

Structured Edge Detection for Improved Object Localization using the Discriminative Generalized Hough Transform

Eric Gabriel¹, Ferdinand Hahmann¹, Gordon Böer¹, Hauke Schramm^{1,2} and Carsten Meyer^{1,2}

¹*Institute of Applied Computer Science, Kiel University of Applied Sciences, Kiel, Germany*

²*Department of Computer Science, Faculty of Engineering, Kiel University (CAU), Kiel, Germany*

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Abstract: Automatic localization of target objects in digital images is an important task in Computer Vision. The Generalized Hough Transform (GHT) and its variant, the Discriminative Generalized Hough Transform (DGHT), are model-based object localization algorithms which determine the most likely object position based on accumulated votes in the so-called Hough space. Many automatic localization algorithms - including the GHT and the DGHT - operate on edge images, using e.g. the Canny or the Sobel Edge Detector. However, if the image contains many edges not belonging to the object of interest (e.g. from other objects, background clutter, noise etc.), these edges cause misleading votes which increase the probability of localization errors. In this paper we investigate the effect of a more sophisticated edge detection algorithm, called Structured Edge Detector, on the performance of a DGHT-based object localization approach. This method utilizes information on the shape of the target object to substantially reduce the amount of non-object edges. Combining this technique with the DGHT leads to a significant localization performance improvement for automatic pedestrian and car detection.

1 INTRODUCTION

The first step in many automatic Computer Vision systems is the localization of objects of interest in a given digital image. In this paper, object localization refers to estimating the coordinates of a given reference point (e.g. the center of gravity) of the target object in any test image. A bounding box around the target object can then be predicted as described in Section 3.3. Object localization is a prerequisite for many subsequent automatic image processing algorithms, e.g. automatic segmentation of organ structures in medical images (Ecabert et al., 2008), automatic object classification (Hahmann et al., 2012; Hahmann et al., 2014), automatic object tracking (Andriluka et al., 2008) etc. Approaches to automatic object localization in still images can i.a. be grouped into sliding-window approaches and model-based voting frameworks. A popular model-based object localization algorithm is the Generalized Hough Transform (GHT) (Ballard, 1981). Here, a template of the target object is created by specifying a set of model points representing the object shape, together with the offset of each model point to a specified reference point.

Applied to a test image, the model casts votes for likely object transformations, e.g. translations, and the parameter set with the highest number of votes provides the detected object position and, potentially, further transformations. This framework has been extended in (Ruppertshofen et al., 2010) to the Discriminative Generalized Hough Transform (DGHT). Here, a weight is assigned to each model point, characterizing its importance for localization of the target object on the given training database; these weights are optimized by a discriminative training algorithm (Ruppertshofen et al., 2010). The main advantage of the GHT / DGHT approach is its robustness with regard to image noise and object occlusion due to the voting mechanism (Ballard, 1981; Ruppertshofen, 2013).

Most object localization approaches do not work directly on raw images, but first perform automatic edge detection, leading to a binary edge image (Gavrila, 2000; Chaohui et al., 2007) (see Figures 1 a,b and 2 a,b). This is because an edge image often describes the object shape sufficiently well, while drastically reducing the computational effort for a subsequent localization algorithm. Often, the Canny Edge Detection algorithm (Canny, 1986) is used due to its

