

# Active Shape Models with SIFT Descriptors and MARS

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Keywords: Facial Landmark, Active Shape Model, Multivariate Adaptive Regression Splines.

Abstract: We present a technique for locating landmarks in images of human faces. We replace the 1D gradient profiles of the classical Active Shape Model (ASM) (Cootes and Taylor, 1993) with a simplified form of SIFT descriptors (Lowe, 2004), and use Multivariate Adaptive Regression Splines (MARS) (Friedman, 1991) for descriptor matching. This modified ASM is fast and performs well against existing techniques for automatic face landmarking on frontal faces.

## 1 INTRODUCTION

In this paper we use the Active Shape Model (ASM) of (Cootes et al., 1995) for locating facial landmarks, but use a simplified form of SIFT (Lowe, 2004) descriptors for template matching, replacing the 1D profiles used in the classical model. Additionally, we use Multivariate Adaptive Regression Splines (MARS) (Friedman, 1991) to efficiently match these descriptors around the landmark. We also introduce techniques for significantly decreasing their computational load, making SIFT based ASMs useable in practical applications.

First a brief overview of ASMs. For details see (Cootes and Taylor, 2004). A *landmark* represents a distinguishable point present in most of the images under consideration, for example the nose tip (Figure 1). A set of landmarks forms a face shape. The ASM starts the search for landmarks from the mean

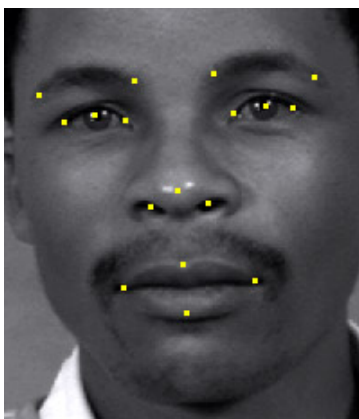


Figure 1: A landmarked face (Milborrow et al., 2010).

training face shape aligned to the position and size of the image face determined by a global face detector. It then repeats the following two steps until convergence:

(i) Suggest a new shape by adjusting the current positions of the landmarks. To do this at each landmark it samples image patches in the neighborhood of the landmark's current position. The landmark is then moved to the center of the patch which best matches the landmark's model descriptor. (The landmark's model descriptor is generated during model training prior to the search.)

(ii) Conform the suggested shape to a global shape model. This pools the results of the individual matchers and corrects points that are obviously mispositioned. The shape model is necessary because each matcher sees only a small portion of the face and cannot be completely reliable (Figure 2).

The entire search is repeated at each level in an image pyramid, typically four levels from coarse to fine resolution. In this paper our focus is on step (i), the template matching step. We leave step (ii) unchanged.

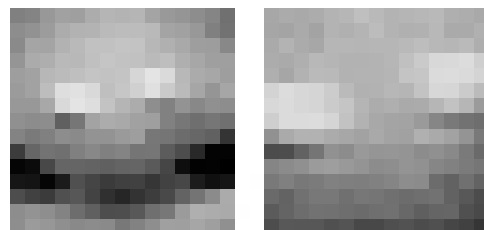


Figure 2:  $15 \times 15$  patches of the nose tip in Figure 1. The left patch is at half image scale; the right is at full scale.

## 2 RELATED WORK

Numerous proposals have been made to replace the 1D profiles of the classical ASM. We mention just a few SIFT based schemes, emphasizing facial applications. (Zhou et al., 2009) use SIFT descriptors with Mahalanobis distances. They report improved eye and mouth positions on the FGRCv2.0 database. (Li et al., 2009) use SIFT descriptors with GentleBoost. (Kanaujia and Metaxas, 2007) use SIFT descriptors with multiple shape models clustered on different face poses. (Belhumeur et al., 2011) use SIFT descriptors with SVMs and RANSAC. They report excellent fits, albeit at speeds orders of magnitude slower than ours. (Shi and Shen, 2008) use SIFT descriptors in hierarchical ASM models for medical images. SIFT descriptors for face data are also used in (Querini and Italiano, 2012; Rattani et al., 2007; Zhang and Chen, 2008; Zhang et al., 2011).

