

DEPTH PREDICTION AT HOMOGENEOUS IMAGE STRUCTURES

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Abstract: This paper proposes a voting-based model that predicts depth at weakly-structured image areas from the depth that is extracted using a feature-based stereo method. We provide results, on both real and artificial scenes, that show the accuracy and robustness of our approach. Moreover, we compare our method to different dense stereo algorithms to investigate the effect of texture on performance of the two different approaches. The results confirm the expectation that dense stereo methods are suited better for textured image areas and our method for weakly-textured image areas.

1 Introduction

In this paper, we are interested in prediction of depth at homogeneous image patches (called *monos* in this paper) from the depth of the edges in the scene using a voting model. We start by creating a representation of the input stereo image pair in terms of local features corresponding to edge-like structures and monos (as introduced in (Krüger et al., 2004) and in section 2). The depth at edge-like features is extracted using a feature-based stereo method introduced in (Pugeault and Krüger, 2003). This provides a 3D-silhouette of the scene which however can include strong outliers and ambiguous interpretations in particular when large disparities and low thresholds on matching similarities are used (figure 1). The depth of a certain mono, then, is voted by the 3D edge-like features that are part of this 3D-silhouette.

A typical scenario with extracted 3D information (using stereo) is shown in figure 1. We see that stereo computation produces strong outliers which prohibit a direct application of a *surface interpolation* process as it is not trivial to differentiate between the outliers and the reliable stereo information. Moreover, 3D features that should be reliable at the edges of the road turn out not to share a common surface nor a common 3D line (see figure 1(c)). Therefore, applying a surface interpolation method on such input data is ex-

pected to lead to an erroneous interpretation of the scene. In this paper, we will show that our depth prediction method is able to cope with these situations.

We compare our depth prediction method with a few dense stereo methods (with local as well as global optimizations) on real and artificial scenes where the amount of texture can be controlled to see the effect of texture on the performance of the different approaches. We show that dense stereo methods are best suited for textured image areas whereas our method performs well on homogeneous or weakly-textured image areas or edges. The results suggest a combination of both approaches into a single model that can perform well at both textured and homogeneous or weakly-textured image areas.

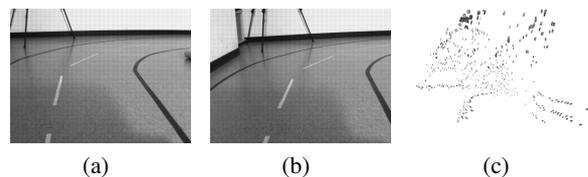


Figure 1: (a-b) An input stereo pair. (c) Results of a feature-based stereo algorithm (taken from (Pugeault and Krüger, 2003)).

1.1 Related studies

The work (Grimson, 1982) can be regarded as the pioneer of surface interpolation studies. In (Grimson, 1982), Grimson proposed fitting square Laplacian functionals to surface orientations at existing 3D points utilizing a *surface consistency constraint* called 'no news is good news'. The constraint argues that if two image points do not have a contrast difference in-between, then they can be assumed to be on the same 3D surface (see (Kalkan et al., 2006) for a quantification of this assumption). (Grimson, 1982) assumes that 3D orientation is available, and the input 3D points are dense enough for second order differentiation.

In (Guy and Medioni, 1994), 3D points with surface orientation are interpolated using a perceptual constraint called *co-surfacity* which produces a 3D association field (which is called the Diabolo field by the authors) similar to the association field used in 2D perceptual contour grouping studies. If the points do not have 3D orientation, they estimate the 3D orientation first (by fitting a surface model locally) and then apply the surface interpolation step.

The most relevant studies to our paper are (Hoff and Ahuja, 1989; Lee et al., 2002). They both argued that stereo matching and surface interpolation should not be sequential but rather simultaneous. (Hoff and Ahuja, 1989) fits local planes to disparity estimates from zero-crossings of a stereo pair to estimate rough surface estimates which are then interpolated taking into account the occlusions, whereas in this paper, we are concerned with predictions (1) of higher level features, (2) using long-range relations and (3) voting mechanisms. Moreover, as the authors have tested their approach only on very textured scenes, the applicability of the approach to homogeneous image areas is not clear. (Lee et al., 2002) employs the following steps: A dense disparity map is computed, and the disparities corresponding to inliers, surfaces and surface discontinuities are marked and combined using tensor voting. The surfaces are then extracted from the dense disparities using marching cubes approach.