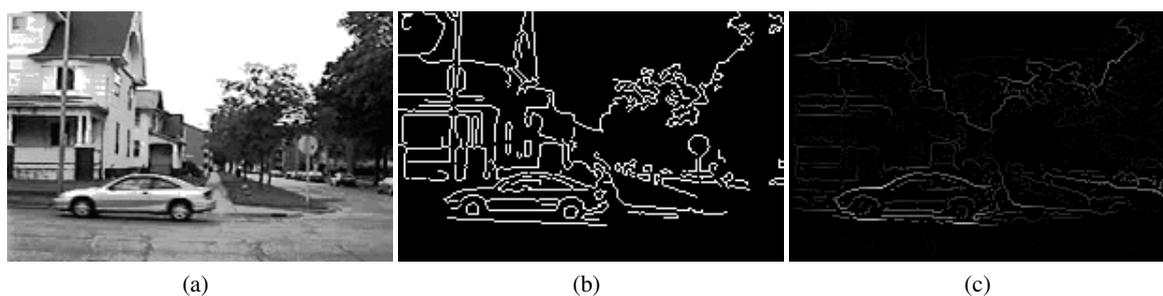


Figure 1: (a) Input image (b) Canny edge image (low thresh.: 0.6; high thresh.: 0.9) (c) Edge output of Structured Edge Detector (trained for car edge detection + sharpening).



Figure 2: (a) Input image (b) Output of Structured Edge Detector (c) Input image (d) Output of Structured Edge Detector (both trained for car edge detection + sharpening).

efficiency (see Figure 1b). In the context of the GHT / DGHT, this leads to impressive object localization performance on a large variety of tasks with limited target object variability (Ecabert and Thiran, 2004; Ruppertshofen et al., 2010). However, in many object recognition tasks the images are often characterized by a highly variable background composed of many confounding objects and structures, clutter etc. (see e.g. Figures 1 - 3). In those cases, the Canny Edge Detection leads to many unwanted edges which cast votes in addition to the required edge pixels of the target object (Figure 1b). Thus, the voting pattern may be significantly perturbed, potentially leading to a mislocalization.

Recently, an improved edge detection algorithm has been proposed (Dollár and Zitnick, 2013). The main idea is to learn from training data the appearance of target object edge pixels in order to discriminate them from the edge pixels of all other structures. In this way, confusing edges can be suppressed, so that the target object(s) in the image are better pronounced (see Figures 1c and 2). Thus, this technique potentially avoids the generation of many Hough space votes which do not arise from the target object and may therefore substantially improve the localization performance.

In this work, we compare the Structured Edge Detector (Dollár and Zitnick, 2013; Dollár and Zitnick, 2014) to a standard Canny Edge Detector in the context of DGHT-based automatic object localization. In particular, we quantitatively analyze the object localization performance with the two edge detectors in two real-world tasks, namely pedestrian and car local-

ization. We obtain significant performance improvements on both tasks when using the Structured Edge Detector, as compared to Canny Edge Detection. The results demonstrate that the GHT / DGHT framework can be successfully applied to automatic object localization scenarios with a large degree of variability with respect to background and clutter.

The rest of the paper is organized as follows: The Canny Edge Detection and the Structured Edge Detection algorithms are briefly summarized in Section 2, followed by a short presentation of the DGHT object localization approach. The databases used in our study, experimental results and analyses are reported in Section 3. A discussion and conclusion can be found in Sections 4 and 5.

2 METHODS

2.1 Edge Detection

2.1.1 Canny Edge Detection

In 1986 John Francis Canny introduced a general and robust approach for edge detection in images (Canny, 1986). The values of the first derivatives in horizontal and vertical direction, G_x and G_y , are obtained by applying the Sobel operator to the input image smoothed with a Gaussian filter to reduce noise. Using these values, the gradient magnitude and the edge direction can be calculated:



Figure 3: Examples of confusing Canny edges and background clutter in pedestrian localization. **(Left)** Input image **(middle)** Canny edge image **(right)** Output of Structured Edge Detector (trained for ped. edge detection).

$$G = \sqrt{(G_x)^2 + (G_y)^2} \quad (1)$$

$$\theta = \arctan(G_y, G_x) \quad (2)$$

The resulting edges are thinned using non-maximum suppression (NMS). Subsequently, the remaining edge pixels are classified using a high and a low threshold value. Edges above the high threshold (strong edges) are kept, whilst edges below the low threshold are discarded. Edges between the low and the high threshold are so called weak edges. Whether they will remain in the resulting edge image is determined by hysteresis, i.e. those edges are kept only if there is a strong edge within the respective 8-connected neighborhood. Examples of Canny edge images are provided in Figures 1b and 3.