Multivariate Adaptive Regression Splines (MARS) is a general purpose regression technique introduced by Jerome Friedman in a 1990 paper (Friedman, 1991). MARS has been shown to perform well in diverse applications e.g. (Leathwick et al., 2005; Vogel et al., 2010), although it is apparently not well known in the image processing community. For our purposes the principal advantage of MARS over related nonparametric regression methods like SVMs is its prediction speed. Also making it attractive are short training times and interpretability of the models it creates

## 3 SIFT DESCRIPTORS

A descriptor for template matching captures some distinguishing quality of the image feature in question. In the ASM context, we want descriptors to capture the nature of say the inner corner of the left eye. A simple example is the “gradient descriptor”, which takes the form of an array with the same dimensions as the image patch; each element of the array is the gradient or gradient magnitude at the corresponding pixel in the patch. Typically the descriptor is normalized to unit length. The classical ASM uses 1D gradient descriptors. Gradients are invariant to affine lighting changes, but not to other changes, so researchers have devised more sophisticated techniques.

In this section we give an overview of the SIFT descriptors which form the basis of the “HAT” descriptors used in our version of the ASM. The next section will then describe how HAT descriptors differ from SIFTs. We chose SIFT descriptors for investigation because of their well known good sensi-

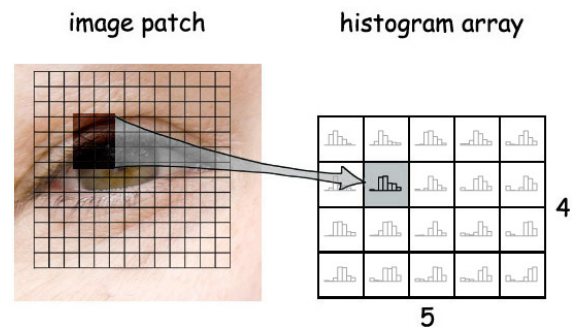


Figure 3: An area in the patch maps to a cell in the histogram array.

tivity and specificity properties. Details can be found in David Lowe’s paper (Lowe, 2004). Precedents for the orientation histograms used in SIFT can be found in e.g. (Belongie et al., 2002; Freeman and Roth, 1995).

The SIFT descriptor takes the form of an array of histograms (Figure 3). The descriptor is generated from a rectangular patch around the image point of interest. Ignoring interpolation for now, coordinates in the patch map to cells in the histogram array. We use a  $15 \times 15$  patch and an array of  $4 \times 5$  histograms. These dimensions were determined during our ASM training; other values are also in common use. The low spatial resolution of the histogram array helps provide immunity to small changes within the patch while still picking up overall structure.

Each histogram describes the distribution of gradient orientations in its region of the patch. We use 8 bins per histogram, thus  $360/8 = 45$  degrees per bin. The gradient magnitude at a pixel is added to the histogram bin designated for its orientation, down-weighted for smoothness by the Gaussian distance of the pixel from the center of the patch. The array of histograms is stored internally as a vector with  $4 \times 5 \times 8 = 160$  elements.

In the non-interpolated setup just described, a small change in the patch position may cause a large change to the descriptor as the mapping for a pixel jumps abruptly from one histogram to another. We thus linearly interpolate, or “smear out”, a pixel’s contribution across adjacent histograms. The contribution of a pixel which maps to the border between histogram cells is divided equally between the histograms. A pixel which maps to the center of a cell affects only the histogram in that cell.

Likewise a small change in the orientation at a pixel can cause an abrupt jump in assignment from one histogram bin to another. We therefore also interpolate orientations across histogram bins. A gradient with a  $45^\circ$  orientation is shared equally between the

bin for  $0-45^\circ$  and the bin for  $45-90^\circ$ .

