulated Gaussian filters and 10th order Gaussian derivative filters for more robust detection of keypoints. Edge Foci [44] and [12] use edge information for robustness against illumination changes. Overall, these methods have consistently improved the performance of keypoint detectors on the standard dataset [26], but still suffer severe performance drop when applied to outdoor scenes with temporal differences.

One of the major drawbacks of handcrafted methods are that they cannot be easily adapted to the context, and consequently lack flexibility. For instance, SFOP [10] works well when calibrating cameras and WADE [33] shows good results when applied to objects with symmetries. However, their advantages are not easily carried on to the problem we tackle here, such as finding similar outdoor scenes [19].

Learned Keypoint Detectors Although work on keypoint detectors were mainly focused on handcrafted methods, some learning based methods have already been proposed [30, 38, 16, 28]. With FAST, [30] introduced Machine Learning techniques to learn a fast corner detector. However, learning in their case was only aimed toward the speed up of the keypoint extraction process. Repeatability is also considered in the extended version FAST-ER [31], but it did not play a significant role. [38] trained the Wald-Boost classifier [36] to learn keypoints with high repeatability on a pre-aligned training set, and then filter out an initial set of keypoints according to the score of the classifier. Their method, called TaSK, is probably the most related to our method in the sense that they use pre-aligned images to build the training set. However, the performance of their method is limited by the initial keypoint detector used.

Recently, [16] proposed to learn a classifier which detects *matchable* keypoints for Structure-from-Motion (SfM) applications. They collect *matchable* keypoints by observing which keypoints are retained throughout the SfM pipeline and learn these keypoints. Although their method shows significant speed-up, they remain limited by the quality of the initial keypoint detector. [28] learns convolutional filters through random sampling and looking for the filter that gives the smallest pose estimation error when applied to stereo visual odometry. Unfortunately, their method is restricted to linear filters, which are limited in terms of flexibility, and it is not clear how their method can be applied to other tasks than stereo visual odometry.

We propose a generic scheme for learning keypoint detectors, and a novel efficient regressor specified for this task. We will compare it to state-of-the-art handcrafted methods as well as TaSK, as it is the closest method from the literature, on several datasets.

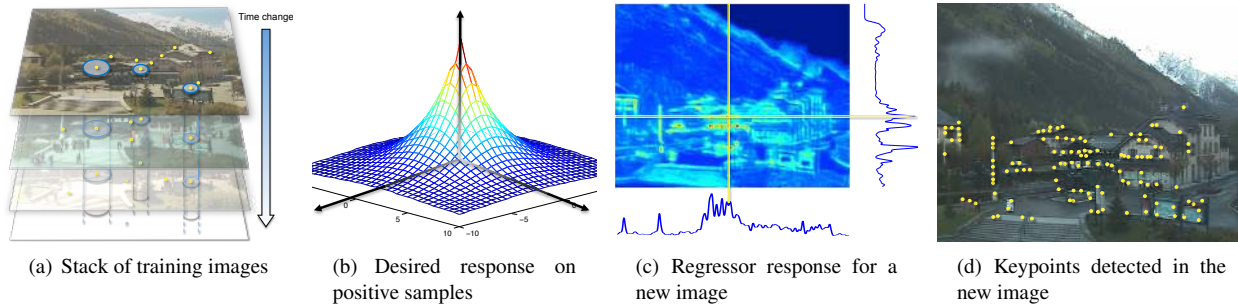


Figure 2: Overview of our approach. We rely on a stack of training images, captured from the same viewpoint but under different illuminations (a), and a simple method to select good keypoints to learn. We train a regressor on image patches to return peaked values like in (b) at the keypoint locations, and small values far from these locations. Applying this regressor to each patch of a new image gives us a score map such as the one in (c), from which we can extract keypoints as in (d) by looking for local maxima with large values.

3. Learning a Robust Keypoint Detector

In this section, we first outline our regression-based approach briefly and then explain how we build the required training set. We will formalize our algorithm and describe the regressor in more details in the following section.

3.1. Overview of our Approach

Let us first assume that we have a set of training images of the same scene captured from the same point of view but at different seasons and different times of the day, such as the set of Fig. 2(a). Let us further assume that we have identified in these images a set of locations that we think can be found consistently over the different imaging conditions. We propose a practical way of doing this in Section 3.2 below. Let us call *positive samples* the image patches centered at these locations in each training image. The patches far away from these locations are *negative samples*.

To learn to find these locations in a new input image, we propose to train a regressor to return a value for each patch of a given size of the input image. These values should have a peaked shape similar to the one shown in Fig. 2(b) on the positive samples, and we also encourage the regressor to produce a score that is as small as possible for the negative samples. As shown in Fig. 2(c), we can then extract keypoints by looking for local maxima of the values returned by the regressor, and discard the image locations with low values by simple thresholding. Moreover, our regressor is also trained to return similar values for the same locations over the stack of images. This way, the regressor returns consistent values even when the illumination conditions vary.