Our work is different from the above mentioned works in that: Our approach does not assume that the input stereo points are dense enough to compute their 3D orientation. Instead, our method relies on the 3D line-orientations of the edge segments which are extracted using a feature-based stereo algorithm (proposed in (Pugeault and Krüger, 2003)). The second difference is that we employ a voting method which is different from tensor-voting ((Lee and Medioni, 1998; Lee et al., 2002)) in that it allows long-range interactions in empty image areas and only in certain direc-

tions in much less computations than tensor-voting, in order to predict *both* the depth and the surface orientation.

We would like to distinguish *depth prediction* from *surface interpolation* because surface interpolation assumes that there is already a dense depth map of the scene available in order to estimate the 3D orientation at points (see, *e.g.*, (Grimson, 1982; Guy and Medioni, 1994; Lee and Medioni, 1998; Lee et al., 2002; Terzopoulos, 1988)) whereas our understanding of depth prediction makes use of only 3D line-orientations at edge-segments which are computed using a feature-based stereo proposed in (Pugeault and Krüger, 2003).

1.2 Contributions and outline

Our contributions can be listed as:

- A novel voting-based method for predicting depth at homogeneous image areas using just the 3D line orientation at 3D local edge-features.
- Our votes have reliability measures which are based on the coplanarity statistics of 3D local surface patches provided in (Kalkan et al., 2007).
- Comparison with dense stereo on real and artificial scenes where we control the amount and the type of texture to see the effect on performance of the different approaches. We show that different approaches are suited to different kinds of image settings (*i.e.*, textured/weakly-textured), and the results suggest that a combination of different approaches is suitable for a model that can perform well in all kinds of images.

The paper is organized as follows: In section 2, we introduce how the images are represented in terms of local image features. Section 3 describes the 2D and 3D relations between the local image features that are utilized in the depth prediction process. Section 4 explains how the depth prediction is performed. In section 5, the results are presented and discussed. Finally, section 6 concludes the paper with a summary and outlook.

2 Visual Features

The visual features that we utilize (called *primitives* in the rest of the paper) are local, multi-modal features that were introduced in (Krüger et al., 2004).

An edge-like primitive can be formulated as:

$$\pi^e = (\mathbf{x}, \theta, \omega, (\mathbf{c}_l, \mathbf{c}_m, \mathbf{c}_r)), \quad (1)$$

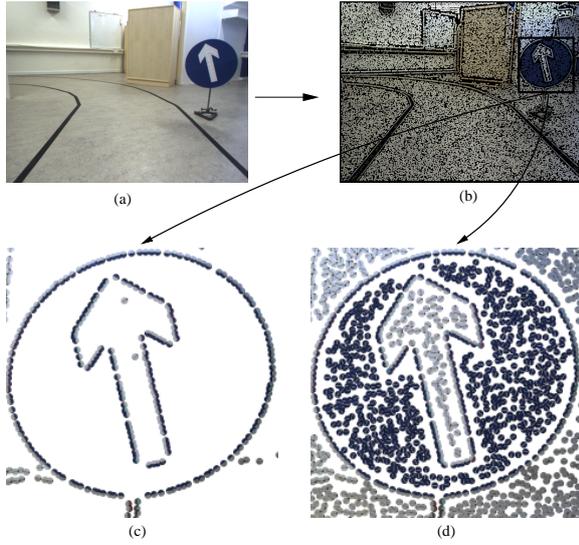


Figure 2: Extracted primitives (b) for the example image in (a). Magnified edge primitives and edge primitives together with monos are shown in (c) and (d) respectively.

where \mathbf{x} is the image position of the primitive; θ is the 2D orientation; ω represents the contrast transition; and, $(\mathbf{c}_l, \mathbf{c}_m, \mathbf{c}_r)$ is the representation of the color, corresponding to the left (\mathbf{c}_l), the middle (\mathbf{c}_m) and the right side (\mathbf{c}_r) of the primitive.

As the underlying structure of a homogeneous image structure is different from that of an edge-like structure, a different representation is needed for homogeneous image patches (called *monos* in this paper):

$$\pi^m = (\mathbf{x}, \mathbf{c}), \quad (2)$$

where \mathbf{x} is the image position, and \mathbf{c} is the color of the mono. See (Krüger et al., 2004) for more information about these modalities and their extraction. Figure 2 shows extracted primitives for an example scene.