Our tests verified that the Gaussian spatial down-weighting and all three interpolations (horizontally and vertically across histograms, and across bins within a histogram) are necessary for optimum fits in ASMs, although computationally demanding.

Finally, we take the square root of each element of the descriptor vector and normalize the resulting vector to unit length. Taking the square root reduces the effect of extreme values such as the bright spots on the nose tip in Figure 1. Normalizing to unit length gives invariance to linear changes in image contrast. (Invariance to the absolute illumination level is already achieved because we are using gradients not gray levels.) Actually, taking the square root is what we use in our ASM; SIFT descriptors in their original form use a slightly more complicated scheme.

## 4 HAT DESCRIPTORS

This section presents the descriptors used in our model. They are essentially unrotated SIFT descriptors with a fixed scale. In this paper it is convenient to use the term Histogram Array Transforms (HATs) for these descriptors.

HAT descriptors can be generated much more quickly than descriptors in the standard SIFT framework. Speed is important because to locate the landmarks in a face we need to evaluate something like 25 thousand descriptors. (Using typical parameters:  $68 \text{ landmarks} \times 4 \text{ pyramid levels} \times 4 \text{ model iterations} \times 5 \times 5 \text{ search grid} = 27\text{k}$ .)

### 4.1 No Automatic Scale Determination

Readers familiar with SIFT will be aware that the overview of descriptors in Section 3 does not mention the overall SIFT framework in which the descriptors are used (Lowe, 2004). This framework first does a time consuming scale-space analysis of the image to discover which points in the image are “keypoints”. It also discovers the intrinsic scale of each of these keypoints.

In contrast, in ASMs the keypoints are pre-determined — they are the facial landmarks — and the face is prescaled to a constant size before the ASM search begins. (Our implementation scales to an eye-mouth distance of 100 pixels.) Thus we do not need SIFTs automatic determination of scale. The ASM descriptor patches are a fixed size. The ASM uses a simple 4 octave image pyramid and the search proceeds one pyramid level at a time. SIFT’s sub-octave

DOG pyramid where multiple levels are analyzed simultaneously is unnecessary.

### 4.2 No Patch Orientation

In the SIFT framework once the intrinsic scale of a descriptor has been determined there is an additional preprocessing step (omitted in Section 3): the local structure of the image around the point of interest is analyzed to determine the predominant gradient orientation, and the descriptor is formed from a patch rotated to this direction. The orientation is computed by looking for peaks in an orientation histogram (independent of the histograms in the descriptor array).

In our ASM, however, before the search begins we rotate the entire image so the eyes are horizontal (after locating the eyes with the OpenCV eye detectors (Castrillón Santana et al., 2007)). Thus the automatic orientation described in the previous paragraph is unnecessary, and in our experiments actually reduced the quality of fit. We also found it unnecessary to orientate the descriptors to the shape boundary as is often done in ASMs. Some rotational variation will still remain (not every face is the same, and the eye detectors sometime give false positives on the eyebrows or fail to find eyes, causing mis-positioning of the ASM start shape), and so we must also rely on the intrinsic invariance properties of the descriptors.

### 4.3 Precalculation of Mapping from Patch to Histogram Array

When generating a SIFT or HAT descriptor, each pixel in the patch must be mapped to a position in the array of histograms. Calculating this mapping takes time, especially for scaled and rotated patches, and must be done each time we generate a descriptor.

But HATs do not use such scaling or rotation, and the mapping therefore depends only on the histogram array dimensions ( $4 \times 5$ ) and the image patch width (15 pixels), which remain constant through the ASM search. Thus we can precalculate the mapping indices just once for all descriptors (or once per pyramid level if we use different patch sizes at different pyramid levels). In our software this precalculation reduced total ASM search times by 40%.