3.2. Creating the Training Set

As shown in Fig. 3, to create our dataset of positive and negative samples, we first collected series of images from outdoor webcams captured at different times of day and

different seasons. We identified several suitable webcams from the *AMOS* dataset [18]—webcams that remained fixed over long periods of time, protected from the rain, etc. We also used panoramic images captured by a camera located on the top of a building.

To collect a training set of positive samples, we first detect keypoints independently in each image of this dataset. We use SIFT [23], but other detectors could be considered as well. We then iterate over the detected keypoints, starting with the keypoints with the smallest scale. If a keypoint is detected at about the same location in most of the images from the same webcam, its location is likely to be a good candidate to learn.

In practice we consider that two keypoints are at about the same location if their distance is smaller than the scale estimated by SIFT and we keep the best 100 repeated locations. The set of positive samples is then made of the patches from *all* the images, including the ones where the keypoint was not detected, and centered on the average location of the detections.

This simple strategy offers several advantages: we keep only the most repeatable keypoints for training, discarding the ones that were detected only infrequently. We also introduce as positive samples the patches where a highly repeatable keypoint was missed. This way, we can focus on the keypoints that can be detected reliably under different conditions, and correct the mistakes of the original detector.

To create the set of negative samples, we simply extract patches at locations that are far away from the keypoints used to create the set of positive samples.

4. An Efficient Piece-wise Linear Regressor

In this section, we first introduce the form of our regressor, which is made to be applied to every patch from an image efficiently, then we describe the different terms of the proposed objective function to train for detecting keypoints

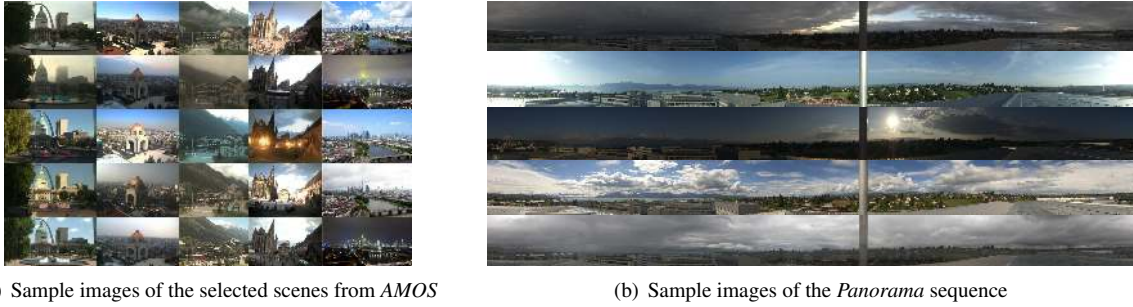


Figure 3: Example figures from the *Webcam* dataset. The *Webcam* dataset is composed of six scenes from various locations: (a) five scenes taken from the Archive of Many Outdoor Scenes (AMOS) dataset [18], namely *StLouis*, *Mexico*, *Chamonix*, *Courbevoie*, and *Frankfurt*. (b) *Panorama* scenes from the roof of a building which shows a 360 degrees view.

reliably, and finally we explain how we optimize the parameters of our regressor to minimize this objective function.

4.1. A Piece-wise Linear Regressor

Our regressor is a piece-wise linear function expressed using Generalized Hinging Hyperplanes (GHH) [4, 42]:

$$\mathbf{F}(\mathbf{x}; \omega) = \sum_{n=1}^N \delta_n \max_{m=1}^M \mathbf{w}_{nm}^\top \mathbf{x} , \quad (1)$$

where \mathbf{x} is a vector made of image features extracted from an image patch, ω is the vector of parameters of the regressor and can be decomposed into $\omega = [\mathbf{w}_{11}^\top, \dots, \mathbf{w}_{MN}^\top, \delta_1, \dots, \delta_N]^\top$. The \mathbf{w}_{nm} vectors can be seen as linear filters. The parameters δ_n are constrained to be either -1 or +1. N and M are meta-parameters which control the complexity of the GHH. As image features we use the three components of the LUV color space and the image gradients—horizontal and vertical gradients and the gradient magnitude—computed at each pixel of the \mathbf{x} patches.

[42] showed that any continuous piecewise-linear function can be expressed in the form of Eq. (1). It is well suited to our keypoint detector learning problem, since applying the regressor to each location of the image involves only simple image convolutions and pixel-wise maximum operators, while regression trees require random access to the image and the nodes, and CNNs involve higher-order convolutions for most of the layers. Moreover, we will show that this formulation also facilitates the integration of different constraints, including constraints between the responses for neighbor locations, which are useful to improve the performance of the keypoint extraction.

Instead of simply aiming to predict the score computed from the distance to the closest keypoint in a way similar to what was done in [34], we argue that it is also important to distinguish the image locations that are close to keypoints from those that are far away. The values returned by the regressor for image locations close to keypoints should have

a local maximum at the keypoint locations, while the actual values for the locations far from the keypoints are irrelevant as long as they are small enough to discard them by simple thresholding. We therefore first introduce a classification-like term that enforces the separation between these two different types of image locations. We also rely on a term that enforces the response to have a local maximum at the keypoint locations, and a term that regularizes the responses of the regressor over time. To summarize, the objective function \mathcal{L} we minimize over the parameters ω of our regressor can be written as the sum of three terms:

$$\underset{\omega}{\text{minimize}} \quad \mathcal{L}_c(\omega) + \mathcal{L}_s(\omega) + \mathcal{L}_t(\omega) . \quad (2)$$

4.2. Objective Function

In this subsection we describe in detail the three terms of the objective function introduced in Eq. (2). The individual influences of each term are evaluated empirically and discussed in Section 5.4.

