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Joint Estimation of Deformable Motion and Photometric Parameters in Single View Video

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Overview

We present a method for joint deformation and illumination parameter estimation from monocular image sequences exploiting direct image information. We are particularly interested in augmented reality applications, where a new texture is rendered onto a moving and deforming surface in the original video in real-time. Realistic retexturing not only requires geometric registration but also photometric parameter retrieval for convincing illusion. Taking into account the photometric part by relaxing the brightness constancy assumption of the estimation not only allows realistic augmentation results but also improves spatial tracking.

Joint Motion and Illumination Estimation

We describe the spatial deformation of the surface in the image plane in a dense pixel displacement field and the photometric changes in a dense pixel intensity scale field and parameterize these fields with a deformable model that is presented as a planar triangulated regular 2D mesh with K vertices $\mathbf{v}_k, (k=1...K)$

Deformation

$$\mathbf{D}(\mathbf{x}_i) = \sum_{i\in\{a,b,c\}} \beta_i \delta\mathbf{v}_i$$

Photometric changes

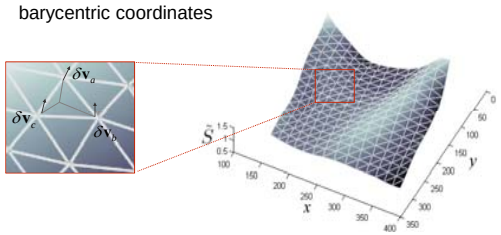
$$\mathcal{S}(\mathbf{x}_i) = \sum_{i\in\{a,b,c\}} \beta_i \mu_i$$

Higher order interpolation is also possible

$\delta\mathbf{v}_i$ three surrounding vertex displacements

$\delta\mu_i$ photometric parameters

β_i barycentric coordinates



The resulting parameter vector modeling the deformable motion and illumination changes is then given by concatenating the parameters of each vertex:

$$\mathbf{\Theta} = \left(\delta v_{x_1},..,\delta v_{x_K},\delta v_{y_1},..,\delta v_{y_K},\delta\mu_1,..,\delta\mu_K\right)^T$$

Generally, estimating the parameter vector leads to minimizing a cost function that consists of two terms:

$$\hat{\mathbf{\Theta}} = \mathrm{argmin}_{\mathbf{\Theta}}\left(E_D(\mathbf{\Theta}) + \lambda\cdot E_S(\mathbf{\Theta})\right)$$

DataTerm

We relax the optical flow constraint equation allowing for multiplicative deviations from brightness constancy:

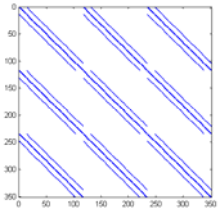
$$I\left(\mathbf{x}+\mathbf{D}(\mathbf{x}), t+\delta t\right) = \tilde{\mathcal{S}}(\mathbf{x})\cdot I(\mathbf{x},t)$$

The data term then is given by the Sum of Squared Differences. We perform a hierarchical estimation scheme and on each level the above equation is approximated with a Gauss-Newton approximation by applying a first-order Taylor expansion:

$$E_D = \sum_{\mathbf{x}\in\Re}\left(\nabla I(\mathbf{x})\cdot\mathbf{D}(\mathbf{x}) + \frac{\partial I(\mathbf{x})}{\partial t} - S(\mathbf{x})\cdot I(\mathbf{x})\right)^2$$

To regularize the optical flow field and the illumination scale field we incorporate the mesh-based motion and illumination model represented by the parameter vector $\mathbf{\Theta}$ This leads to a cost function of the following form:

$$E_D(\mathbf{\Theta}) = \left\|\mathbf{J}\cdot\mathbf{\Theta} - \mathbf{b}\right\|^2$$



$$\mathbf{H} \approx \mathbf{J}^T\mathbf{J}$$

The sparse structure of the Gauss-Newton approximation of the Hessian is exploited to solve the normal equations of the Linear Equation System. For a higher order interpolation, like B-splines or thin-plate splines can be formed in a similar way but the matrix is less sparse.

