Can We Jointly Register and Reconstruct Creased Surfaces by Shape-from-Template Accurately?

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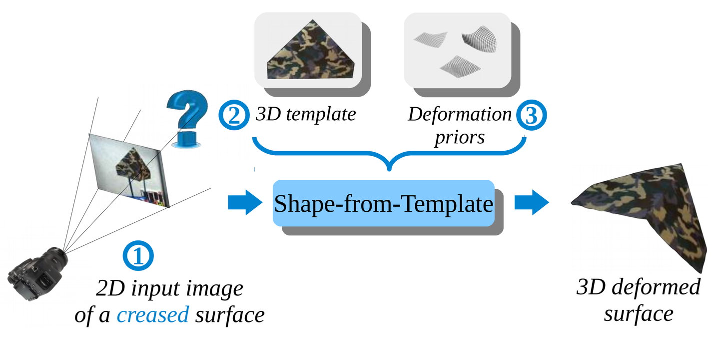
Context and Motivations

Shape-from-Template:
3D reconstruction using the apparent **motion** of features between one single image and a 3D textured template

Needs textured surfaces

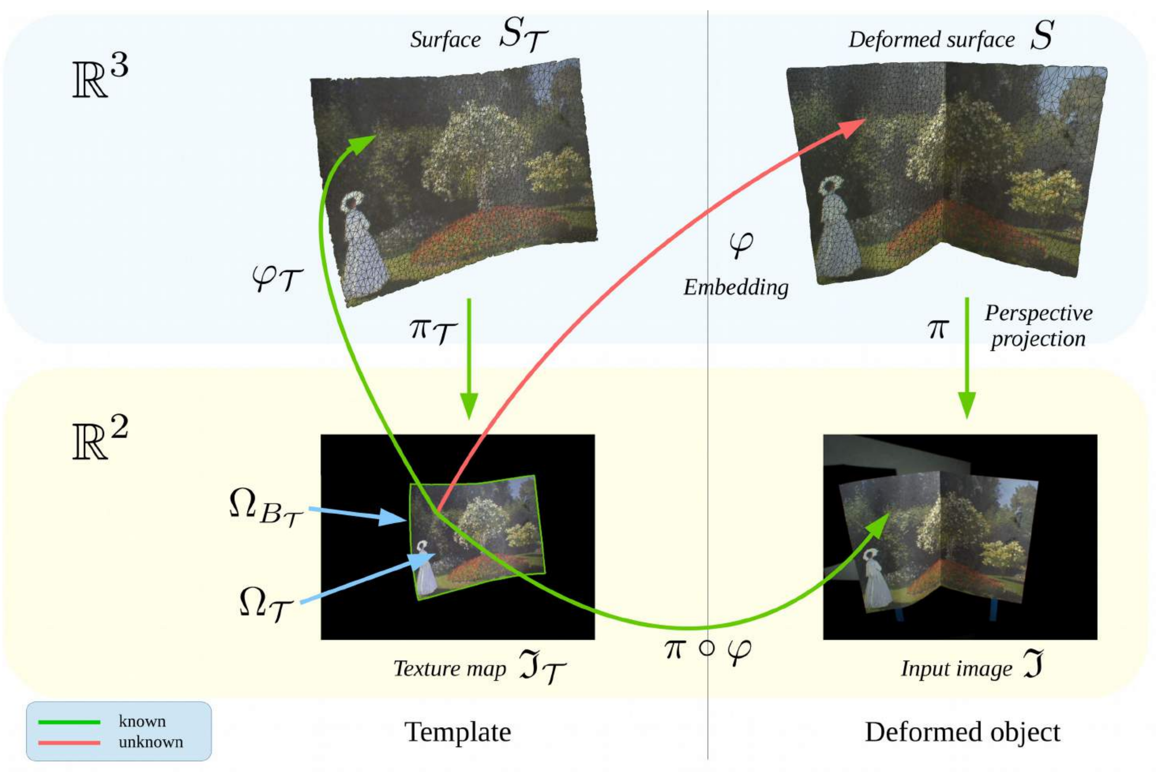
Assumes smooth deformations

- Usual regularizers [2,3]
- Reduction dimensionnality [4]