Other variants of edge detection based on first or second order derivatives exist, see e.g. (Shrivakshan and Chandrasekar, 2012) or anisotropic Gaussian filtering (Knossow et al., 2007; Montesinos and Magnier, 2010). Their evaluation is however beyond the scope of this work.

2.1.2 Structured Edge Detection

Recently, Dollár and Zitnick introduced a novel machine learning approach for detecting edges, which incorporates information on the object of interest (Dollár and Zitnick, 2013; Dollár and Zitnick, 2014). Their approach utilizes the fact that patches of edges show common forms of local structure like straight lines or T-junctions or similar (Dollár and Zitnick, 2014). Thus, a learning framework, like Random Forests, can be applied to assign an output edge patch to features extracted from an input image patch. As features, Dollár and Zitnick use pixel-lookups

and pairwise-difference features of 13 channels (three color, two magnitude and eight orientation feature channels). However, since the space of observed image patches is high-dimensional and complex, it is mapped to a discrete space based on ideas of structured learning (Nowozin and Lampert, 2011; Kotschieder et al., 2011), thus enabling an efficient training of Random Forests (Breiman, 2001). For a test image, the trained detector is applied to densely sampled, overlapping image patches. The resulting edge patch predictions which refer to the same image pixel are locally averaged after applying a sharpening procedure in order to reduce diffusion. This is done by aligning each predicted edge patch to the underlying image patch data.

Using the novel edge detection algorithm which runs at real-time, Dollár and Zitnick obtained state-of-the-art accuracy on two contour datasets and demonstrated cross-dataset generalization (Dollár and Zitnick, 2013; Dollár and Zitnick, 2014).

2.2 Object Localization

2.2.1 Generalized Hough Transform

The Generalized Hough Transform (GHT), introduced by Ballard in 1981 (Ballard, 1981), is a general and well-known model-based approach for object localization, which belongs to the category of template-matching techniques. Each model point m_j is represented by its coordinates with respect to the reference point.

The GHT transforms a feature image, in our case an edge image, into a parameter space, called Hough space, utilizing a simple voting procedure. The

Hough space consists of accumulator cells (Hough cells), representing possible target point locations and, potentially, shape model transformations. The number of votes per accumulator cell reflects the degree of matching between the (transformed) model and the feature image.

Since each additional parameter in a model transformation directly increases the computational complexity of the algorithm, we restrict the model transformation to a simple translation in this work. Moderate object variability with respect to shape, size, and rotation is not explicitly parameterized, but implicitly learned into the model by appropriately placing model points as indicated by the training data.

The voting procedure, which transforms a feature image X into the Hough space H (with discrete elements c_i) by using the shape model M , can be described by

$$H(c_i, X) = \sum_{\forall m_j \in M} f_j(c_i, X) \quad (3)$$

with¹

$$f_j(c_i, X) = \sum_{\forall e_i \in X} \begin{cases} 1, & \text{if } c_i = \lfloor (e_i - m_j) / \rho \rfloor \\ & \text{and } |\varphi_{e_i} - \varphi_{m_j}| < \Delta\phi \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

The quantized Hough space H (with quantization parameter ρ) consists of Hough cells c_i that accumulate the number of matching pairs of all model points m_j and feature points e_i . Each Hough cell c_i represents a target hypothesis whose coordinates in image space are given by $\lfloor (c_i + 0.5) \cdot \rho \rfloor$.

$f_j(c_i, X)$ determines how often model point m_j votes for Hough cell c_i for the given feature image X . However, note that a voting is only possible, if the orientation² of the model and feature point, φ_{m_j} and φ_{e_i} , respectively, has a small difference of below $\Delta\phi$. The most likely target point location results from the Hough cell $\tilde{c}(X)$ with the highest number of votes, corresponding to the best match between the model M and the feature image X :

$$\tilde{c}(X) = \arg \max_{c_i} H(c_i, X) \quad (5)$$

2.2.2 Discriminative Generalized Hough Transform

The Discriminative Generalized Hough Transform (DGHT) extends the Generalized Hough Transform (Section 2.2.1) by an individual weighting scheme for

the J model points m_j of the shape model M , optimized by a discriminative training algorithm.