Classification-Like Loss \mathcal{L}_c As explained above, this term is useful to separate well the image locations that are close to keypoints from the ones that are far away. It relies on a max-margin loss, as in traditional SVM [7]. In particular, we define it as:

$$\mathcal{L}_c(\omega) = \gamma_c \|\omega\|_2^2 + \frac{1}{K} \sum_{i=1}^K \max(0, 1 - y_i \mathbf{F}(\mathbf{x}_i; \omega))^2 , \quad (3)$$

where γ_c is a meta-parameter, $y_i \in \{-1, +1\}$ is the label for the sample \mathbf{x}_i , and K is the number of training data.

Shape Regularizer Loss \mathcal{L}_s To have local maxima at the keypoint locations, we enforce the response of the regressor to have a specific shape at these locations. For each positive sample i , we force the response shape by defining a loss term related to the desired response shape \mathbf{h} , similar to the

one used in [34] and shown in Fig. 2(b):

$$\mathbf{h}(x, y) = e^{\alpha(1 - \frac{\sqrt{x^2 + y^2}}{\beta})} - 1, \quad (4)$$

where x, y are pixel coordinates with respect to the center of the patch, and α, β meta-parameters influencing the sharpness of the shape.

However, we want to enforce only the general shape and not the scale of the responses to not interfere with the classification-like term \mathcal{L}_c . We therefore introduce an additional term defined as:

$$\mathcal{L}_s(\omega) = \frac{\gamma_s}{K_p} \sum_{i|y_i=+1} \sum_n \left\| \mathbf{w}_{n\eta_i(n)} * \mathbf{x}_i - (\mathbf{w}_{n\eta_i(n)}^\top \mathbf{x}_i) \mathbf{h} \right\|_2^2, \quad (5)$$

where $*$ denotes the convolution product, K_p is the number of positive samples; γ_s is a meta-parameter for weighting the term that will be estimated by cross-validation. $\eta_i(n) = \arg \max_m \mathbf{w}_{nm}^\top \mathbf{x}_i$ is used to enforce the shape constraints only on the filters that contribute to the regressor response of the max operator.

It turns out that it is more convenient to perform the optimization of this term in the Fourier domain. If we denote the 2D Fourier transform of $\mathbf{w}_{nm}, \mathbf{x}_i$, and \mathbf{h} as $\mathbf{W}_{nm}, \mathbf{X}_i$, and \mathbf{H} , respectively, then by applying Parseval's theorem and the Convolution theorem, Eq. (5) becomes ².

$$\mathcal{L}_s(\omega) = \frac{\gamma_s}{K_p} \sum_{i|y_i=+1} \sum_n \mathbf{W}_{n\eta_i(n)}^\top \mathbf{S}_i^\top \mathbf{S}_i \mathbf{W}_{n\eta_i(n)}, \quad (6)$$

where

$$\mathbf{S}_i = (\text{diag}(\mathbf{X}_i) - \mathbf{X}_i \mathbf{H})^\top. \quad (7)$$

This way of enforcing the shape of the responses is a generalization of the approach of [29] to any type of shape. In practice, we approximate \mathbf{S}_i with the mean over all positive training samples for efficient learning. We also use Parseval's theorem and the feature mapping proposed in Ashraf *et al.*'s work [2] for easy calculation ².

Temporal Regularizer Loss \mathcal{L}_t To enforce the repeatability of the regressor over time, we force the regressor to have similar responses at the same locations over the stack of training images. This is simply done by adding a term \mathcal{L}_t defined as:

$$\mathcal{L}_t(\omega) = \frac{\gamma_t}{K} \sum_{i=1}^K \sum_{j \in \mathcal{N}_i} (\mathbf{F}(\mathbf{x}_i; \omega) - \mathbf{F}(\mathbf{x}_j; \omega))^2, \quad (8)$$

where \mathcal{N}_i is the set of samples at the same image locations as \mathbf{x}_i but from the other training images of the stack. γ_t is again a meta-parameter to weight this term.

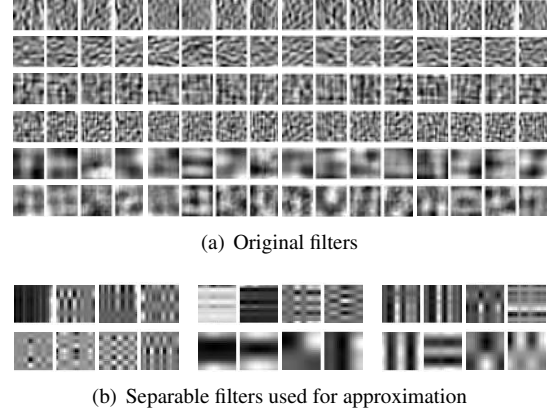


Figure 4: (a) The original 96 linear filters \mathbf{w}_{nm} learned by our method on the *StLouis* sequence. Each row corresponds to a different image feature, respectively the horizontal image gradient, the vertical image gradient, the magnitude of the gradient, and the three color components in the LUV color space. (b) The 24 separable filters learned for each dimension independently using the method of [35]. Each original filter can be approximated as a linear combination of the separable filters, which can be convolved with the input images very efficiently.