We tackle the problem of reconstructing surface creases

Problem Modeling



Deformation parameters
$\mathbf{x} = \{\mathbf{x}_1, \ldots, \mathbf{x}_N\}$

- Embedded by φ
- Triangular regular dense mesh

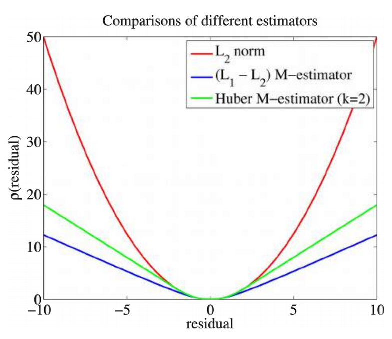
allows complex deformation modeling

Bending Constraint C_{bend}

- M-estimator allows piecewise smooth 3D reconstructions by reducing influence of high errors

$$C_{bend}(\mathbf{x}) = \int_\Omega \rho \left(\frac{\partial^2 \varphi(\mathbf{u};\mathbf{x})}{\partial \mathbf{u}^2} \right) d\Omega,$$

In red, high error in bending constraint



- Comparison of $(\ell_1\text{-}\ell_2)$ and *Huber* M-estimators (bending weight and *Huber* hyper-parameter)

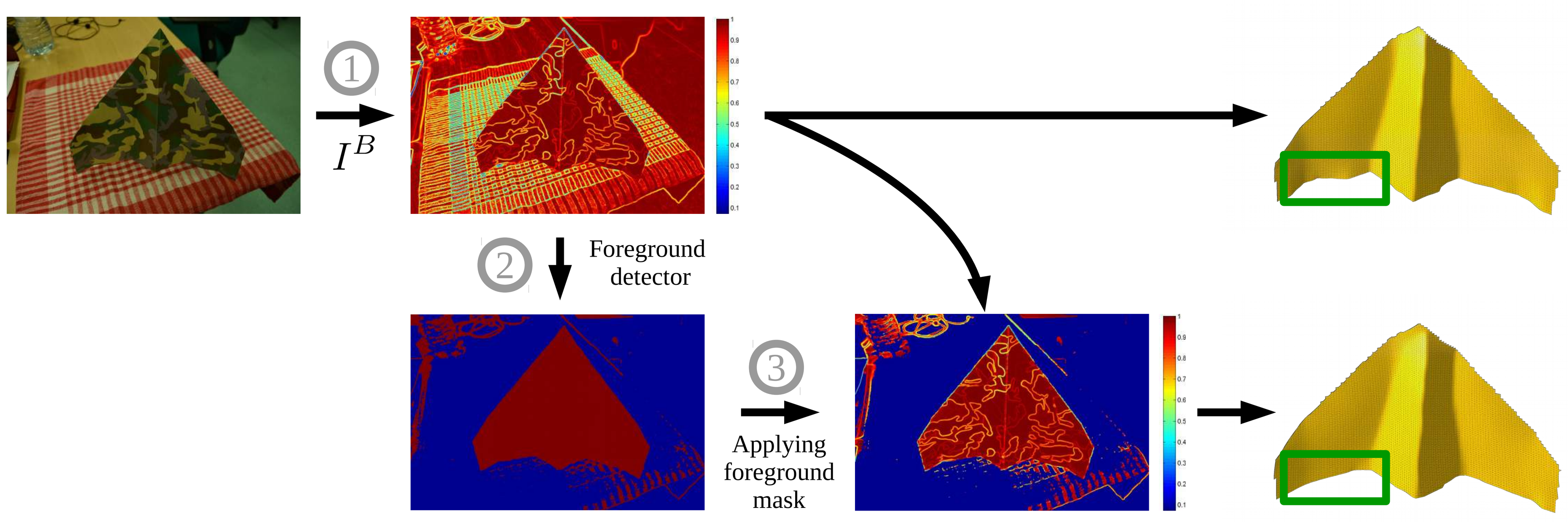
M-estimator retained: $(\ell_1\text{-}\ell_2)$ $\quad \rho(\mathbf{y}) = 2\left(\sqrt{1 + ||\mathbf{y}||_2^2/2} + 1\right)$