π^e is a 2D feature which can be used to find correspondences in a stereo framework to create 3D primitives (as introduced in (Pugeault and Krüger, 2003)) with the following formulation:

$$\Pi^e = (\mathbf{X}, \Theta, \Omega, (\mathbf{C}_l, \mathbf{C}_m, \mathbf{C}_r)), \quad (3)$$

where \mathbf{X} is the 3D position; Θ is the 3D orientation; Ω is the phase (i.e., contrast transition); and, $(\mathbf{C}_l, \mathbf{C}_m, \mathbf{C}_r)$ is the representation of the color, corresponding to the left (\mathbf{C}_l), the middle (\mathbf{C}_m) and the right side (\mathbf{C}_r) of the 3D primitive.

In this paper, we estimate the 3D representation Π^m of monos which stereo fails to compute:

$$\Pi^m = (\mathbf{X}, \mathbf{n}, \mathbf{c}), \quad (4)$$

where \mathbf{X} and \mathbf{c} are as in equation 2, and \mathbf{n} is the orientation (i.e., normal) of the plane that locally represents the mono.

3 Relations between Primitives

The sparse and symbolic nature of primitives allows the following relations to be defined on them. These relations are used in deciding which features are allowed to make a depth prediction.

3.1 Co-planarity

Two 3D edge primitives Π_i^e and Π_j^e are defined to be co-planar if their orientation vectors lie on the same plane, i.e.:

$$\text{cop}(\Pi_i^e, \Pi_j^e) = 1 - |\mathbf{proj}_{t_j \times v_{ij}}(t_i \times v_{ij})|, \quad (5)$$

where v_{ij} is the vector $(\mathbf{X}_i - \mathbf{X}_j)$; t_i and t_j denote the vectors defined by the 3D orientations Θ_i and Θ_j , respectively; and, $\mathbf{proj}_{\mathbf{u}}(\mathbf{a})$ is the projection of vector \mathbf{a} over vector \mathbf{u} .

3.2 Linear dependence

Two 3D primitives Π_i^e and Π_j^e are defined to be linearly dependent if the *three* lines which are defined by (1) the 3D orientation of Π_i^e , (2) the 3D orientation of Π_j^e and (3) v_{ij} are identical. Due to uncertainty in the 3D reconstruction process, in this work, the linear dependence of two spatial primitives Π_i^e and Π_j^e is computed using their 2D projections π_i^e and π_j^e . We define the linear dependence of two 2D primitives π_i^e and π_j^e as:

$$\text{lin}(\pi_i^e, \pi_j^e) = |\mathbf{proj}_{v_{ij}} t_i| \times |\mathbf{proj}_{v_{ij}} t_j|, \quad (6)$$

where t_i and t_j are the vectors defined by the orientations θ_i and θ_j .

3.3 Co-colority

Two 3D primitives Π_i^e and Π_j^e are defined to be co-color if their parts that face each other have the same color. In the same way as linear dependence, co-colority of two spatial primitives Π_i^e and Π_j^e is computed using their 2D projections π_i^e and π_j^e . We define the co-colority of two 2D primitives π_i^e and π_j^e as:

$$\text{coc}(\pi_i^e, \pi_j^e) = 1 - \mathbf{d}_c(\mathbf{c}_i, \mathbf{c}_j), \quad (7)$$

where \mathbf{c}_i and \mathbf{c}_j are the RGB representation of the colors of the parts of the primitives π_i^e and π_j^e that face each other; and, $\mathbf{d}_c(\mathbf{c}_i, \mathbf{c}_j)$ is Euclidean distance between RGB values of the colors \mathbf{c}_i and \mathbf{c}_j .

Co-colority between an edge primitive π^e and a mono primitive π^m , and between two monos can be defined similarly (not provided here).

4 Formulation of the Model

For the prediction of the depth at monos, we developed a voting model. Voting models are suitable for producing a result from data which includes outliers. In a voting model, there are a set of voters that state their *opinion* about a certain event e . A voting model combines these votes in a reasonable way to make a decision about the event e .

