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TNO innovation
for life

Real time vision in the loop for mechatronics applications

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Mechatronics event, Veldhoven, march 24th 2011

TNO



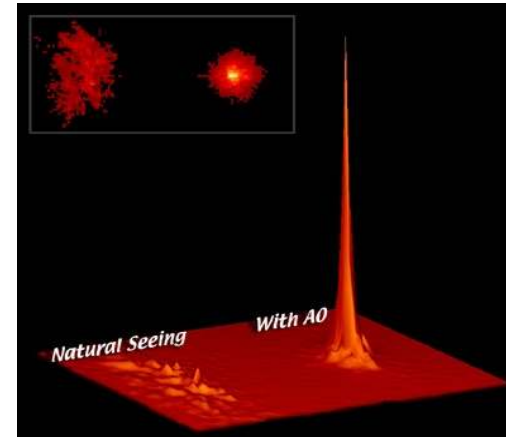
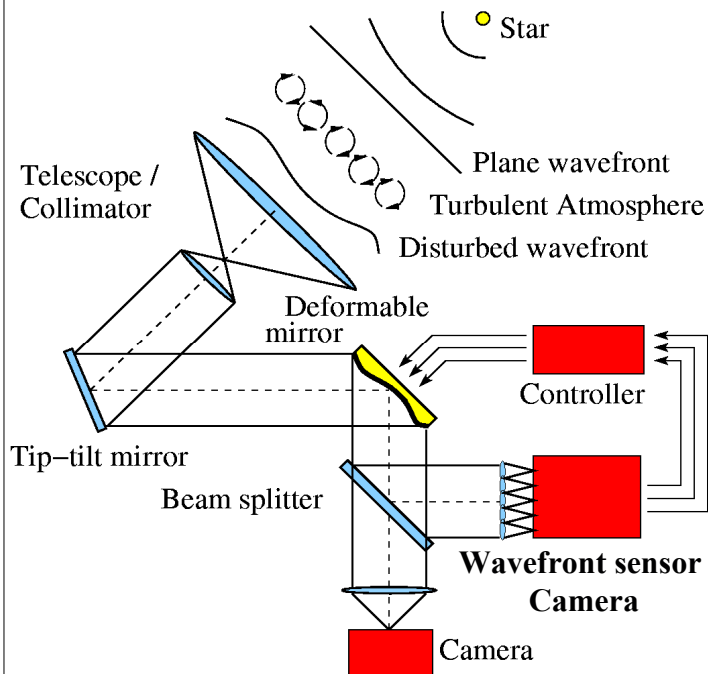
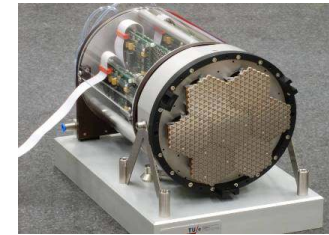
Vision in the loop

- › Project in cooperation with Tu/e, supported by an IOP precision technology grant.
- › Application examples
- › Why isn't it straight forward?
- › Demonstrator project: image controlled 2D mask translation at 5KHz loop rate
 - › Pattern alignment algorithm
 - › Cascaded motion control system
 - › Component choice and considerations
 - › Tuning for faster lap times
 - › Loop shaping
- › Results
- › Future perspective

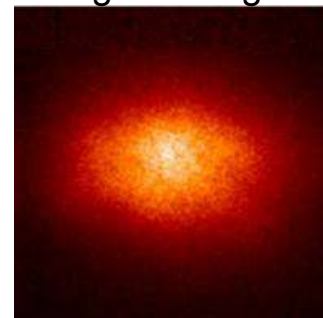


Application example: Space / adaptive optics

- ▶ Goal: Improve resolution of telescope images
- ▶ How: Control concept based on prediction of atmospheric turbulence: MIMO, System Identification.
- ▶ Result: AO error is 20 – 50% of common error



original image



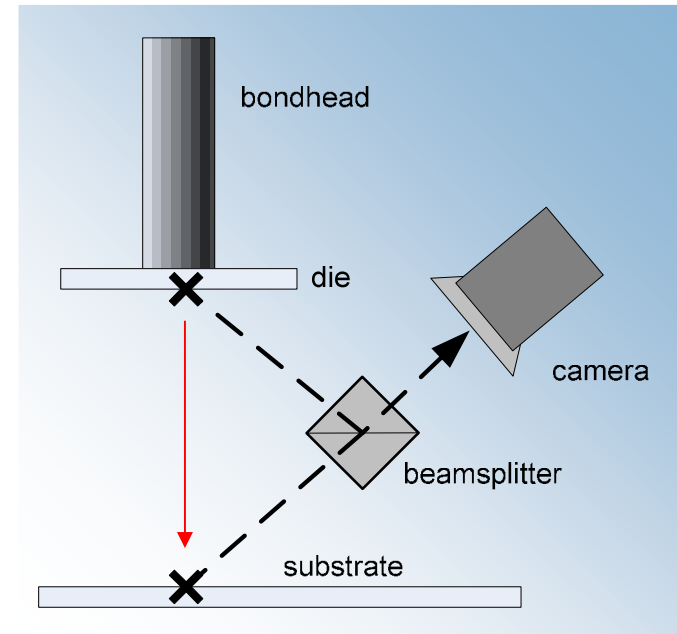
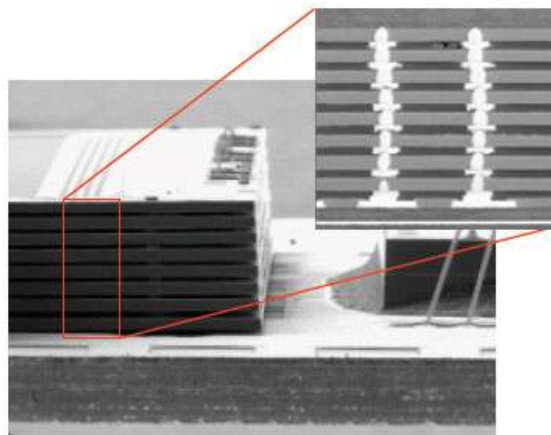
corrected





