Towards Automatic Generation of Formal Models for Highly Automated Manufacturing Systems

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Outline

1. Research Questions
2. Automated Manufacturing Systems
3. Digitalization
4. Learning Formal models
   - Background
   - Automata Learning
   - Active Learning Applied to a Simulated Robotic Arm
   - Integrating Active and Passive Learning
5. Wrapping up
   - Summary of Contributions
   - Future Work

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Research Questions

- RQ1 How does the manufacturing industry generally handle errors and perform maintenance? And what are the challenges faced?

- RQ2 How can operators be supported with tools and processes that will make it possible to make more data driven decisions?

- RQ3 Is it feasible to automatically learn formal models of manufacturing and systems? If so, what would be required to make it a reality?

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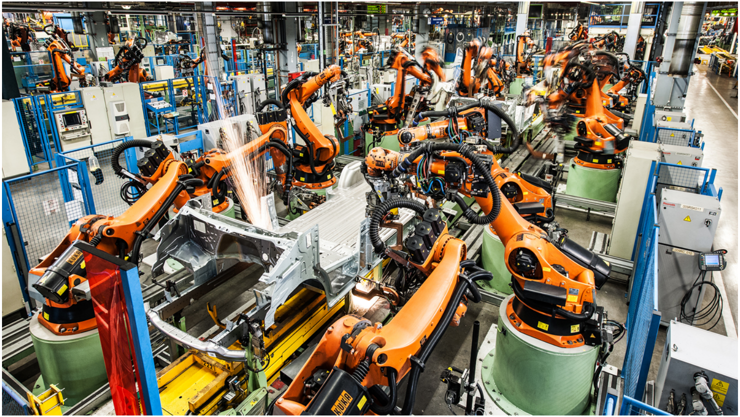
Automated Manufacturing Systems

Integration of software and machinery that perform manufacturing processes autonomously.



Automated Manufacturing Systems

- Complexity of manufacturing systems is increasing
- Writing correct software to control the systems is difficult
- Once operational, it is difficult to evaluate the stations to ensure there are no deviations from expected behavior
- Tools to evaluate the performance of manufacturing systems are scarce

Survey

To get a better idea about the problems faced by the operators, we conducted a survey involving NEVS, Scania, GKN Aerospace, and Volvo. The issues discussed were:

- Knowledge transfer between operators
- Lack of training and support for operators on the actual station
- Software bugs after commissioning, hot fixes usually end up introducing more bugs
- Restart after a power outage or emergency stop

Survey

Digitalization

- Knowledge transfer between operators
- Lack of training and support for operators on the actual station

Application of Formal Methods

- Software bugs after commissioning, hot fixes usually end up introducing more bugs
- Restart after a power outage or emergency stop

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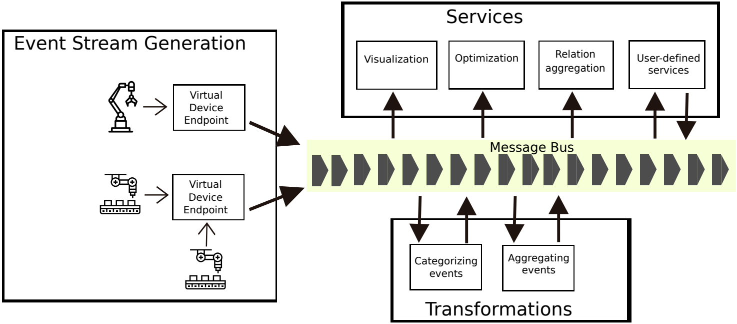
Connecting to the Factory Floor



Architecture

- Event Driven Architecture
- Easy to add and remove devices
- Support for new and legacy systems

Virtual Device

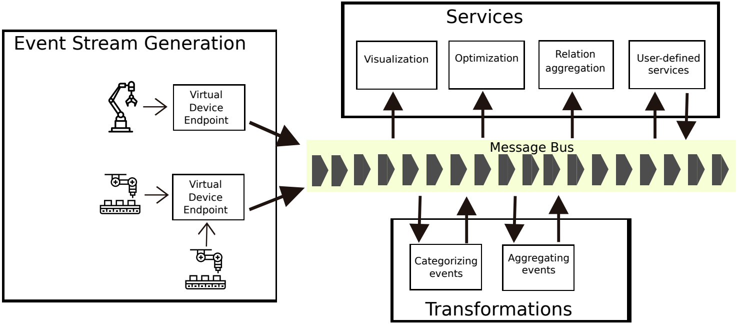
Robot actions are converted to event streams by the Virtual Device

