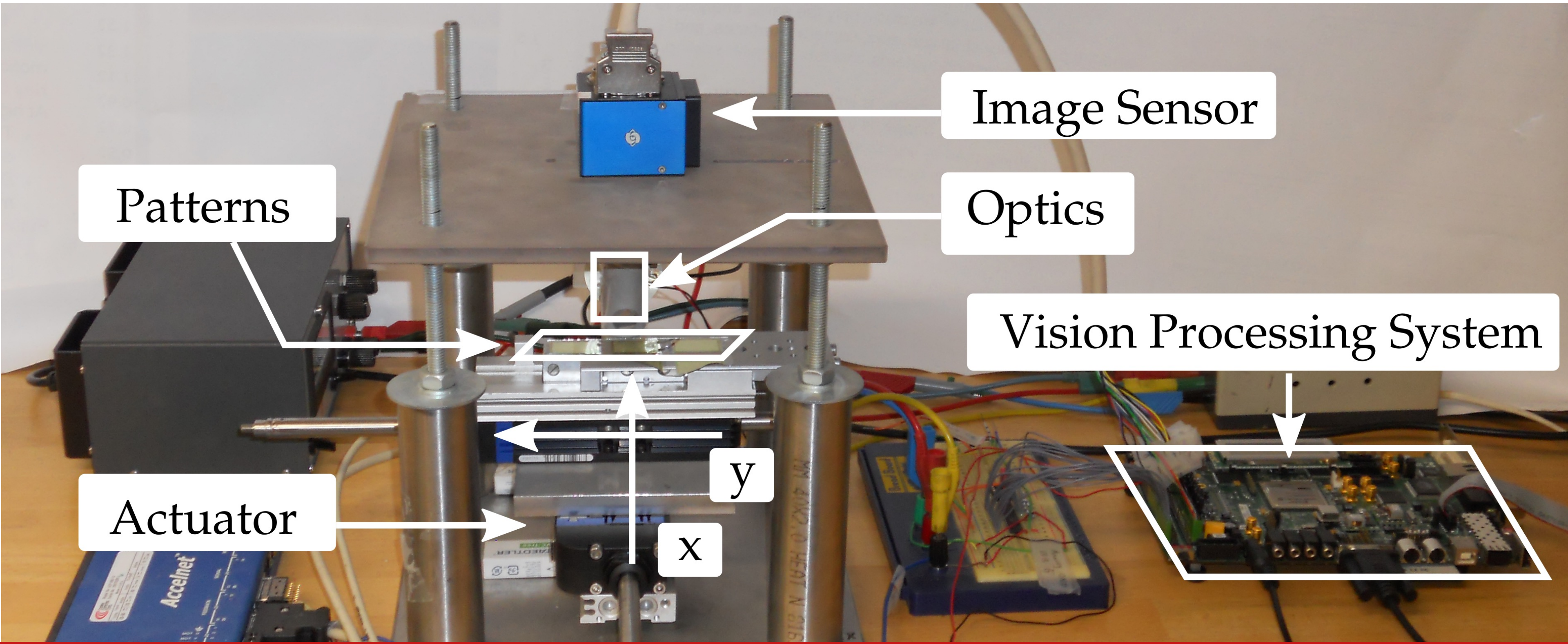

Cross-domain Modeling and Optimization of High-speed Visual Servo Systems

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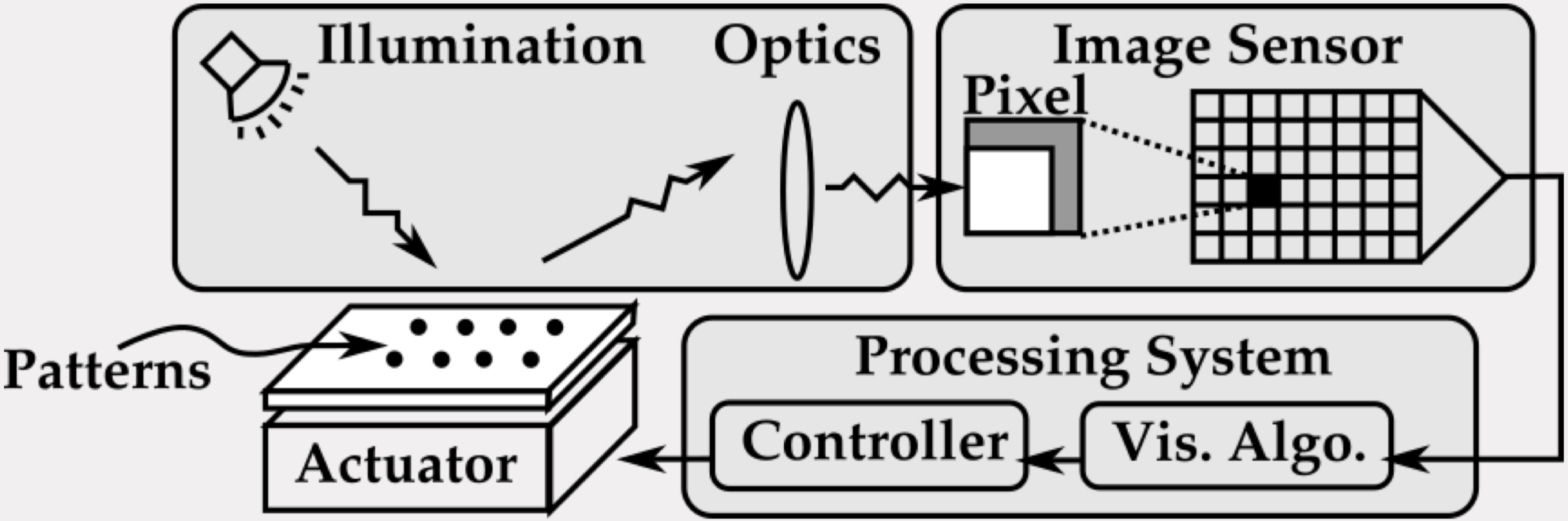
Henk Corporaal, Eindhoven University of Technology
Pieter Jonker, Delft University of Technology
Henk Nijmeijer, Eindhoven University of Technology

Visual Servo Systems: a Multi-domain View



Focus: **controlled** and **structured** environments.

