One-shot pattern projection for dense and accurate 3D acquisition in structured light

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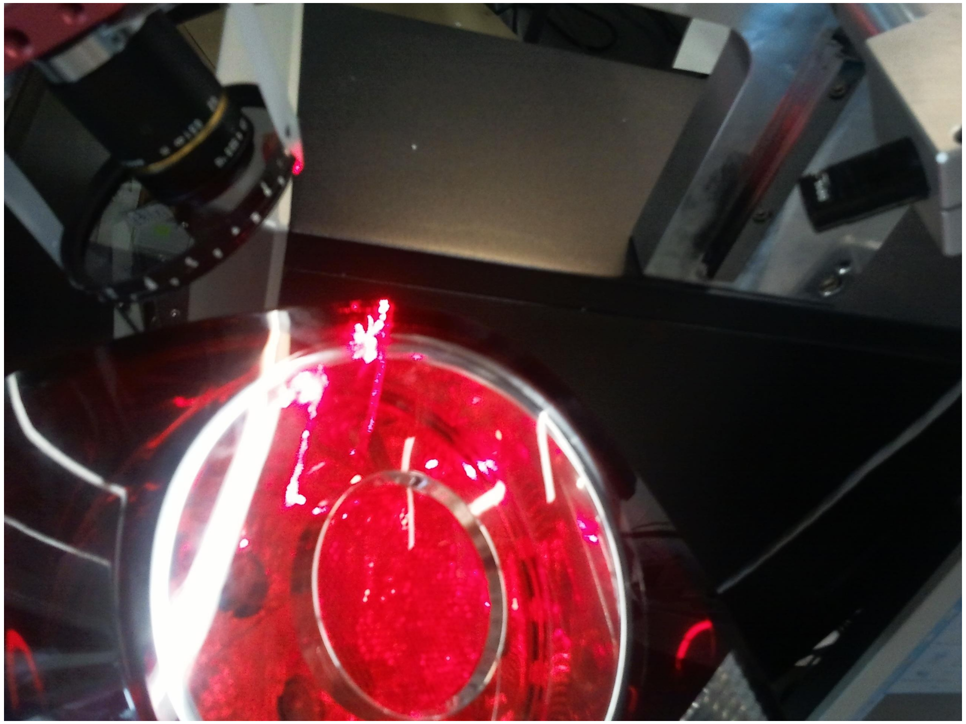
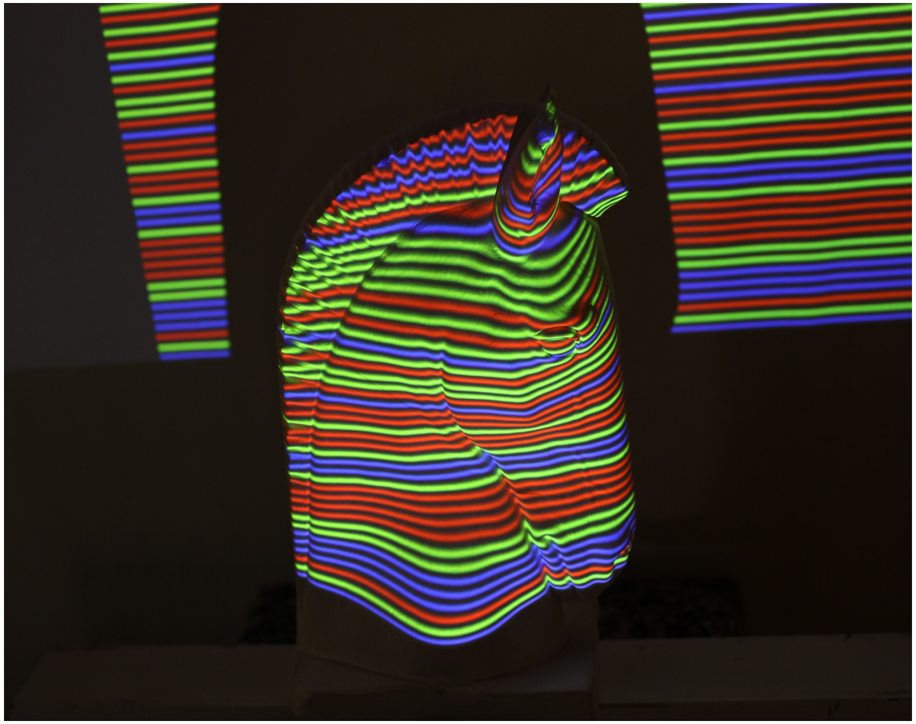
Active stereovision

3D acquisition is used by any device aiming to understand the environment where is being involved or where an action is required. Stereovision is used to this end.

Active stereovision solves the problem of finding correspondences in low textured surfaces.

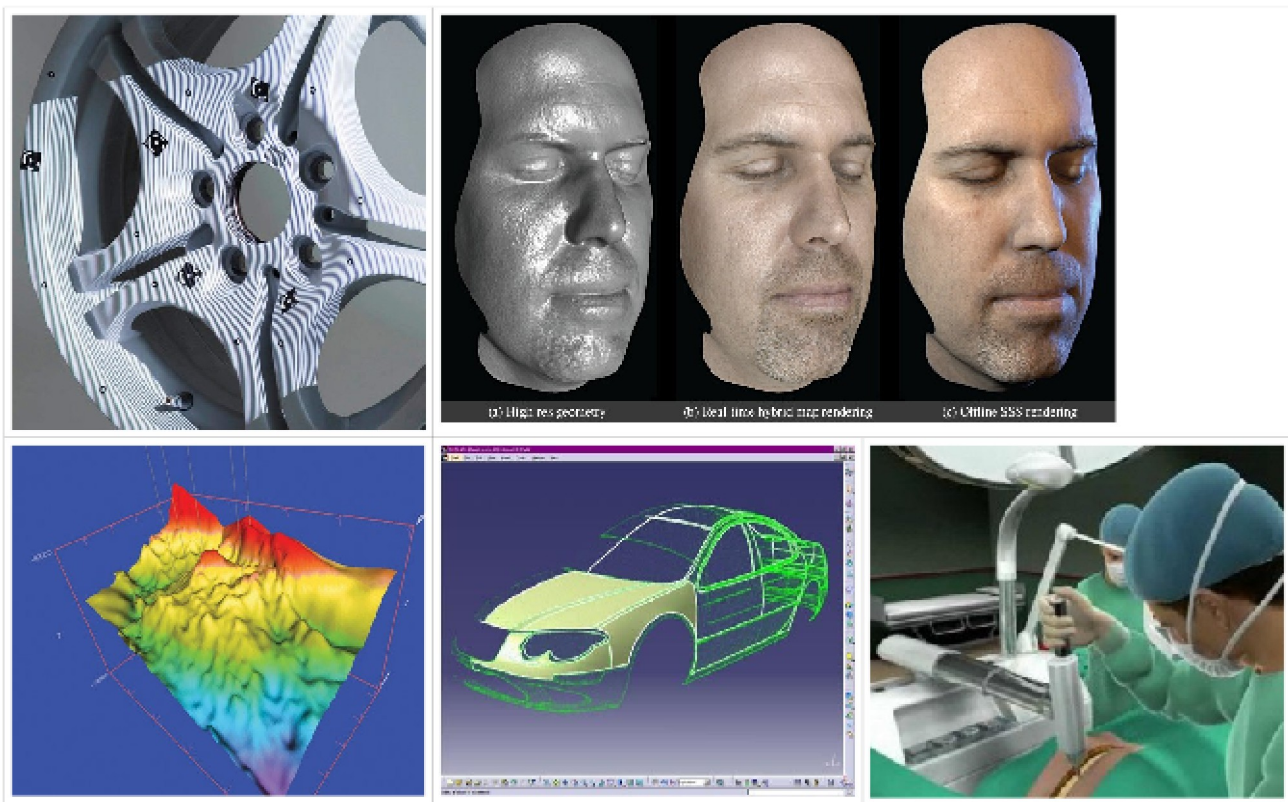
A camera is substituted by an active device like a Digital Light Projector (active).





Motivation

Active stereovision is used in many applications: range sensoring, industrial inspection, reverse engineering, object recognition, 3D map building, 3D surgery, biometrics...



Challenges and proposed solutions in CSL

Dynamic scenarios → One-shot projection.

High level of detail → Dense reconstruction.

Absolute depth acquisition → Absolute coding.

Accuracy.