### 4.4 Descriptor Caching

In an ASM search we repeatedly revisit the same image coordinates while iterating the models. Additionally, at coarse pyramid levels the search areas of nearby points overlap. We therefore save HAT descriptors for reuse. In practice we get a cache hit rate

of over 65% (over 65% of the requests for a descriptor can be satisfied by using a saved descriptor). Caching reduces search time by a further 70%.

## 5 DESCRIPTOR MATCHING METHODS

Once we have the descriptor of an image patch, we need a measure of how well the descriptor matches the facial feature of interest. This section reviews some standard techniques for descriptor matching, leading to the MARS models used in our ASM. (Note that at each landmark the ASM looks only for the single best match in the search region, and so we need be concerned only with the relative quality of match.)

A simple approach is to take the Euclidean distance between the descriptor and the mean training descriptor for the landmark in question. This gives every histogram bin equal weight, but that is inappropriate because pixels on certain edges will be more important than pixels elsewhere. Furthermore, a high variance bin is likely to add more noise than information.

The Mahalanobis distance gives more important bins more weight (it considers a bin important if it has low variance in the training set), and takes into consideration interaction between bins. The Mahalanobis distance is the optimal measure to the extent that the distribution of the bins' values is Gaussian, which is at most only approximately true for count data like histogram bins (Figure 4). Calculating the Mahalanobis distance is slow (proportional to the square of the number of elements in the descriptor; in our case  $160 \times 160 = 26k$ ).

Within the standard SIFT framework for key-point matching, descriptors are matched using nearest neighbors, but that would be very slow for ASMs, and for all landmarks would require a large amount of memory.

Another tack is regression, using sample descriptors on and around the correct position of the landmarks in training images to train a model that estimates match quality as a function of the elements

of the descriptor. Linear regression would be a first choice, but this assumes that the effect of a bin on the match is proportional to its value, and a straightforward application of linear regression makes the assumption that it is unnecessary to account for interactions between bins. These assumptions may be simplistic given that we are looking for a pattern of pixels. To test that there is enough data to make more complicated regression assumptions, we trained Support Vector Machines (SVMs) for matching HAT descriptors, which did indeed outperform the other methods mentioned above. However, SVMs are slow. At each landmark the SVM after training typically has over a thousand support vectors. To evaluate a descriptor we have to take the dot product of the descriptor vector with each of these vectors ( $160 \times \text{say } 1000 = 160k$  operations).

We thus turned to Multivariate Adaptive Regression Spline (MARS) models (Friedman, 1991). MARS models give ASM results that are almost as good as SVMs and are much faster. In our software, MARS decreased total search time by over 80%. An overview of MARS will be given in the next section.

We mention also that in our tests linear SVMs gave slightly worse fits than the RBF SVMs we used above. Random Forests (Breiman, 2001) gave not quite as good fits and took roughly the same time (but we did not do extensive tuning of Random Forests). Single CART style trees (Breiman et al., 1984) did not give good fits.

We generated regression training data as follows. This regimen was reached after some experimentation but we do not claim it is optimal. At the landmark of interest in each training face, we generated (i) three negative training descriptors at  $x$  and  $y$  positions randomly displaced by 1 to 6 pixels from the "true" (i.e., manually landmarked) position of the landmark, and (ii) a positive training descriptor at the true position of the landmark. To bypass issues with imbalanced data, we duplicated this positive descriptor thrice so there were equal numbers of positive and negative training descriptors. We regressed on this data with the positive training descriptors labeled with 0 and the negative training descriptors all labeled with 1 irrespective of their distance from the true position of the land-