Challenges and Proposed Solutions

Challenge 1

Limitations of visual feedback: low **sample rate,** large **delay,** coarse **quantization**.

Proposed solution:

Design template for high-speed vision processing.

Challenge 2

Cross-domain couplings and trade-offs.

Proposed solution:

A framework of methods for cross-domain modeling and optimization.

Axiomatic Design: an Example

$\star$: Dependence

0 : Independence

Dependent Parameters — Design Matrix — Design Parameters

$$\begin{array}{r} \text{Sample period} \\ \text{Quantization error} \\ \text{Delay} \\ \text{Controller} \end{array} \begin{bmatrix} h \\ \epsilon \\ \tau \\ K \end{bmatrix} = \begin{bmatrix} \star & 0 & 0 & 0 \\ \star & \star & 0 & 0 \\ \star & \star & \star & 0 \\ \star & \star & \star & \star \end{bmatrix} \begin{bmatrix} I_s \\ alg. \\ arch. \\ P \end{bmatrix} \begin{array}{l} \text{Image sensor} \\ \text{Vision algorithm} \\ \text{Processing architecture} \\ \text{Plant} \end{array}$$

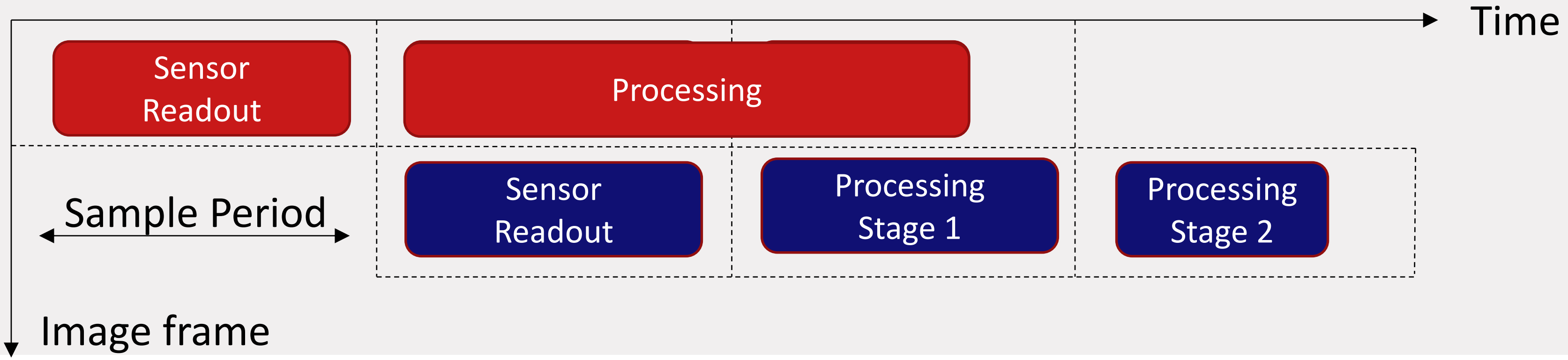
Performance criteria

$$\begin{array}{r} \text{Precision} \\ \text{Bandwidth} \end{array} \left\{ \begin{array}{l} RMSE = f_1(\epsilon, h, \tau, K) \\ BW = f_2(\epsilon, h, \tau, K) \end{array} \right.$$

N. P. Suh, "Axiomatic design theory for systems," Research in Engineering Design, vol. 10, no. 4, pp. 189–209, 1998.

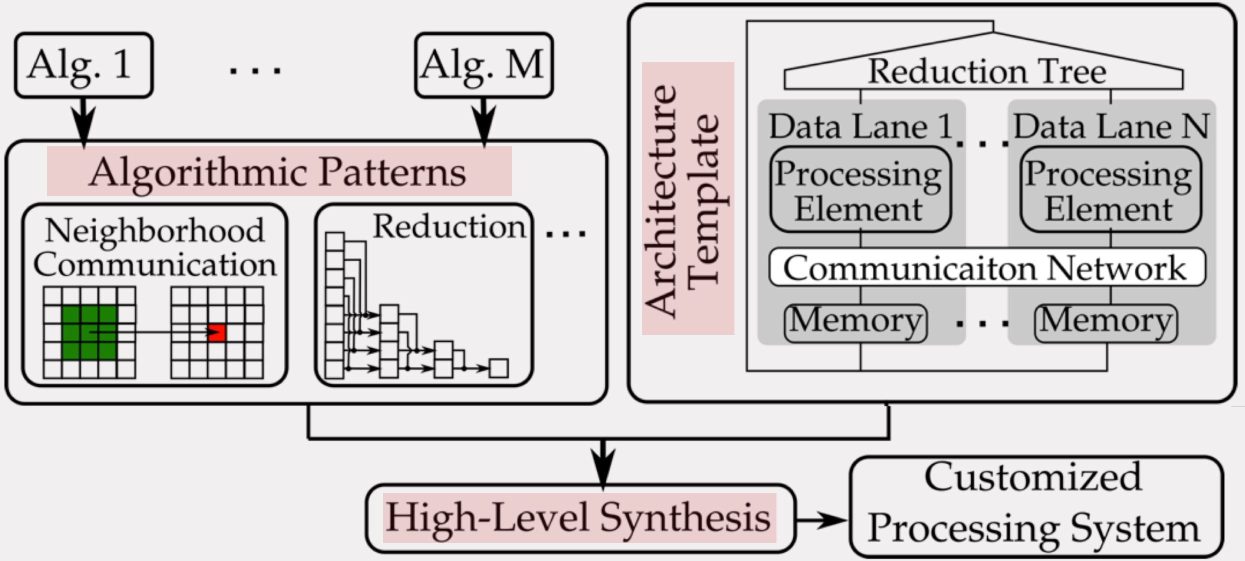
Design Matrix Obtained by Design Template