	One-shot projection	Dense reconstruction	Absolute coding	Accuracy
DeBruijn pattern	✓	✗	✓	✓
Fringes pattern	✓	✓	✗	✓
Multiple phase shifting	✗	✓	✓	✓
Spatial grading	✓	✓	✓	✗

Outline

1. State of the art
2. First approach to one-shot dense reconstruction
3. Automatic window selection in Frequency Transform techniques
4. One-shot absolute pattern for dense reconstruction
5. Registration of single views from structured light
6. Conclusions

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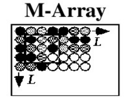
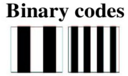
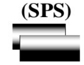
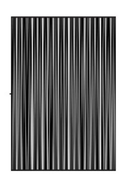
Classification of SL techniques

			Shots	Cameras	Axis	Pixel depth	Coding strategy	Subpixel acc.	Color
SPARSE	SPATIAL Multiplexing	De Bruijn 							
		Non formal							
		M-Array 							
	TIME Multiplexing	Binary codes 							
		N-ary codes							
DENSE		Discrete shifting							
		Single Phase Shifting (SPS) 							
		MultiplePhase Shifting(MPS) 							
	FREQUENCY Multiplexing	Single coding frequency 							
	SPATIAL multiplexing	Grading 							

Shots	Cameras	Axis	Pixel depth	Coding strategy	Subpixel acc.	Color

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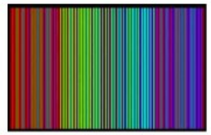
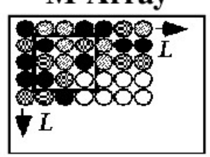
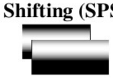
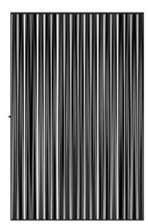
SPARSE	SPATIAL Multiplexing	De Bruijn 	Boyer	1987	1	1	1	C	A	Y	N
			Salvi	1998	1	1	1	C	A	Y	Y
			Monks	1992	1	1	1	C	A	Y	N
			Pages	2004	1	1	1	C	A	Y	N
		Non formal	Forster	2007	1	1	1	C	A	Y	N
			Fechteler	2008	1	1	1	C	A	Y	N
			Tehrani	2008	1	2	1	C	A	N	Y
			Maruyama	1993	1	1	2	B	A	N	Y
			Kawaski	2008	1	1	2	C	A	N	Y
			Ito	1995	1	1	2	G	A	N	Y
			Koninckx	2006	1	1	2	C	P	Y	Y
		M-Array 	Griffin	1992	1	1	2	C	A	Y	Y
			Morano	1998	1	1	2	C	A	Y	Y
			Pages	2006	1	1	2	C	A	Y	N
			Albitar	2007	1	1	2	B	A	N	Y
	TIME Multiplexing	Binary codes 	Posdamer	1982	>2	1	1	B	A	N	Y
			Ishii	2007	>2	1	1	B	A	N	N
			Sun	2006	>2	2	1	B	A	Y	Y
		N-ary codes	Caspi	1998	>2	1	1	C	A	N	N

Classification of SL techniques

					Shots	Cameras	Axis	Pixel depth	Coding strategy	Subpixel accuracy	Color
DENSE	TIME Multiplexing	Discrete shifting	Zhang	2002	>2	1	1	C	A	Y	N
			Sansoni	2000	>2	1	1	G	A	Y	Y
			Guhring	2001	>2	1	1	G	A	Y	Y
		Single Phase Shifting (SPS) 	Srinivasan	1985	>2	1	1	G	P	Y	Y
			Ono	2004	>2	1	1	G	P	Y	Y
			Wust	1991	1	1	1	C	P	Y	N
			Guan	2004	1	1	1	G	P	Y	Y
		MultiplePhase Shifting(MPS) 	Gushov	1991	>2	1	1	G	A	Y	Y
			Pribanić	2009	>2	1	1	G	A	Y	Y
	FREQUENCY Multiplexing	Single coding frequency 	Takeda	1983	1	1	1	G	P	Y	Y
			Cobelli	2009	1	1	1	G	P	Y	Y
			Su	1990	2	1	1	G	P	Y	Y
			Hu	2009	2	2	1	G	P	Y	Y
			Chen	2007	1	1	1	C	P	Y	N
			Yue	2006	1	1	1	G	P	Y	Y
			Chen	2005	2	1	1	G	P	Y	Y
			Berryman	2008	1	1	1	G	P	Y	Y
			Gdeisat	2006	[illegible]	1	1	G	P	Y	Y
			Zhang	2008	[illegible]	1	1	G	P	Y	Y
			Lin	1995	2	1	1	G	P	Y	Y
			Huang	2005	>2	1	1	G	P	Y	Y
			Jia	2007	2	1	1	G	P	Y	Y
			Wu	2006	1	1	1	G	P	Y	Y
			Fernandez	2010	1	1	1	C	A	Y	N
	SPATIAL multiplexing	Grading 	Carrihill	1985	1	1	1	G	A	Y	N
			Tajima	1990	1	1	1	C	A	Y	N

FREQUENCY MULTIPLEXING: phase decoding is performed in the frequency domain.

Fourier Transform
Recovered sinusoidal pattern $I(x,y)=a(x,y)+c(x,y)\cdot e^{2\pi f_{\phi}\cdot y}+c*(x,y)\cdot e^{-2\pi f_{\phi}\cdot y}$

$$\phi(x,y)=imag(\log(c(x,y)))$$

$$h(x,y)=\frac{L\cdot\Delta\phi(x,y)}{\Delta\phi(x,y)-2\pi f_0 d} \longrightarrow \left\{\begin{array}{l}\text{Fails for h>L/3d}\\ \text{Freq. overlapping}\end{array}\right.$$

Dense reconstruction methods

FREQUENCY MULTIPLEXING: phase decoding is performed in the frequency domain.

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Recovered sinusoidal pattern $I(x,y)=a(x,y)+c(x,y)\cdot e^{2\pi f_\phi \cdot y}+c*(x,y)\cdot e^{-2\pi f_\phi \cdot y}$

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Windowed Fourier Transform: input signal is split into segments.

$$Sf(u,v,\epsilon,\eta)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\cdot g(x-u,y-v)\cdot\exp(-j\epsilon x-j\eta y)\,dx\,dy$$

Optimal width? Get carrier freq. $\Longleftrightarrow$ Freq.overlapping

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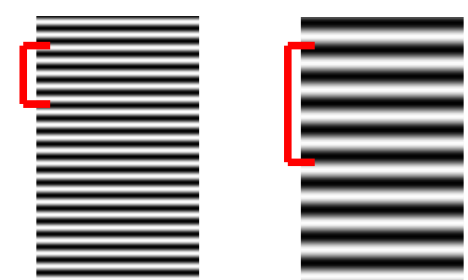
Optimal width? Get carrier freq. ⟺ Freq.overlapping

Wavelet Transform: <u>freq. decreases</u> ⟹ window size <u>increases.</u>
Dyadic net: the size of the wavelet is modified by the factor 2j.



Discussion

1. The ultimate techniques study:
   - One-shot pattern projection (spatial multiplexing).
   - Dense reconstruction (phase shifting and Frequency multiplexing).

2. Frequency multiplexing achieves these two points. However, errors arise due to frequency overlapping and the unwrapping step.
   - Frequency overlapping caused by a sub-optimal windowing.
   - Unwrapping does not provide absolute coding.

3. Spatial grading is no longer studied, due to its high sensitivity to noise.

Can we skip the phase unwrapping step?

<u>The Remainder Theorem can be used to obtain absolute coding from a wrapped phase</u>

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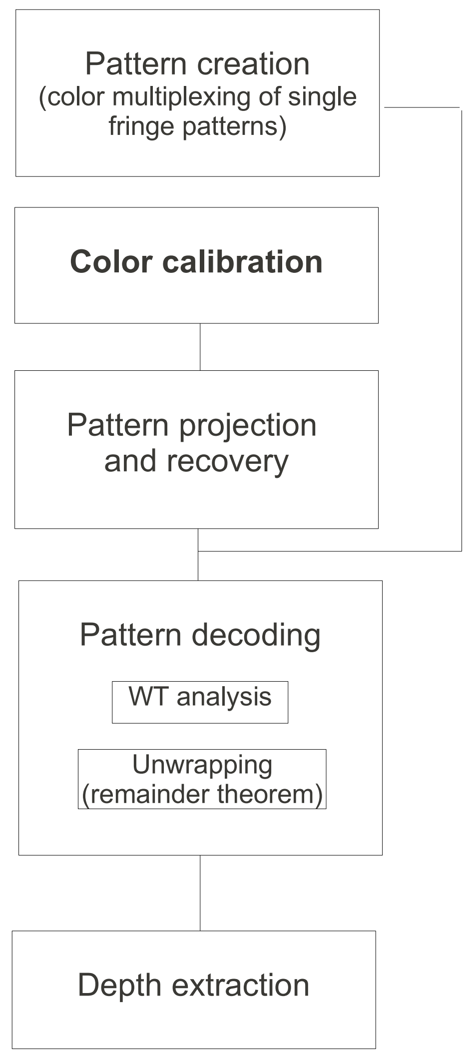
System proposal for WT + Remainder Theorem