Application example: Eye in hand

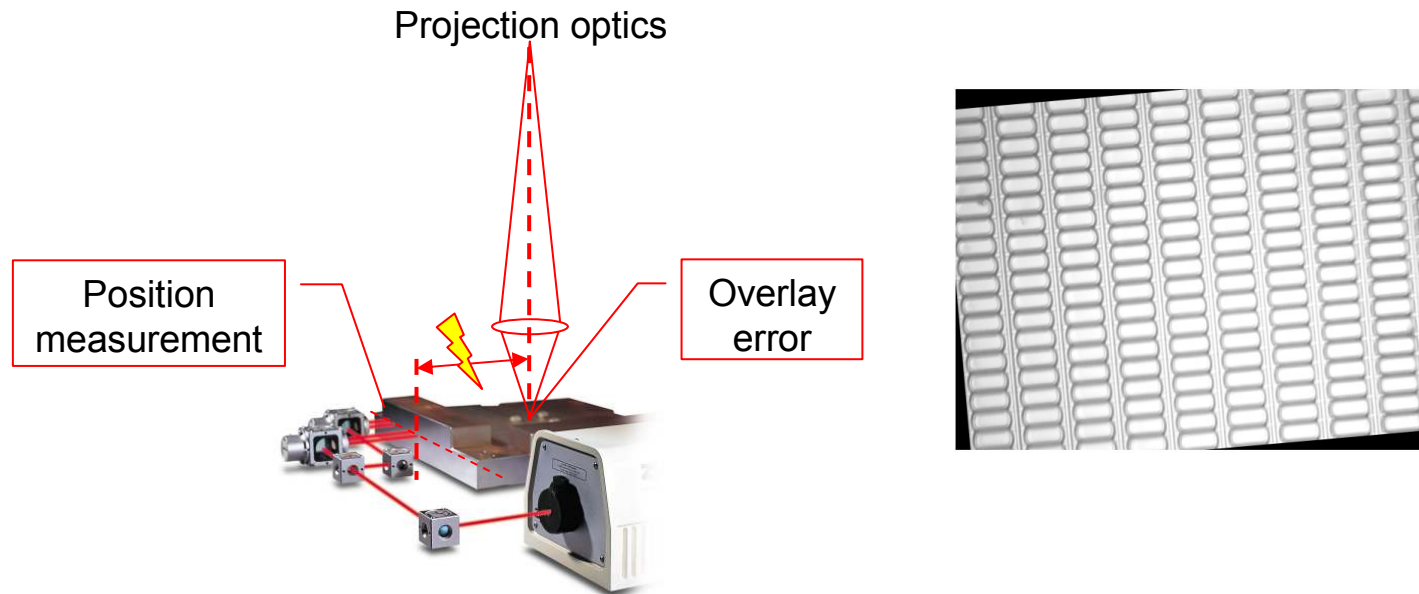
- › camera system to view die *and* substrate
 - › no drift between them
 - › *only* z-axis movement after measurements
- › attach camera system to bondhead
 - › measurement *on the fly*



This slide is from presentation by Bas de Kruif (TNO)
“Integrated measurement for accurate placement of dies”
earlier today @ Mechatronics event march 24th 2011