In the depth prediction problem, the event e to be voted about is the depth and the 3D orientation of a mono π^m , and the voters are the edge primitives $\{\pi_i^e\}$ (for $i = 1, \dots, N_E$) that bound the mono. In this paper, we are interested in the predictions of pairs of π_i^e s, which are denoted by P_j for $j = 1, \dots, N_P$. While forming a pair P_j from two edges π_i^e and π_k^e from the set of the bounding edges of a mono π^m , we have the following restrictions:

1. π_i^e and π_k^e should share the same color with the mono π^m (i.e., the following relations should hold: $coc(\pi_i^e, \pi_k^e) > T_{coc}$ and $coc(\pi_i^e, \pi^m) > T_{coc}$).
2. The 3D primitives Π_i^e and Π_k^e of π_i^e and π_k^e should be on the same plane (i.e., $cop(\Pi_i^e, \Pi_k^e) > T_{cop}$).
3. π_i^e and π_k^e should not be linearly dependent so that they define a plane (i.e., $lin(\pi_i^e, \pi_k^e) < T_{lin}$).

The vote v_i by a pair P_j can be parametrized by:

$$v_i = (\mathbf{X}, \vec{n}), \quad (8)$$

where \vec{n} is the normal of the mono π^m , and \mathbf{X} is its depth.

Each v_i has an associated reliability or probability r_i . They denote how likely the vote is based on the believes of pair P_i . It is suggested in (Kalkan et al., 2007) that the likelihood that a local surface patch is coplanar with a 3D edge feature decreases with the distance between them. Accordingly, we define the reliability r_i of a vote v_i as:

$$r_i = 1 - \frac{1}{\min(d(\pi^m, \pi_1^e), d(\pi^m, \pi_2^e))}, \quad (9)$$

where $d(., .)$ is the Euclidean image distance between two features.

4.1 Bounding edges of a mono

Finding the bounding edges of a mono π^m requires making searches in a set of directions d_i , $i = 1, \dots, N_d$ for the edge primitives. In each direction d_i , starting from a minimum distance R_{min} , the search is performed up to a distance of R_{max} in discrete steps s_j , $j = 1, \dots, N_s$. If an edge primitive π^e is found in direction d_i in the neighborhood Ω of a step s_j , π^e is added to the list of bounding edges and the search continues with the next direction.

4.2 The vote of a pair of edge primitives on a mono

A pair P_i of two edge primitives π_j^e and π_k^e with two corresponding 3D edge primitives Π_j^e and Π_k^e , which are co-planar, co-color and linearly *independent*, defines a plane p with 3D normal \mathbf{n} and position \mathbf{X} .

The vote v_l of Π_j^e and Π_k^e is computed by the intersection of the plane p with the ray l that goes through the mono, π^m , and the optical center of the camera.

4.3 Combining the votes

The votes can be integrated using different ways to estimate the 3D representation Π^m of a 2D mono π^m . One way is to take the weighted average of the votes. Weighted averaging is adversely affected by the outliers. For this reason, we cluster the votes and do the averaging inside the *best* cluster. Let us denote the clusters by c_i for $i = 1, \dots, N_c$. Then,

$$\Pi^m = \arg \max_{c_i} \#c_i. \quad (10)$$

where $\#$ is the cardinality of a cluster. The best cluster can be alternatively chosen to be a cluster which has the highest reliability. In this paper, we adopted the definition in equation 10.

Clustering the votes can filter outliers out whereas it is slow. Moreover, it is not trivial to determine the number of clusters from the data points that will be clustered.

In this paper, we implemented (1) a histogram-based clustering where the number of bins is fixed, and the best cluster is considered to be the bin with the most number of elements, and (2) a clustering algorithm where the number of clusters is determined automatically by making use of a cluster-regularity measure and maximizing this measure iteratively.

(1) is a simple but fast approach whereas (2) is considerably slower due to the iterative-clustering step. Our investigations showed that (1) and (2) produce similar results (the comparative results are not provided in this paper). For this reason, we have adopted (1) as the clustering method for the rest of the paper.

4.4 Combining the predictions using area information

3D surfaces project as areas into 2D images. Although one surface may project as many areas in the 2D image, it can be assumed most of the time that the image points in an image area are part of the same 3D surface.

