Autocorrelation-based Fiducial Markers for Traceability

Fitting a Homography to Observations of Its Differential

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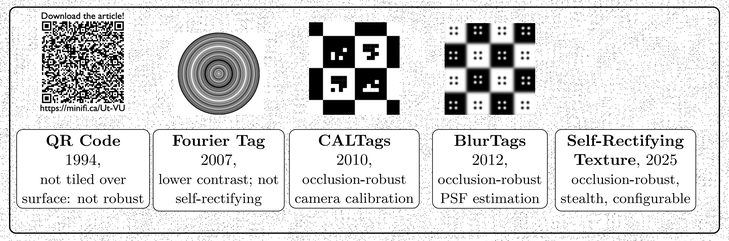
Fiducial Markers for Product Traceability Applications

Traditional fiducial markers require high-contrast spatial landmarks for rectification. These are unsuitable for product traceability as they can be tampered.

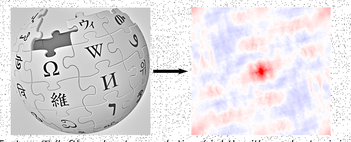


- We seek stealth markers that cover the entire surface, are robust to occlusion or intentional damage, and enable reliable complex surface rectification.

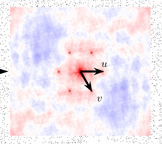
Self-rectifying Textures Embed Landmarks in the Autocorrelation Domain

Instead of using spatial landmarks, we create landmarks in the autocorrelation domain by superimposing three copies of a texture T with relative shifts u and v. This is done by the operator $\mathrm{J}_{u,v}$:

$$\mathrm{J}_{u,v}T = T + T(\cdot - u) + T(\cdot - v).$$

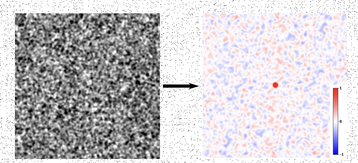


Texture T (left) and autocorrelation (right), with peak at origin.

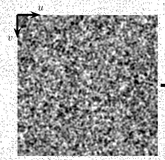


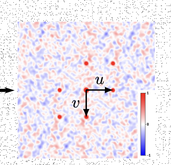
The autocorrelation of $\mathrm{J}_{u,v}T$ yields a fundamental hexagon.

Using subtle textures T (e.g., noise patterns or sparse point clouds) makes the superimposed copies $\mathrm{J}_{u,v}T$ suitable for repetition across a surface while preserving the landmarks (autocorrelation peak locations).Importantly their superposition remains imperceptible to the naked eye.



Texture (left) and autocorrelation (right), peak at origin.



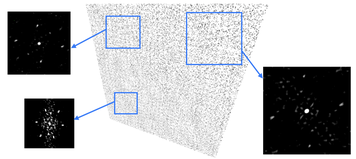


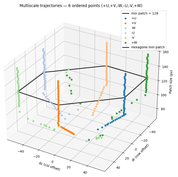
Fundamental hexagon.

Local hexagon ⇒ Affine A_i ⇒ Global H

Autocorrelation and Sub-pixel peak detection

Illustration of a self-rectifying texture $\mathrm{J}_{u,v}T$ subject to a homographic deformation H. We recover the distortion by estimating the corresponding homography from the detected autocorrelation peaks (u, v).





The two peaks u and v defining the hexagon in the autocorrelation R of each patch are refined simultaneously to obtain sub-pixel accuracy. Selecting the best pair with energy maximization gives the fundamental hexagon that maximizes the autocorrelation and the corresponding minimal stable patch P_i where u_{fin} and v_{fin} still stable:

$$(u_{fin}, v_{fin}) = \underset{u \neq v \in \mathcal{P}}{\operatorname{argmax}} \; 2\big(\bar{R}(u) + \bar{R}(v) + \bar{R}(u - v)\big)\,.$$

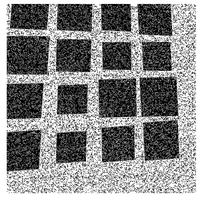
Local Observation and Patchwise rectification