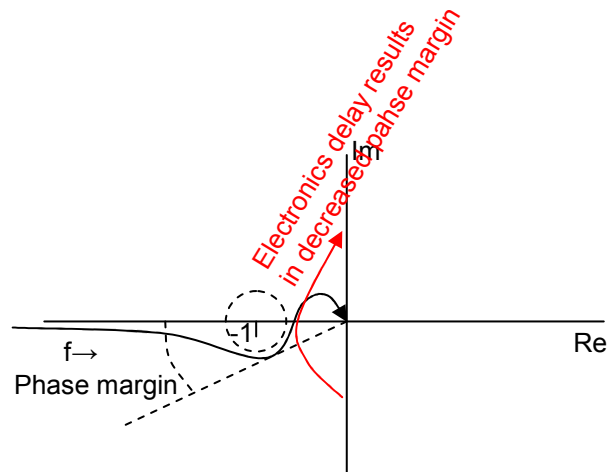
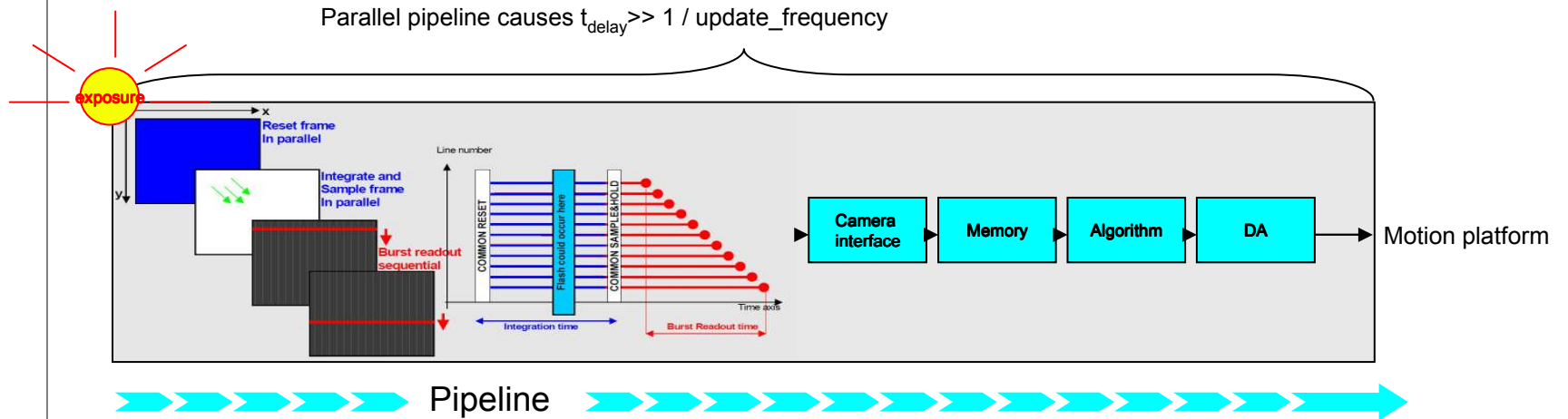
Application example: Litho metrology



- › Position is measured, but if we could only control overlay at the focal point of the projection optics. Eliminating calibrations, (pre)alignment, temperature control, vibration isolation.....
- › New: upcoming challenge of amorph stretching of flexible substrates for systems on a foil.



Why isn't it straight forward?



$$\text{Extra_delay} = t_{\text{electronics_delay}} \cdot f_{\text{control}} \cdot 360 \text{ deg}$$

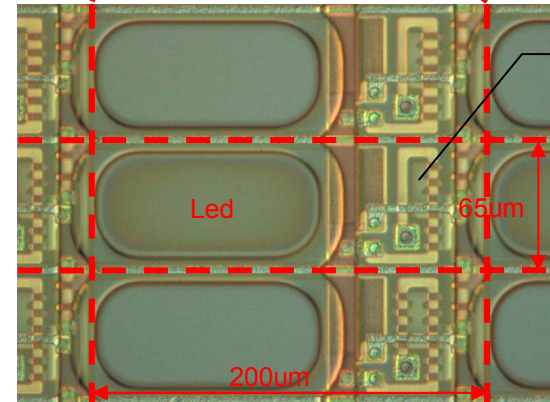
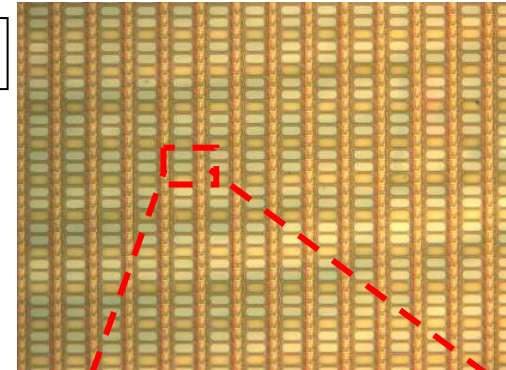
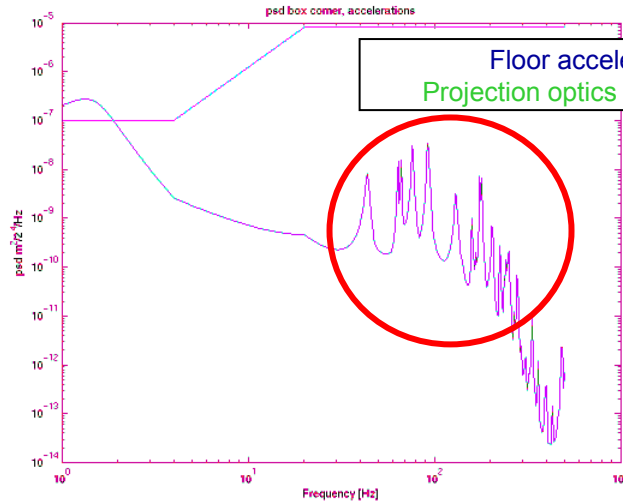
signal delay (msec)	System frequency (Hz)			
	10	5	200	500
10	180,00	36,00	720,00	1800,00
5	90,00	18,00	360,00	900,00
2	36,00	7,20	144,00	360,00
1	18,00	3,60	72,00	180,00
0,5	9,00	1,80	36,00	90,00
0,4	7,20	1,44	28,80	72,00
0,3	5,40	1,08	21,60	54,00
0,2	3,60	7,20	14,40	36,00
0,1	1,80	3,60	7,20	18,00