During the voting procedure of Equation 3, the individual model point weights λ_j are incorporated as described in Equation 6:

$$H(c_i, X) = \sum_{\forall m_j \in M} \lambda_j f_j(c_i, X) \quad (6)$$

with $f_j(c_i, X)$ as in Equation 4.

In GHT-based approaches, the quality of the localization highly depends on the quality of the model. A good model has to fulfill two important conditions: A high correlation with the feature image on the target point location and a small correlation at confusable objects. In the DGHT, this is achieved by an iterative training procedure. It starts with an initial model that is generated by superimposing annotated feature images at the reference point. The model point weights λ_j are optimized using a Minimum Classification Error (MCE) approach, and model points with a low absolute weight are eliminated. At last, the model is extended by target structures from training images which still have a high localization error. This procedure is repeated until all training images are used or have a low localization error. A more detailed description of the technique can be found in (Rupertshofen, 2013).

2.2.3 Shape Consistency Measure

As a result of the iterative training procedure (see Section 2.2.2), the DGHT models may cover medium object variability (e.g. regarding size, aspect) by containing model points representing the most important modes of variation observed in the training data. In the GHT / DGHT voting procedures (Eqs. 3 and 6, respectively), it can be seen that these points vote independently for a localization hypothesis c_i . This means that $f_j(c_i, X)$ is not influenced by $f_k(c_i, X)$, $\forall j \neq k$. In practice, however, these dependencies exist since mutually exclusive variations should not be allowed to accumulate their votes for the same Hough cell c_i . For example, a subset of the model points may represent a frontal view of a person, and a different subset a side view of a person. While it is reasonable to incorporate aspect variations into the Hough model, the voting of model points from mutually exclusive variation types should not be mixed. This is, since a Hough cell might coincidentally get a large number of votes from different variants which may lead to a mislocalization.

To this end, (Hahmann et al., 2015) suggested to analyse the pattern of model points voting for a particular Hough cell c_i . More specifically, this model

¹Note that $\lfloor \mathbf{a} \rfloor$ denotes the floor of each component of \mathbf{a} .

²I.e. the gradient direction as in Eq. 2

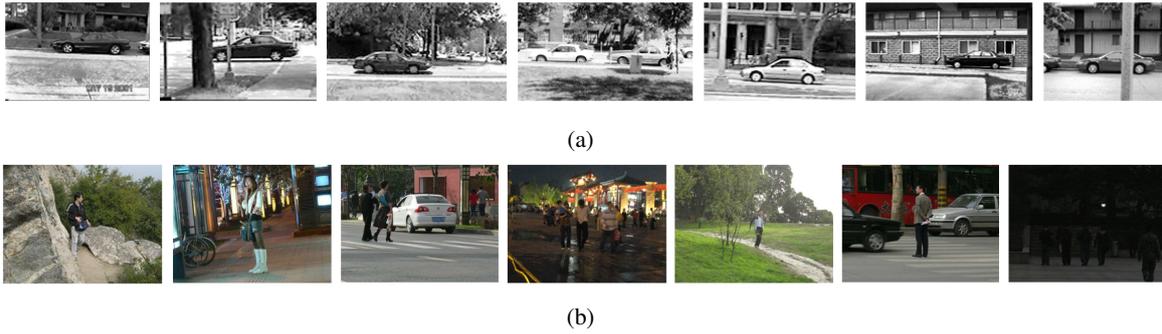


Figure 4: Sample images of (a) UIUC Car Database and (b) subset of IAIR-CarPed.

