Substrate requirements to enable durability & accuracy in structured light-based 3D sensing

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Optical Physics & Systems
Advanced Optics

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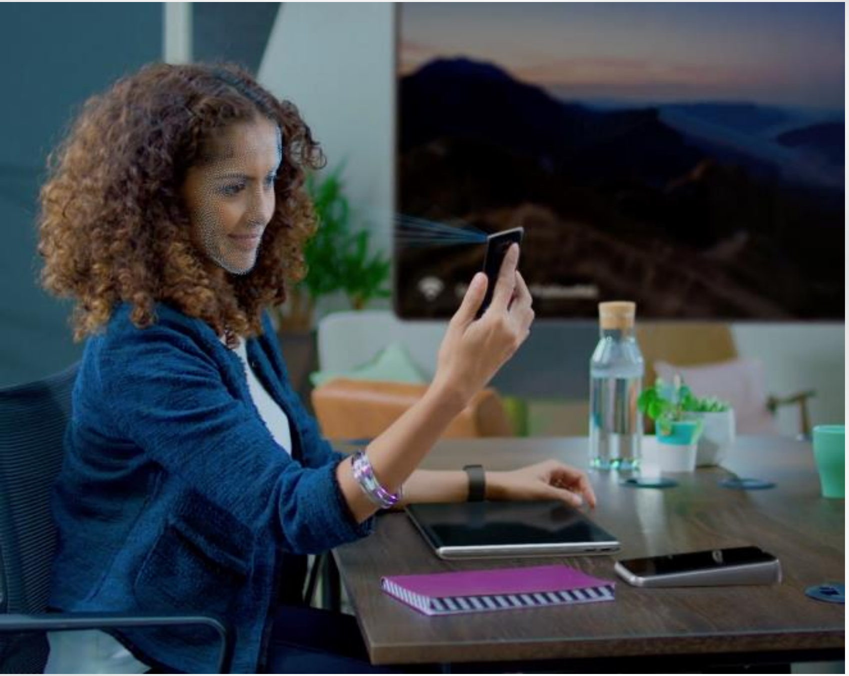
Presentation Outline



I. Overview of structured light 3D sensing
   - Design and role of the pattern projector

II. Optical modelling of the impact of temperature changes to the projector performance for common materials

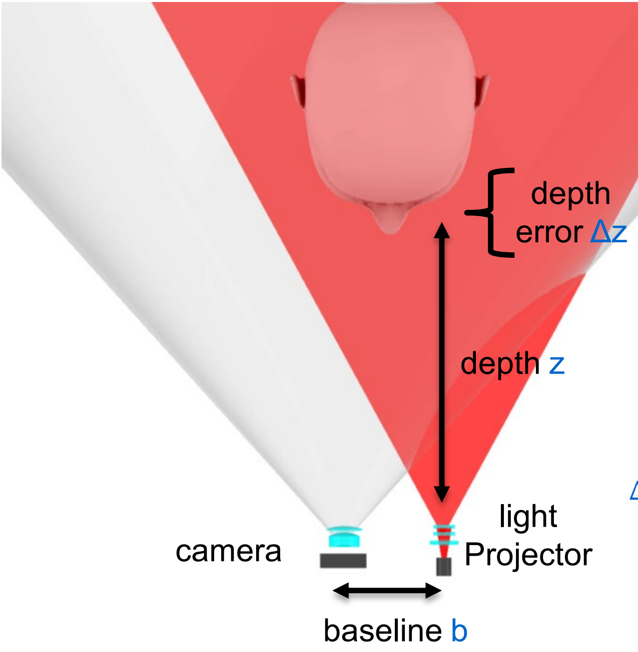
III. Measurements using commercially-available SLI projectors

