A New Approach for Specular Surface Reconstruction Using Deflectometric Methods

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Abstract: Large specular industrial components like engine hoods and bumpers require a multitude of image acquisition configurations for optical surface inspection: as the domain of measurement tends to decrease with curvature, the surface must be inspected part by part. Surface points along the border of neighboring and slightly overlapping patches can be estimated by a monocular stereo approach followed by numerical surface reconstruction. By initial value estimation only at patch boundaries, we achieve a computational-cost and hardware-wise optimal solution for the robust deflectometric reconstruction.

1 Introduction

The challenge in inspecting specular objects is that the object under test is not directly observable but rather images of the surrounding scene. This property can be exploited in optical metrology by a method known as deflectometry or Shape-from-Specular-Reflection: a sequence of gray value patterns encodes the positions on a pattern generator like a LC display for every viewing ray emitted from the optical center of a camera.

This encoding is usually done using gray-code patterns or phase-shift methods [Pér01], [GP98]. For an example of a fast phase-shift method we refer the reader to the paper by Huang and Zhang [HZ06].

Our experimental setup is shown in Figure 1 on the right hand side. For the deflectometric reconstruction, we are using a smart sensor consisting of camera, LC display and computer for generating, controlling, and examination of the pattern series. The employment of an robot allows us to position the sensor repetitively and with high accuracy. Using a robot based setup is instrumental in integrating our sensors and methods in practical applications where handling systems are very common.

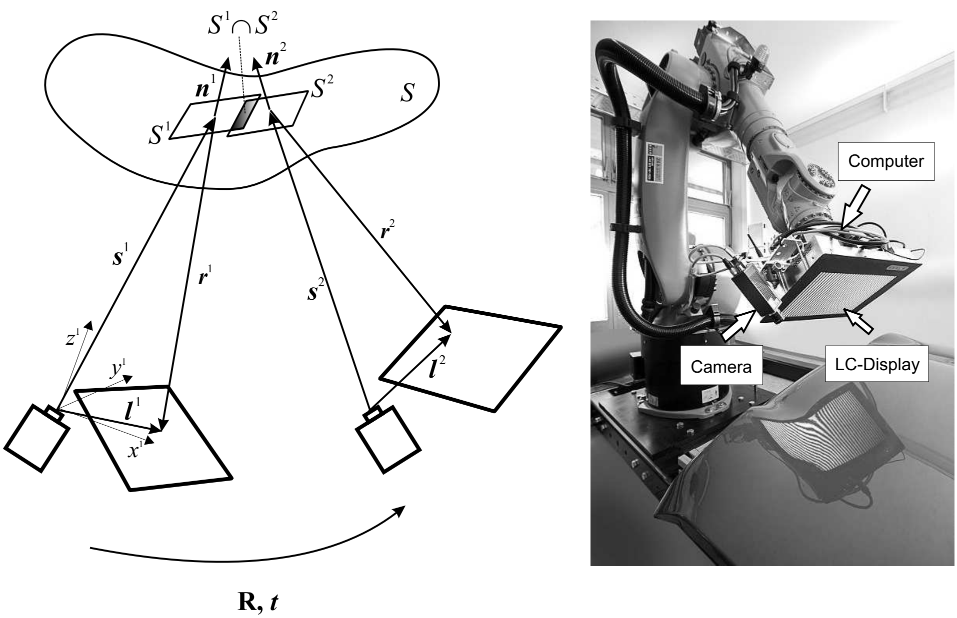

Figure 1: Left: Geometry of reflection for two positions of the sensor
Right: Smart sensor for deflectometric measurement

2 Deflectometric problem

In the formulation of the deflectometric problem for one single surface patch, we are following the presentation given in [WBB07].

The only assumption we can make about the object under test is that the surface normal must bisect the angle between the incoming and outgoing ray, on which the subsequent reconstruction procedure is based.