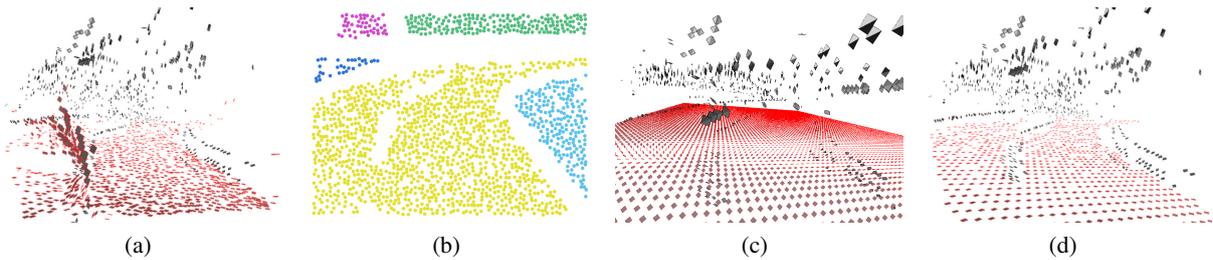


Figure 3: **(a)** The predictions on the surface of the road for the input images shown in figure 1 (predictions are marked with red boundaries). The predictions are scattered around the plane of the road, and there are wrong predictions due to strong outliers in the computed stereo. The figure is a snapshot from our 3D displaying software. **(b)** Segmentation of one of the input images given in figure 1 into areas using region-growing based on primitives. **(c)** The surface extracted from the predictions shown in (a). **(d)** The predictions from (a) that are corrected using the extracted surface shown in subfigure (c).

Figure 3(a) shows the predictions of a surface. Due to strong outliers in the stereo computation, depth predictions are scattered around the surface that they are supposed to represent. We show that it is possible to segment the 2D image into areas based on intensity similarity and combine the predictions in areas to get a cleaner and more complete surface prediction.

We segment an input image I into areas A_i , $i = 1, \dots, N_A$ using co-colority (see section 3) between primitives utilizing a simple region-growing method; the areas are grown until the image boundary or an edge-like primitive is hit. Figure 3(b) shows the segmentation of one of the images from figure 1.

In this paper, we assume that each A_i has a corresponding surface S_i defined as follows:

$$S_i(x, y, z) = ax^2 + by^2 + cz^2 + dxy + eyz + fxz + gx + hy + iz = 1. \quad (11)$$

Such a surface model allows a wide range of surfaces to be represented, including spherical, ellipsoid, quadratic, hyperbolic, conic, cylindrical and planar surfaces.

S_i is estimated from the predictions in A_i by solving for the coefficients using a least-squares method. As there are nine coefficients, such a method requires at least nine predictions to be available in area A_i . For the predictions shown in figure 3(a), the estimated surface is shown in figure 3(c) using a sparse sampling.

Having an estimated S_i for an area A_i makes it possible to *correct* the mono predictions using the estimated surface S_i : Let \mathbf{X}_n be the intersection of the surface S_i with the ray that goes through π^m and the camera, and \mathbf{n}_n be the surface normal at this point (defined by $\mathbf{n}_n = (\delta S_i / \delta x, \delta S_i / \delta y, \delta S_i / \delta z)$). \mathbf{X}_n and \mathbf{n}_n are respectively the corrected position and the orientation of mono Π^m .

Corrected 3D monos for the example scene is shown in figure 3(d). Comparison with the initial predictions which are shown in figure 3(a) concludes that

(1) outliers are *corrected* with the extracted surface representation, and (2) orientations and positions are qualitatively better.

Surface information can further be used to remove the strong outliers in the 3D edge features that are extracted using stereo.

5 Results

We compared the following: (1) our depth prediction method *without* surface corrections (DeP); (2) a phase-based (PB) dense stereo from (Sabatini et al., 2007); (3) squared sum of differences (SSD) as the matching function with a winner-take-all approach; (4) absolute differences as the matching function with a scanline optimization (SO); and, (5) absolute differences with a dynamic programming optimization (DP). See (Brown et al., 2003) for information about (3)-(5).

Dense stereo methods (3)-(5) are taken from (Scharstein and Szeliski, 2001), and their parameters are adjusted for a good performance as suggested in (Scharstein and Szeliski, 2001). SO and DP involve a global optimization step which is expected to improve results and perform better compared to winner-take-all approaches. As for PB, the reliability threshold was set to 0 for better comparability. The images which the dense stereo algorithms are applied to were rectified and downsampled (if needed).