good
ok
killing
 Limit of acceptable added delay

Project goal



Demonstrator project: image controlled 2D mask translation at 5KHz update rate



Driver feature size ~2.5um

$$\sigma_{DA}(\omega_{bw}) := \sqrt{\int_{\min}^{\max} \text{PSD}_{\text{MLA_DA}}(s, \omega_{bw}) \cdot \frac{1}{s^4} d(s)}$$

$$\sigma_{DA}(\omega_{bw}) = 0.165 \text{ nm}$$

High tech submicron machinery integrated with automated logistics, air flow, water cooling etc requires high bandwidth control. Experience learns that often control loops with >200Hz bandwidth are required to sufficiently suppress Vibrations => project goal feedback rate at 5000Hz



Pattern alignment algorithm

Zoom, integrate the image in horizontal and vertical direction & correlate

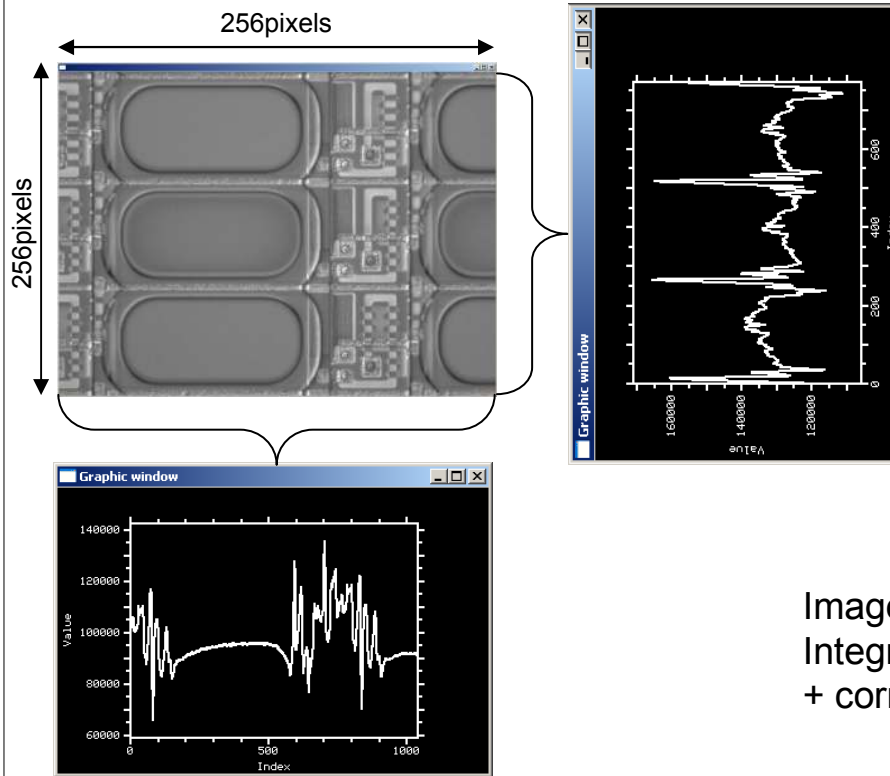
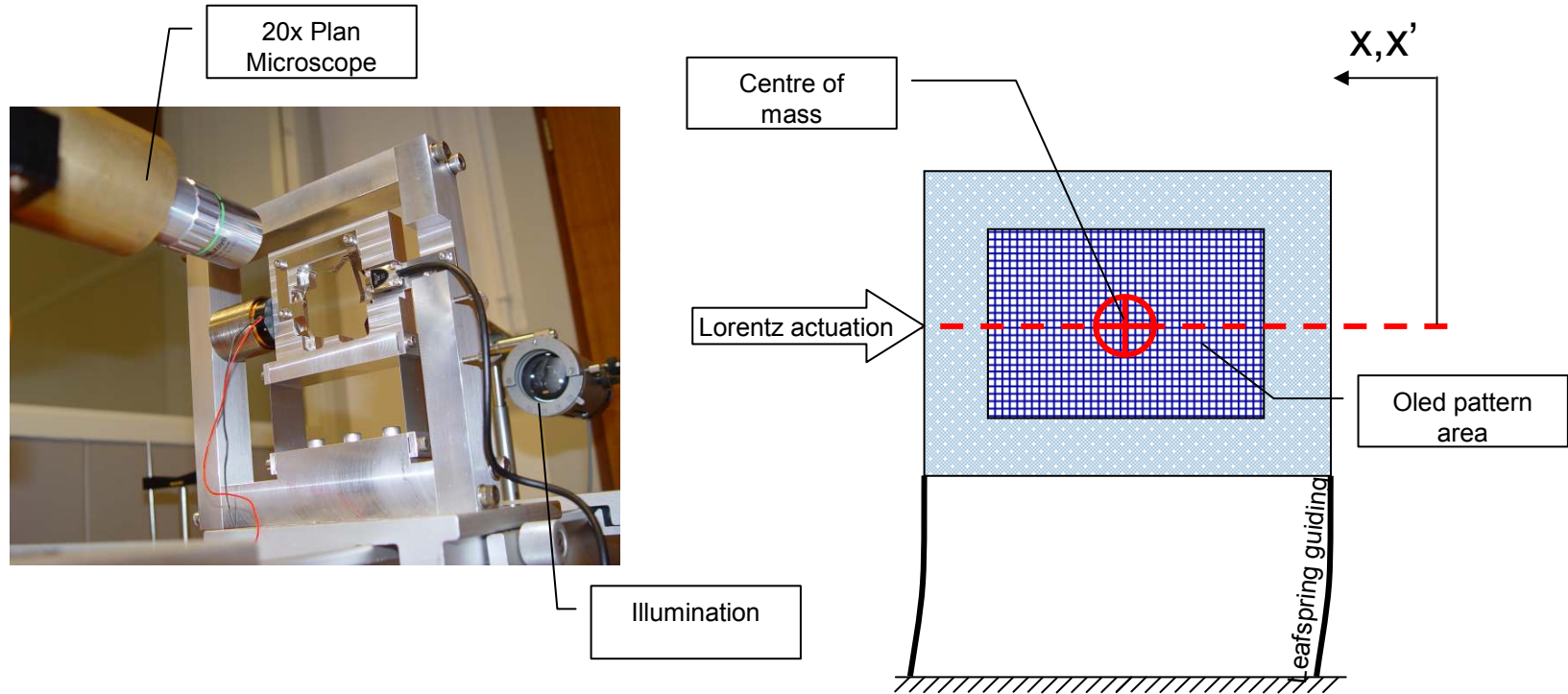