In the following i denotes the index of the considered surface patch S^i. Let $\boldsymbol{s}^i$ and $\boldsymbol{r}^i$ be the observation ray and its reflection, respectively (see Figure 1 left). Given the locus of the measured feature $\boldsymbol{l}^i\left(\frac{\boldsymbol{s}^i}{\|\boldsymbol{s}^i\|}\right) = \boldsymbol{s}^i + \boldsymbol{r}^i$, the sum $\boldsymbol{a}^i = \frac{\boldsymbol{s}^i}{\|\boldsymbol{s}^i\|} + \frac{\boldsymbol{r}^i}{\|\boldsymbol{r}^i\|}$ will be tangential to the unknown surface. With the definition of $\boldsymbol{b}^i = \boldsymbol{s}^i \times \boldsymbol{l}^i$, the theorem of Malus and Dupin can be reformulated as normal field equations in local sensor coordinates in the following way:

$$\langle \boldsymbol{a}^i(\boldsymbol{x}^i), \boldsymbol{n}^i(\boldsymbol{x}^i)\rangle = 0, \tag{1a}$$

$$\langle \boldsymbol{b}^i(\boldsymbol{x}^i), \boldsymbol{n}^i(\boldsymbol{x}^i)\rangle = 0 \tag{1b}$$

with $\langle \boldsymbol{a}^i, \boldsymbol{b}^i \rangle = 0$ and $\boldsymbol{x}^i \in \Omega \subseteq \mathbb{R}^3$. As a result of measurement of $\boldsymbol{l}^i\left(\frac{\boldsymbol{s}^i}{\|\boldsymbol{s}^i\|}\right)$ and system calibration, the vector fields $\boldsymbol{a}^i$ and $\boldsymbol{b}^i$ are well defined in an arbitrary volume Ω.

Surface curves $\boldsymbol{p}^i(\tau)$ and $\boldsymbol{q}^i(\tau)$ can be obtained by integration along these vector fields from an suitable starting point in Ω. This fact can be stated in the form of the *characteristic* ODE system for the patch S^i:

$$\frac{d\boldsymbol{p}^i(\tau)}{d\tau} = \boldsymbol{a}^i\left(\boldsymbol{p}^i(\tau)\right), \quad \boldsymbol{p}^i(0) = \boldsymbol{s}_0^i, \tag{2a}$$

$$\frac{d\boldsymbol{q}^i(\tau)}{d\tau} = \boldsymbol{b}^i\left(\boldsymbol{q}^i(\tau)\right), \quad \boldsymbol{q}^i(0) = \boldsymbol{p}_0^i \in \boldsymbol{p}^i(\tau). \tag{2b}$$

Once knowing an initial value $\boldsymbol{s}_0^i$ for the problem (2), it is possible to reconstruct the surface patch S^i.

So we can define the deflectometric problem as follows: reconstruct the surface S^i integrating the normal field equation (1) given the measured deflectance map $\boldsymbol{l}^i\left(\frac{\boldsymbol{s}^i}{\|\boldsymbol{s}^i\|}\right)$ and some a priori information, which could be either a surface model with fixed degrees of freedom [SCP05] or a set of at least one known surface point obtained from stereo methods [BS03], shape-from-shading [BWB06], or by using optical flow [LBRB07].

3 Deflectometric surface reconstruction

Knowing that there is at least one point $\boldsymbol{s}_0^i$ necessary to reconstruct the surface and knowing the transformation between two measurements, the rotation matrix $\mathbf{R}$ and translation vector $\boldsymbol{t}$, we are applying a stereo method to calculate those points in the intersection of two patches $S^1 \cap S^2$. For the detailed description of an applicable stereo algorithm, we refer the reader to [WBB07].

Evaluating points only in the intersection of patches, contrary to established stereo techniques [KLKH05, PT05], we can choose $\|\boldsymbol{t}\|$ to be maximal. As it is well known from stereo vision that a larger stereo basis yields a higher measurement accuracy, our approach yields an optimal estimation of the necessary points for the following numerical reconstruction.

Given those starting points $\{\boldsymbol{s}_0^i\}$, it is possible to apply different reconstruction methods:

1. Direct integration of the surface via characteristics expansion [WBB07].
2. Level-set approaches [WBB07, CLL07], facilitating the reconstruction of surfaces even with holes. In Figure 2, the reconstruction of a pool billiard ball patch using level sets is shown.
3. Fitting of surface models (like spline models) to the normal field [KD04].