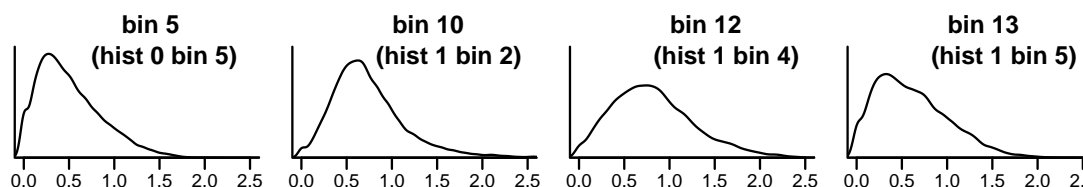


Figure 4: Non-Gaussianity is evident in the distribution of values across the training set in example histogram bins. Without the square root mentioned in Section 3, these would be even more non-Gaussian (the square root pulls in the long right tail). These examples are for the bottom left eyelid in the full scale image.

mark.

## 6 MARS

We give a brief overview of MARS by way of an example. The MARS formula to estimate the descriptor match at the bottom left eyelid in the full scale image is

$$\begin{aligned}
 match &= 0.026 & (1) \\
 &+ 0.095 \max(0, 1.514 - b_5) & (2) \\
 &+ 0.111 \max(0, 2.092 - b_{10}) & (3) \\
 &+ 0.258 \max(0, b_{12} - 1.255) & (4) \\
 &- 0.108 \max(0, 1.574 - b_{13}) & (5) \\
 &\dots & (6)
 \end{aligned}$$

where the  $b_i$  are HAT descriptor bins 0... 159. There happen to be 17 terms in the formula; we have shown

just the first few. The MARS model building algorithm generated the formula from the training data. There is a similar formula for each landmark at each pyramid level.

The bins enter the formula via the *max* functions rather than directly as they would in a linear model. The *max* functions are characteristic of MARS. They allow nonlinear dependence on the value of a bin and contain the effect of a bin to a range of its values. The effect of two of the bins is shown in Figure 5. The same bin can appear in multiple terms, allowing complex non-monotonic regression surfaces (but always piecewise linear).

MARS has included only certain histogram bins in the formula (there are 160 bins but only 17 terms in our example). HAT descriptors lend themselves to this kind of variable selection. The innate structure of the image feature makes some bins more important than others. Furthermore, the trilinear interpolation



Figure 5: The effect of bins 10 and 12 in terms (3) and (4) in the MARS formula above (with the other bins fixed at their median values). The estimated quality of match is increased by low values in bin 10 and/or high values in bin 12. From Figure 4, high values in bin 12 are uncommon. Low values are common but uninformative.