- Provides the integration layer
- Captures and publishes device data onto the message bus
- Header defines resource name, location and time

Event Message

$\langle resource, location, timestamp, data\rangle$

Connecting to the Factory Floor



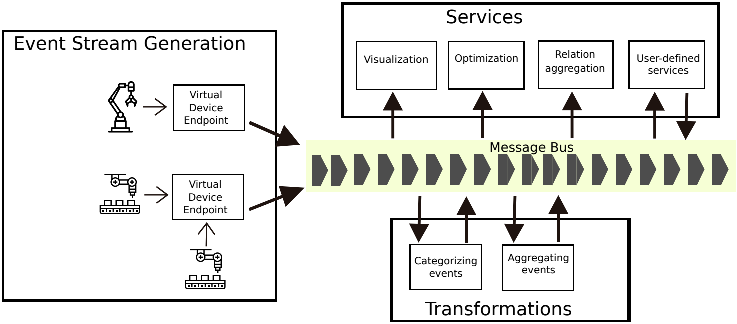
Transformations

Events are then transformed by a series of transformation endpoints into an usable abstraction.

Robot operation

$\langle Name, Starttime, Endtime, Resource, Operationtype \rangle$

Connecting to the Factory Floor

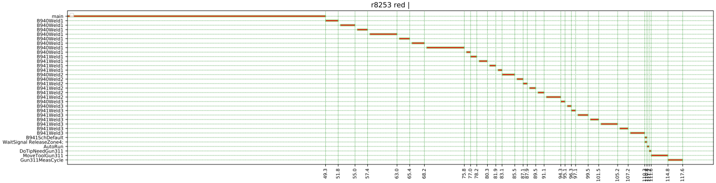


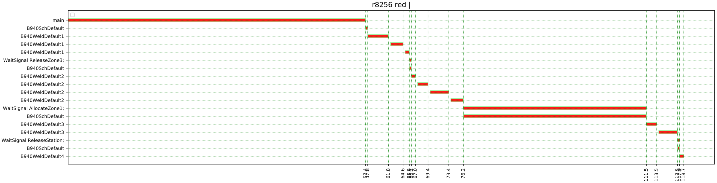
Services

Services continuously perform computations on events based on user requirements.

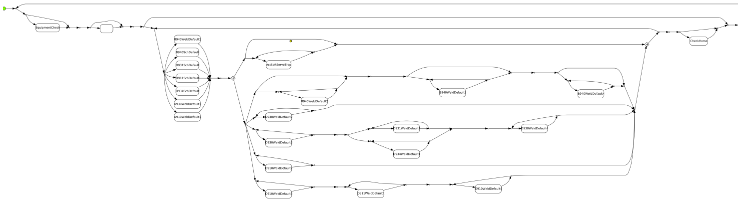
- Calculation of performance indicators
  - Cycle times, wait times
  - Resource Utilization
- Process Visualizations
- Prediction Services
- Simulation of a Digital Twin

