Abstract

This tutorial describes the integrating value of software in complex systems. The extensive use of software technology to integrate other technologies has a significant impact on the product characteristics and on the product creation organization and process. This tutorial provides insight in the relation between software and the system, and it provides insight in the consequences for the product and the organization. Some recommendations are provided to cope with these consequences.
Program

- Case: the waferstepper and it’s context
- The role of software in general
- Levels of abstraction
- Software -> System Functionality and Qualities
- Requirements perspective
- Evolution and Growth
- Why do we always have problems with software?
- Conclusion
What is a waferstepper

source
reticle
lens
wafer
From stepping to scanning

**stepper:** static exposure of field

**scanner:** dynamic exposure through slit

- **stepper:**
  - n
  - n+1
  - Step

- **scanner:**
  - 250 mm/s
  - Wafer
  - Reticle
  - Slit
  - Static exposure of field
  - Dynamic exposure through slit

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ASMLstepperVsScanner
Key specifications waferstepper

**imaging**

- 130 nm line width
- 10 nm critical dimension

**alignment**

- 45 nm overlay

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ASMLkeySpecifications
Moore’s law

line width in nm

1997 1999 2001 2003 2005 2007

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ASMLmooreslaw
Overlay budget (1999)

- **Process overlay**: 80 nm
- **Matched machine**: 60 nm
- **Single machine**: 30 nm
- **Process dependency**: 5 nm
- **Matching accuracy**: 5 nm
- **Lens matching**: 25 nm
- **Stage grid accuracy**: 5 nm
- **Stage overlay**: 12 nm
- **Position accuracy**: 7 nm
- **Alignment repro**: 5 nm
- **Stage Al. pos. meas. accuracy**: 4 nm
- **System adjustment accuracy**: 2 nm
- **Global alignment accuracy**: 6 nm
- **Off axis pos. meas. accuracy**: 4 nm
- **Sensor repro**: 3 nm
- **Blue align sensor repro**: 3 nm
- **Interferometer stability**: 1 nm
- **Frame stability**: 2.5 nm
- **Tracking error WS**: 2 nm
- **Tracking error RS**: 1 nm
- **Tracking error X, Y**: 2.5 nm
- **Tracking error phi**: 75 nrad
- **Metrology stability**: 5 nm
- **Off axis pos. meas. sensor repro**: 3 nm
- **Off axis sensor repro**: 3 nm
- **Tracking error phi**: 75 nrad

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ASMLOverlayBudget
Everything influences overlay

Overlay Influence Diagram.
(Maarten Bonnema, 19-3-1999)
Exercise 1, 10 minutes

Make a 3 picture description (What, How, biggest challenge) of your own system.
Fab Context of Waferstepper

- processing
- tracks
- metrology
- matching
- contamination
- operator
- wafer
- reticules
- semiconductor design
- reticule production
- reticule logistics
- maintenance
- fab layout
- fab cost model
- fab infrastructure
- fab automation
- SPC
- yield optimization
- wafer logistics
- inspection and monitoring
- fab cost
- logistics
- utilization
- fab
- metrology
- yield
- operator
- devices
- resist
- fab
- automation
- logistics
Business Context

- Yield
- Value of performance (MHz)
- CD control
- Key driver trade-off

Other players:
- Equipment vendors
- System integrators
- Lease companies
- Fab designers
- Consultants
- Mask makers
- Resist makers
- Wafer makers
- OEM’s: laser
- Intimate partners: lens

Business models of the customer:
- Design houses
- Foundries
- Vertical integration

Limited number of customers;
Many systems per customer
Human Context: Stakeholders

"external"

- customer
- purchaser
- decision maker
- user
- operator
- maintainer

"internal"

- managers
  - business manager
  - marketing manager
  - product manager
  - operational manager
  - project leader
  - sales manager
  - quality manager
  - manufacturing engineers

- engineers
  - system engineers
  - experts
  - outsourcing engineers
  - customer support

- suppliers
  - component manufacturer
  - outsourced design

"other"