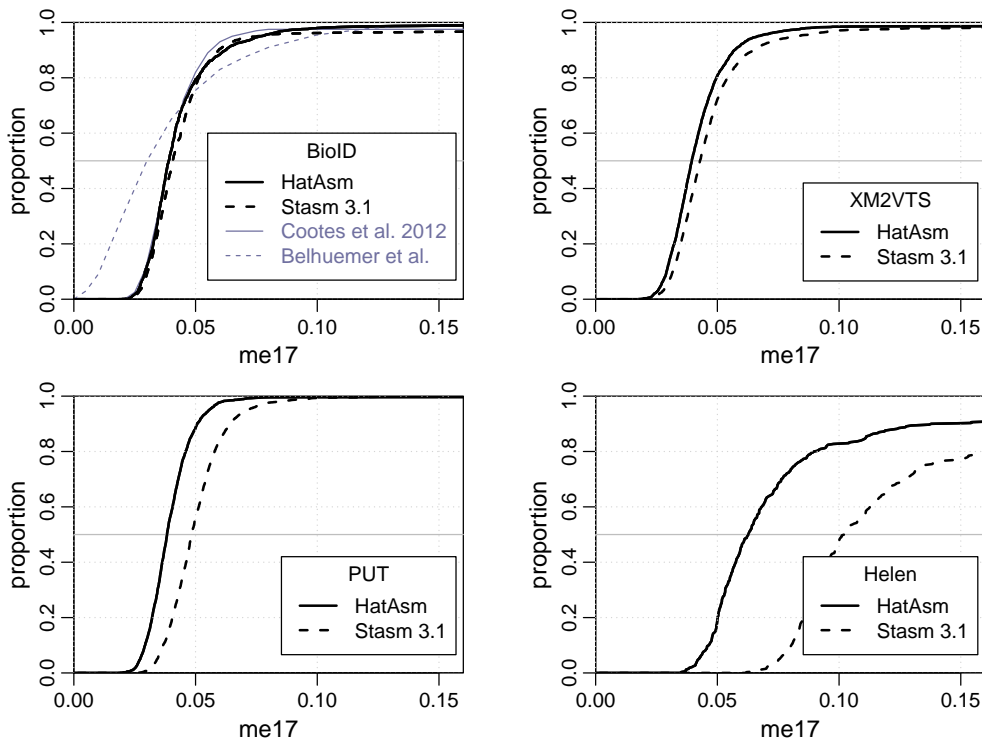


Figure 6: me17 distributions comparing our HatAsm to Stasm Version 3.1.

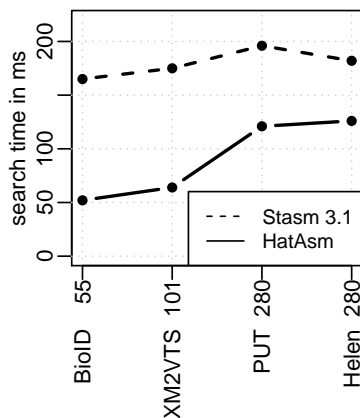


Figure 7: Search times (excluding face detection). The databases are arranged in order of mean inter-pupil distance (shown after the database name on the horizontal axis). Times were measured on a 3.4 GHz i7 with the same datasets as Figure 6. Our software allows 64 bit executables and use of OpenMP, but for impartial comparison we used 32 bit Microsoft VC10 builds without OpenMP for testing both implementations.

induces collinearities between nearby bins. When matching, it may therefore make little difference if we use a bin or its neighbor. The MARS model building algorithm will arbitrarily (depending on noise) pick one or the other. Once the bin is in the formula, the other bin can be ignored as it brings little new information. Usually the final formula is so short that evaluating it is quicker than it would be to say take the Euclidean distance between two descriptors. Exploiting structure in the data saves unnecessary calculation and reduces noise from uninformative variables.

Further details on MARS can be found in (Friedman, 1991) and perhaps more accessibly in (Hastie et al., 2009). We compiled the MARS formulas as C++ code directly into our application. We performed MARS model selection (i.e. optimization of the number of terms) not by using the standard MARS Generalized Cross Validation but by optimizing descriptor match performance on a tuning set. With smaller training sets (less than a thousand faces) our experience has been that linear models can perform as well as MARS. MARS also allows interactions between variables, but interactions do not appear to give better fits in this setting unless large data sets are used (ten thousand faces).

## 7 EXPERIMENTS

To summarize, our model differs from the classical ASM simply in that it incorporates HAT descriptors and uses MARS to measure descriptor matches. In

this section we refer to this model as a “HatAsm” model.

We compare the model primarily to the open source Stasm landmarker (Milborrow and Nicolls, 2008). (Stasm outperformed other public landmarkers in three of the four tests in a comprehensive 2013 study (Çeliktutan et al., 2013). Stasm uses a combination of 1D and square gradient descriptors with Mahalanobis distances.) We used the version of Stasm current at the time of writing (Version 3.1), which was trained on the MUCT data (Milborrow et al., 2010). For these tests we trained our ASM on the same data (using the training regimen described at the end of Section 5). We also used the same OpenCV frontal face detector (Lienhart and Maydt, 2002) as Stasm to find the face and for initialization the ASM start shape. After preliminary experimentation on independent data, for the tests here our model uses 1D gradient descriptors at the coarsest pyramid level and on the jaw points at all pyramid levels, and HAT descriptors otherwise.