Gantt Visualization

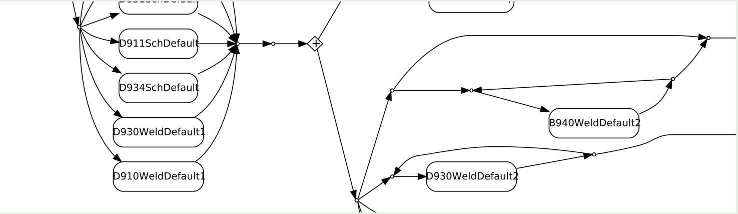




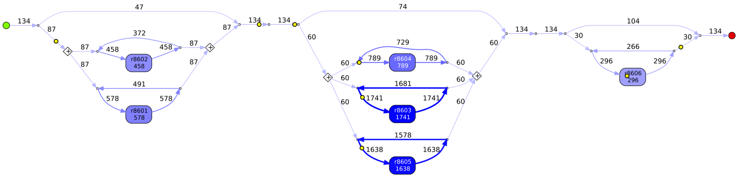
Behavioral Visualization



A closer look



Resource Visualization



Video

Visualization

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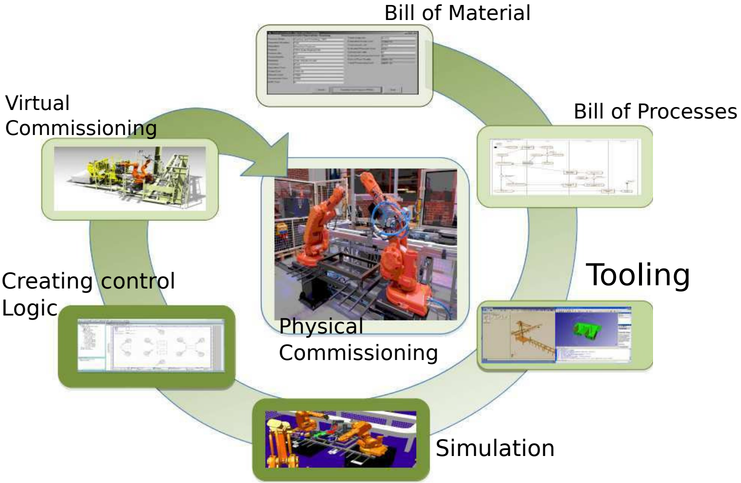
Virtual Preparation and Commissioning in a nutshell

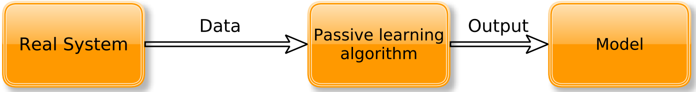


Formal Methods

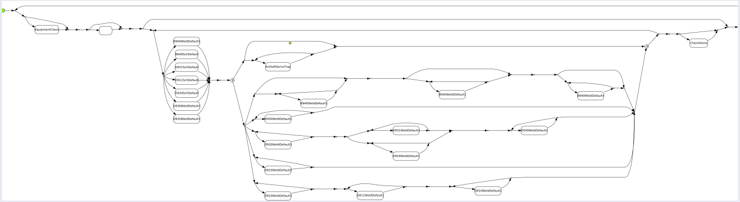
- Mathematical techniques for specification and verification of systems
- Formal Models: Less ambiguous way to define the behavior of the system
- Verification: Checks if the model satisfies the specifications
- Synthesis: Calculate a controller that satisfies the specifications
- Challenges: Hard to model physical systems – error prone process when done manually

Is there then a possibility to automate the calculation of a formal model?

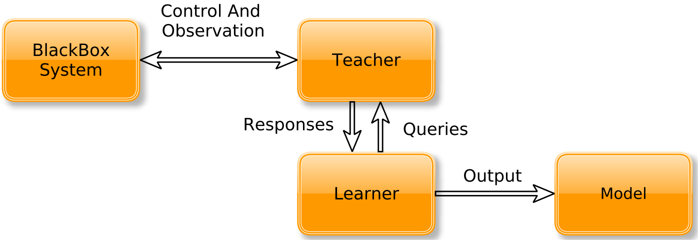
Passive Learning



Behavioral Model



Active Learning

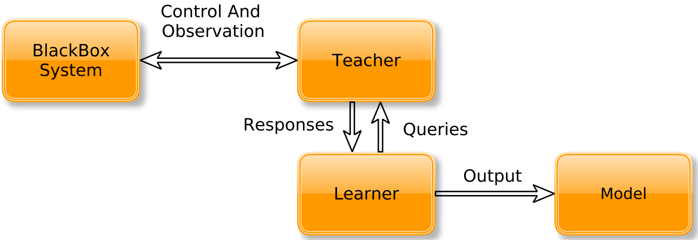


The L^* Algorithm

Learning regular sets from queries and counterexamples. Dana Angluin. Information and Computation, 1987

- Famously called L^*
- L^* makes it possible to learn deterministic automata

Active Learning



Learner Queries

- Membership queries $w \in L_m$?
- Equivalence queries $\mathcal{L}(H) = L$?