IV. Comparison and interpretation of the results

Structured-light 3D Sensing

Depth error depends on baseline, distance, and subpixel resolution

Schematic view of a structured light sensor



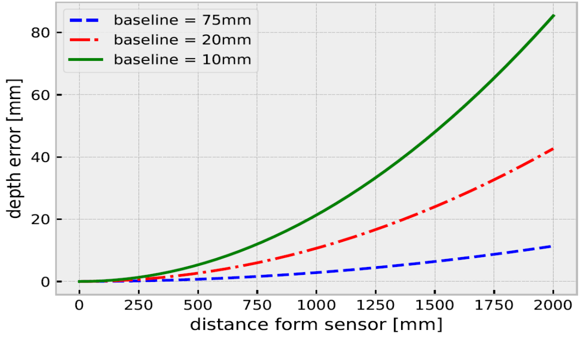
Depth error:

$$\Delta z = \frac{z^2}{bf}\Delta d$$

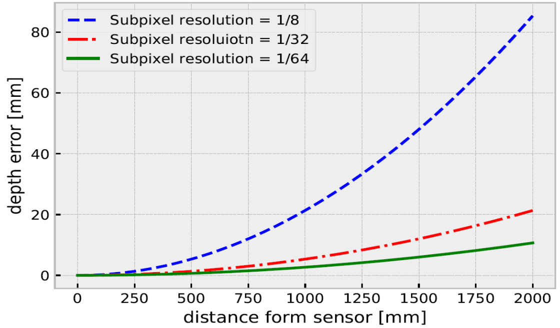
f = focal length

Δd = disparity resolution

Depth error depends on baseline and distance from sensor



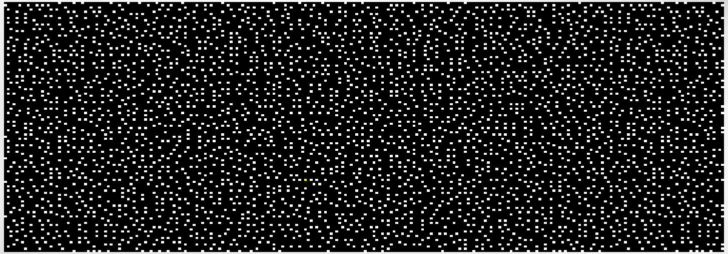
Short baseline systems require increased subpixel resolution to achieve the same depth error

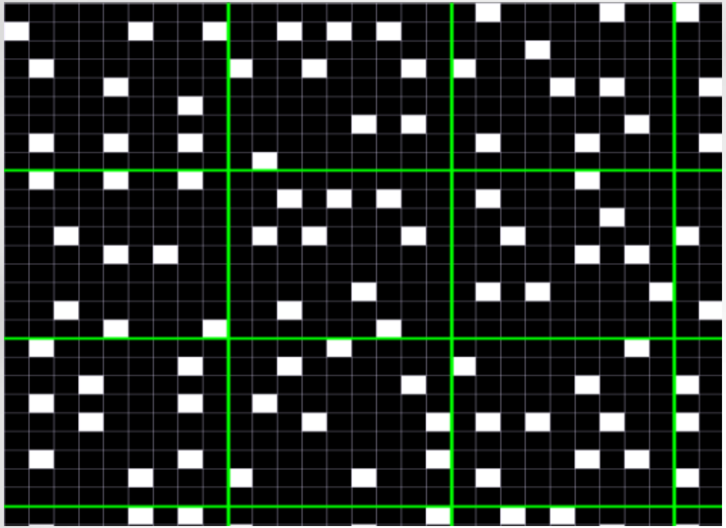


P. Zanuttigh, G. Marin, C. Dal Mutto, F. Dominio, L. Minto, G.M. Cortelazzo, "Time-of-Flight and Structured Light Depth Cameras", Technology and Applications, ISSBN 978-3-319-30971-2

Structured-light Patterns

DeBrujin / M-Patterns allow fast, error tolerant, and subpixel accurate reconstruction





High subpixel resolution requires a pattern to be:

- Insensitive to disorders, deficiency and permutations
- High contrast vs background to distinguish pattern uniquely vs artifacts
- High spatial sampling of the scene or objects