point pattern is classified into a class "regular shape" Ω_r (representing e.g. frontal view of a person or a side view of a person) and a class "irregular shape" Ω_i . Note that the exact number of votes from a model point m_j for a particular cell c_i is less relevant than the distance $d(c_i, c_k)$ between cell c_i and the closest cell c_k in the neighborhood of c_i for which the model point m_j voted for. Therefore, the attribute vector

$$R(c_i, X) = \{r_1(c_i, X), r_2(c_i, X), \dots, r_J(c_i, X)\} \quad (7)$$

is introduced with

$$r_j(c_i, X) = \min_{c_k} \begin{cases} d(c_i, c_k), & \text{if } f_j(c_k, X) \geq 1 \\ & \text{and } d(c_i, c_k) < \vartheta \\ \vartheta, & \text{otherwise} \end{cases} \quad (8)$$

and $d(a, b) = \max_t |a_t - b_t|$. A value $\alpha = r_j(c_i, X) < \vartheta$ indicates that the model point m_j voted in a $(2\alpha + 1) \times (2\alpha + 1)$ neighborhood around c_i . The parameter ϑ serves as a maximum limit up to which a relation from model point m_j to Hough cell c_i can be assumed. Above this (experimentally optimized) limit of seven cells a link between m_j and c_i is unlikely and therefore the exact distance is irrelevant for the analysis of the voting pattern. The attribute vector $R(c_i, X)$ is used as input for a Random Forest Classifier, which is trained on appropriate training data to discriminate the two classes. For a test image X , a (D)GHT model is applied to generate a Hough space $H(c_i, X)$ and a list of most probable object positions c_i (which correspond to an ordered list of the maxima in Hough space). For each candidate c_i , the attribute vector $R(c_i, X)$ is calculated from Eqs. 7 and 8, and the Random Forest Classifier is used to calculate the probability $p(\Omega_r | R(c_i, X))$ that the set of model points, voting for c_i , has a regular shape.

The obtained probability is used in the localization procedure as an additional weighting factor for the Hough space votes, changing Eq. 5 to

$$\tilde{c}(X) = \arg \max_{c_i} p(\Omega_r | R(c_i, X)) \cdot H(c_i | X) \quad (9)$$

We refer to the Random Forest classification of the Hough voting pattern, Eq. 9, as Shape Consistency

Measure (SCM). To generate the required attribute vectors for the training of the Random Forest Classifier, the DGHT is applied to each training image. Then the class labels Ω_r and Ω_i are assigned to the individual Hough cells of the training images using the following rule: Cells with a localization error below a threshold ε_1 are labelled as class Ω_r while those with an error of above ε_2 are assigned to class Ω_i . Hypotheses which cannot be assigned to either class are not used in the Random Forest training in order to ensure a better discrimination between the two classes.

3 EXPERIMENTS

3.1 Databases

In this work, we apply our object localization framework (consisting of DGHT and SCM, Eq. 9) to two kinds of feature images: Edge images generated by applying the Canny Edge Detector (Section 2.1.1) and the Structured Edge Detector (Section 2.1.2). In particular, we evaluate the performance of the Canny and Structured Edge Detector as features for the DGHT on two datasets:

The first one is the *UIUC Car Database* (Agarwal and Roth, 2002; Agarwal et al., 2004). Here, we use the 550 positive car training images for model training, all 1050 training images (550 positive and 500 negative) for the training of the Shape Consistency Measure and the 170 single-scale test images for performance evaluation.

The second database, used for pedestrian localization, is a subset of the *IAIR-CarPed database* (Wu et al., 2012). We filtered the dataset for images containing pedestrians and computed the mean height (150 px). In order to include size variability to a moderate extent, we decided for a pedestrian height range of approximately 25% of the mean height. This leads to a pedestrian height range of 130 to 170 pixels. We keep all images containing pedestrians of a size

within this range and discard images containing only smaller ones. Images with larger pedestrians were downsampled by a random factor such that the scaled pedestrian height falls into the specified range. Following this procedure we obtain 457 images, of which the first 300 were used to train the DGHT model and the SCM and the remaining 157 images were used for evaluation. In the test set only pedestrians within the size range remain annotated.