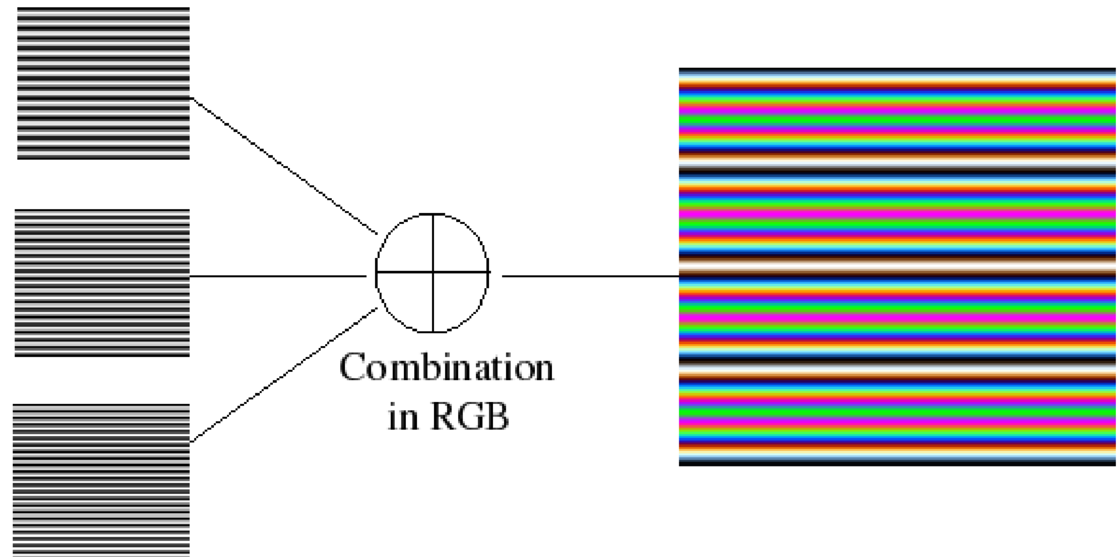
Pattern creation and decoding

The remainder theorem

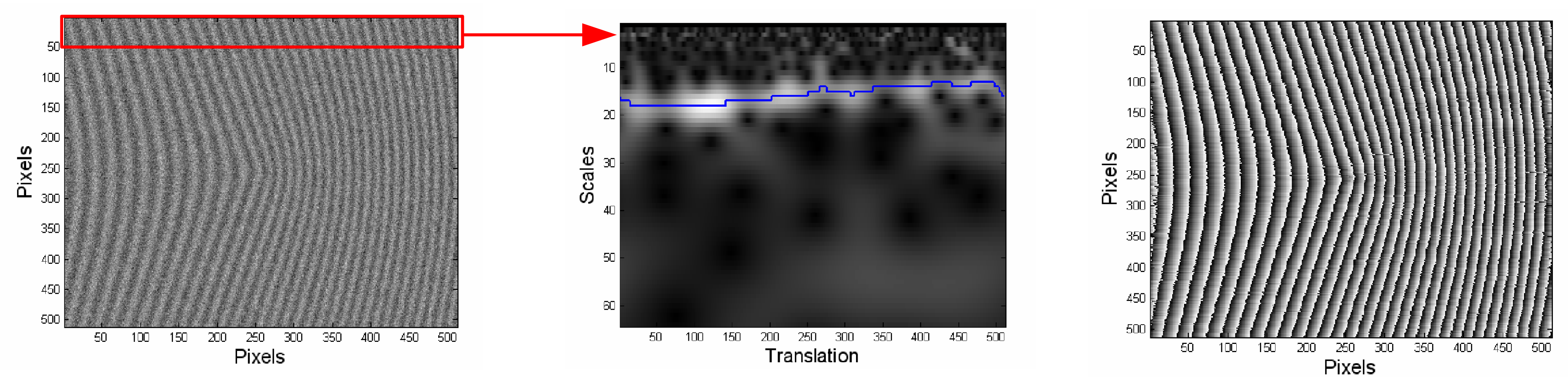
"Given two arbitrary fringe patterns where their frequencies are relative prime numbers between them (i.e., their greatest common divisor is 1):

$$\Phi_{absol} = k_1 \lambda_1 + \phi_{Ri} = k_2 \lambda_2 + \phi_{Ri}$$

That is, the absolute value can be extracted from a combination of the relative phase values of every fringe pattern.



2D WT



Discussion

The dyadic net used in WT does not consider little frequency variations in the fringe pattern.
The unwrapping algorithm smoothes rapid changing surfaces.

⇩

Errors arise under presence of discontinuities and slopes.

- **Algorithm for the adaptive selection of the best analysis mother signal, in terms of frequency and shape?**
- **New unwrapping approach?**

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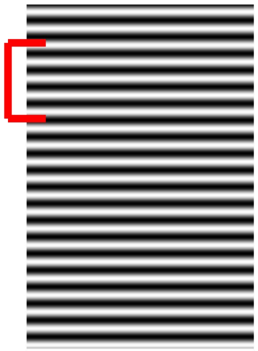
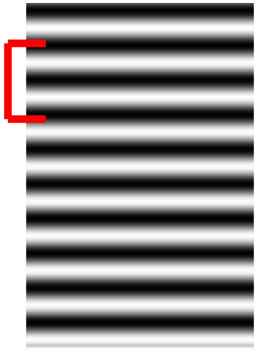
Comparative study between WFT and WT

WFT is given by:

$$Sf(u,v,\epsilon,\eta)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\cdot g(x-u,y-v)\cdot \exp(-j\epsilon x-j\eta y)\,dx\,dy$$

being (x,y), (ξ,η) the translation and frequency coordinates, and g(x,y) the windowing function.



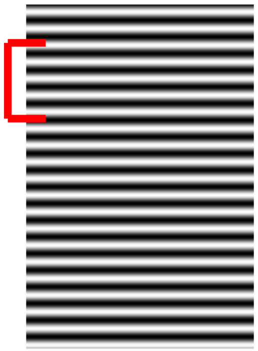


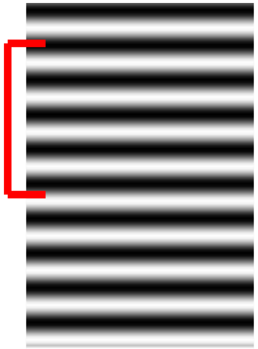
WT (continuous) is given by:

$$WT_f(a,\theta,u,v)=\frac{1}{a}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\cdot\psi\left[\frac{(x-u\cdot c(\theta))-(y-v\cdot s(\theta))}{a},\frac{(x-u\cdot s(\theta))-(y-v\cdot c(\theta))}{a}\right]dx\,dy$$

In discrete applications we compute the dilation factor *a* like $a=2^k$ where:

$$k(y)=0.5+\log_2\left(\frac{f_c}{f_0}\right)-\log_2\left(\frac{\phi_x'}{2\pi f_0}\right)$$

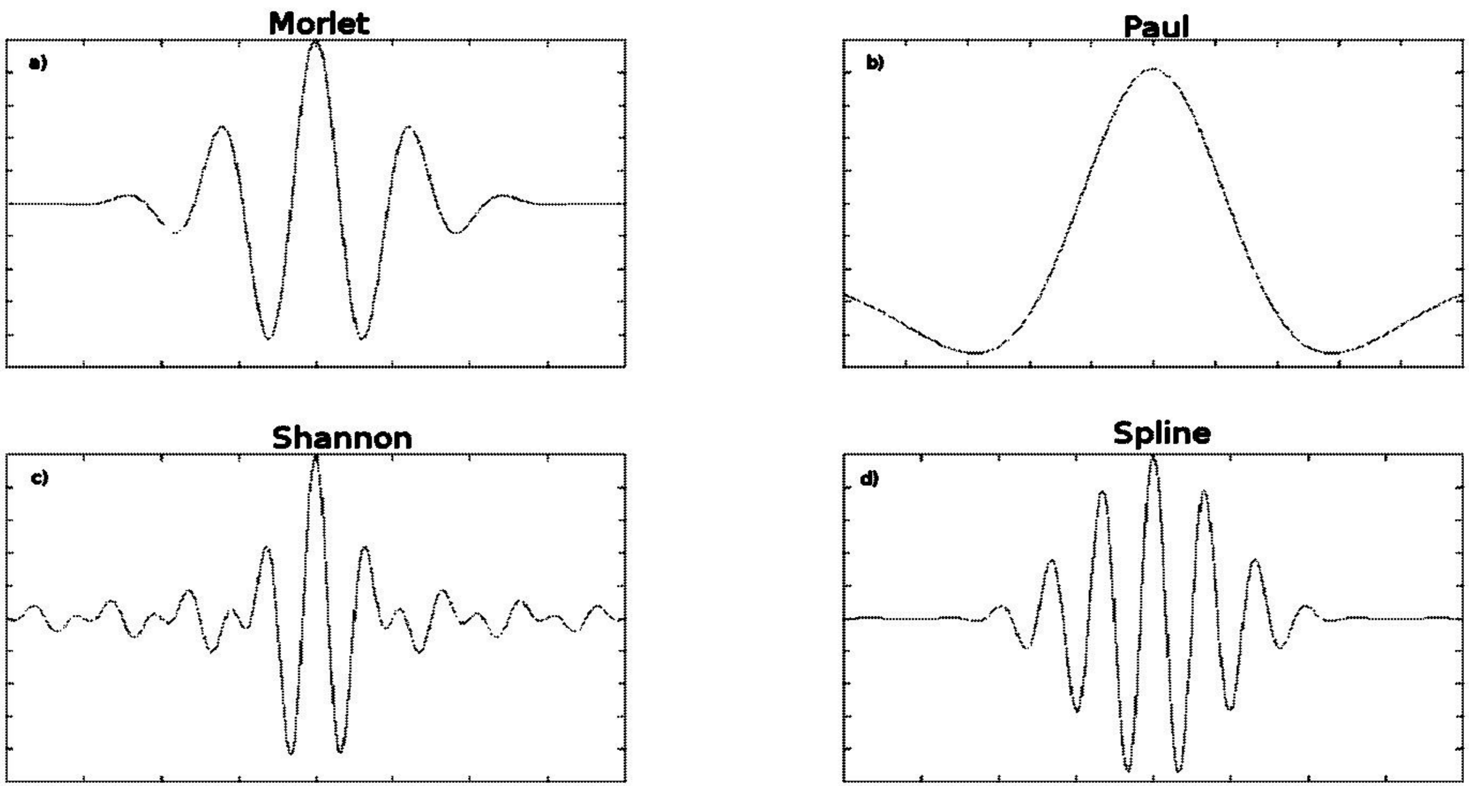




Problem: the change introduced by the dyadic net is too high for fringe pattern.
WT performs better with signals having a wide range of frequencies.