We present results in terms of the *me17* measure (Cristinacce and Cootes, 2006), which is the mean distance between 17 internal face points (Figure 1) located by the search and the corresponding manually landmarked points, divided by the distance between the manual eye pupils. Depending on the application, other fitness measures may be more appropriate, but the *me17* is widely used and forms a convenient baseline. Tests using other distance measures gave results similar to those shown here.

Figure 6 shows results on four different datasets disjoint from the training data. (As is common practice, we show results as the cumulative distribution of fits. The quicker an S curve starts and the faster it reaches the top, the better the model.) Our implementation outperforms Stasm 3.1 on all sets except arguably on the BioID data.

The BioID graph also shows the results of (Belhumeur et al., 2011). Apart from the poor performance above the 75th percentile, the Belhumeur et al. results are to our knowledge the best published results on this set (excluding papers which report results on subsets or re-marked versions of the BioID data). However, their landmarker takes on the order of a second per landmark, whereas ours processes the entire face in about 50ms. We also show the results of (Cootes et al., 2012), who estimate the position of a point by combining the positions estimated by Random Forest regressions on nearby patches. The improved results near the top of their curve are perhaps due to their use of a commercial face detector which almost certainly outperforms the OpenCV detector.

Both our HatAsm and Stasm are limited to near-

frontal views by their reliance on a frontal face detector, so are inappropriate for the Helen set (Le et al., 2012) with its wide range of poses, but our implementation fares significantly better.

Figure 7 compares search times. Our implementation is faster than Stasm. The (Cootes et al., 2012) Random Forest technique (not shown in Figure 7) is faster than ours, but they fit only 17 points (we fit 76).

**Details.** The HatAsm and Stasm 3.1 curves include all faces in the BioID (Jesorsky et al., 2001), XM2VTS (Messer et al., 1999), and PUT (Kasinski et al., 2008) sets, and the designated test of the Helen set (Le et al., 2012). Faces not found by the face detectors are included in these curves, with an me17 of infinity. For the PUT set several extra points needed for calculating me17s were manually added before testing began. For the Helen set we approximated the pupil and nose points needed for me17s from neighboring points, introducing noise to the results (but equally for both implementations). The Belhumeur et al. and Cootes et al. curves were transcribed from figures in their papers. All other curves were created by running software on a local machine.

**Publication Note.** Techniques in this paper have now been integrated into Stasm to form Stasm Version 4.0. Documented source code is available at [www.milbo.users.sonic.net/stasm](http://www.milbo.users.sonic.net/stasm).

## 8 DISCUSSION AND FUTURE DIRECTIONS

We have shown that HAT descriptors together with MARS work well with ASMs. HAT descriptors outperform gradient based descriptors. HAT descriptors with MARS bring significant computational advantages over SIFT descriptors with Mahalanobis distances or SVMs.

An obvious next step would be to investigate other modern descriptors such as GLOH (Mikolajczyk and Schmid, 2005), SURF (Bay et al., 2006), or HOG (Dalal and Triggs, 2005) descriptors (our HAT descriptors are the same as one variant of HOGs, RHOGs). Evidence from other domains indicate that such alternatives per se may not give fit improvements over HATs.

In (Milborrow et al., 2013) we extend the model to non-frontal faces.

In recent years researchers have paid considerable attention to improving the way the template and shape models work together. Instead of the rigid separation between template matching and the shape model of the classical ASM, one can build a combined model

that jointly optimizes the template matchers and shape constraints. An early example is the Constrained Local Model of (Cristinacce and Cootes, 2006). An informative taxonomy is given in (Saragih et al., 2010). Such an approach would probably improve HAT based landmarks. The advantages of HATs are diminished by the classical ASM shape model (the improvement of HATS over square gradient descriptors is significantly larger before the shape constraints are applied). The match response surfaces over the search regions are smoother for HATs than for square gradient descriptors, and this might ease the difficult optimization task.

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