Sample images of both datasets are shown in Figure 4.

3.2 Experimental Setup and System Parameters

As a first edge detector, we use the Canny Edge Detector. Here, we specifically optimize the low and high threshold for each localization task. This is done by qualitatively assessing the Canny edge images on a sample basis, searching for a tradeoff between keeping essential edges of the target object and not having too much background clutter. For the UIUC Car Database we use a high threshold percentage of 0.9 and a low threshold percentage of 0.6. For the pedestrian localization task on the IAIR-CarPed subset we use a high threshold percentage of 0.8 and a low threshold percentage of 0.5.

As a second edge detector, we use the Structured Edge Detector from Dollár and Zitnick. For computing the structured edges we use publicly available code³. As explained in Section 2.1.2, the Structured Edge Detector must be trained with domain-specific, annotated edge images. In our case, we use the *cars_side* category of Caltech-101 database (Fei-Fei et al., 2006) and the PennFudan dataset (Wang et al., 2007) for cars and pedestrians, respectively⁴. In this manner, the specific Structured Edge Detectors are trained to highlight edges belonging to the respective object category and suppress background edges or those of non-target objects. We refer to the domain-specific Structured Edge Detector as SSE.

For comparison, we also used a general purpose Structured Edge Detector provided by Dollár and Zitnick. This edge detector is trained on the general BSDS500 segmentation dataset (Arbelaez et al., 2011) and is referred to as GSE.

The experiments for the different edge images on both datasets are conducted as follows:

³<http://research.microsoft.com/en-us/downloads/389109f6-b4e8-404c-84bf-239f7cbf4e3d>, accessed: 2015-09-16

⁴We use these databases and not UIUC and IAIR for the training of the specific structured edge detectors, because the former already provide a ground truth contour annotation.

First, the different feature images (Canny, GSE and SSE) are generated for both datasets, which serve as input images for the DGHT training. Then, a DGHT model is trained for each feature type and dataset using the iterative training process according to Section 2.2.2. The quantization parameter ρ is set to 2 in x - and y -direction and $\Delta\Phi$ to 16 for all experiments. Afterwards, the Shape Consistency Measure (SCM) is trained by applying the resulting DGHT model to each training image and extracting localization hypotheses below ϵ_1 ⁵ as samples for Ω_r and above ϵ_2 ⁶ as samples for Ω_i (see Section 2.2.3) with ϑ set to 7. After these training steps both the DGHT model and the SCM are applied to the test image set, where the same edge detection algorithm as in training is applied to each test image. Then, for each test image X we compute the best localization hypothesis $\tilde{c}_i(X)$ according to Eq. 9.

3.3 Results

In order to classify whether the best localization hypothesis $\tilde{c}_i(X)$ per image X is a correct localization, we use the common PASCAL VOC overlap measure (Everingham et al., 2010):

$$a_0 = \frac{\text{area}(B_p \cap B_{gt})}{\text{area}(B_p \cup B_{gt})}, \quad (10)$$

where $B_p \cap B_{gt}$ refers to the intersection and $B_p \cup B_{gt}$ to the union of the predicted bounding box B_p and the ground truth bounding box B_{gt} . For a correct detection the overlap measure a_0 must exceed 0.5.

Because this measure needs a predicted bounding box, we need to obtain B_p from the best localization hypothesis $\tilde{c}_i(X)$. In the UIUC single-scale test set, we take the fixed object width and height as the width and height of B_p around $\tilde{c}_i(X)$ as the center point. For pedestrian localization in the size range of 130 to 170 px, we take the mean object width and height as the width and height of B_p around $\tilde{c}_i(X)$ as the center point.

The localization and detection results for the UIUC single-scale test set and for the test subset of IAIR-CarPed are shown in Table 1 and 2, respectively. A bar chart of the localization accuracies on both datasets with the investigated edge detection algorithms is presented in Figure 6. Since multi-object detection is currently not being addressed in our localization framework, please note that all reported results are with respect to the overlap score a_0 of the best hypothesis $\tilde{c}_i(X)$ with respect to the closest ground truth

⁵5 and 10 for UIUC and IAIR, respectively.