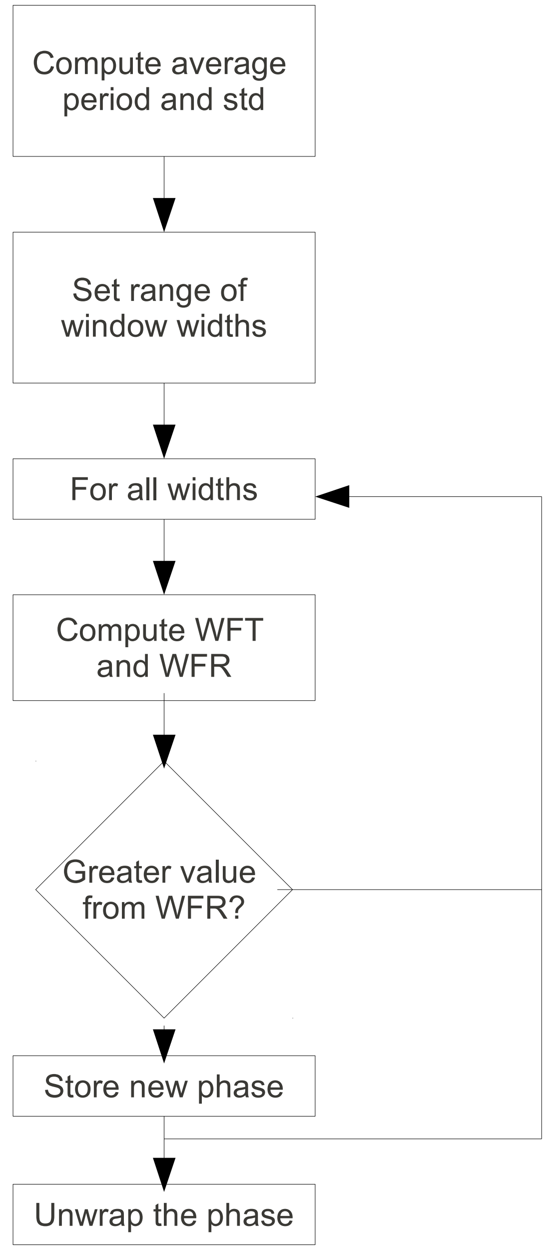
Comparative study between WFT and WT

On the other hand, mother wavelet having low-pass shape perform optimal WT fringe analysis, thanks to the good localization in both frequency and space.



Is it possible to perform a fine adaptation of the window size, while preserving the analysis with mother wavelets?

Proposed algorithm for automatic WFT



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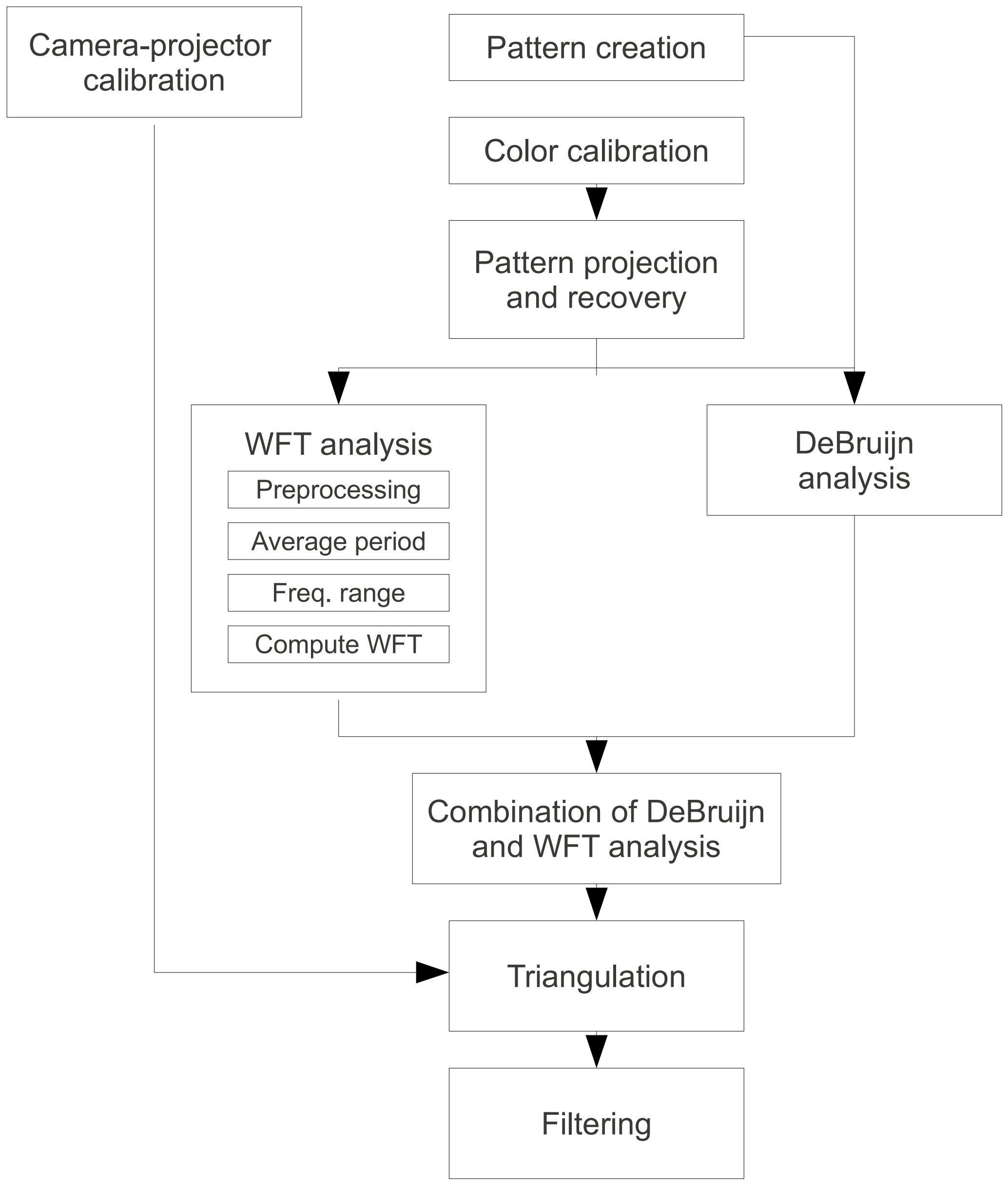
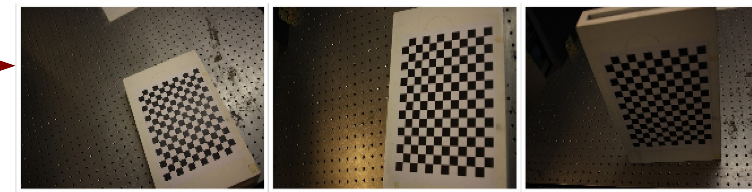
Proposed algorithm for one-shot dense pattern



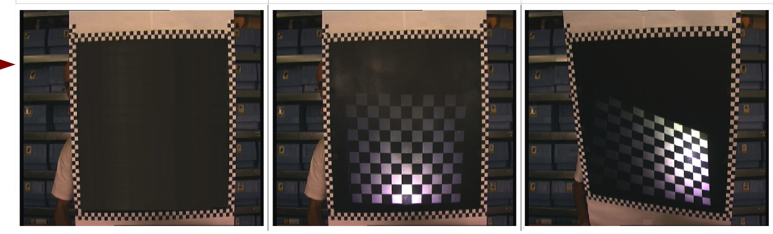
Camera-projector calibration

We propose a 3D Least Squares estimation technique with 2D calibration object.
The projector is regarded as the inverse of a camera.