Boundary Constraint C_{bound}

- Projects the 3D surface boundaries in boundariness map ~ potential well

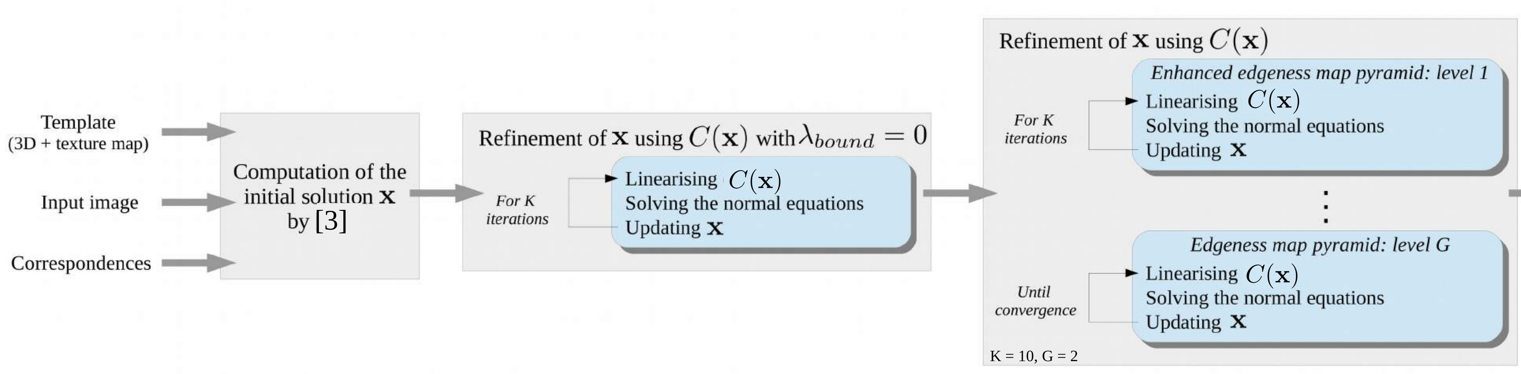
$$C_{bound}(\mathbf{x}) = \int_{\Omega_B} \rho\left(I^B\left((\pi \circ \varphi)(\mathbf{u}_j;\mathbf{x})\right)\right) d\Omega, \quad \text{with} \quad I^B = \exp\left(-\frac{|\nabla I^G|}{\sigma^B}\right)$$

- Enhancement of boundariness map: color-based foreground detector to reduce false boundary edges (from background clutter or texture)



Solution Strategy

- **Initialization** with an existing solution [3]
- Non-convex **refinement**
  - Minimization of cost function $C(\mathbf{x})$ for a dense mesh of $\mathcal{O}(10^4)$ vertices
  - Gauss-Newton optimization with sparse Cholesky solver for normal equations
  - Two-stage optimization with images pyramid for boundary constraint



Conclusion

- Modeling and optimization framework to register and reconstruct accurately smooth and creased 3D surfaces from a single image and a deformable 3D template
- Creases modeled by a dense mesh with a robust bending constraint led by an M-estimator
- Use of boundary constraint for a more accurate registration and color-based foreground detector to improve convergence
- Future works: arbitrary topologies and dynamic crease modeling

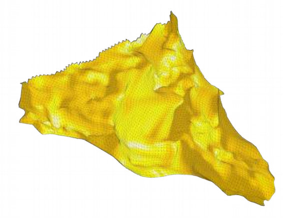
Previous Attempts

	Smooth deformations	Non-smooth deformations
Convex formulation	✓	✓
Non-convex formulation	✓	✗

Closest work:
convex formulation of [1]

- correspondences are not sufficiently informative
- does not use smoothing

Input image



Reconstruction from [1]

Contributions

(i) implicitly model surface creases without knowing a priori their location through an M-estimator for **bending** constraint
(ii) introduce **boundary** constraint to complement motion constraint which is sparse
(iii) use **statistical color models** to help disambiguate non-boundary edges