4.3. Learning the Piece-wise Linear Regressor

Optimization After dimension reduction using Principal Component Analysis (PCA) applied to the training samples to decrease the number of parameters to optimize, we solve Eq. (2) through a greedy procedure similar to gradient boosting. We start with an empty set of hyperplanes $\mathbf{w}_{n,m}$ and we iteratively add new hyperplanes that minimize the objective function until we reach the desired number (we use $N = 4$ and $M = 4$ in our experiments). To estimate the hyperplane to add, we apply a trust region Newton method [22], as in the widely-used LibLinear library [9].

After initialization, we randomly go through the hyperplanes one by one and update them with the same Newton optimization method. Fig. 4(a) shows the filters learned by our method on the *StLouis* sequence. We perform a simple cross-validation using grid search in log-scale to estimate the meta-parameters γ_c, γ_s , and γ_t on a validation set.

Approximation To further speed up our regressor, we approximate the learned linear filters with linear combinations of separable filters using the method proposed in [35]. Convolutions with separable filters are significantly faster than convolutions with non-separable ones, and the approximation is typically very good. Fig. 4(b) shows an example of such approximated filters.

² See Appendix in the supplemental material for derivation

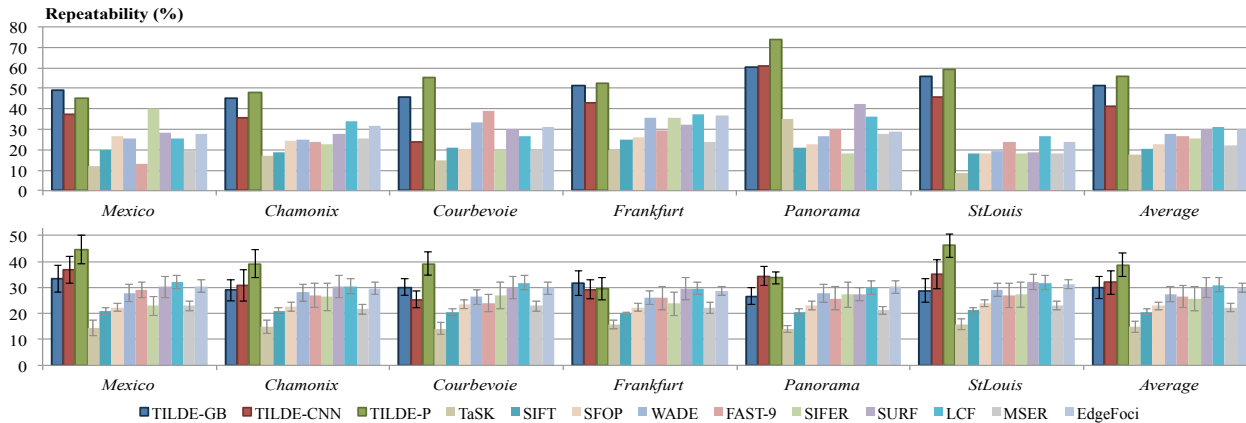


Figure 5: Repeatability (2%) score on the *Webcam* dataset. **Top:** average repeatability scores for each sequence trained on the respective sequences. **Bottom:** average repeatability score when trained on one sequence (the name of the training sequence is given below each graph) and tested on all other sequences. Although the gap reduces on the bottom graph, our method significantly outperforms the state-of-the-art in both cases, which shows that our method can generalise to unseen scenes.

5. Results

In this section we first describe our experimental setup and present both quantitative and qualitative results on our *Webcam* dataset and the standard *Oxford* and *EF* dataset.

5.1. Experimental Setup

We compare our approach to TaSK, SIFT, SFOP, WADE, FAST-9, SIFER, SURF, LCF, MSER, and EdgeFoci³. In the following, our full method will be denoted TILDE-P. TILDE-P24 denotes the same method, after approximation of the piece-wise linear regressor using 24 separable filters.

To evaluate our regressor itself, we also compared it against two other regressors. The first regressor, denoted TILDE-GB, is based on boosted regression trees and is an adaptation of the one used in [34] for centerline detection to keypoint detection, with the same parameters used for implementation as in the original work. The second regressor we tried, denoted TILDE-CNN, is a Convolutional Neural Network, with an architecture similar to the LeNet-5 network [20] but with an additional convolution layer and a max-pooling layer. The first, third, and fifth layers are convolutional layers; the first layer has a resolution of 28×28 and filters of size 5×5 , the third layer has 10 feature maps of size 12×12 and filters of size 5×5 , and the fifth layer 50 feature maps of size 4×4 , and filters of size 3×3 . The second, fourth, and sixth layers are max-pooling layers of size 2×2 . The seventh layer is a layer of 500 neurons fully connected to the previous layer, which is followed by the eighth layer which is a fully-connected layer with a sigmoid activation function, followed by the final output layer. For the output layer we use the l_2 regression cost function.