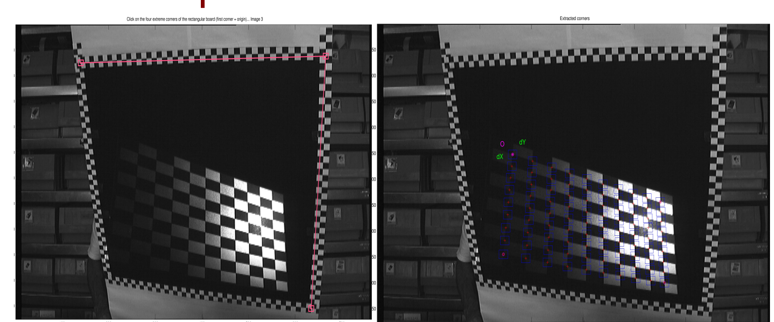
Camera calibration
De Bouguet (Zhang's)



Projection of a checkerboard onto
A planar surface



Extract 3D coordinates
of the marked points
Known relative distances

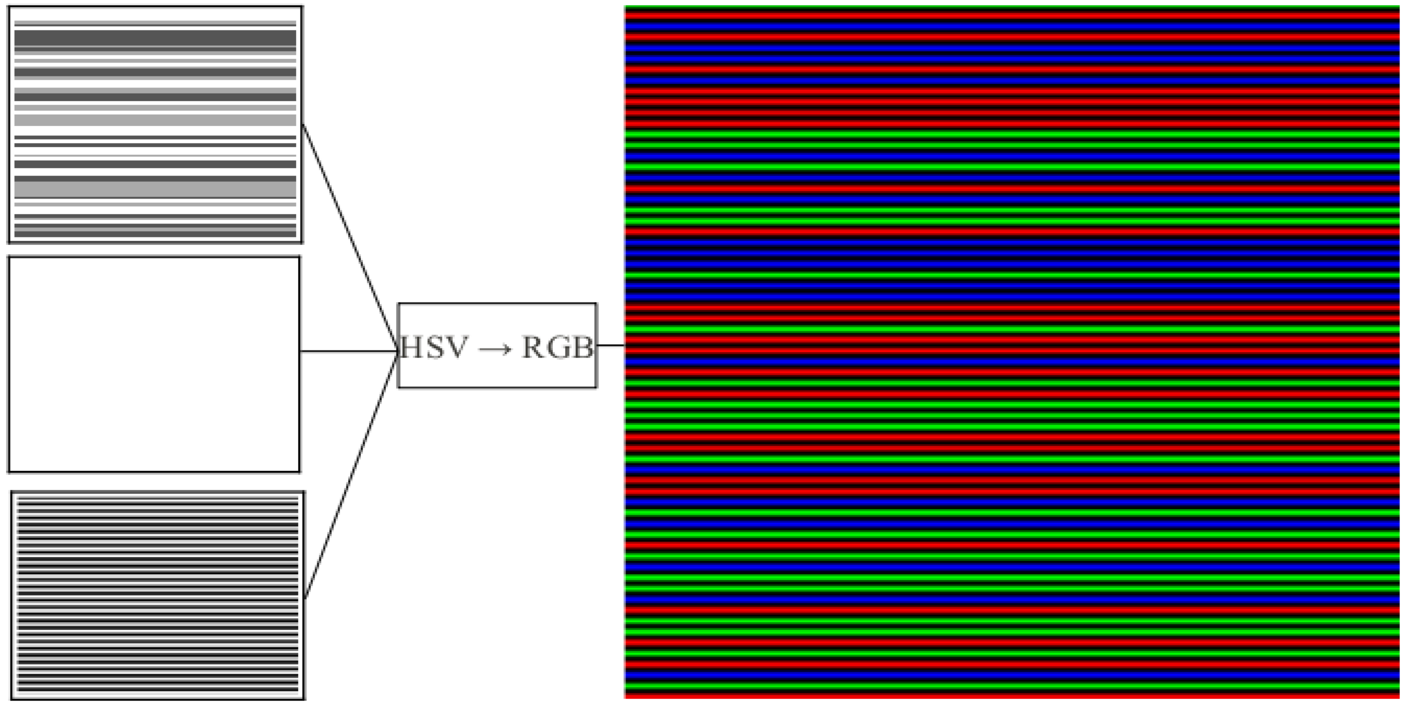


Compute homography
2D-3D points

Compute 3D points of the
Projected pattern

Calibrate the projector

Pattern creation



Generated in the HSV space to minimize the crosstalk efect in the fringes (in V channel).

•<u>Hue channel</u>: k-ary DeBruijn sequence with *n = 3* and *k=4* (length n^k = 64 fringes).

• <u>Saturation channel</u>: 1 for all pixels (max).

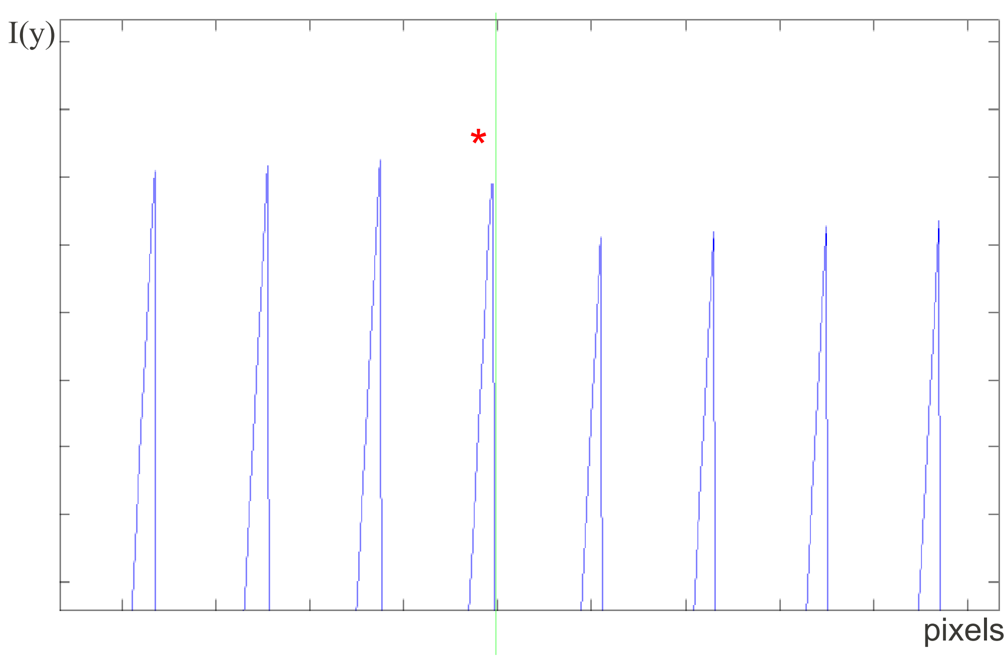
• <u>Value channel</u>: sinusoidal signal $I(x,y)=0.5+0.5\cdot\cos(2\pi f_0 y)$

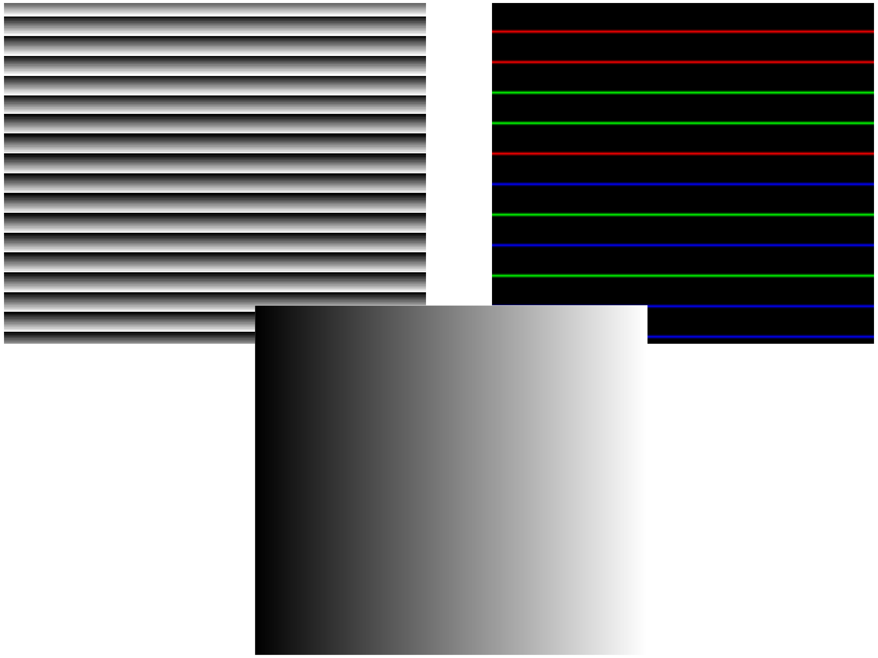
where x = 1,.. n and $f_0=\frac{64}{n}$

Combination of DeBruijn and wrapped phase

Due to the 2D nature of WFT (which may include some frequencies of adjacent positions in the Fourier Transform), the phase value of an specic position may have some deviation.

This efect is corrected by shrinking or expanding the wrapped phase accordingly to the DeBruijn correspondences for the maxima, using non-linear 4th order regression.