Image 256x256 pixels of 700nm
Integrate in horizontal and vertical direction
+ correlation to measure translations



2DOF case, but 1DOF Mechanical set up

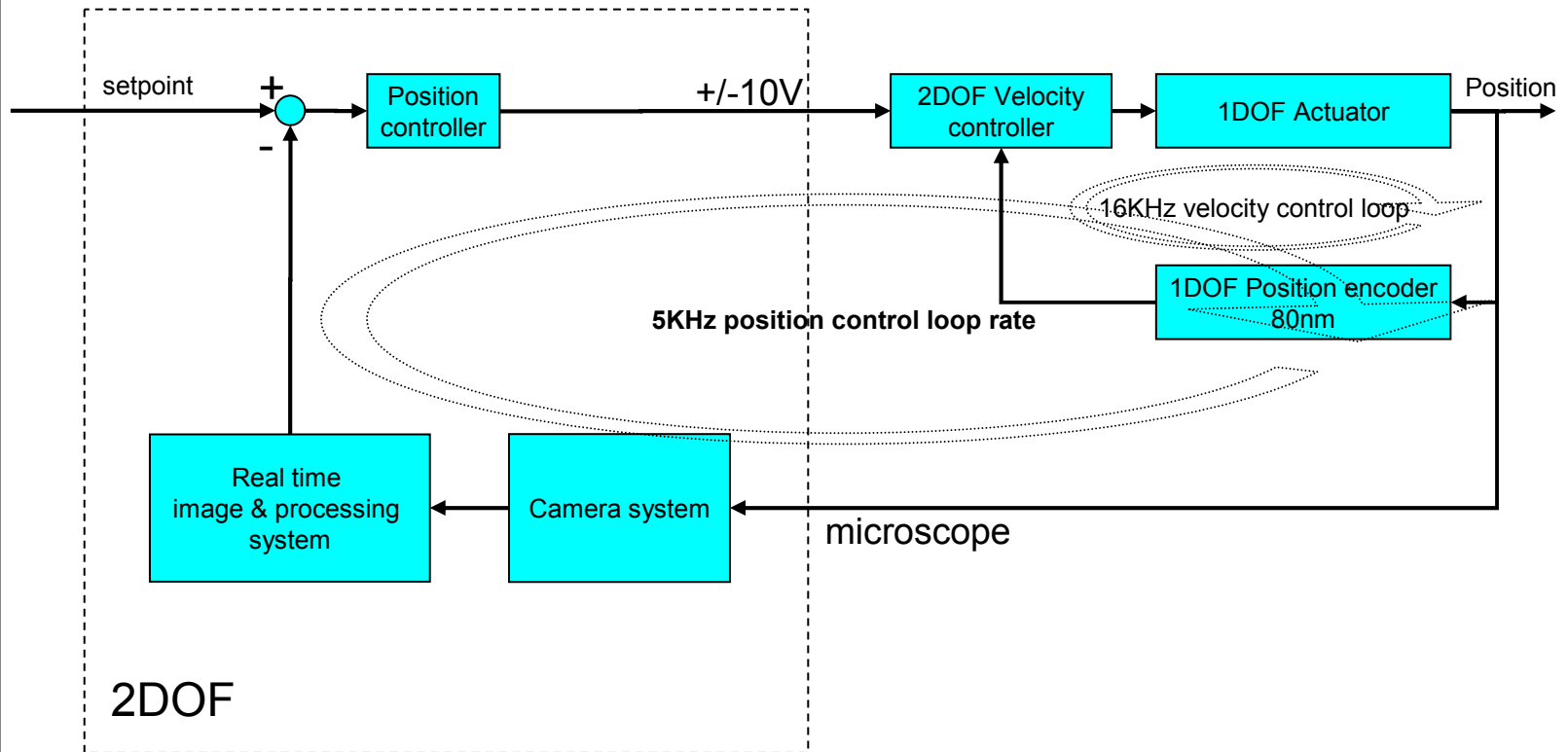


Stroke 4mm
1st resonance frequency at 425Hz



Cascaded motion control system

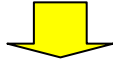
5KHz image update rate for position control



Cascade control with velocity controller adds linearisation, increases phase margin with 90deg + extra bonus: adds integral safety system to the development platform.



Image sensor selection



Type	Cypress Lupa-1300-2	Micron MT9M413
Pixels	1280x1024	←
Pixel pitch	14um	12um
Imaging area	17.92x14.34mm (diagonal 22.95mm)	15.36x12.28mm