Smoothness Term

In order to incorporate prior knowledge on the smoothness of the deformation and illumination fields we penalize the discrete second derivative of the motion and illumination parameters in the mesh in a smoothness term:

$$E_S(\mathbf{\Theta}) = \left\|\tilde{\mathbf{L}}\cdot\mathbf{\Theta}\right\|^2$$

Distance Weighted Laplacian Matrix

One important property of using direct image information is that less image information, i.e. small image gradients, in a region automatically leads to a higher local weighting of the smoothness constraint in the resulting equation system.

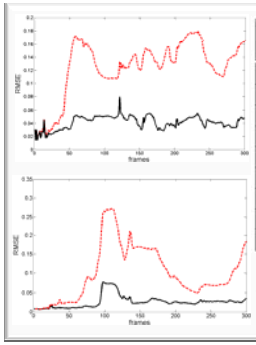
The resulting linear equation system can be efficiently solved in a Least Squares sense on each resolution level:

$$E(\mathbf{\Theta}) = \left\|\begin{pmatrix}\mathbf{J}\\ \lambda\tilde{\mathbf{L}}\end{pmatrix}\mathbf{\Theta} - \begin{pmatrix}\mathbf{b}\\ \mathbf{0}\end{pmatrix}\right\|^2$$

Experimental Validation

RMSE Based RegistrationEvaluation

We calculate the Root Mean Squared Error (RMSE) between the synthetic image, generated from the current geometrical and photometrical parameters, and the original current frame over all image pixels in the mesh region for several video sequences. Taking illumination parameters into account significantly reduces the mean RMSE over the entire sequence by up to 74%.

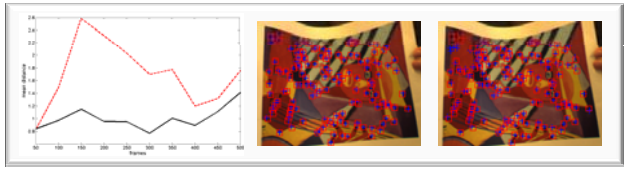


Sequence	RMSE with classical OF	RMSE with our approach	reduction
Picasso	0.0306	0.0204	33.33%
Flower1	0.1364	0.0415	69.57%
Flower2	0.1245	0.0376	69.80%
Art	0.1016	0.0258	74.61%
Flower3	0.1286	0.0385	70.06%
Shirt	0.0630	0.0405	35.71%
Pattern	0.0632	0.0213	66.30%
Cloth1	0.0877	0.0443	49.49%
Cloth2	0.0976	0.0513	47.44%

Comparison of the RMSE between a synthetic frame generated with the estimated parameter with classical optical flow (red) and our approach (black) and the current frame

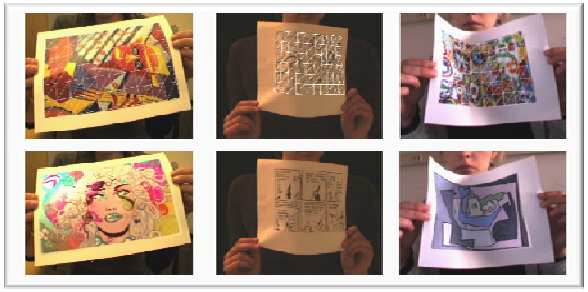
Point Based Registration Evaluation

We additionally calculated the distance between the estimated position of feature points to manually selected ground truth points. The mean difference between the estimated positions and the manually labeled ground truth position describes the geometric registration error. This additional evaluation approach is chosen to evaluate geometric registration accuracy separately from photometric registration. We can reduce the mean distance between the estimated and the ground truth position by approximately 40%.



Retexturing Results

The geometrical and photometrical parameters are exploited to retexture a deforming surface in monocular images by establishing a shading map from the photometric parameters.



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