⁶15 and 25 for UIUC and IAIR, respectively.

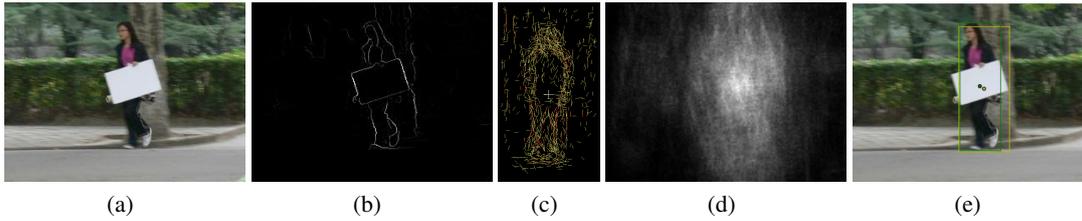


Figure 5: Sample localization with: (a) Input image (b) Structured Edge Detection output (c) Learned model for pedestrian detection (d) Hough space (e) Resulting localization; yellow: prediction, green: ground truth annotation.

Table 1: Localization results on UIUC single-scale.

Accuracy: $\frac{\# \text{ of images with } a_0 > 0.5}{\text{total \# of images}}$; Localization error: distance of $\tilde{c}_i(X)$ to closest ground truth annotation in pixel.

Feature	Accuracy [%]	Mean a_0 [%]	Mean loc. error [px]
Canny	96.47	77.69	4.46
GSE	97.65	79.72	4.39
SSE	100.00	82.83	3.13

Table 2: Localization results on IAIR-CarPed subset database.

Accuracy: $\frac{\# \text{ of images with } a_0 > 0.5}{\text{total \# of images}}$; Localization error: distance of $\tilde{c}_i(X)$ to closest ground truth annotation in pixel.

Feature	Accuracy [%]	Mean a_0 [%]	Mean loc. error [px]
Canny	85.35	64.19	20.07
GSE	91.08	69.65	12.56
SSE	92.99	69.27	15.71

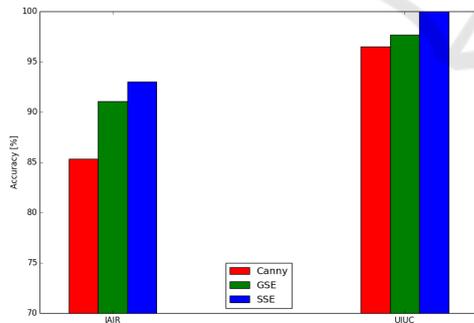


Figure 6: Localization accuracies of the different edge detectors (see Section 2.1) for both databases.

annotation per test image X only. Therefore, the accuracy denotes the number of images with a correct localization, i.e. the overlap between the predicted and the closest ground truth bounding box according to Eq. 10 must exceed 0.5, in relation to the total amount of test images.

4 DISCUSSION

In the car localization task on the UIUC single-scale set, using task-specific structured edges (SSE) instead of Canny edges improves localization accuracy from 96.47% to 100%. This is because the trained car SSE edge detector can successfully suppress many confusing edges of non-target objects as in the example in Figure 7. Here, the maximum in Hough space incidentally arising from non-object-related edges, which is observed for Canny edges and leads to a wrong object localization, disappears when using SSE features. Instead, the object-related edges lead to a maximum in Hough space at the (almost) correct object position (see Figure 7). The accuracy of the GSE features rank in between (97.65%). This means that without an additional category-specific training effort the localization accuracy compared to Canny edges can still be improved, although less than with task-specific structured edges.