$$\begin{array}{r} \text{Sample period} \\ \text{Quantization error} \\ \text{Delay} \\ \text{Controller} \end{array} \begin{bmatrix} \boxed{h} \\ \epsilon \\ \tau \\ K \end{bmatrix} = \begin{bmatrix} \star & 0 & 0 & 0 \\ \star & \star & 0 & 0 \\ \star & \star & \star & 0 \\ \star & \star & \star & \star \end{bmatrix} \begin{bmatrix} \boxed{I_s} \\ alg. \\ arch. \\ P \end{bmatrix} \begin{array}{l} \text{Image sensor} \\ \text{Vision algorithm} \\ \text{Processing architecture} \\ \text{Plant} \end{array}$$



Delay: Coupling of Algorithm and Architecture

Approach: **(1) algorithmic patterns (2) architecture template (3) high-level synthesis**



Delay of Vision Processing

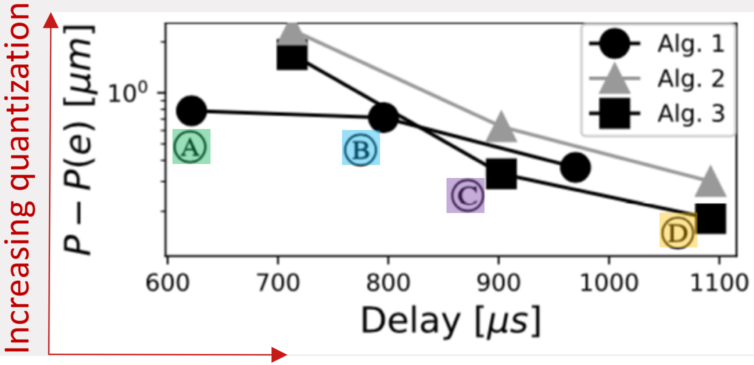
Case Study

3 image sensor sizes

3 configurations of architecture

3 vision algorithms

Alg.	Image size	Lanes	h [μs]	Δ [μm]	τ [μs]	Label
1	120×75	120	450	0.78	621.6	A
	160×100	160	600	0.71	795.6	B
	200×125	200	750	0.36	969.6	-
2	120×75	120	450	2.35	712.8	-
	160×100	160	600	0.63	902.4	-
	200×125	200	750	0.3	1092	-
3	120×75	120	450	1.68	712.8	-
	160×100	160	600	0.33	902.4	C
	200×125	200	750	0.18	1092	D



(A)(B)(C)(D) are Pareto-optimal configurations

TU/e

Performance After Controller Optimization

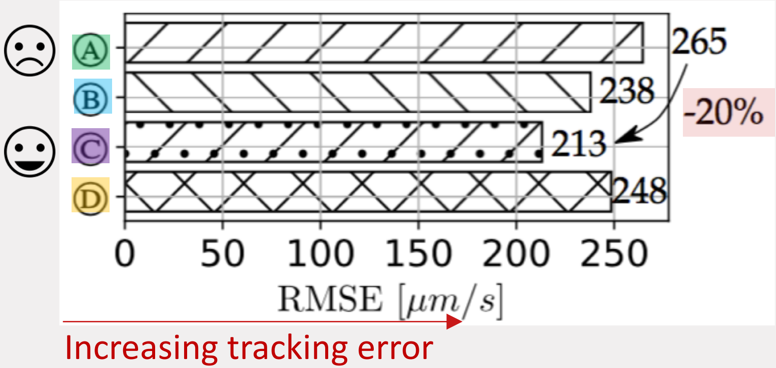
Motion Error Vision Error

(a) Precision →
(b) Bandwidth →

$$\begin{cases} \boxed{RMSE} = f_1(\boxed{\epsilon}, h, \tau, K) \\ BW = f_2(\epsilon, h, \tau, K) \end{cases}$$