DeBrujin sequences known from combinatorial mathematics can produce a pseudo-random pattern where each sub-pattern doesn't repeat within a given sub-aperture:

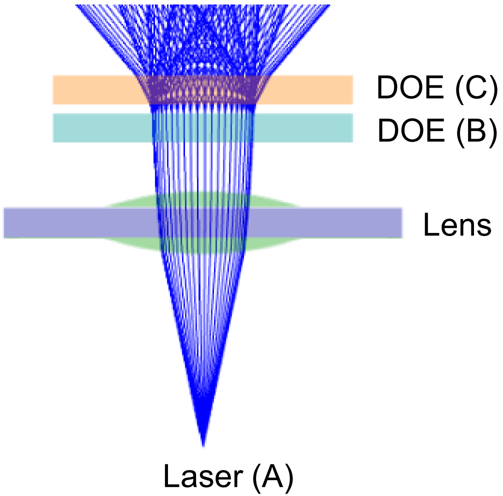
- Each sub-window is unique and easy to identify
- Designed to be error-tolerant to missing pixels
- Use of auto-correlation kernels for fast disparity evaluation

H. Morita, K. Yajima, S. Sakata, "Reconstruction of surfaces of 3-d objects by m-array pattern projection method", in: IEEE International Conference on Computer Vision, 1988, pp. 468–473.

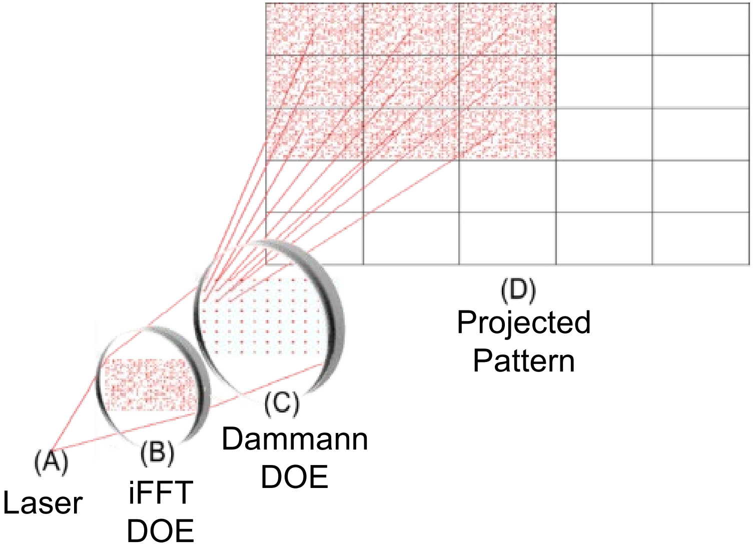
Pattern Projector Designs

A structured light projector includes laser(s), imaging optic(s), and DOEs for pattern generation

Schematic design of a generic pattern projector using 2 DOEs:



Combining a laser source with a DOE can create a dot pattern. Dammann DOEs allow to create a large field of view replicating the dot pattern over the Dammann grid:



M. J. Landau, B. Y. Choo, P. A. Beling, "Simulating Kinect Infrared and Depth Images," IEEE Transactions on Cybernetics. 2015

DOE Design Approaches

iFFT DOEs to create the pattern and Dammann DOEs to create the FOV

Dammann DOEs deliver best efficiency and largest FOV

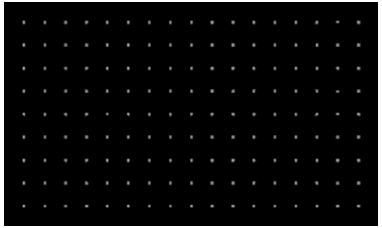
- Designed to have equal intensity in multiple diffraction
- Grating period determines angular distance between the individual orders
- Sub-features inside the grating period determine the largest angle or field of view (FOV) of the grating

U. Karckhardt, N. Streibl, “Design of Dammann-gratings for array generation”, Optics Communications 74(1-2):31-36 , (1989).