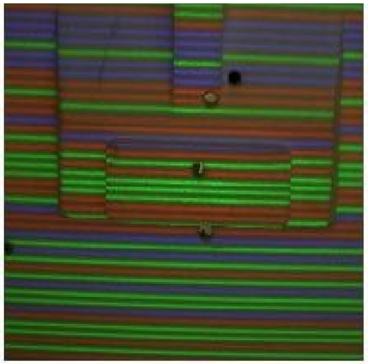


A full (dense) correspondences map is obtained.

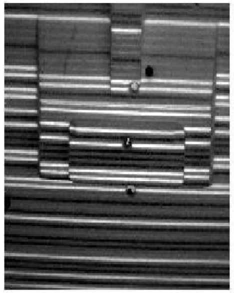
Qualitative results

Input image

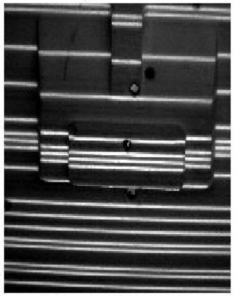
Rectified image



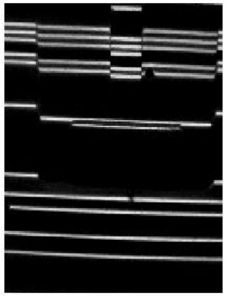
Red channel



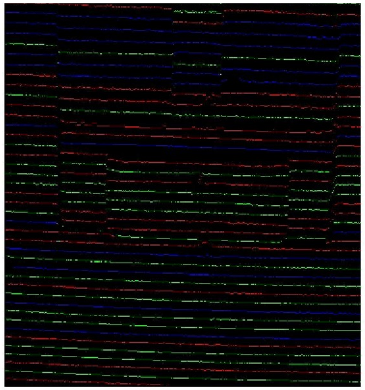
Green channel



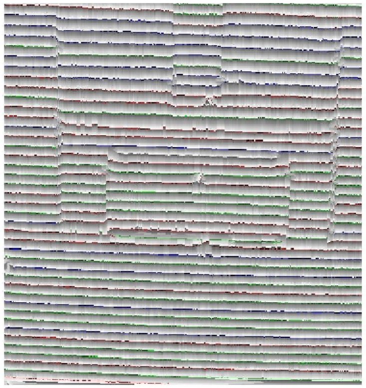
Blue channel

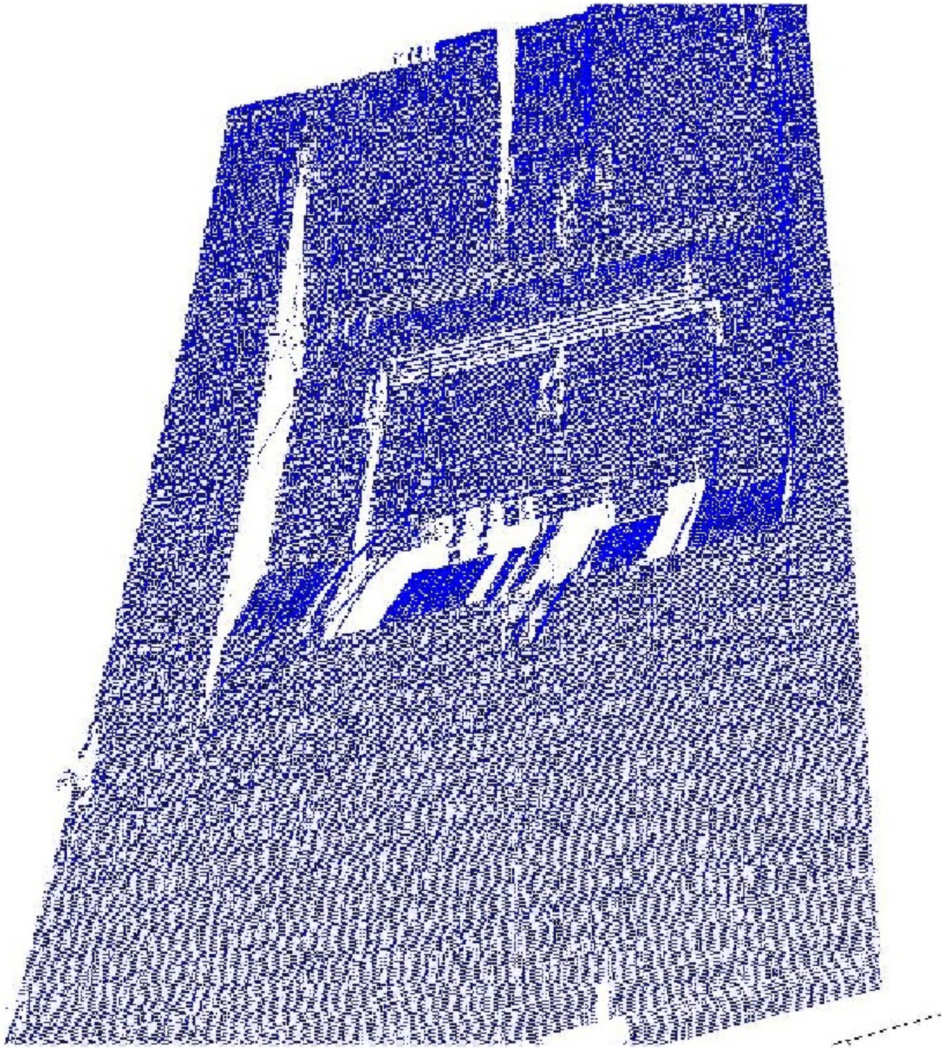


Color slits



Wrapped phase





Qualitative results

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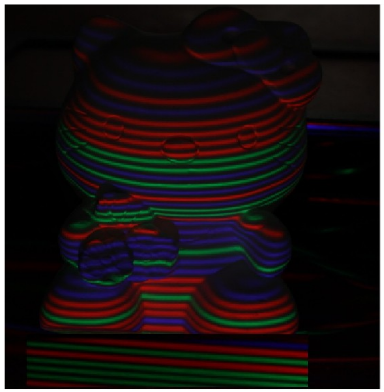
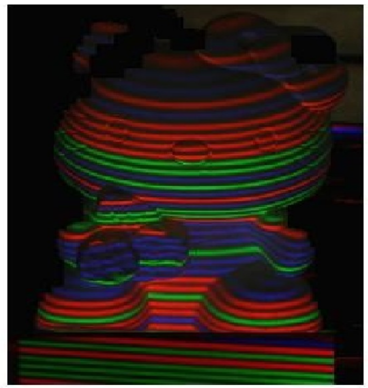
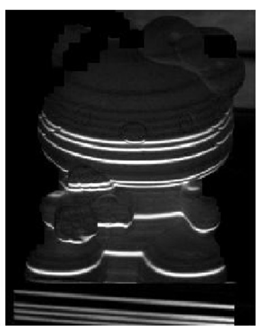


Rectified image

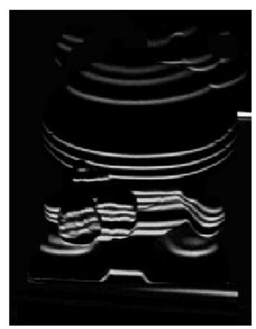


Red channel

Green channel



Blue channel



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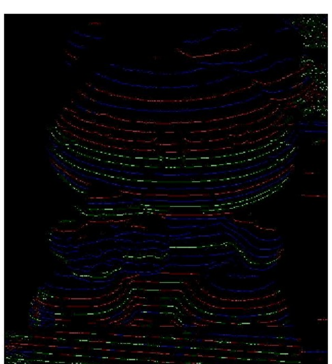
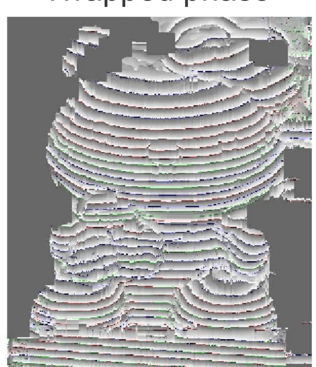
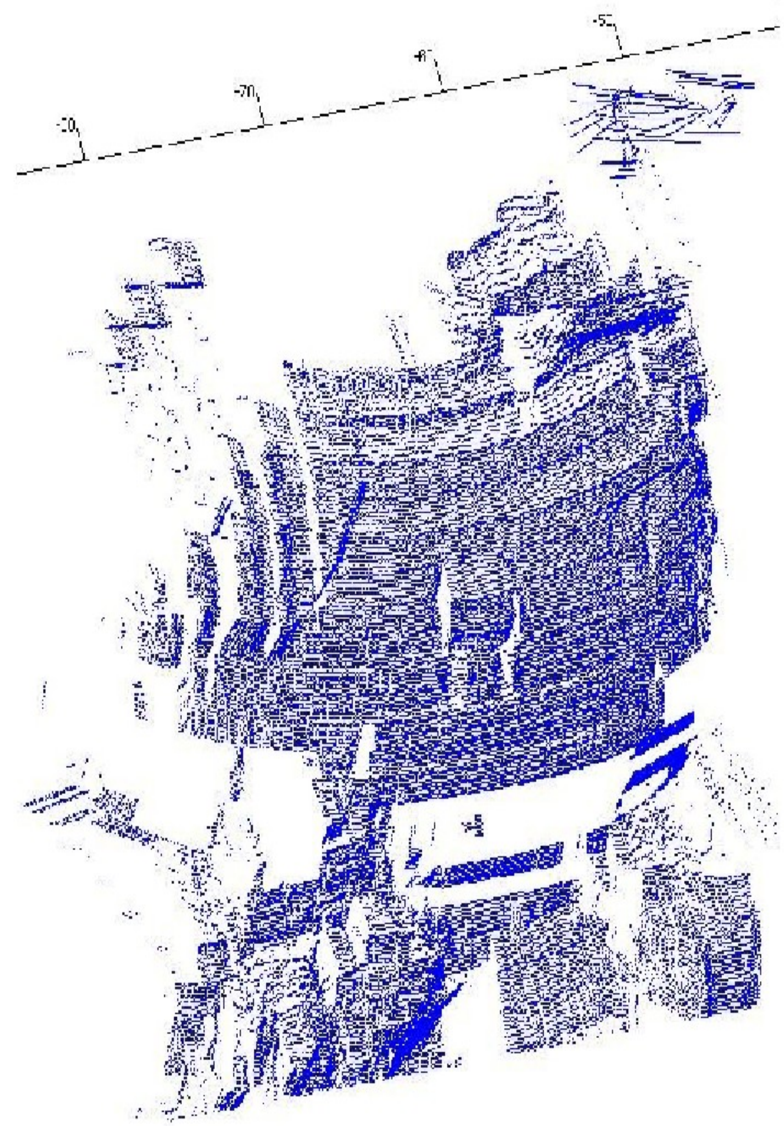