Shutter	global instantaneous shutter	←
Fullframe rate	500Hz 655Mpixel/sec	490Hz 642Mpixel/sec
ROI selection	X&Y decimation for faster frame rates, may be performed dynamically but requires 1 or 2 frames	Y decimation for faster frame rates
Full well (e)	30000	63000
Read noise (e)	37	41
Quantum Efficiency	0.35	0.25
Fill Factor	0.6	0.4

Gigabit ethernet

128MByte/sec

Firewire 3200

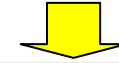
400MByte/sec

Camera Link (Full spec)**765MByte/sec**

We choose the Cypress Lupa and utilize this image sensor with an ROI of 256x256pixels @ 5KHZ.



Hardware architecture selection

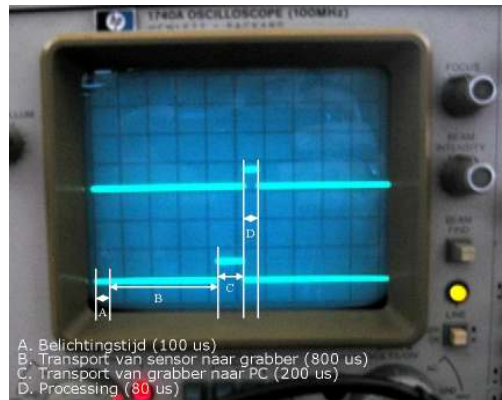
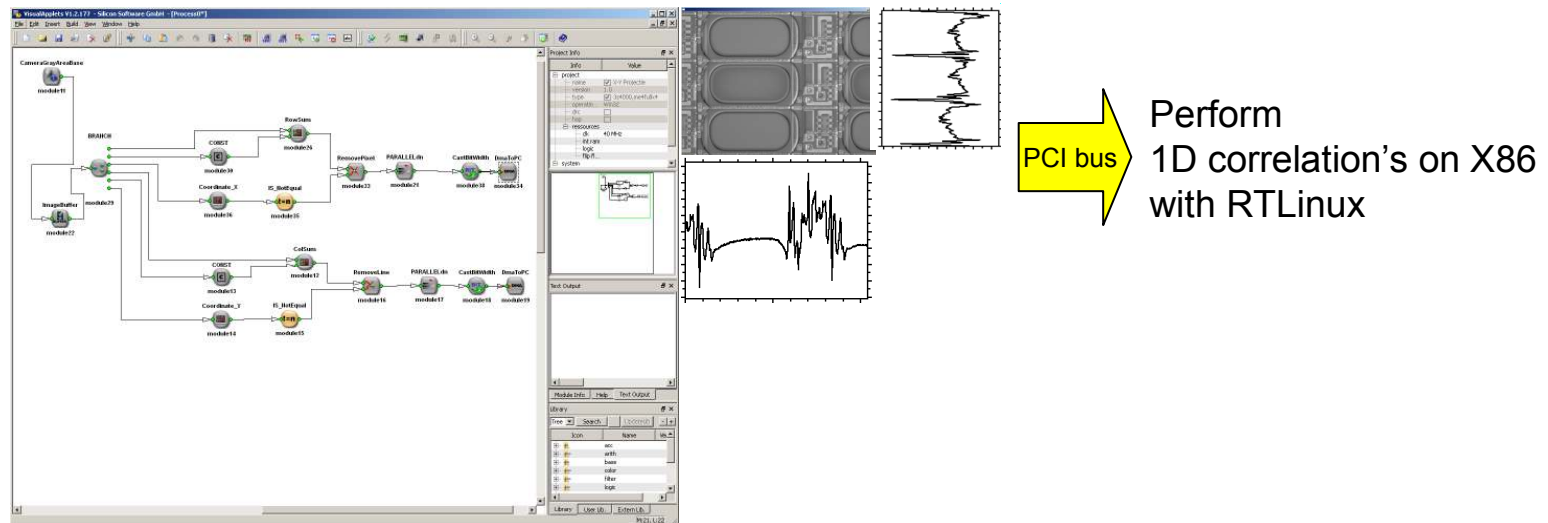