17x9 Dammann Design:

Enlarged grating period:

Far field diffraction pattern:



iFFT DOEs for arbitrary patterns and distortion compensation

- Designed using Gerchberg Saxton Algorithm combined with spherical wave propagation to allow non-paraxial gratings for larger angle ranges
- Usually includes a blackout region to avoid repetition of pattern
- Binary iFFT DOEs are therefore symmetric around the 0-order

G. N. Nguyen, K. Heggarty, P. Gerard, P. Meyrues, “Iterative scalar algorithm for the rapid design of wide-angle diffraction Fourier elements”, https://portail.telecom-bretagne.eu/publi/public/fic_download.jsp?id=20919

DeBrujin Pattern Design:

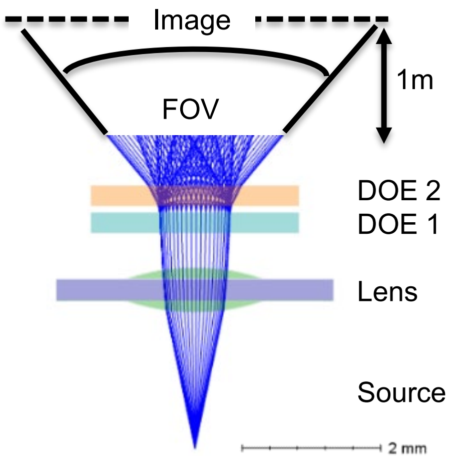
Non-periodic grating structure:

Far field diffraction pattern:

Simulation of Different Materials

Commonly used DOE materials have significant difference in CTE and dn/dt

Setup of the optical model:



Comp.	Included	Parameters
DOE2	dn/dt, CTE	p = 7.6um, orders, ±4, t = 0.5mm
DOE1	dn/dt, CTE	p = 15.3µm, orders +1, -1, t = 0.5mm
Lens	dn/dt, CTE	EFL = 2.51mm, t = 0.5 mm
Source	NA	λ =850nm, constant

Comparison of the materials used for simulation:

Property		PMMA *	NIL Polymer **	Corning SG 3.4	Corning HPFS®
CTE	ppm/°C	72	130	3.17	0.57
Refractive index		1.48	1.56	1.51	1.45
Thermal conductivity	W/m°K	0.21	0.19	1.09	1.38
dn/dT (550nm)	ppm/°C	-105	-230	3.41	8.66

- More than 2 magnitudes difference in CTE and dn/dt

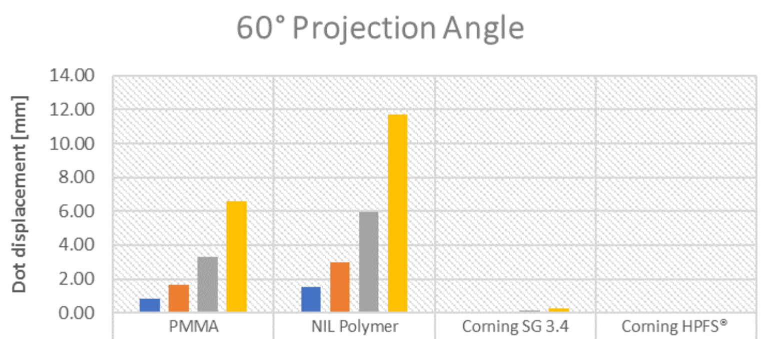
Model assumes DOEs and Lens without manufacturing errors.
Element positions (x,y,z) are kept constant.