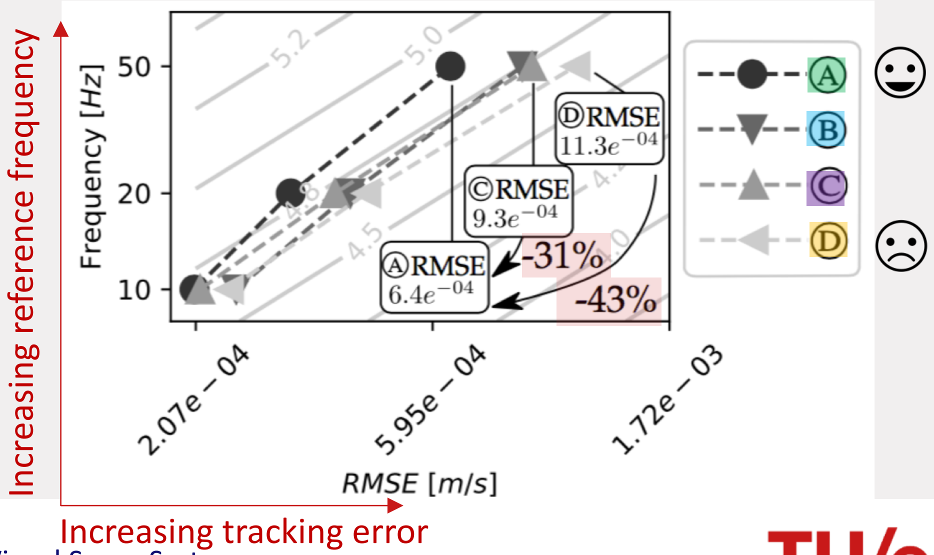
(a) Precision

Root-Mean-Squared-Error (RMSE)
of tracking a constant reference



(b) Bandwidth

Error of tracking sinusoidal signals
of different frequencies



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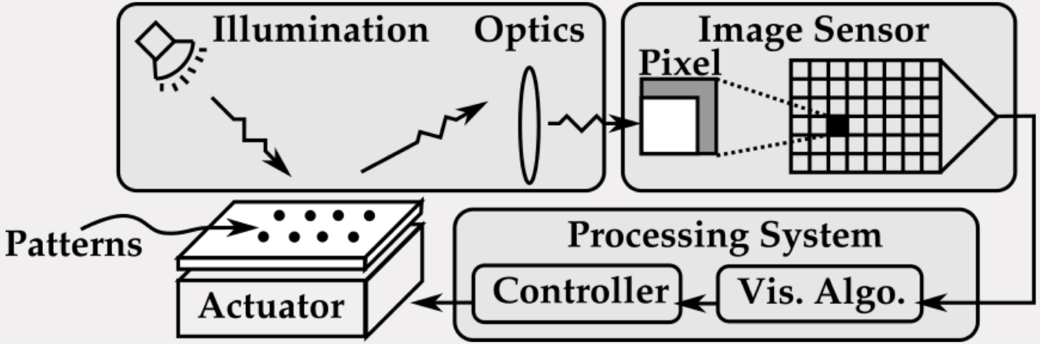
Conclusions

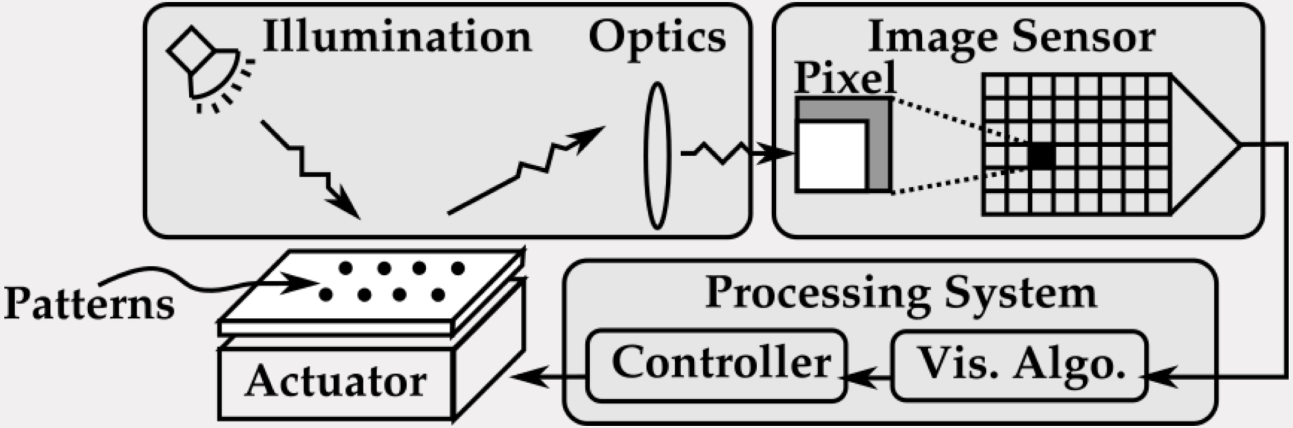


1. Cross-domain modeling and optimization are **necessary**. Demonstrated improvement:
   - **20%** for tracking a constant reference.
   - **43%** for high-bandwidth applications.
2. The demonstrated improvements are ***only achievable by*** cross-domain modeling and optimization.
3. This paper provides **effective** methods for such a purpose.

Thank you.

Backup Slides

Visual Servo Systems: a Multi-domain View



Focus on **high-speed** visual servo systems in **structured environments**.

- Require little adaptability. **Predefined patterns** are often used.
- Typically optimized for **accuracy** and **bandwidth**.

Modeling Sample Period and Measurement Error

$$\begin{bmatrix} \boxed{h} \\ \boxed{\epsilon} \\ \tau \\ K \end{bmatrix} = \begin{bmatrix} \star & 0 & 0 & 0 \\ \star & \star & 0 & 0 \\ \star & \star & \star & 0 \\ \star & \star & \star & \star \end{bmatrix} \begin{bmatrix} I_s \\ alg. \\ arch. \\ P \end{bmatrix}$$

Exposure time

Number of pixels

$$h = t_{exp} + \frac{N_p}{R_d}$$

Sample period

Rate of readout

Quantization function

$$\epsilon = Q(x) - x = \Delta \left\lfloor \frac{x}{\Delta} + \frac{1}{2} \right\rfloor - x$$

Measurement error

Sensitivity

TU/e

Modeling Measurement Error

$$\begin{array}{r} \text{Sample period} \\ \text{Quantization error} \\ \text{Delay} \\ \text{Controller} \end{array} \begin{bmatrix} h \\ \boxed{\epsilon} \\ \tau \\ K \end{bmatrix} = \begin{bmatrix} \star & 0 & 0 & 0 \\ \star & \star & 0 & 0 \\ \star & \star & \star & 0 \\ \star & \star & \star & \star \end{bmatrix} \begin{bmatrix} I_s \\ alg. \\ arch. \\ P \end{bmatrix} \begin{array}{l} \text{Image sensor} \\ \text{Vision algorithm} \\ \text{Processing architecture} \\ \text{Plant} \end{array}$$