Regarding the pedestrian localization task, the conclusions from the car localization task can be confirmed, however, in a harder task exhibiting size variability and much more confusable background structures (see Figure 4b). We obtained accuracy values of 85.35% for Canny, 91.08% for GSE and 92.99% for SSE, respectively. These numbers demonstrate that also the pedestrian localization performance can be substantially increased using specifically trained SSE features. When qualitatively inspecting the error cases of the SSE experiment, in eight of the eleven mislocalizations, however, pedestrians were localized (see Figure 8), but their height is not within the allowed size range from 130 to 170 px (Section 3.1) and therefore those pedestrians are not annotated leading to an overlap a_0 of 0%. When slightly enlarging the annotated size range to 120 to 180 px the localization accuracies are 89.17% (Canny), 94.27% (GSE) and 95.54% (SSE), respectively.

To assess the statistical significance of the accuracy, we assume a binomial distribution for the detection results per image (correctly localized versus not correctly localized, corresponding to $a_0 > 0.5$ ver-



Figure 7: Example feature images and localization results on UIUC (rows 1 - 4) and IAIR (rows 5 - 8); Odd rows: Canny Edge Detection, even rows: Structured Edge Detection (SSE) **(First column)** Input image **(Second column)** Edge image **(Third column)** Hough space **(Fourth column)** Localization result; yellow: prediction, green: ground truth annotation. (Best viewed in color).

sus $a_0 \leq 0.5$, respectively), and calculate the 95%-Clopper-Pearson confidence interval for the accuracy (see Table 3). On both tasks, the localization accuracy of the SSE edges is beyond the confidence interval for the localization accuracy using Canny edges, demonstrating a significant improvement in localization accuracy by structured edges compared to Canny

edges. On the pedestrian localization task, this also holds when using GSE edges.

To assess statistical significance of the continuous overlap parameter a_0 when using category-specific structured edges as input features, we use the non-parametric Wilcoxon-Mann-Whitney test (Wilcoxon, 1945; Mann and Whitney, 1947), since a_0 is not nor-

Table 3: Clopper-Pearson intervals for the experiment results.

Dataset	Feature	CP Interval
UIUC	Canny	[92.48%, 98.69%]
	SSE	[97.85%, 100.0%]
IAIR	Canny	[78.83%, 90.48%]
	SSE	[87.81%, 96.45%]

mally distributed (p -values of all experiments in the Shapiro-Wilk tests (Shapiro and Wilk, 1965) are $< 10e-3$). Comparing the independent groups Canny and SSE for both datasets in the Wilcoxon-Mann-Whitney test, we obtain p -values of $9.86e-6$ and 0.001872 for UIUC and IAIR, respectively. Thus, the mean overlap value a_0 for the SSE edge detection tests is larger at the 95% confidence level than the mean overlap for the Canny Edge Detection tests.

Additionally, we statistically evaluated the resulting localization errors for Canny and SSE edge features in the same way as described above. We obtain p -values of 0.005118 and 0.001696 for UIUC and IAIR, respectively. Therefore, the mean localization error for the SSE edge detection tests is lower at the 95% confidence level than the mean localization error for the Canny Edge Detection tests.

5 CONCLUSIONS

We have shown that the object localization performance obtained by the voting-based DGHT approach in real-world tasks with variable background and clutter can be significantly improved by a sophisticated edge detection algorithm, namely the Structured Edge Detector. This applies to general structured edge features without additional training effort as well as category-specific Structured Edge Detectors in particular. More precisely, we obtained absolute improvements in localization accuracy of 3.53% and 7.64% on a car and pedestrian localization task, respectively. We conclude that the DGHT framework can be successfully used for object localization also in real-world images with larger and more variable background.

In future work, we aim to integrate an intelligent edge detection mechanism into the voting framework and to explore strategies to handle object variability (e.g. object size, rotation) as well as multi-object and multi-class localization.



Figure 8: Error case: Detected pedestrian is not within the annotated height range of 130-170 px. Bounding box colors: yellow: prediction; green: ground truth annotation; red: not in ground truth, because height $\notin [130, 170]$ px. (Best viewed in color).

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