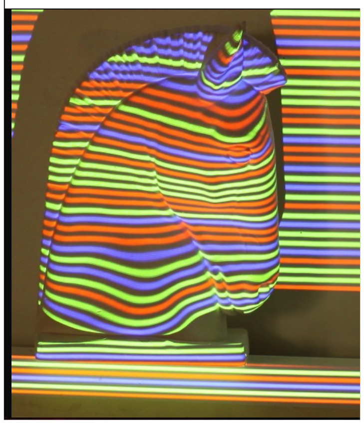
Wrapped phase



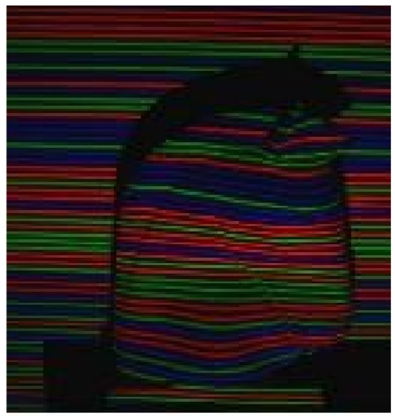


Qualitative results

Input image



Rectified image

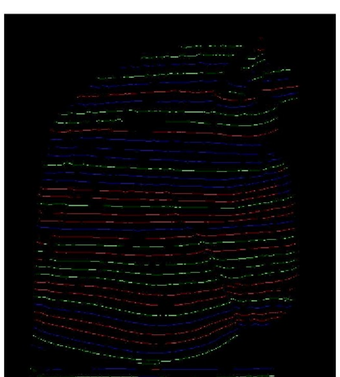


Red channel

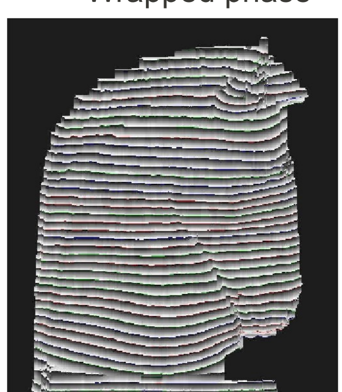
Green channel

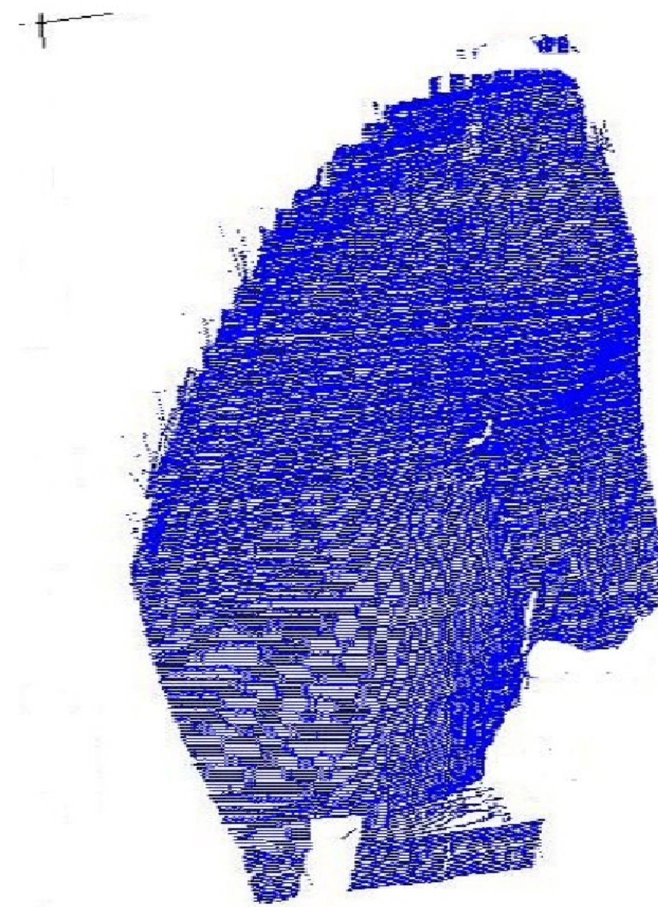
Blue channel

Color slits



Wrapped phase





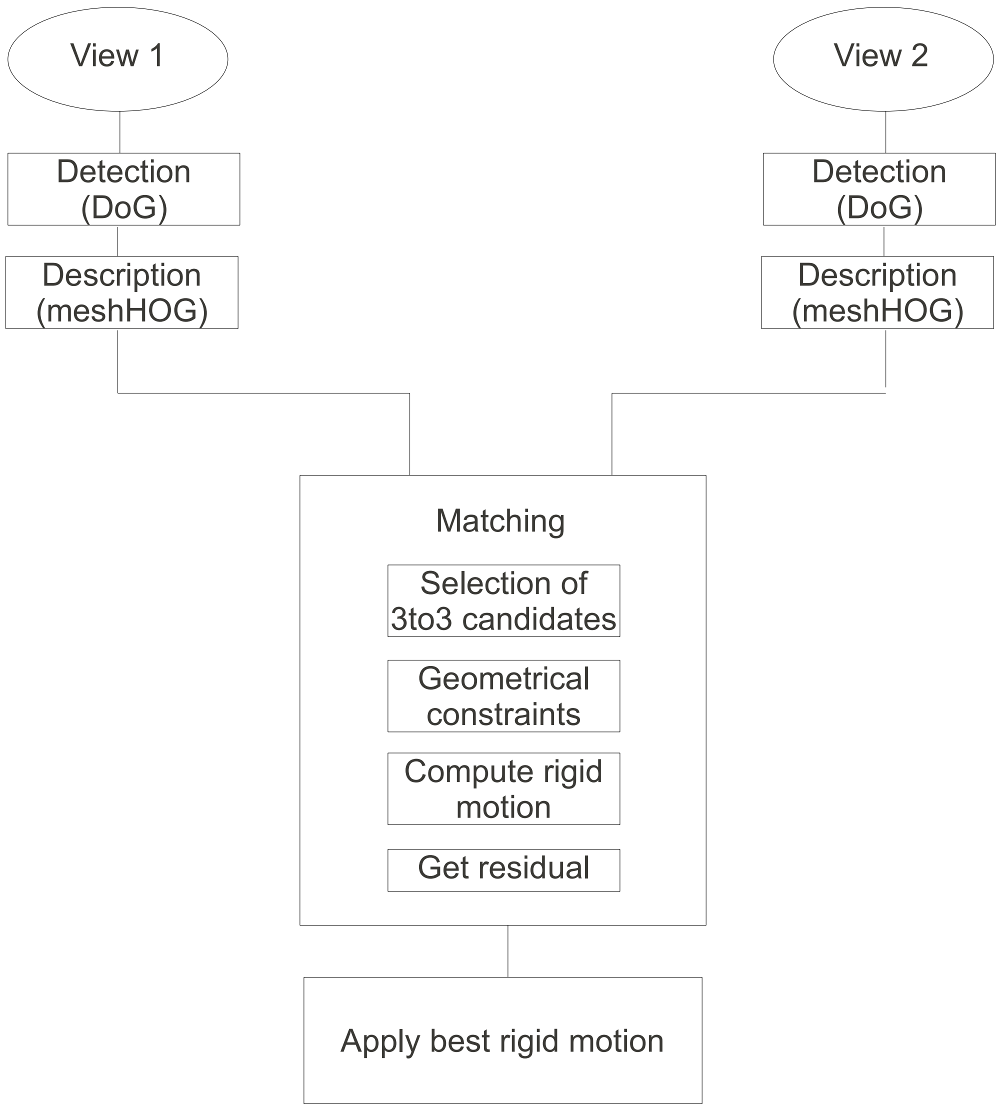
Quantitative results and discussion

Technique	Average (mm)	Std (mm)	3D points	Patterns	Time (s)
Monks et al.	1,31	1,19	13899	1	45,29
Posdamer et al	1,56	1,40	25387	14	32,18
Guhring	1,52	1,33	315273	24	158,22
Pribanic et al.	1,12	0,78	255572	18	165,65
Carr. And Hummel	11,9	5,02	202714	1	150,57
Proposed technique	**1,18**	**1,44**	**357200**	**1**	**160,75**