Quantization function

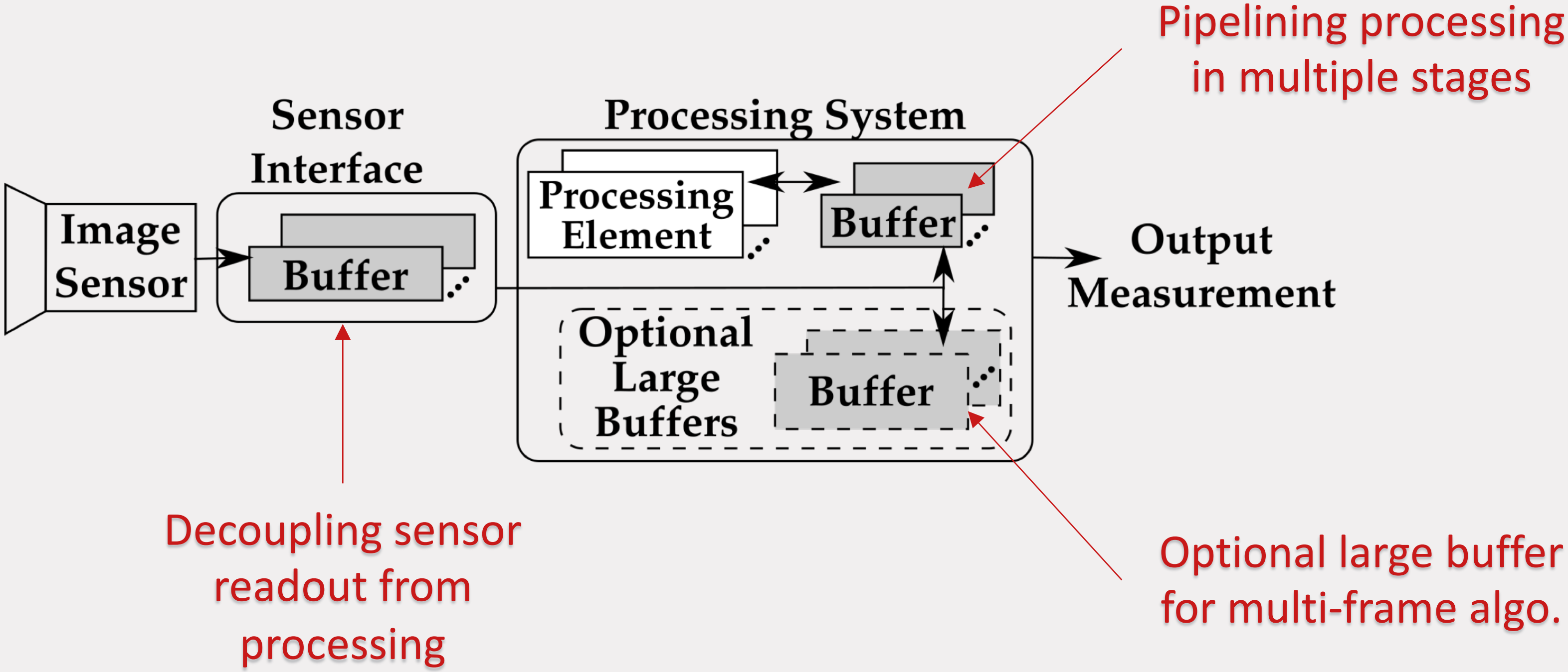
$$\epsilon = Q(x) - x = \Delta \left\lfloor \frac{x}{\Delta} + \frac{1}{2} \right\rfloor - x$$

Quantization error

Position of image frame

sensitivity

Design Template of High-speed Vision Systems



Controller Gain

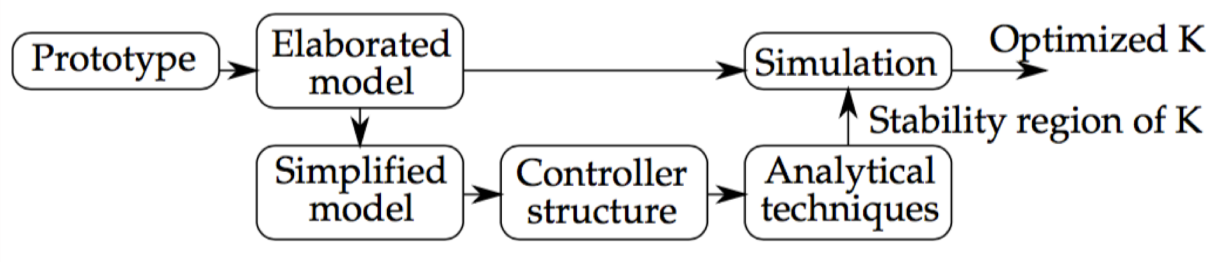
$$\begin{bmatrix} h \\ \epsilon \\ \tau \\ K \end{bmatrix} = \begin{bmatrix} \star & 0 & 0 & 0 \\ \star & \star & 0 & 0 \\ \star & \star & \star & 0 \\ \star & \star & \star & \star \end{bmatrix} \begin{bmatrix} I_s \\ alg. \\ arch. \\ P \end{bmatrix}$$

Simplify dependency of K

$$\begin{bmatrix} h \\ \epsilon \\ \tau \end{bmatrix} = \begin{bmatrix} \star & 0 & 0 \\ \star & \star & 0 \\ \star & \star & \star \end{bmatrix} \begin{bmatrix} I_s \\ alg. \\ arch. \end{bmatrix}$$

$$K = \begin{bmatrix} \star & \star & \star & \star \end{bmatrix} \begin{bmatrix} h \\ \epsilon \\ \tau \\ P \end{bmatrix}$$

Optimizing K: analytical method and simulaiton



Controller Gain

$$\begin{bmatrix} h \\ \epsilon \\ \tau \\ K \end{bmatrix} = \begin{bmatrix} \star & 0 & 0 & 0 \\ \star & \star & 0 & 0 \\ \star & \star & \star & 0 \\ \star & \star & \star & \star \end{bmatrix} \begin{bmatrix} I_s \\ alg. \\ arch. \\ P \end{bmatrix}$$