The results of our model as well as DP and PB (with two different thresholds) is shown in figure 4 for a real scene which includes occlusion and texture. We see that our method is able to provide comparable performance to dense stereo algorithms. Although our algorithm performs well on textured surfaces, the effect of the wrong predictions from the occluding edges are visible especially around the traffic sign. Moreover, due to the uncertainty on the

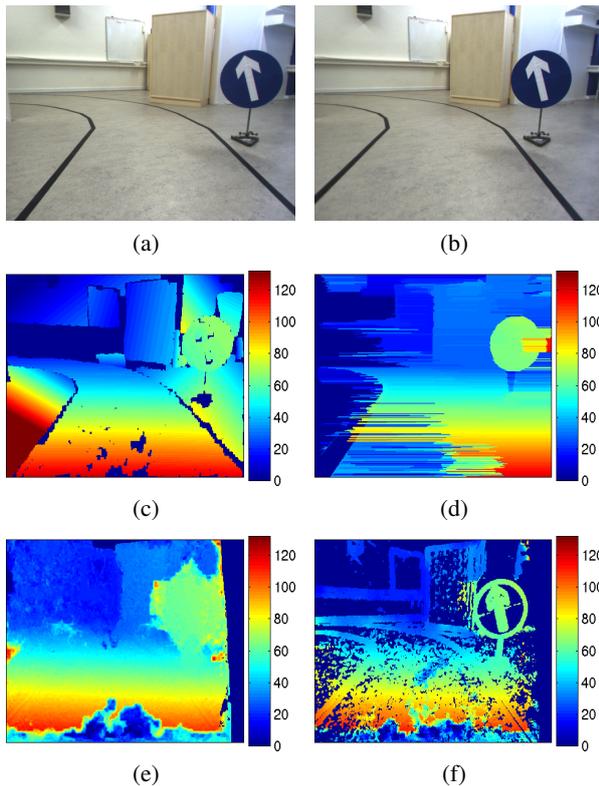


Figure 4: Experiment results on a road scene. **(a,b)** Input stereo pair. **(c)** The predictions of our model as a disparity map. **(d)** Disparity map from DP. **(e)** Disparity map from PB. **(f)** Subfigure (e) after a small threshold (0.001).

left edge of the road and as least-squares fitting is affected by the outliers adversely, the surface on the left is badly reconstructed. Occlusions are a problem for dense stereo algorithms as well (as seen in *e.g.*, figure 4(e)). DP however can perform better on occluded areas due to its global optimization; however, DP does not produce results on the left side of the scene. As shown in figure 4(f) for PB, using a reliability threshold on the disparity values can get rid of most of the outliers in figure 4(e), however, lowering the threshold decreases the most of the inliers of the disparity map.

Another example is shown in figure 5, which shows that in spite of limited 3D information from feature-based stereo, our method is able to predict the surfaces. Figure 5 shows that our method is able to utilize little information at the right side of the road to predict the 3D information.

The comparisons are performed on an artificial scene where the texture could be modified in order to see the behaviours of the different approaches. The texture is *white* noise, and the amount of texture is

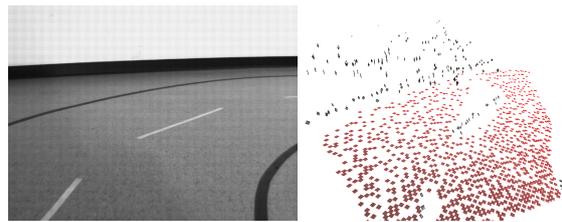


Figure 5: Experiment results on a lab road scene. **Left:** Left image of the input stereo pair. **Right:** The predictions of our model shown in our 3D displaying software.

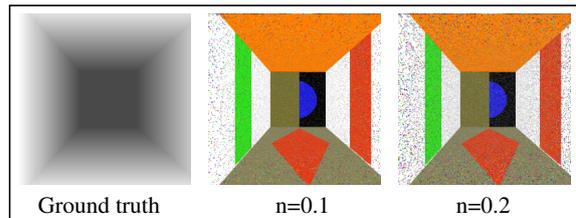


Figure 6: A subset of the textured artificial images that have been used. Added texture is *white* noise with a frequency n .

controlled by the frequency ($n \in [0, 0.2]$) of the white-noise. We tried n up to 0.2 because the images get over-textured for bigger values of n . A subset of the input images are shown in figure 6.