- government
- customer's customer
- banks, insurance
Multitude of Disciplines

- Lithography
- Mechanics
- Dynamics
- Imaging
- Optics
- Measurement

- Construction
- Materials
- Optical materials
- Coatings
- Lasers
- Lamps
- Dose control
- SW control
- Home sensors
- Capacitive sensors
- Hall sensors
- Real time executives
- Digital signal processing
- Analog signal processing
- Pre-amplifiers
- Light sensor
- Energy
- Uniformity
- Bandwidth
- Pulse timing
- Frequency
- Pre-amplifiers
- Digital signal processing
- Analog signal processing
- Real time executives
- Hall sensors
- Capacitive sensors
- Home sensors
- SW control
- Dose control
- Lamps
- Lasers
- Coatings
- Optical materials
- Construction materials
- Construction
- Measurement
- Imaging
- Optics
- Dynamics
- Mechanics
- Lithography

- Motors
- Actuators
- Servo's
- C&T
- Robotics
- Air showers
- Cooling
- Vacuum clamping
- Mirrors
- Measurement lasers
- Real time executives
- Digital infrastructure
- Analogue
- Pre-amplifiers
- Sensor signal processing
- Real time executives
- Hall sensors
- Capacitive sensors
- Home sensors
- SW control
- Dose control
- Lamps
- Lasers
- Coatings
- Optical materials
- Construction materials
- Construction
- Measurement
- Imaging
- Optics
- Dynamics
- Mechanics
- Lithography

- Temperature sensitivity
- Sensitivity
- UV sensitivity
- Transmission
- Reflection
- Modes
- Stiffness
- Energy
- Pulse
- Timing
- Frequency
- Bandwidth
- Uniformity
- Pre-amplifiers
- Sensor signal processing
- Real time executives
- Hall sensors
- Capacitive sensors
- Home sensors
- SW control
- Dose control
- Lamps
- Lasers
- Coatings
- Optical materials
- Construction materials
- Construction
- Measurement
- Imaging
- Optics
- Dynamics
- Mechanics
- Lithography

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- INSEtechnologies
Complexity of Waferstepper Context

market, business

fab context

waferstepper

multitude of disciplines

stakeholders

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INSEcomplexity
Symptom: Delays appear during Integration

Do you have any design issues for the design meeting?

The default answer is: No.

During integration numerous problems become visible

scheduled closing date
realized closing date
integration and test
delay
Exercise 2, 10 minutes

Make a 3 picture description (Application context, Value chain, technologies) of your own system.
Relative Contribution of SW

The diagram illustrates the relative contribution of different fields over time:

- **Physics/Chemistry, etc.**
- **Mechanics**
- **Electronics**
- **Software (SW)**

**1970**

**2000**

**Relative effort**

**100%**

The diagram shows an increasing relative effort in software over time, with other fields maintaining or decreasing their contributions.
Control Hierarchy along Technology axis

- Human user
  - Application SW
    - Control SW
      - Digital electronics
        - Analog or power electronics
          - Mechanical device
          - Optical device
          - Sensor
  - Feedback
Characterization of disciplines
Exponential Pyramid, from requirement to bolts and nuts

- $10^0$
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$
- $10^7$

**number of details**

- System
- Multi-disciplinary
- Mono-disciplinary

**research focus**

- System

**requirements**

- Design decisions

**parts connections lines of code**

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From Components to System Qualities

- Components:
  - source
  - mirrors
  - fiducials
  - lens elements
  - flaps
  - air showers

- Subsystems:
  - laser
  - lens
  - stages
  - handlers
  - electronics infra

- Functions:
  - prepare
  - transport wafer
  - align and calibrate
  - scan and expose
  - transport reticle

- System Qualities:
  - overlay
  - CD control
  - productivity

- Overlay:
  - prepare
  - transport wafer
  - align and calibrate
  - scan and expose
  - transport reticle

- CD Control:
  - prepare
  - transport wafer
  - align and calibrate
  - scan and expose
  - transport reticle

- Productivity:
  - prepare
  - transport wafer
  - align and calibrate
  - scan and expose
  - transport reticle

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ATlayers
Role of Software

- Components
- Subsystems
- Functions
- System qualities

SW implements functionality
Determines emerging qualities
Make a toplevel decomposition of the software in your system and estimate the amount of software of the constituting parts
When SW engineers demand "requirements",
then they expect \textit{frozen} inputs
to be used for
the design, implementation and validation
of the software
System vs Software Requirements

- **System Requirements**: Multi-disciplinary
- **Software Requirements**: Mono-disciplinary

The pyramid illustrates the number of details required for system and software requirements, increasing exponentially from multi-disciplinary to mono-disciplinary.
Why is the Software Requirement Specification so Large?