	GPU processing	IBM Cell processor	FPGA	x86 +RTOS		FPGA grabber + X86 + RTOS
I/O	CameraLink →grabber →PCI →Nvidia →PCI →DA	CameraLink →grabber →Cell →DA	CameraLink →FPGA →DA	CameraLink →grabber →PCI →x86 →DA		CameraLink →FPGA →PCI →x86 →DA
Camera exposure to actuator delay	Millisecs due to IO overhead	<0.25millisec with custom interface	<0.25millisec	0.5millisec		0.25millisec
Delay jitter	--	--	++	+		++
Processing power	++	+	+++	+/-		+++
Processing power scalability	+++	++	+	+		+
Implementation effort	+/-	-	--	++		+
Flexibility	+	-	--	++		+
Future proof	+	+/-	-	++		+
HW-price @ small quantities	+	--	-	++		+



Tuning for faster lap times

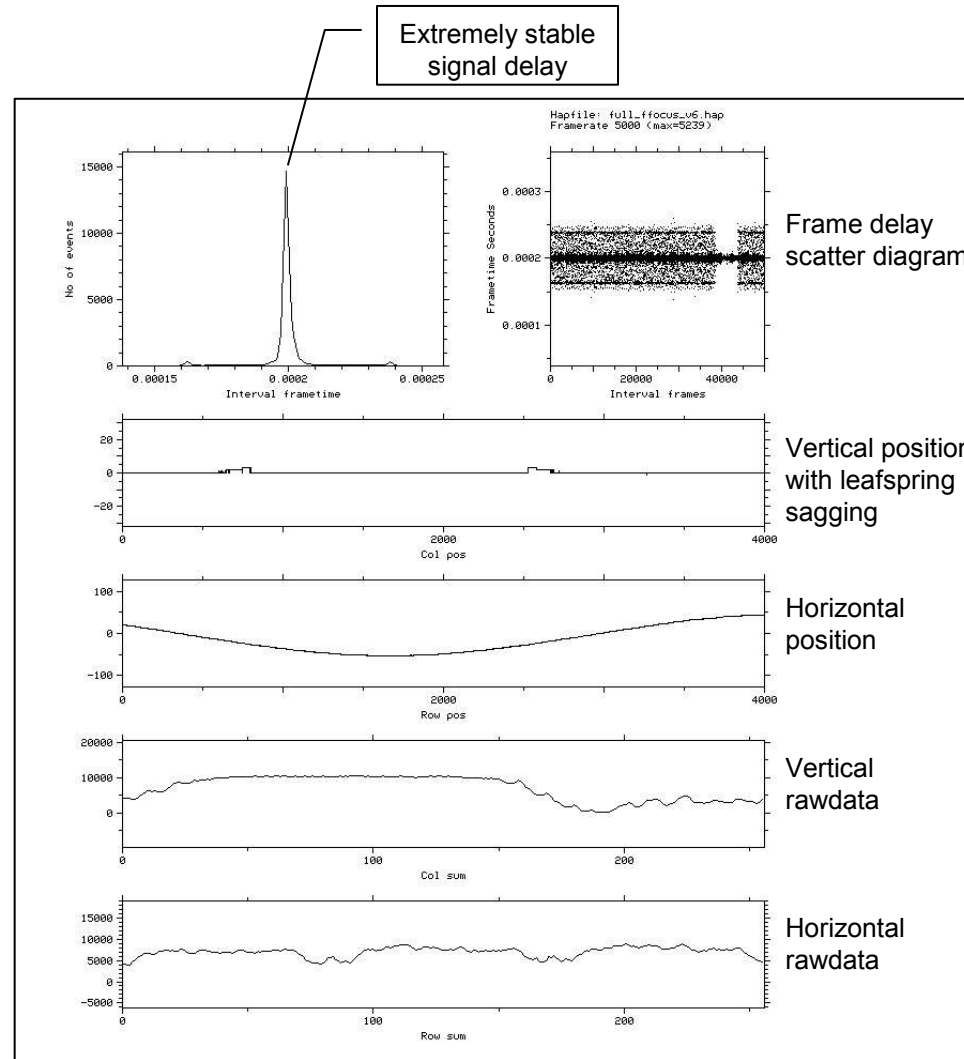
To decrease delays, image processing is performed during reception of the image by the FPGA