Simplify dependency of K

$$\begin{bmatrix} h \\ \epsilon \\ \tau \end{bmatrix} = \begin{bmatrix} \star & 0 & 0 \\ \star & \star & 0 \\ \star & \star & \star \end{bmatrix} \begin{bmatrix} I_s \\ alg. \\ arch. \end{bmatrix}$$

$$K = \begin{bmatrix} \star & \star & \star & \star \end{bmatrix} \begin{bmatrix} h \\ \epsilon \\ \tau \\ P \end{bmatrix}$$

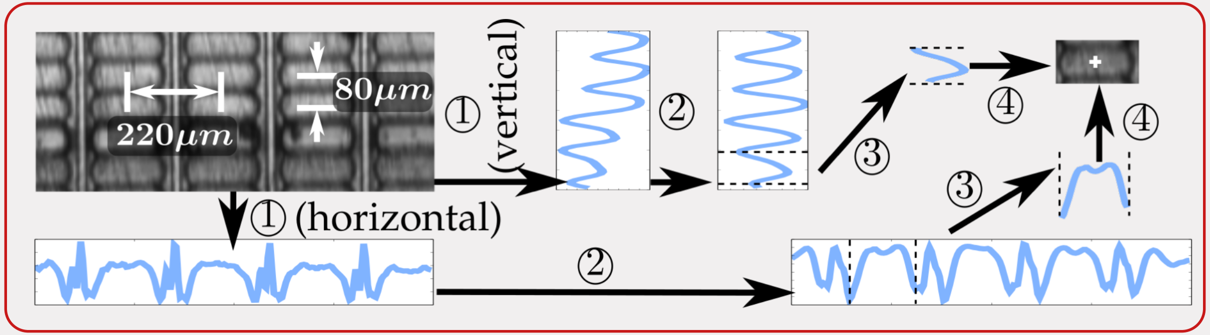
Image Sensors

IMAGE SIZES AND THEIR PROPERTIES.

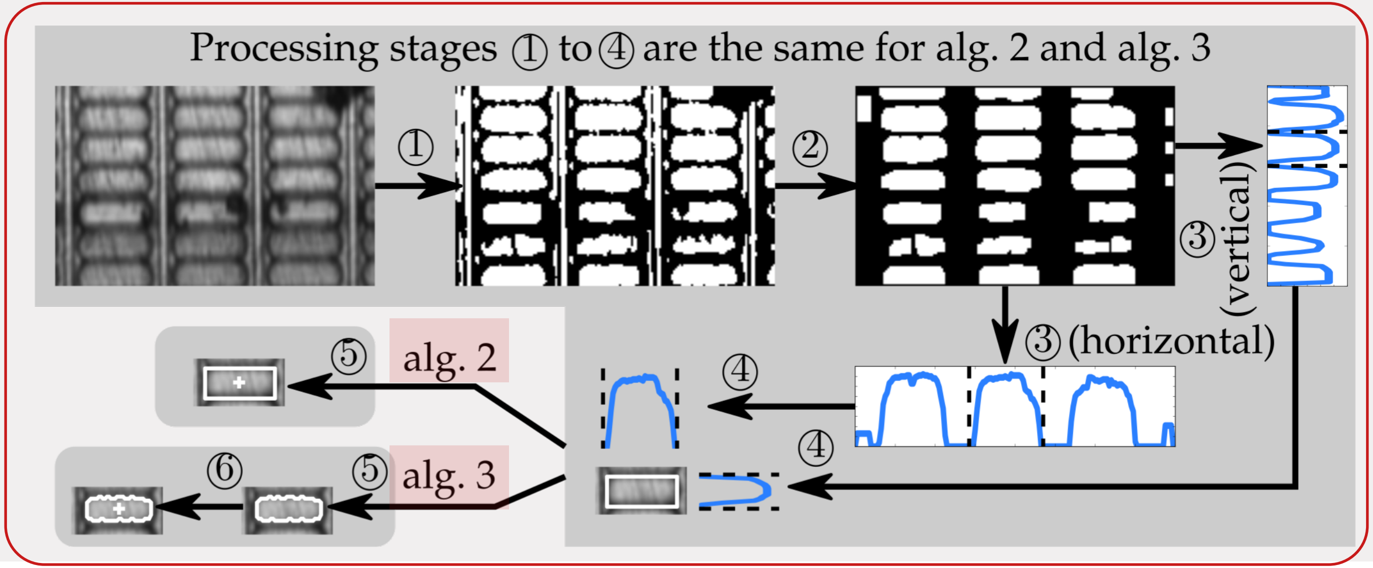
Image size $[px]$	Image Type	Resolution $[\mu m/px]$
120×75	synthetic by downsampling	6.67
160×100	in-situ measurement	5
200×125	synthetic by upsampling	4

Vision Algorithms

Algorithm 1 :



Algorithm 2 & 3 :



Processing Stages of Vision Algorithms

PROCESSING STAGES OF THREE VISION ALGORITHMS.

Stages	Algorithm 1	Algorithm 2	Algorithm 3
①	projection	binarization	binarization
②	1D filter	2D filter	2D filter
③	segmentation	projection	projection
④	1D moment	segmentation (bounding box)	segmentation (bounding box)
⑤	-	2D moment (bounding box)	segmentation (contour)
⑥	-	-	2D moment (contour)