³See the supplementary material for implementation details.

5.2. Quantitative Results

We thoroughly evaluated the performance of our approach using the same repeatability measure as [31], on our *Webcam* dataset, and the *Oxford* and *EF* datasets. The repeatability is defined as the number of keypoints consistently detected across two aligned images. As in [31] we consider keypoints that are less than 5 pixels apart when projected to the same image as repeated. However, the repeatability measure has two caveats: First, a keypoint close to several projections can be counted several times. Moreover, with a large enough number of keypoints, even simple random sampling can achieve high repeatability as the density of the keypoints becomes high.

We therefore make this measure more representative of the performance with two modifications: First, we allow a keypoint to be associated only with its nearest neighbor, in other words, a keypoint cannot be used more than once when evaluating repeatability. Second, we restrict the number of keypoints to a small given number, so that picking the keypoints at random locations would result with a repeatability score of only 2%, reported as *Repeatability (2%)* in the experiments.

We also include results using the standard repeatability score, 1000 keypoints per image, and a fixed scale of 10 for our methods, which we refer to as *Oxford Stand.* and *EF Stand.*, for comparison with previous papers, such as [26, 44]. Table 1 shows a summary of the quantitative results.

5.2.1 Repeatability on our Webcam Dataset

Fig. 5 gives the repeatability scores for our *Webcam* dataset. Fig. 5-top shows the results of our method when trained on each sequence and tested on the same sequence, with

Table 1: Repeatability performance of our best regressors. The best results are in bold. Our approach provides the highest repeatability, when using our piece-wise linear regressor. Note that on *Oxford* and *EF* datasets the performance are slightly better when using smaller number of separable filters to approximate the original ones, probably because the approximated filters tend to be smoother.

#keypoints	<i>Webcam</i>		<i>Oxford</i>		<i>EF</i>	
	(2%)	<i>Stand.</i>	(2%)	<i>Stand.</i>	(2%)	<i>Stand.</i>
TILDE-GB	33.3	54.5	32.8	43.1	16.2	
TILDE-CNN	36.8	51.8	49.3	43.2	27.6	
TILDE-P24	40.7	58.7	59.1	46.3	33.0	
TILDE-P	48.3	58.1	55.9	45.1	31.6	
FAST-9	26.4	53.8	47.9	39.0	28.0	
SFOP	22.9	51.3	39.3	42.2	21.2	
SIFER	25.7	45.1	40.1	27.4	17.6	
SIFT	20.7	46.5	43.6	32.2	23.0	
SURF	29.9	56.9	57.6	43.6	28.7	
TaSK	14.5	25.7	15.7	22.8	10.0	
WADE	27.5	44.3	51.0	25.6	28.6	
MSER	22.3	51.5	35.9	38.9	23.9	
LCF	30.9	55.0	40.1	41.6	23.1	
EdgeFoci	30.0	54.9	47.5	46.2	31.0	

the set of images divided into disjoint train, validation, and test sets. Fig. 5-bottom shows the results when we apply our detector trained on one sequence to all other unseen sequences from the *Webcam* dataset. We significantly outperform state-of-the-art methods when using a detector trained specifically to each sequence. Moreover, while the gap is reduced when we test on un-seen sequences, we still outperform all compared methods by a significant margin, showing the generalization capability of our method.

5.2.2 Repeatability on Oxford and EF Datasets

In Fig. 8 we also evaluate our method on *Oxford* and *EF* datasets. *Oxford* dataset is simpler in the sense that it does not exhibit the drastic changes of the *Webcam* dataset but it is a reference for the evaluation of keypoint detectors. *EF* dataset on the other hand exhibits drastic illumination changes and is very challenging. It is therefore interesting to evaluate our approach on these datasets.

Instead of learning a new keypoint detector on this dataset, we apply the detector learned using the *Chamonix* sequence from the *Webcam* dataset. Our method still achieves state-of-the-art performance. We even significantly outperform state-of-the-art methods in the case of the *Bikes*, *Trees*, *Leuven* and *Rushmore* images, which are outdoor scenes. Note that we also obtain good results for *Boat* which has large scale changes, although we currently do not consider scale in learning and detecting. Repeatability

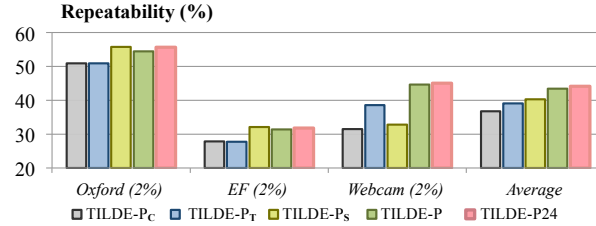


Figure 6: Effects of the three terms of the objective function, and of the approximation using separable filters.