Applying patches (sight cones) with dense overlapping (Figure 2) allows for generating a closed border curve ∂S_0. Using the proposed stereo approach, the positions and normals on ∂S_0 are known. Inserting the parametrization of the surface patch S^i in local sensor coordinates

$$S^i = \{(x, y, z)^{\mathrm{T}} | z = f^i(x, y)\}, \quad \boldsymbol{n} = \begin{pmatrix} -\partial_x f^i \\ -\partial_y f^i \\ 1 \end{pmatrix} \tag{3}$$

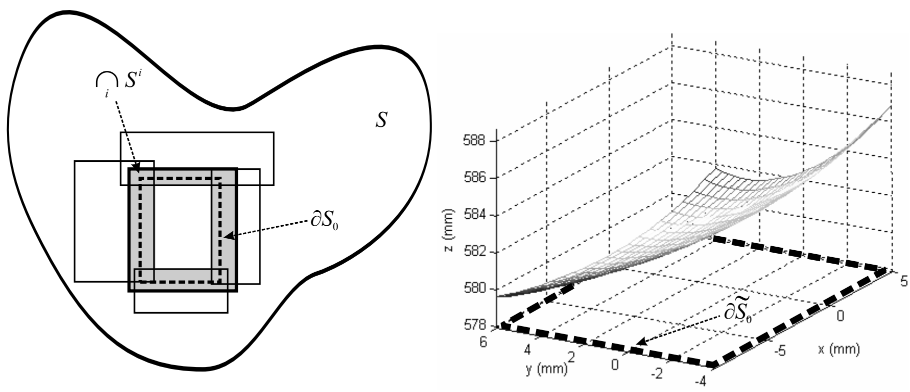

Figure 2: Left: Surface patches and boundary value curve
Right: Surface patch reconstructed by level set method.

in equation (1), this leads to the boundary value formulation of the deflectometric problem:

$$a_x^i \frac{\partial f^i}{\partial x} + a_y^i \frac{\partial f^i}{\partial y} = a_z^i, \tag{4a}$$

$$b_x^i \frac{\partial f^i}{\partial x} + b_y^i \frac{\partial f^i}{\partial y} = b_z^i, \tag{4b}$$

$$f^i(x,y) = \psi^i(x,y), \quad \psi^i : \partial\tilde{S}_0 \to \mathbb{R}, \tag{4c}$$

$$\nabla f^i(x,y) = \boldsymbol{\varphi}^i(x,y), \quad \boldsymbol{\varphi}^i : \partial\tilde{S}_0 \to \mathbb{R}^2, \tag{4d}$$

where $\boldsymbol{a}^i = (a_x^i, a_y^i, a_z^i)^{\mathrm{T}}$ and $\boldsymbol{b}^i = (b_x^i, b_y^i, b_z^i)^{\mathrm{T}}$ are defined as above, and $\partial\tilde{S}_0$ denotes the projection of ∂S_0 onto the xy- plane.

4 Conclusion

The article presents a new method for the surface reconstruction of complex specular free-forms. Using deflectometric stereo methods only for the estimation of surface points at patch boundaries yields an optimal reconstruction strategy.

In particular we have the following advantages:

1. Minimal image acquisition costs due to deploying a monocular stereo setup and only slightly overlapping sight cones.

2. Achievement of an optimal smooth reconstructed surface due to the direct measurement of position and surface normal at boundary points.

3. Maximal stereo basis ($\|\boldsymbol{t}\| \to max$) while estimating points at the patch boundaries leading to an initial value estimation of optimal accuracy for the subsequent

numerical reconstruction process.

4. Possibility of employing different numerical surface reconstruction procedures like level-set methods, characteristics expansion, or solving the deflectometric boundary value problem Eq. (4).

5. Possibility of reconstruction of at least two neighboring surface patches S_i from one initial value in the intersection $\bigcap_i S^i$.

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