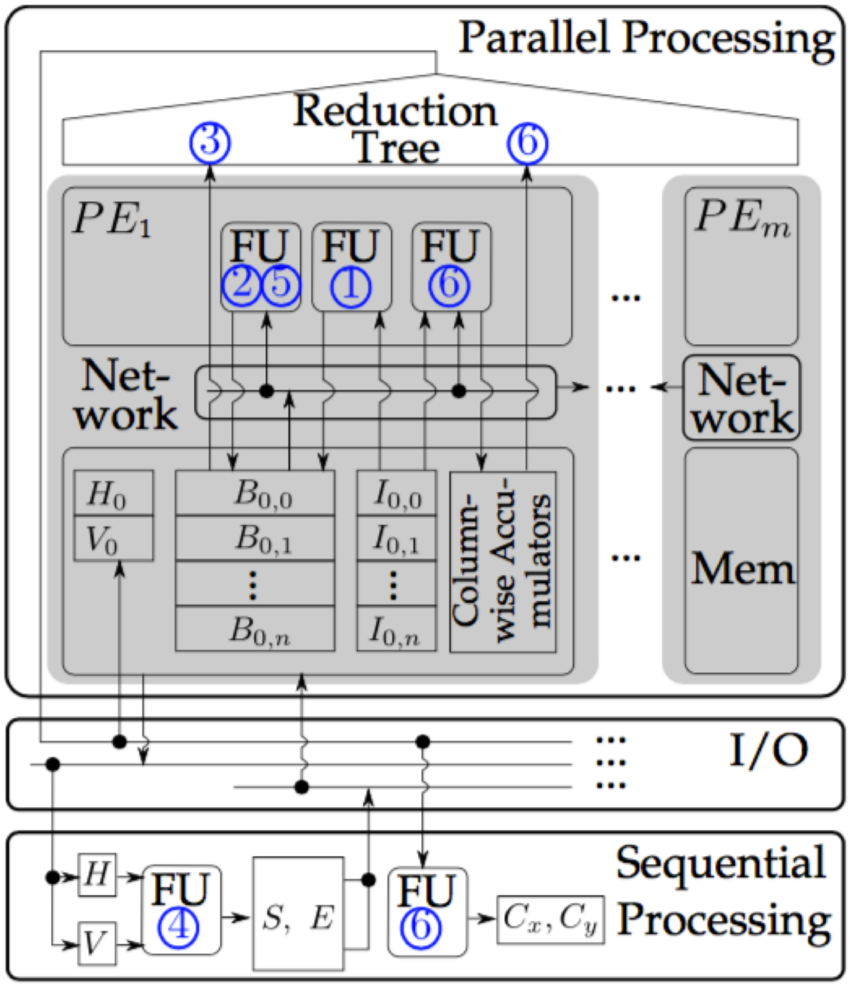
Vision Algorithm 3: Complexity Analysis

COMPLEXITY ANALYSIS AND MAPPING OF ALGORITHM 3.

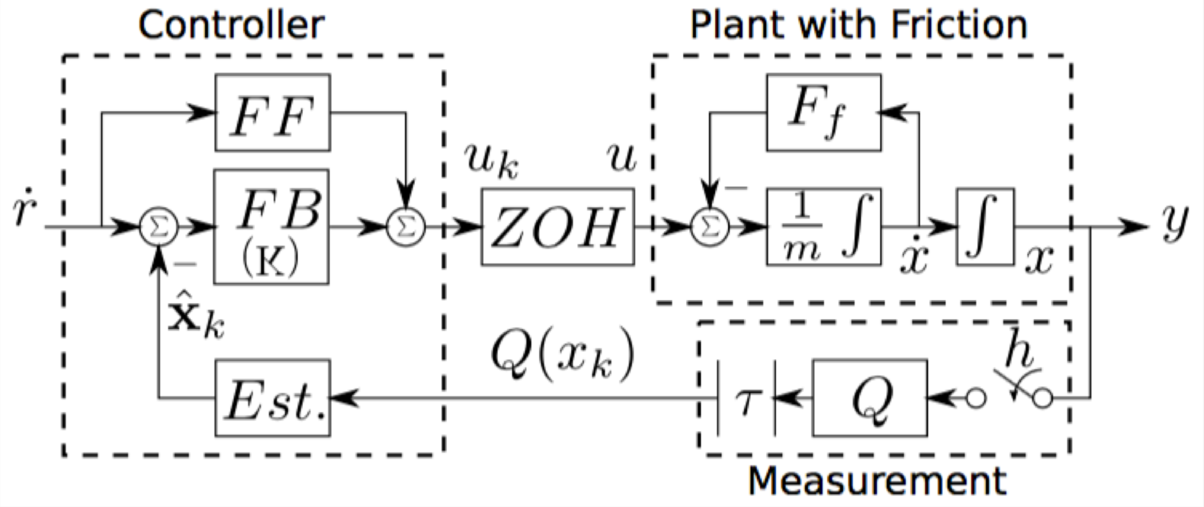
Step	Complexity	Alg. Pattern	Mapping
1	$O(m \times n)$	Local	Parallel proc.
2	$O(m \times n)$	Neighbor	Parallel proc.
3	$O(m \times n)$	Reduction	Parallel proc.
4	$O(m + n)$	Scan	Sequential proc.
5	$O(m \times n)$	Local	Parallel proc.
6	$O(m \times n)$	Reduction	Parallel proc.

TU/e

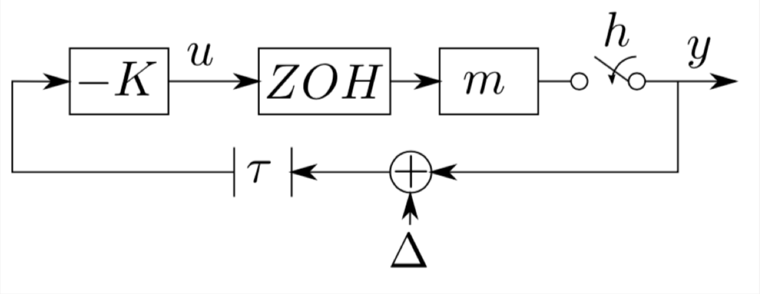
Vision Algorithm 3 on Architecture Template



System Diagram



Simplified model for analytical methods:
quantized sampled-data system with time delay.