* *K. Iga, Y. Kokubu, Encyclopedic Handbook of Integrated Optics, CRC Press, ISBN1420027816, (2005)*

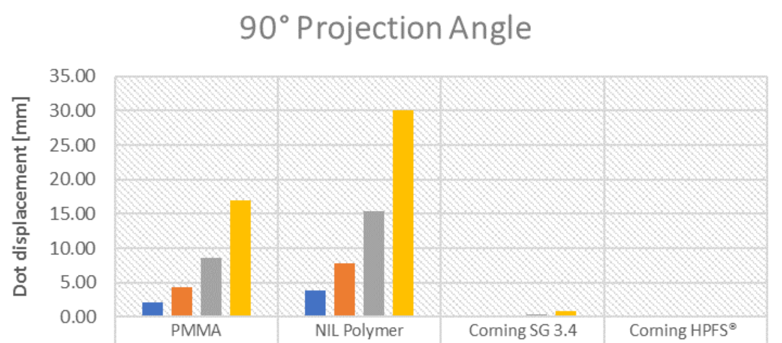
** *A. Schleunitz , J. J. Klein , R. Houbertz, M. Vogler , G. Gruetzner, Towards High Precision Manufacturing of 3D Optical Components using UV-Curable Hybrid Polymers, Optical Interconnects XV, Proc. of SPIE Vol. 9368, (2015)*

Simulation Results

Displacement of the pattern dependent on temperature change, position and material

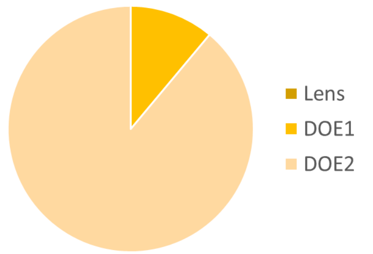


	PMMA	NIL Polymer	Corning SG 3.4	Corning HPFS®
ΔT=15°C	0.83	1.50	0.04	0.01
ΔT=30°C	1.66	2.99	0.07	0.01
ΔT=60°C	3.30	5.94	0.15	0.03
ΔT=120°C	6.57	11.73	0.29	0.05



	PMMA	NIL Polymer	Corning SG 3.4	Corning HPFS®
ΔT=15°C	2.15	3.88	0.10	0.02
ΔT=30°C	4.30	7.72	0.19	0.03
ΔT=60°C	8.55	15.30	0.38	0.07
ΔT=120°C	16.91	30.03	0.76	0.14

Contribution by component:

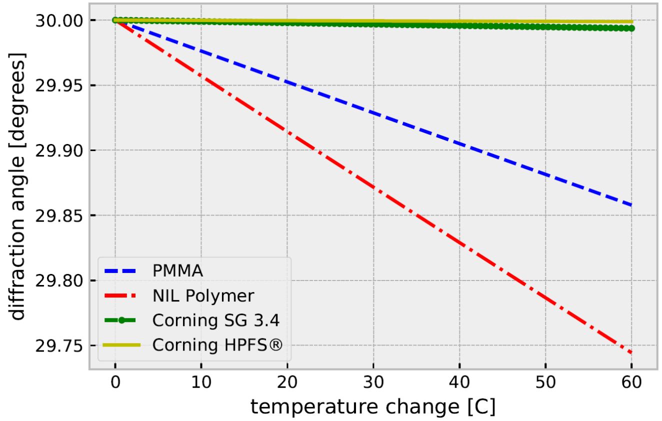


- Simulations show the DOE with the largest angle range to be most sensitive
- CTE effect on the DOE grating period is the driving property
- Fused silica has significant better performance than higher CTE materials

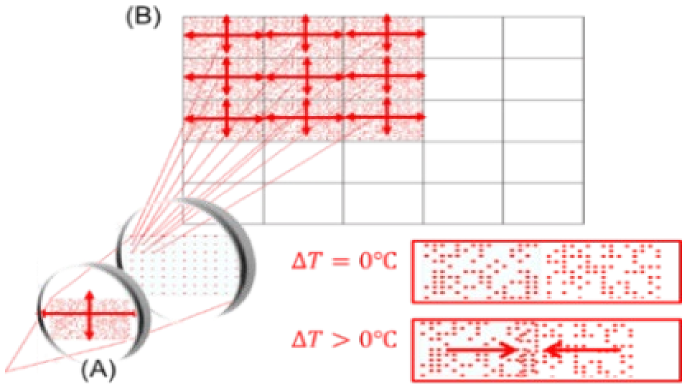
A temperature change using a higher CTE material causes a change in the grating period, resulting in a change to the diffraction angle for the DOE