The expectation is to see that dense stereo methods perform poor on weakly-structured scenes where our model should make good predictions. When the amount of texture is increased, dense stereo methods should perform better, and the predictions made by our model should degrade because an increase in texture causes the features to be less reliable and noisy.

For evaluation against a ground truth d_G , we used two disparity error measures: Root-Mean-Squares (RMS) and Bad-Matching-Percentage (BMP). RMS is the standard measure that has been used in the literature for evaluating the performance of stereo algorithms (see, *e.g.*, (Scharstein and Szeliski, 2001)):

$$\text{RMS}(\mathcal{S}) = \left(\frac{1}{\#\mathcal{S}} \sum_{\mathbf{p} \in \mathcal{S}} |d_C(\mathbf{p}) - d_G(\mathbf{p})|^2 \right)^{1/2}, \quad (12)$$

where \mathcal{S} is the set of points with disparity information; and, $d_C(\mathbf{p})$ and $d_G(\mathbf{p})$ are respectively the computed and the ground truth disparity information at point \mathbf{p} .

BMP measure (taken from (Scharstein and Szeliski, 2001)) is defined as follows:

$$\text{BMP}(\mathcal{S}) = \frac{1}{\#\mathcal{S}} \sum_{\mathbf{p} \in \mathcal{S}} (|d_C(\mathbf{p}) - d_G(\mathbf{p})| > 1), \quad (13)$$

RMS errors in figure 7(a) shows that our method is more accurate than dense stereo methods. Comparison with BMP errors in figure 7(b) suggests RMS

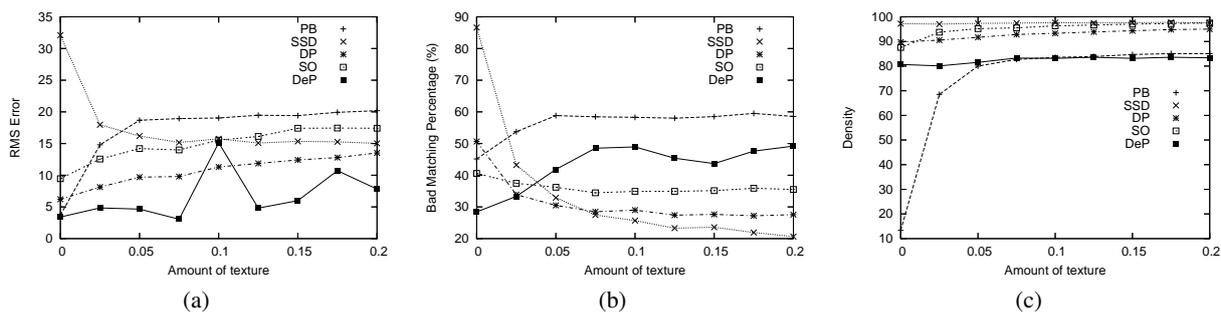


Figure 7: Performance of different algorithms on the artificial scene in figure 6 for different amount of texture using RMS (a), BMP (b) measures. The densities are shown in (c).

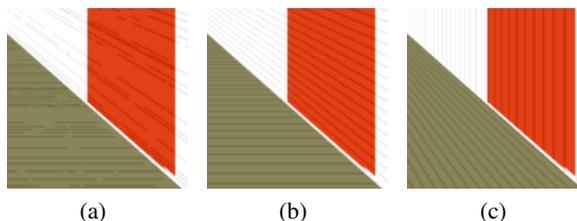


Figure 8: Weak lines applied on the artificial scene from figure 6. Due to space constraints, only portions of the images are provided. (a) Irregular lines. (b) Regular horizontal lines. (c) Regular vertical lines.

evaluation of dense methods are affected by the outliers. In general, we see that when there is no texture, our method is better than dense methods; the reverse is the case when the image is textured. The density plot in figure 7(c) confirms that our method can produce highly dense disparity maps at untextured images.

We compared the performance of the different approaches using a different texture on the same artificial scene from figure 6. The type of texture is weak lines (see figure 8): regularly sampled vertical and horizontal lines, and irregularly sampled and sized lines. The performance of dense stereo methods and our model are shown in figure 9. Again we observe that our depth prediction method can provide comparable results to DP, and better results than other approaches.