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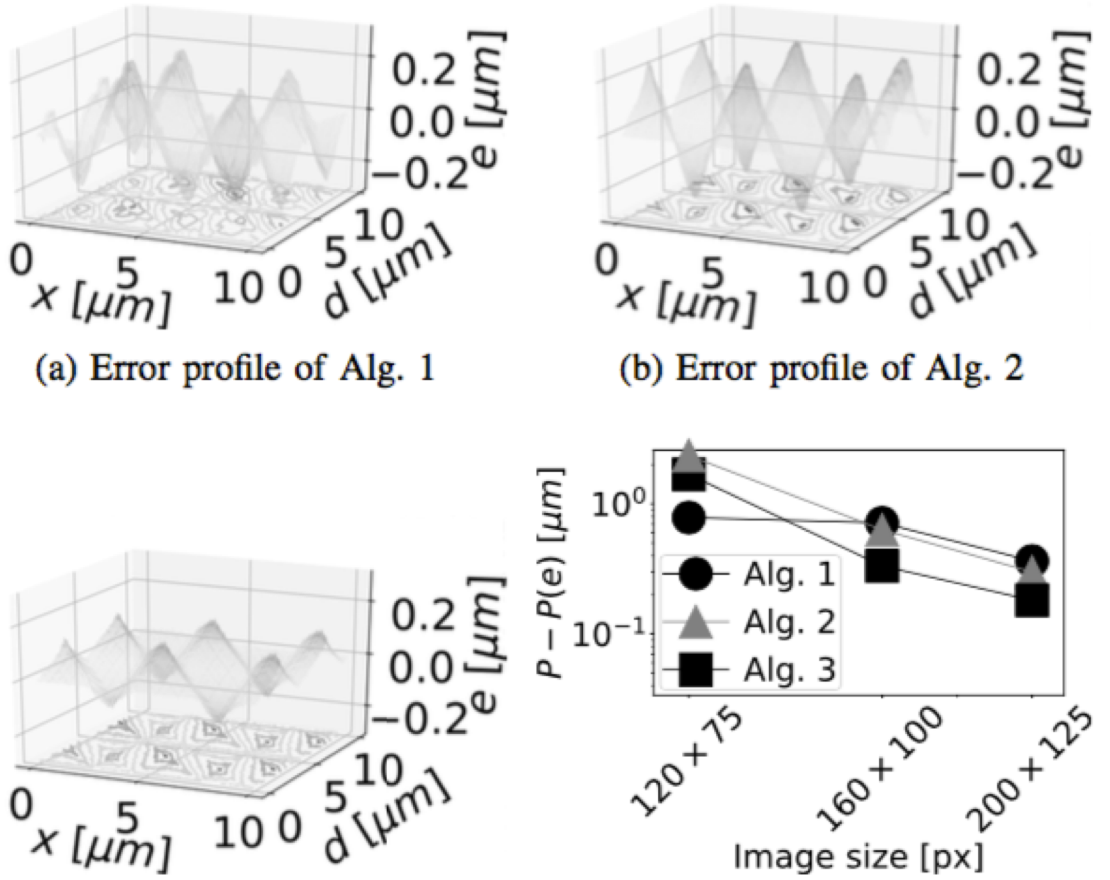
Quantization Error

Error “e” depends on image position “x” and displacement “d”. Vision algorithms is lumped into function “g()”.

$$e(x, d) = g(x + d) - g(x) - d.$$



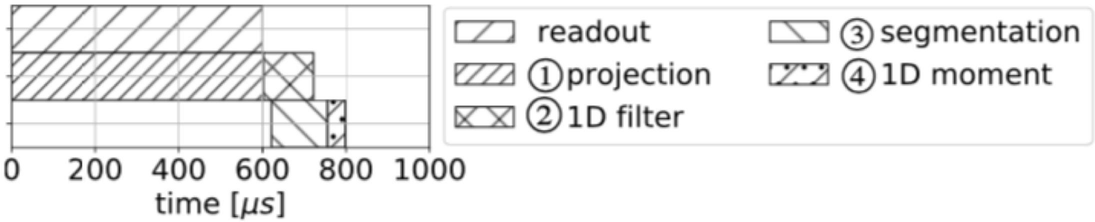
(a) Error profile of Alg. 1

(b) Error profile of Alg. 2

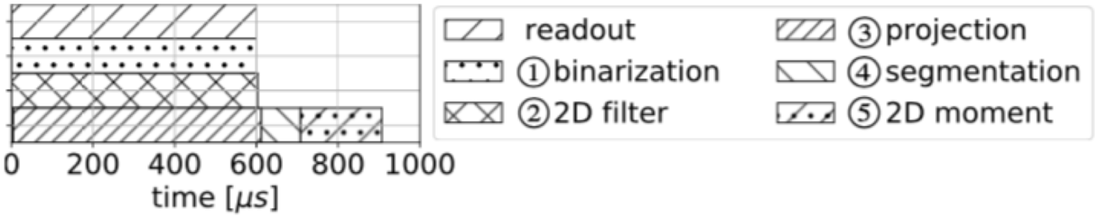
(c) Error profile of Alg. 3

(d) P-P(e) of different image sizes.

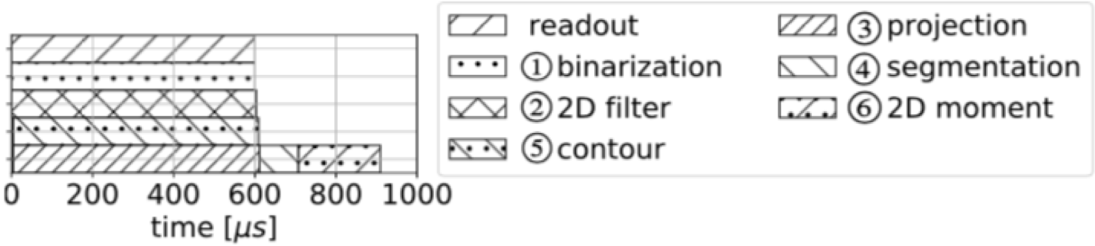
Sample Period and Delay



(a) Timing profile of Alg. 1



(b) Timing profile of Alg. 2



(c) Timing profile of Alg. 3

Tracking Errors of a Constant Reference