- software subsystem
- user interface
- system behavior
- operational choices
- synergy, tools, ...
- limited computing resources
- control of physical subsystems: sensors, actuators
And why is it never up-to-date?

![Diagram showing the relationship between number of details and changes in software systems.](image-url)
Exercise 4, 2 minutes

How many pages are in your Software Requirements Specification?
Block Diagram of a Waferstepper

- Laser
- Light source
- Illuminator
- Beam shaping
- Reticle stage positioning
- Lens projection
- Wafer stage positioning
- C&T contamination, temperature
- Reticle handler input/output
- Wafer handler input/output
- System control coordination
- Measurement, levelling
Control Hierarchy of a Waferstepper

- System control coordination
- Ethernet
- Laser
- Illuminator
- Lens
- Measurement
- C&T
- Reticle stage
- Reticle handler
- Wafer stage
- Wafer handler
- Vertical motion
- Horizontal motion

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FAIcontrolHierarchy
Frequency of Control Actions

- trend with increasing performance requirements

- SW sampling per die per wafer per batch per day maintenance
- 10^-3 1 10^3 10^6
- seconds

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- FAicontrolFrequency
## Evolution of System Control

<table>
<thead>
<tr>
<th>1990</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 kloc</td>
<td>2000 kloc</td>
</tr>
</tbody>
</table>

### User Interface
- Static calibration
- Simple sequencer
- Data store

### Infrastructure
- Data store

### Production and Installation Support
- Monitoring and optimization
- Metro
- Job control
- Exposure control
- Dynamic calibration

### Automation Interface
- Feedforward
- Monitoring
Consequences of Evolution

- **Performance and functionality demands**
  - causes **Complexity**
  - threatens **Reliability**

  **loss of overview** (150kloc fits in 1 mind, 2Mloc not)
  - (more than?) exponential increase of coupling
    - 1:1 relation HW:SW becomes n:m relation

  **autonomous subsystems**
  - paradigm shift!
  - integrated system
Exercise 5, 10 minutes

Visualize the (SW) evolution of your system. What is your current phase?
Different Focus of Software and System Engineering

**System engineering focus**
- **qualities**
  - productivity
  - image quality
  - reliability
- **concepts**
  - domain requirements
  - models
- **concerns**
  - integral design (quality, balance)
  - system context
  - lifecycle
  - operational processes
- **education**
  - principles
  - heuristics
  - analysis and synthesis
  - processes

**SW engineering focus**
- **qualities**
  - functionality
  - maintainability
  - variability
- **concepts**
  - structure
  - (generic) mechanisms
- **concerns**
  - configuration management
  - release procedure
  - tools
  - SW processes
  - SW problems, change requests
- **education**
  - principles
  - heuristics
  - analysis and synthesis
  - processes
  - languages
  - operating systems
  - algorithms
  - formal methods

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TSAITfocus
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MVmechanismArchitecture
Caricature of Physics Systems View

- Laser
- Illuminator
- Sensor
- Reticle
- Lens
- Aerial Image
- Wafer
- Pulse-freq, bw, wavelength, ...
- Uniformity
- NA
- Abberations
- Transmission
Relation SW and Physics

- Laser
- Illuminator
- Sensor
- Reticule
- Lens
- Wafer
- Aerial Image
- NA (Numerical Aperture)
- Abberations
- Transmission

Pulse-freq, bw, wavelength, ...

Measure
Adjust
Calibrate
Analyse
Process
Log
Control
Symptoms of too isolated SW efforts

**symptoms**

- SW people are clustered together
- SW is alpha tested before system integration
- SW team uses own specification and design process
- SW specification is in SW jargon or formalism

**counter measures**

- colocation per function, subsystem or quality
- continuous system integration
- higher level processes are shared
- interaction between SW, HW and system engineers
Exercise 6, 5 minutes

What is the degree of integration or isolation of SW in your organization?
Different Mindsets and Characteristics

**System**
- product: sellable self-sustained entity
- operating in a broader context

**different focus:**
- "qualities"
- "concerns"
- "concepts"
- "education"

**HW engineering**
- tangible
- concrete
- goods flow costs & lead times
- physics laws

**SW engineering**
- intangible
- abstract
- no goods flow costs
- "everything is possible"