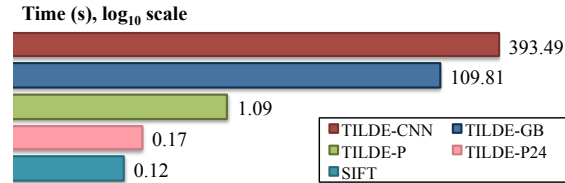


Figure 7: Time comparison for the full pipeline of our various regressors compared with the SIFT detector. Evaluations were run on the same machine on an 640×418 image.

score shown here is lower than what was reported in previous works [26, 31] as we consider a smaller number of keypoints. As mentioned before, considering a large number of keypoints artificially improves the repeatability score.

5.3. Qualitative Results

We also give in Fig. 9 some qualitative results on the task of matching challenging pairs of images captured at different days under different weather conditions. Our matching pipeline is as follow: we first extract keypoints in both images using the different methods we want to compare, compute the keypoints descriptors, and compute the homography between the two images using RANSAC. Since the goal of this comparison is to evaluate keypoints not descriptors, we use the SIFT descriptor for all methods. Note that we also tried using other descriptors [3, 32, 6, 1, 21] but due to the drastic difference between the matched images, only SIFT descriptors with ground truth orientation and scale worked. We compare our method with the SIFT [23], SURF [3], and FAST-9 [31] detectors, using the same number of keypoints (300) for all methods. Our method allows to retrieve the correct transformations between the images even under such drastic changes of the scene appearance.

5.4. Effects of the Three Loss Terms

Fig. 6 gives the results of the evaluation of the influence of each loss term of Eq. (2) by evaluating the performance of our detector without each term. We will refer to our method when using only the classification loss as TILDE-PC, when using both classification loss and the temporal regularization as TILDE-PT, and when using the classification loss and the shape regularization as TILDE-PS.

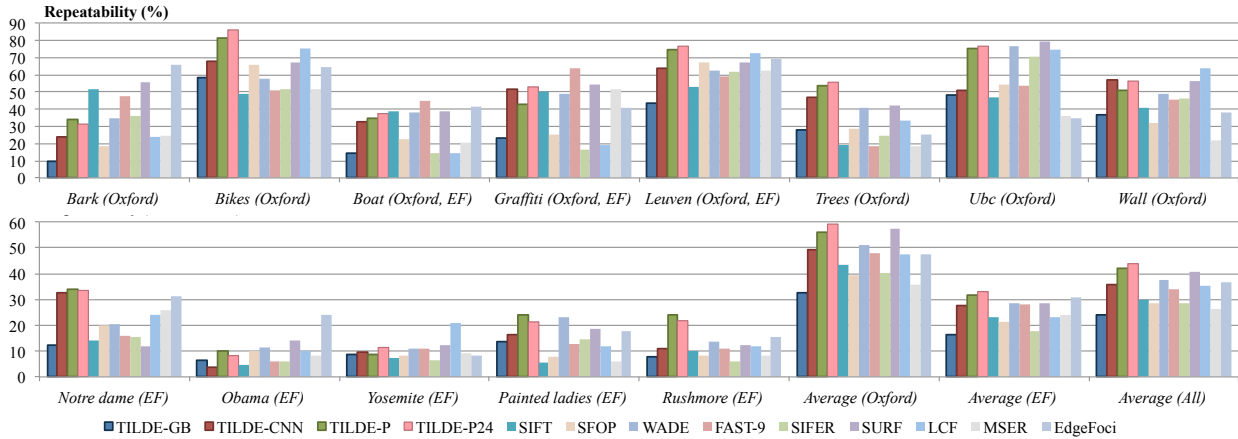


Figure 8: Repeatability (2%) score on the *Oxford* and *EF* datasets. Our methods are trained on the *Chamonix* sequence from the *Webcam* dataset and tested on *Oxford* and *EF* datasets.

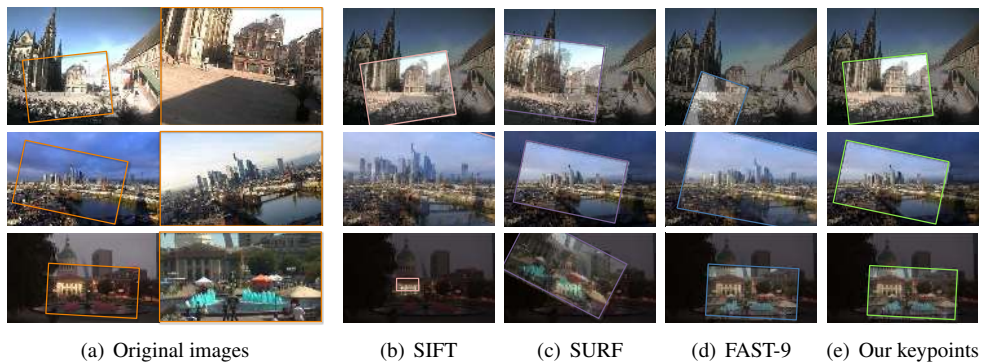


Figure 9: Qualitative results on several images from different sequences. From top to bottom: *Courbevoie*, *Frankfurt*, and *StLouis*. (a) Pairs of images to be matched, with ground truth transformation, transformations obtained with (b) the SIFT detector, (c) the SURF detector, (d) the FAST-9 detector, and (e) our TILDE detector.