	One-shot projection	Dense reconstruction	Absolute coding	Accuracy
DeBruijn pattern	✓	✗	✓	✓
Fringes pattern	✓	✓	✗	✓
Multiple phase shifting	✗	✓	✓	✓
Spatial grading	✓	✓	✓	✗
Proposed method	✓	✓	✓	✓

Outline

A novel pipeline for coarse registration



A novel pipeline for coarse registration

Detection

DoG is applied on 6 different scales of filtering → scale map $M_i^d(v)$:

$$M_i^d(v) = \| n(v) \cdot (g(v, \sigma_i) - g(v, 2\sigma_i)) \|$$

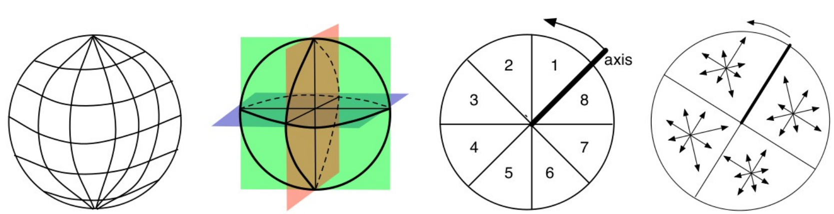
Saliency map = sum of all scale maps.

Description (HoG)

1. Define the n-ring (1% of total).

2. Compute local coord. System (the 2nd direction is the max of 2D histogram).

• HoG = concatenation of 2D histogram.

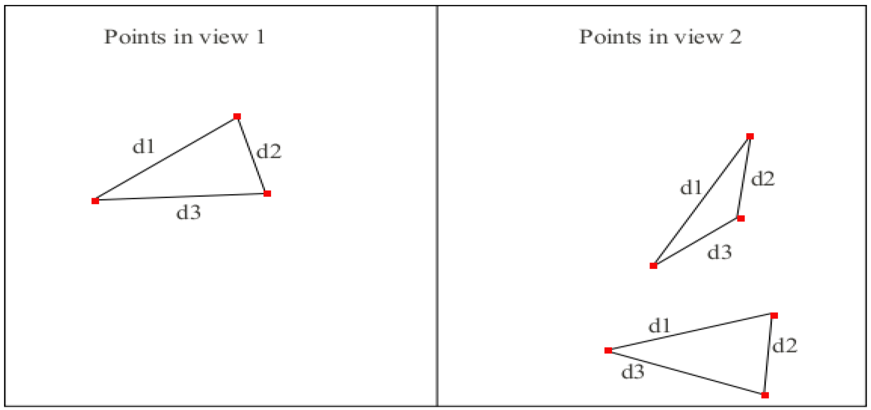


Matching

1. Compute the correlation matrix between the set of keypoint descriptors from the 2 views.

2. Select only the 6 greatest matches.

3. For every pair of random triplets from view 1 and their correspondences in view 2:
   - Check geometrical constraints.
   - Apply rigid motion.
   - Calculate residual.



Outline

1. State of the art
2. First approach to one-shot dense reconstruction
3. Automatic window selection in Frequency Transform techniques
4. One-shot absolute pattern for dense reconstruction
5. Registration of single views from structured light
6. **Conclusions**

Contributions

1. A new classication of the SL approaches present in the literature.
2. A new one-shot dense pattern based on the Remainder Theorem.
3. A study of the best frequency-based analysis for fringe pattern.
4. A new algorithm for the automatic selection of the window size in WFT.
5. A one-shot pattern projection technique for 3D dense reconstruction.
6. A new pipeline for 3D alignment of partial views obtained from SL.

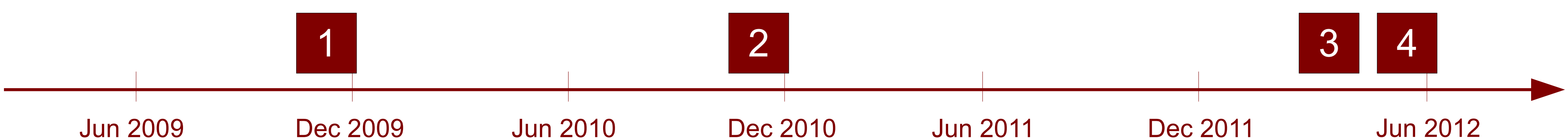
Journals

1. *State of the art:*
   J. Salvi, S. Fernandez, T. Pribanic, "A sate of the art in structured light patterns for surface prolometry", **Pattern Recognition**, 34, pp 2666-2680, 2010. *46 cites*

2. *Automatic window width:*
   S. Fernandez, M. Gdeisat, J. Salvi, D. Burton, "Automatic window size selection in windowed Fourier Transform for 3D reconstruction using adapted mother wavelets prolometry", Optics Communication, 284(12), pp 2797-2807, 2011. *4 cites*

3. *Projector-camera calibration:*
   S. Fernandez, D. Fo, J. Salvi and J. Batlle. “Projector-camera calibration using a planar-based model”. Submitted to International Journal of Pattern Recognition and Articial Intelligence.

4. *One-shot dense pattern:*
   S. Fernandez and J. Salvi. “One-shot absolute pattern for dense reconstruction using DeBruijn coding and WFT”. Submitted to **Image and Vision Computing**.



Publications

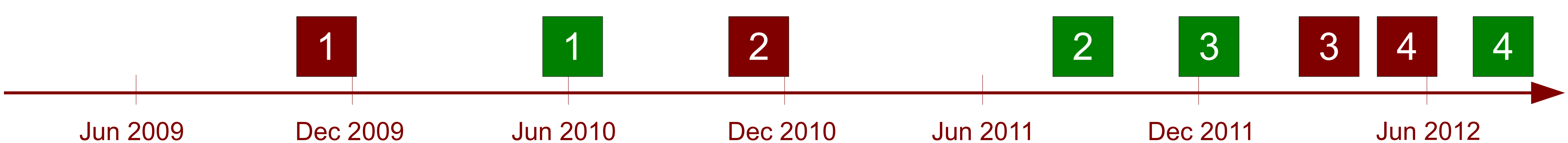
Conferences

1. *First approach:*
   S. Fernandez, J. Salvi and T. Pribanic. “Absolute Phase Mapping for One-shot Dense Pattern Projection”. PROCAMS'2010, IEEE Workshop on Projector-Camera Systems, in conjunction with **CVPR**, Article number 5543483, Pages 64-71, San Francisco (USA) June 18, 2010.

2. Projector-camera calibration:
   S. Fernandez, J. Salvi. “Planar-based Camera-Projector Calibration”. IEEE 7th International Symposium on Image and Signal Processing and Analysis (ISPA 2011), Dubrovnik (Croatia), September 4-6, 2011.

3. *Correspondences with two views:*
   S. Fernandez, J. Forest and J. Salvi. “Active stereo-matching for one-shot dense reconstruction”. International Conference on Pattern Recognition Applications and Methods, Faro (Portugal) 6th/8th February 2012.

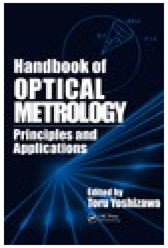
4. *One-shot dense pattern:*
   S. Fernandez, J. Salvi. “A novel structured light method for one-shot dense reconstruction”. IEEE International Conference on Image Processing (**ICIP 2012**). Coronado Spring, Florida (USA), September 30th - October 3th 2012.

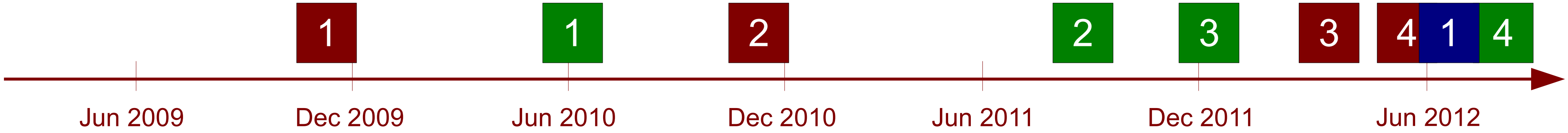


Publications

Book chapters

1. S. Fernandez and J. Salvi, “3D reconstruction strategies in Structured Light”, in Handbook of 3D machine vision: Optical metrology and imaging, compiled by Song Zhang. In press.





One-shot pattern projection for dense and accurate 3D acquisition in structured light

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