Finally, we compared the performance of the algorithms on noisy images (again using the artificial scene used above). This comparison is important because signal to noise ratio at weakly-textured image areas are higher than textured image areas, for the same amount of noise. We added white noise with a frequency between 0 and 0.2 and plotted the performance for different amount of texture (figure 10). The performance of dense methods are severely af-

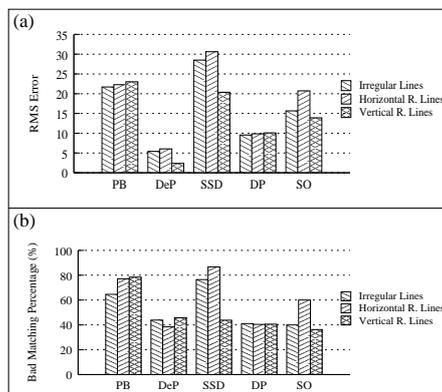


Figure 9: Performance of different algorithms on the artificial scene in figure 8 for different amount of texture (n) using RMS (a) and BMP (b) measures.

ected by noise. Our depth prediction method, on the other hand, is more robust because edge features are less sensitive to noise.

6 Conclusion

In this paper, we introduced a voting model that estimates the depth at homogeneous or weakly-textured image patches from the depth of the bounding edge-like structures. The depth at edge-like structures is computed using a feature-based stereo algorithm, and is used to vote for the depth of a mono, which otherwise is not possible to compute easily due to the correspondence problem.

The results are compared with different dense stereo algorithms in order to state that our feature-based algorithm works well for scenes that dense stereo algorithms are not suited well. Our aim was not to claim that our method or dense methods are better than the other approaches but rather to suggest

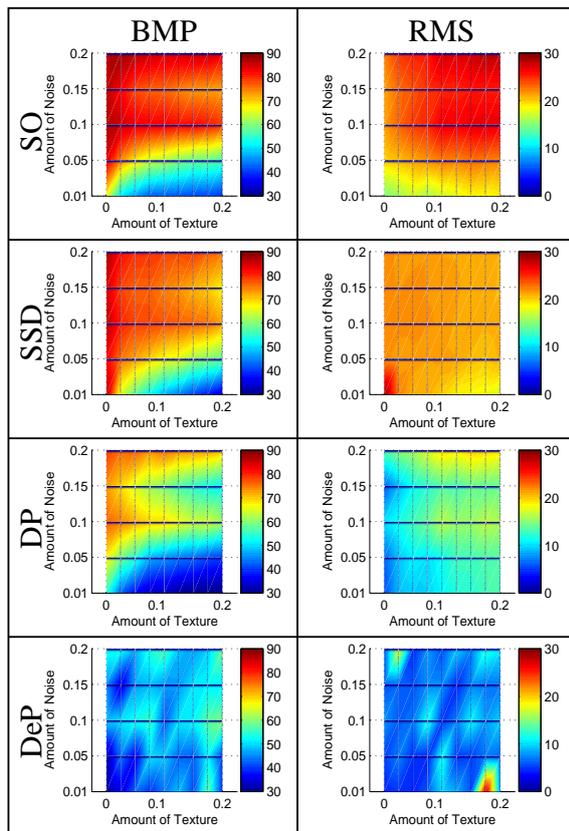


Figure 10: Performance of the different algorithms as a function of white noise and texture (white noise).

a combination of our depth prediction model with a dense stereo algorithm. Such a combination would benefit from both approaches and would be able to work in textured as well as non-textured image areas.

Depth prediction can be regarded as a novel depth cue which functions at a higher stage than other depth cues and interacts with those cues to fill in missing depth information. Currently, only the 3D information from stereo is made use of; however, any other depth cue which can provide 3D line orientation at the edges can be utilized, too.

Depth prediction is along the lines of 3D shape interpretation from the line drawings of objects. We are extending our method by integrating the curvature of the groups in order to make predictions on round surfaces.

We used a different set of images than for example the Middlebury database because our method is more suitable for weakly-textured images, and for surfaces which are big enough to make predictions at. Moreover, non-availability of the camera parameters for these images disallows the application of our depth prediction method, which requires 3D reconstruction

at the edges in order to be able to make depth predictions.

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