Global Cost Function

$C(\mathbf{x}) =$

$C_{crsp}(\mathbf{x})$	Reduces reprojection error of feature-correspondences
$+\lambda_{bound}\, C_{bound}(\mathbf{x})$	Aligns $\Omega_{B_\mathcal{T}}$ to wherever it is visible in the input image
$+\lambda_{iso}\, C_{iso}(\mathbf{x})$	Prevents the surface from extension and contraction (isometry)
$+\lambda_{bend}\, C_{bend}(\mathbf{x})$	Penalizes non-smooth surfaces and reduces the energy at creases

M-estimators norms that fit to outliers/reduce the impact of high errors

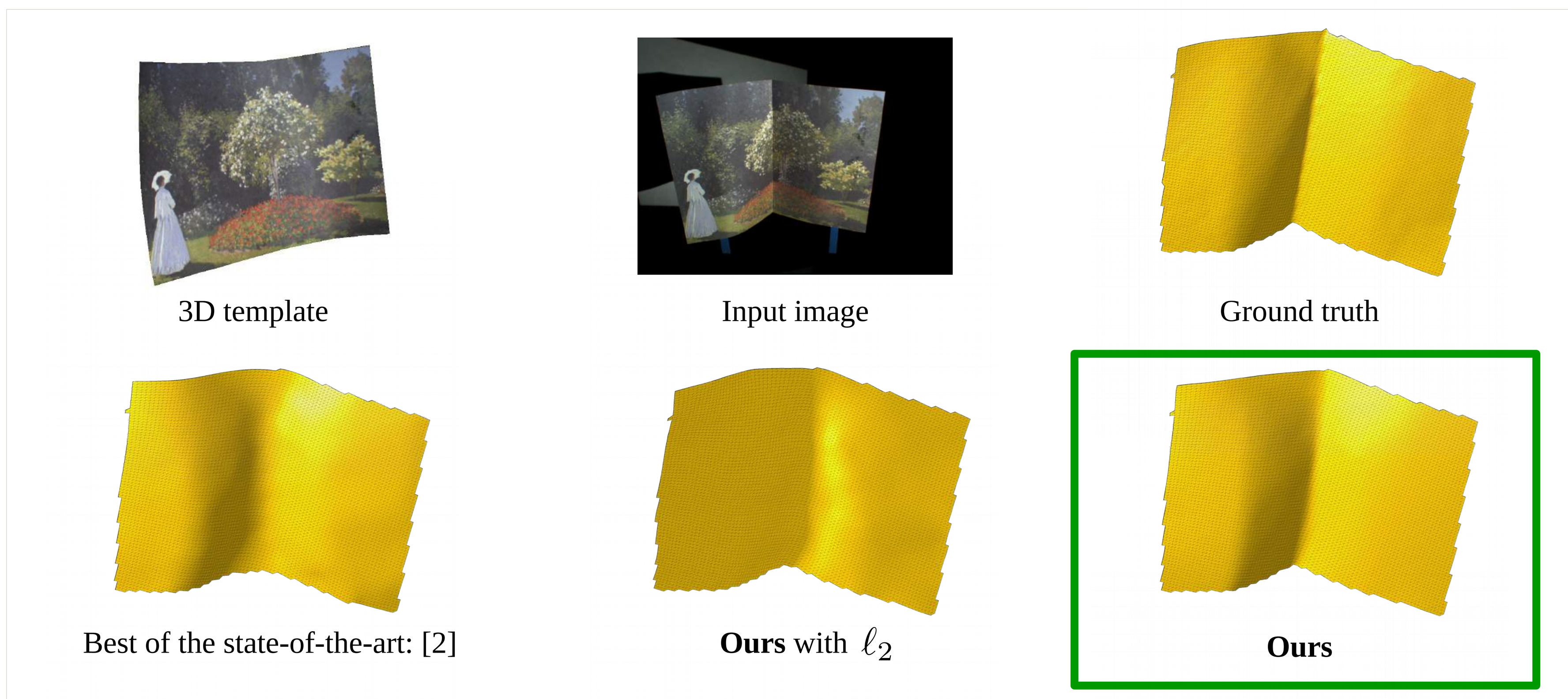
C_{crsp}	to handle mis-matches
C_{bound}	to handle little contrast at edges surface
C_{bend}	to allow piecewise smooth reconstructions