We estimate the differential $\mathbf{A}_i = \nabla_{H^{-1}(y_i)}H$ of the deformation H using the fundamental hexagon. Given the texture $\mathrm{J}_{u,v}T$, we use phase correlation between $\mathrm{J}_{u,v}T$ and local minimal stable patch P_i to estimate the translation:

$$b_i = \underset{\tau \in \mathbb{R}^2}{\operatorname{argmax}} \; \mathcal{F}^{-1}\left(\frac{\widehat{\mathrm{J}_{u,v}T}(\omega)\overline{A_i^{-1}\widehat{P}_i(\omega)}}{\left|\widehat{\mathrm{J}_{u,v}T}(\omega)\overline{A_i^{-1}\widehat{P}_i(\omega)}\right|}\right)(\tau).$$

The first-order Taylor approximation of H around $H^{-1}(y_i) = \mathbf{A}_i^{-1}(y_i - b_i)$ is : $h \mapsto \mathbf{A}_i h + b_i$.
Its inverse, which rectifies the patch around y_i, is

$$h \;\longmapsto\; \mathbf{A}_i^{-1}(h - \mathbf{b}_i)$$



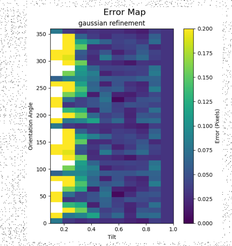
Homography estimation (modulo translation)

Seek a homography $\mathrm{H} \in \mathrm{PGL}(3,\mathbb{R}) \cong \mathrm{SL}(3,\mathbb{R})$ whose differentials match the observed matrices $\mathbf{A}_i$ in y_i.

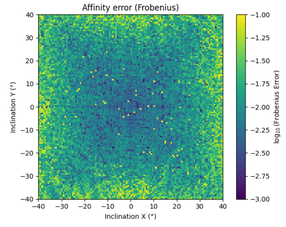
$$\mathrm{H}^* = \underset{\mathrm{H} \in \mathcal{H}}{\operatorname{argmin}} \frac{1}{n}\sum_{i=1}^{n} \left\| \nabla_{\mathrm{H}^{-1}(y_i)}\mathrm{H} - \mathbf{A}_i \right\|_F .$$

Peak detection, inclination angles and occlusion

The first image shows sub-pixel peak detection accuracy, when faced with different tilt deformations oriented at different angles in the affine model : $A = \lambda R_{-\theta}\begin{bmatrix} t & 0 \\ 0 & 1 \end{bmatrix} R_\theta R_\psi$ encodes scale λ, rotation θ, tilt t, and its orientation ψ. Leading to precise local affinity estimation and accurate recovery of the overall deformation.

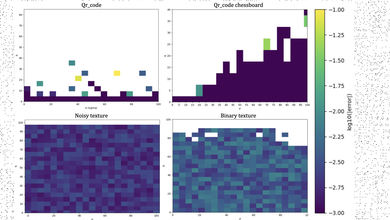


Detection error by tilt.

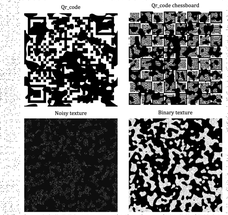


Error $\|\mathbf{A} - \nabla_{\mathrm{H}^{-1}\mathrm{H}}\|_F$.

Landmarks in autocorrelation are robust to occlusion, unlike spatial landmarks, which can be easily destroyed.



$\|\hat{\mathbf{H}} - \mathbf{H}\|_F$. White: not decodable.



Ex : 40% occlusion, blob size 25

Conclusion

Autocorrelation-based textures provide robust, landmark-free rectification from a single image. Their stealth design ensures resilience to occlusion and tampering thanks to the requirement to know the initial shifts and basic texture, thus enabling reliable geometric recovery for large-scale traceability.

References

Hara, Masahiro and Watabe (1998). *Optically readable two-dimensional code and method and apparatus using the same.*

Olson, Edwin (2011). "AprilTag: A robust and flexible visual fiducial system". In: IEEE.