5KHz image rate	time
Illumination	50 μ s
Transport camera -> grabber	200 μ s
Transport grabber -> PC	<20 μ s
Calculate translation by correlation	35 μ s
Total	305 μs



TNO-RDA interface to monitor RTkernel variables

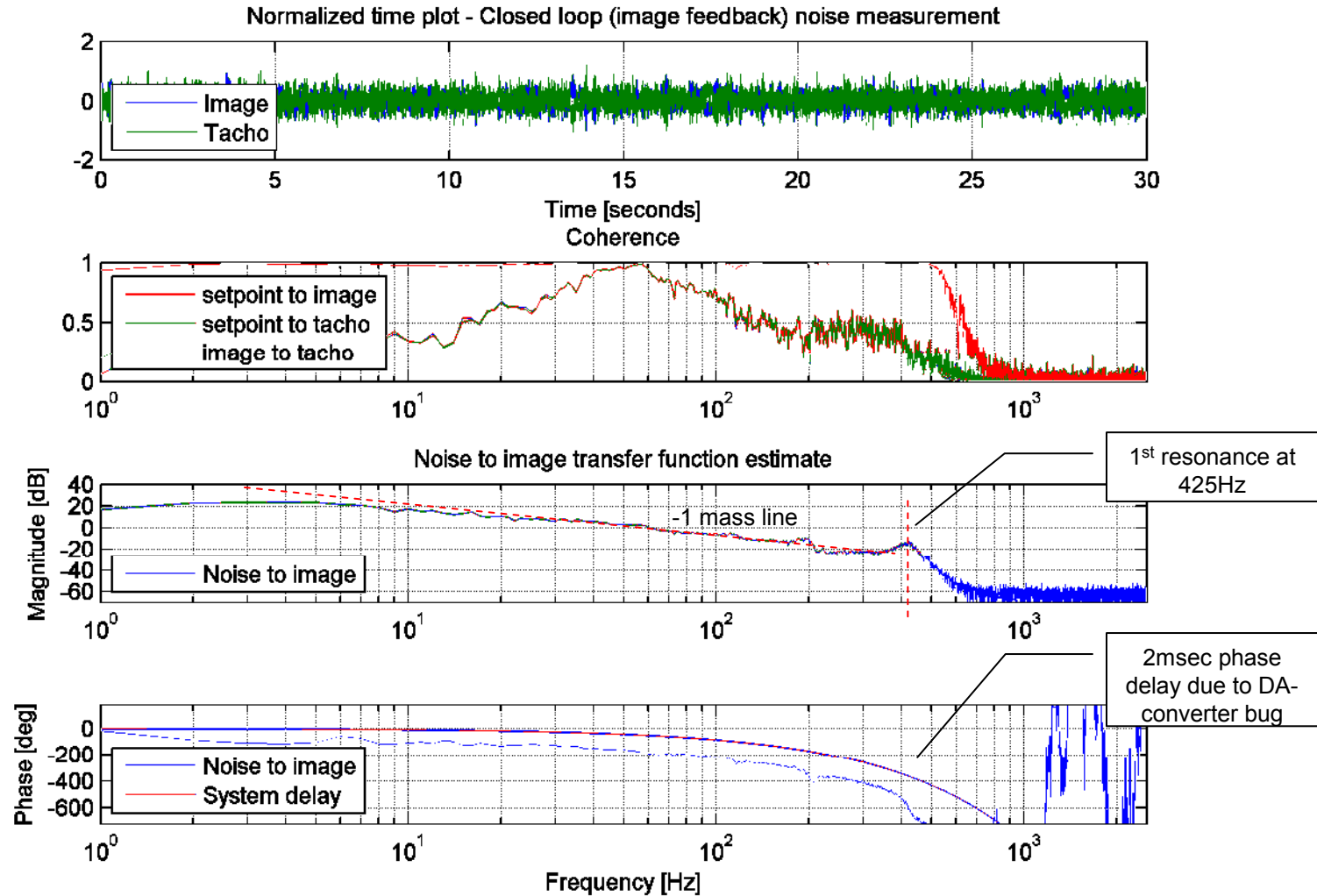


TNO-RDA is a kernel driver providing an API (to Matlab etc) to interface with TNO's data acquisition modules in the RTLinux kernel



System identification

Closed loop bandwidth of 400Hz is feasible





Conclusion

- › It's very well feasible to realise up to 1KHz bandwidth closed loop control systems on basis of high speed imaging. Update rates up to 10KHz are feasible with our state-of-the-art hardware.
- › Our demonstrator should be capable of reaching 400Hz closed loop bandwidth limited by the mechanical system. On going work: so far 80Hz has been reached due to 2msec DA converter bug.
- › In general: due to pipeline effects in imaging systems, emphasize should be on minimizing delay and jitter rather than update rate.
 - › Start processing as soon as first pixels arrive
 - › Implement a cascaded velocity control loop which gives you extra 90deg phase margin
- › All equipment used in the demonstrator is carefully selected commercial, of-the-shelf hardware. Total hardware costs ~ €12.500,-.