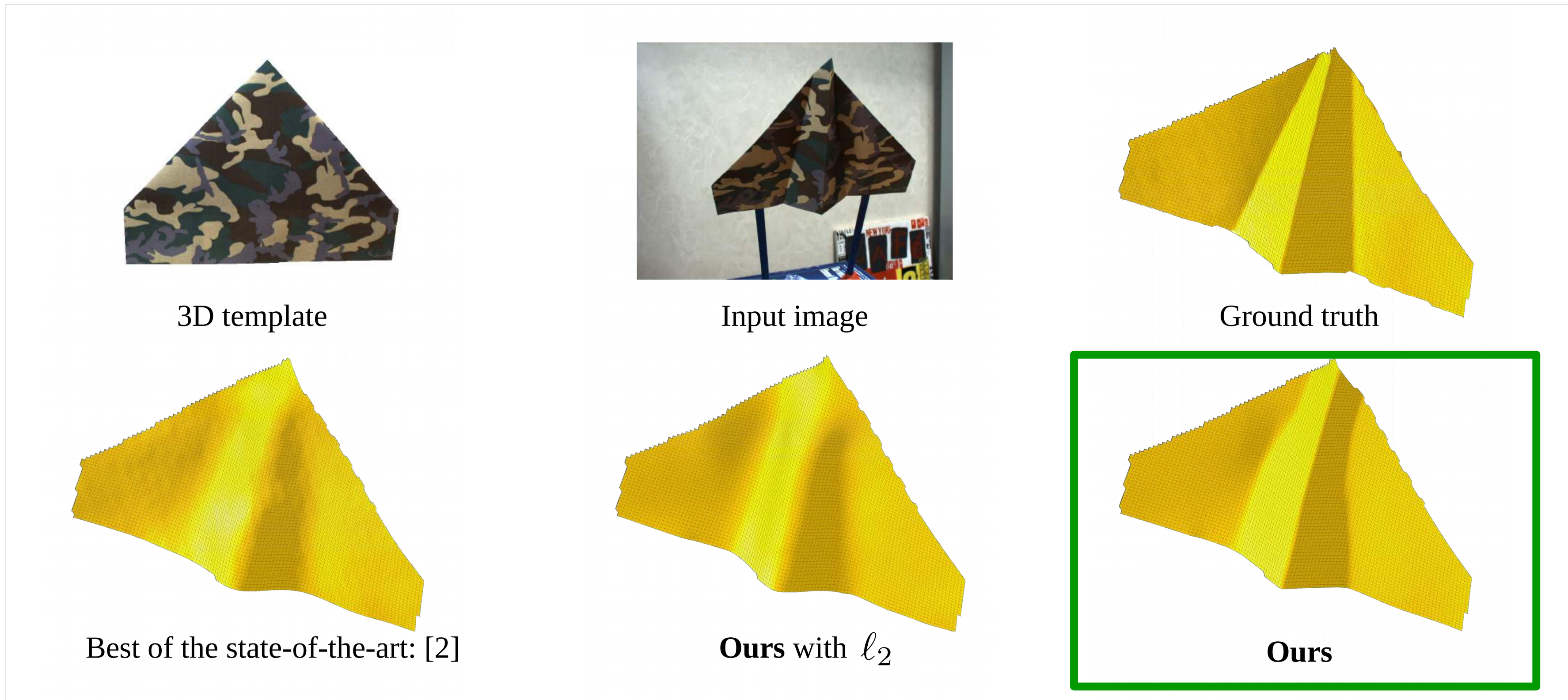
Implementation

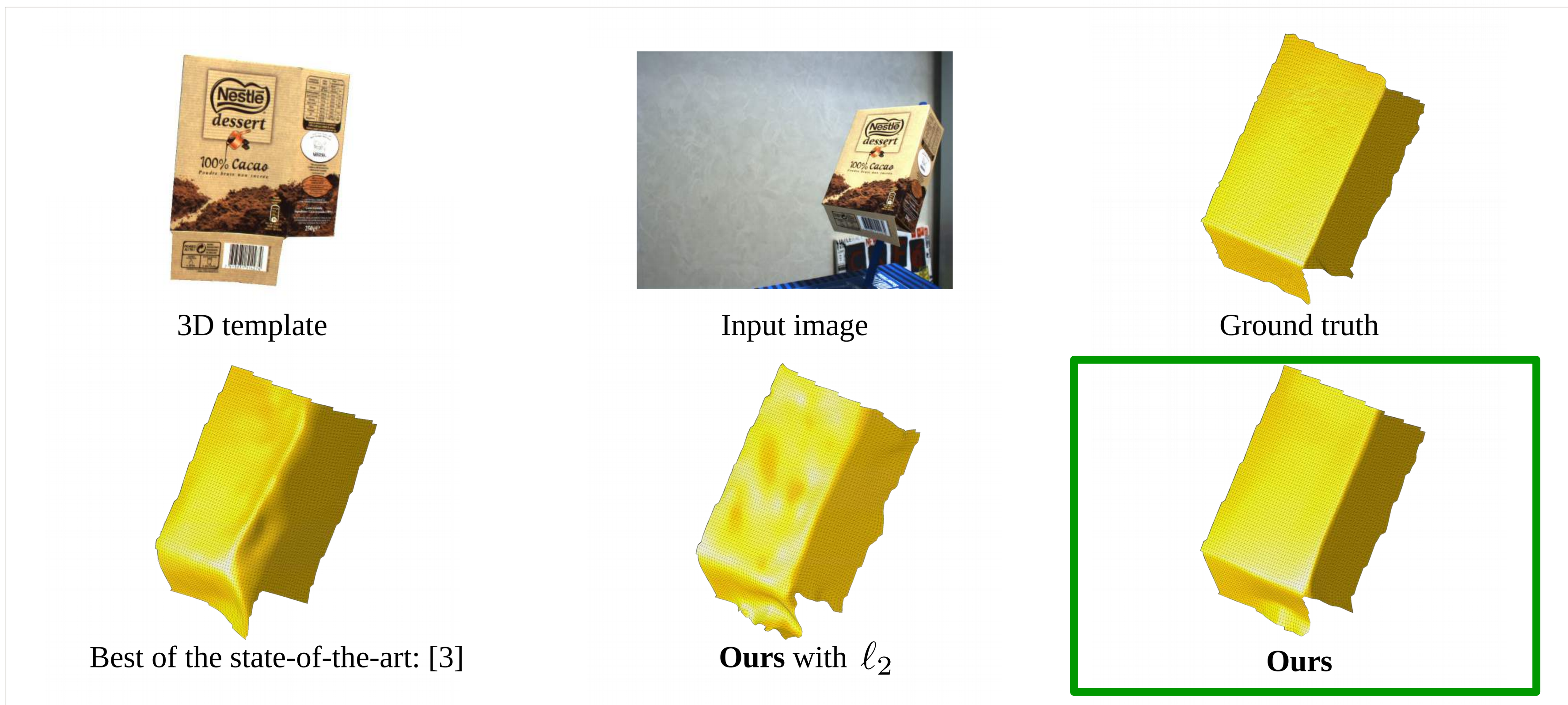
$$\min \sum_i \rho(residual_i)$$

Results

- Real datasets with high-precision (<1 mm) ground truth with structured-light system
- Comparison to SfT state-of-the-art: [1,2,3,4]
- Smooth dataset presented in [3]: small improvement of the 3D mean error
- Quantitative evaluations all over the surface and at the creases: 3D errors and normals
- Better 3D reconstruction at creased regions and all over the surface







References:
[1] Salzmann and Fua, PAMI 2011
[2] Bartoli et al., PAMI 2015
[3] Chhatkuli et al., CVPR 2014
[4] Ngo et al., PAMI 2016