Higher CTE causes a change in the grating period with rising temperature resulting in a lower diffraction angle for the DOE:

Diffraction angle of a DOE: $\sin(\beta_m) = m\frac{\lambda}{p}$



Compound effects can happen when the DOEs use different materials and/or are operated at different temperatures:

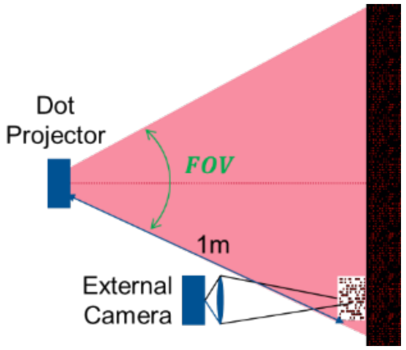


Small angle changes are magnified through the distance between the projector and the objects/scene.

Commercially Available Projectors

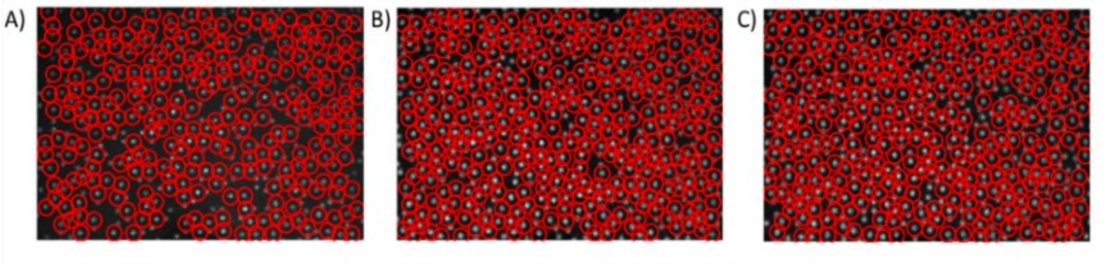
Measurements of the dot-pattern drift with temperature confirm simulations

Measurement Set-up:

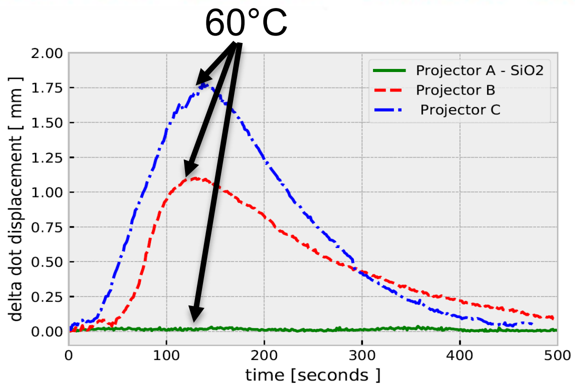


- 3 different projectors evaluated
- Measurement at around 90% of the FOV
- Images captured with separate camera
- Trackpy library used for subpixel accurate position tracking

Patterns from 3 Different Projectors:



Measurement Results:



Trackpy: "Fast, Flexible Particle-Tracking Toolkit", https://soft-matter.github.io/trackpy/v0.3.2/, DOI 10.5281/zenodo.60550

Conclusion

- As presented, the accuracy of the projected pattern in SLI strongly depends on the material used for the components inside the projector.

- 3D sensing device makers have two key considerations when choosing an optical material for the SLI projector.
  - 1.) For highest stability of the pattern, the lowest coefficient of thermal expansion (CTE) is required.
  - 2.) Manufacturability and compatibility with existing semiconductor infrastructure and wafer level processes requires the material must have extremely high purity.

- Corning HPFS® fused silica meets these requirements better than other types of glass and plastic.

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