We achieve the best performance when all three terms are used together. Note that the shape regularization enhances the repeatability on *Oxford* and *EF*, two completely unseen datasets, whereas the temporal regularization helps when we test on images which are similar to the training set.

5.5. Computation Times

Fig. 7 gives the computation time of SIFT and each variant of our method. TILDE-P24 is not very far from SIFT. Note that our method is highly parallelizable, while our current implementation does not benefit from any parallelization. We therefore believe that our method can be significantly sped up with a better implementation.

6. Conclusion

We have introduced a learning scheme to detect keypoints reliably under drastic changes of weather and light-

ing conditions. We proposed an effective method for generating the training set to learn regressors. We learned three regressors, which among them, the piece-wise linear regressor showed best result. We evaluated our regressors on our new outdoor keypoint benchmark dataset. Our regressors significantly outperforms the current state-of-the-art on our new benchmark dataset and also achieve state-of-the-art performances on *Oxford* and *EF* datasets, demonstrating their generalisation capability.

An interesting future research direction is to extend our method to scale space. For example, the strategy applied in [21] to FAST can be directly applied to our method.

Acknowledgement

This work was supported in part by the EU FP7 project MAGELLAN under the grant number ICT-FP7-611526 and in part by the EU project EDUSAFE.

References

- [1] A. Alahi, R. Ortiz, and P. Vandergheynst. FREAK: Fast Retina Keypoint. In *Conference on Computer Vision and Pattern Recognition*, 2012. 7
- [2] A. B. Ashraf, S. Lucey, and T. Chen. Reinterpreting the Application of Gabor Filters as a Manipulation of the Margin in Linear Support Vector Machines. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 32(7):1335–1341, 2010. 5
- [3] H. Bay, A. Ess, T. Tuytelaars, and L. Van Gool. SURF: Speeded Up Robust Features. *Computer Vision and Image Understanding*, 10(3):346–359, 2008. 1, 7
- [4] L. Breiman. Hinging Hyperplanes for Regression, Classification, and Function Approximation. *IEEE Transactions on Information Theory*, 39(3):999–1013, 1993. 4
- [5] M. Brown, G. Hua, and S. Winder. Discriminative Learning of Local Image Descriptors. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 2011. 2
- [6] M. Calonder, V. Lepetit, C. Strecha, and P. Fua. BRIEF: Binary Robust Independent Elementary Features. In *European Conference on Computer Vision*, September 2010. 7
- [7] C. Cortes and V. Vapnik. Support-Vector Networks. *Machine Learning*, 20(3):273–297, 1995. 4
- [8] P. Dollar, Z. Tu, and S. Belongie. Supervised Learning of Edges and Object Boundaries. In *Conference on Computer Vision and Pattern Recognition*, 2006. 2
- [9] R.-E. Fan, K.-W. Chang, C.-J. Hsieh, X.-R. Wang, and C.-J. Lin. LIBLINEAR: A Library for Large Linear Classification. *Journal of Machine Learning Research*, 9:1871–1874, 2008. 5
- [10] W. Förstner, T. Dickscheid, and F. Schindler. Detecting Interpretable and Accurate Scale-Invariant Keypoints. In *International Conference on Computer Vision*, September 2009. 1, 2
- [11] W. Förstner and E. Gülch. A Fast Operator for Detection and Precise Location of Distinct Points, Corners and Centres of Circular Features. In *ISPRS Intercommission Conference on Fast Processing of Photogrammetric Data*, 1987. 1, 2
- [12] W. Guan and S. You. Robust Image Matching with Line Context. In *British Machine Vision Conference*, 2013. 2
- [13] R. Gupta and A. Mittal. SMD: A Locally Stable Monotonic Change Invariant Feature Descriptor. In *European Conference on Computer Vision*, 2008. 1
- [14] R. Gupta, H. Patil, and A. Mittal. Robust Order-based Methods for Feature Description. In *Conference on Computer Vision and Pattern Recognition*, 2010. 1
- [15] C. Harris and M. Stephens. A Combined Corner and Edge Detector. In *Fourth Alvey Vision Conference*, 1988. 1, 2
- [16] W. Hartmann, M. Havlena, and K. Schindler. Predicting Matchability. In *Conference on Computer Vision and Pattern Recognition*, June 2014. 2
- [17] D. Hauagge and N. Snavely. Image Matching Using Local Symmetry Features. In *Conference on Computer Vision and Pattern Recognition*, June 2012. 2
- [18] N. Jacobs, N. Roman, and R. Pless. Consistent Temporal Variations in Many Outdoor Scenes. In *Conference on Computer Vision and Pattern Recognition*, 2007. 2, 3, 4
- [19] P.-Y. Laffont, Z. Ren, X. Tao, C. Qian, and J. Hays. Transient Attributes for High-Level Understanding and Editing of Outdoor Scenes. *ACM Transactions on Graphics*, 33(4):149, 2014. 2
- [20] Y. LeCun, L. Bottou, Y. Bengio, and P. Haffner. Gradient-Based Learning Applied to Document Recognition. *Proceedings of the IEEE*, 1998. 6
- [21] S. Leutenegger, M. Chli, and R. Siegwart. BRISK: Binary Robust Invariant Scalable Keypoints. In *International Conference on Computer Vision*, 2011. 7, 8
- [22] C. J. Lin, R. C. Weng, and S. S. Keerthi. Trust Region Newton Method for Logistic Regression. *Journal of Machine Learning Research*, 9:627–650, 2008. 5
- [23] D. Lowe. Distinctive Image Features from Scale-Invariant Keypoints. *International Journal of Computer Vision*, 20(2), 2004. 1, 3, 7
- [24] P. Mainali, G. Lafruit, K. Tack, L. Van Gool, and R. Lauwereins. Derivative-Based Scale Invariant Image Feature Detector with Error Resilience. *IEEE Transactions on Image Processing*, 23(5):2380–2391, 2014. 2
- [25] P. Mainali, G. Lafruit, Q. Yang, B. Geelen, L. Van Gool, and R. Lauwereins. SIFER: Scale-Invariant Feature Detector with Error Resilience. *International Journal of Computer Vision*, 104(2):172–197, 2013. 2
- [26] K. Mikolajczyk, T. Tuytelaars, C. Schmid, A. Zisserman, J. Matas, F. Schaffalitzky, T. Kadir, and L. Van Gool. A Comparison of Affine Region Detectors. *International Journal of Computer Vision*, 65(1/2):43–72, 2005. 1, 2, 6, 7
- [27] H. Moravec. Obstacle Avoidance and Navigation in the Real World by a Seeing Robot Rover. In *tech. report CMU-RI-TR-80-03, Robotics Institute, Carnegie Mellon University, Stanford University*, September 1980. 1, 2
- [28] A. Richardson and E. Olson. Learning Convolutional Filters for Interest Point Detection. In *International Conference on Robotics and Automation*, pages 631–637, May 2013. 2
- [29] A. Rodriguez, V. N. Boddeti, B. V. Kumar, and A. Mahalanobis. Maximum Margin Correlation Filter: A New Approach for Localization and Classification. *IEEE Transactions on Image Processing*, 22(2):631–643, 2013. 5
- [30] E. Rosten and T. Drummond. Machine Learning for High-Speed Corner Detection. In *European Conference on Computer Vision*, 2006. 2
- [31] E. Rosten, R. Porter, and T. Drummond. Faster and Better: A Machine Learning Approach to Corner Detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 32:105–119, 2010. 1, 2, 6, 7
- [32] E. Rublee, V. Rabaud, K. Konolidge, and G. Bradski. ORB: An Efficient Alternative to SIFT or SURF. In *International Conference on Computer Vision*, 2011. 7
- [33] S. Salti, A. Lanza, and L. D. Stefano. Keypoints from Symmetries by Wave Propagation. In *Conference on Computer Vision and Pattern Recognition*, June 2013. 2
- [34] A. Sironi, V. Lepetit, and P. Fua. Multiscale Centerline Detection by Learning a Scale-Space Distance Transform. In *Conference on Computer Vision and Pattern Recognition*, 2014. 1, 4, 5, 6

- [35] A. Sironi, B. Tekin, R. Rigamonti, V. Lepetit, and P. Fua. Learning Separable Filters. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 37(1):94–106, 2015. [5](#)
- [36] J. Šochman and J. Matas. Waldboost - Learning for Time Constrained Sequential Detection. In *Conference on Computer Vision and Pattern Recognition*, pages 150–157, June 2005. [2](#)
- [37] J. Šochman and J. Matas. Learning a Fast Emulator of a Binary Decision Process. In *Asian Conference on Computer Vision*, pages 236–245, 2007. [2](#)
- [38] C. Strecha, A. Lindner, K. Ali, and P. Fua. Training for Task Specific Keypoint Detection. In *DAGM Symposium on Pattern Recognition*, 2009. [2](#)
- [39] F. Tang, S. Lim, N. Chang, and H. Tao. A Novel Feature Descriptor Invariant to Complex Brightness Changes. In *CVPR*, 2009. [1](#)
- [40] T. Trzcinski, M. Christoudias, P. Fua, and V. Lepetit. Boosting Binary Keypoint Descriptors. In *Conference on Computer Vision and Pattern Recognition*, June 2013. [2](#)
- [41] T. Tuytelaars and K. Mikolajczyk. Local Invariant Feature Detectors: A Survey. *Found. Trends. Comput. Graph. Vis.*, 3(3):177–280, July 2008. [1](#)
- [42] S. Wang and X. Sun. Generalization of Hinging Hyperplanes. *IEEE Transactions on Information Theory*, 51(12):4425–4431, 2005. [4](#)
- [43] Z. Wang, B. Fan, and F. Wu. Local Intensity Order Pattern for Feature Description. In *International Conference on Computer Vision*, 2011. [1](#)
- [44] C. Zitnick and K. Ramnath. Edge Foci Interest Points. In *International Conference on Computer Vision*, 2011. [2](#), [6](#)