Configuration

Operations:

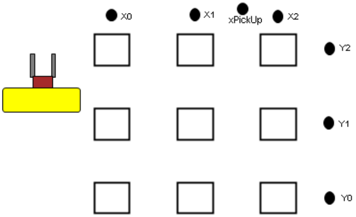
$O\langle \text{PreGuard}, \text{PreActions}, \text{PostGuard}, \text{PostActions}\rangle$

Goal

A predicate over the sensor values to define the marked states

Operation Grip Example

PreGuard : (extended== true && gripping == false)
PreAction : gripper := true
PostGuard : gripping == true
PostAction: -



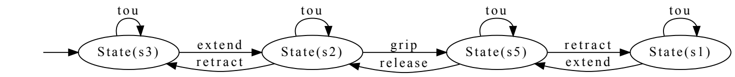
The Interface

- Membership queries (Mq) were obtained by running sequences in the simulator
- Equivalence queries (Eq) were obtained using random walks on the hypothesis

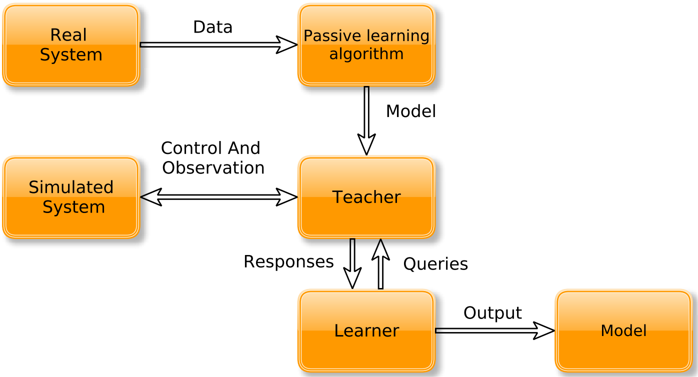
Outcomes

- It was possible to learn a model of the simulated target system
- The system could not easily scale up
- Bottlenecks:
    - Finding counter examples is not always effective in large systems
    - Internal data structure used for L^* is not very efficient for large systems

Graph showing the gripping operation



The L^+


Real System
Data
Passive learning algorithm
Model
Control And Observation
Simulated System
Teacher
Responses
Queries
Learner
Output
Model

Results

		L^+			L^*		
grid	*states*	*obs*	*Eq*	*Mq*	*Time(s)*	*Eq*	*Mq*
2x2	17	30	3	5800	420	5	2980
3x3	37	30	4	12800	2530	8	17600
4x4	65	45	7	38400	4290	9	55230
5x5	101	34	8	59800	6400	10	102780

Outcomes

- Improved performance over the traditional L^*
- Scales better, but still not sufficient for large systems
- Highly dependent on the diversity of logged sequences

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My vision

- A more integrated workflow to developing and maintaining manufacturing systems
- Reusable components playing a central role in development
- Auto-generation of correct and safe code based on requirements
- Visual aid to detect problems
- Virtual Commissioning, Physical Commissioning, and day-to-day maintenance are tightly coupled

RQ 1

How does the manufacturing industry generally handle errors and perform maintenance? And what are the challenges faced?

- Survey of errors and error handling techniques in the industry

Paper 1:

Ashfaq Farooqui, Patrik Bergagård, Petter Falkman, and Martin Fabian. Error Handling Within Highly Automated Automotive Industry: Current Practice and Research Needs. *2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2016, Berlin, Germany.

RQ 2

How can operators be supported with tools and processes that will make it possible to make more data driven decisions?

- Architecture to digitalize and capture data from the factory floor was presented
- Captured data was visualized in different ways to help operators

Paper 2:

Ashfaq Farooqui, Kristofer Bengtsson, Petter Falkman, and Martin Fabian. From Factory Floor to Process Models: A Data Gathering Approach to Generate, Transform, and Visualize Manufacturing Processes. *Submitted for possible journal publication.* 2018

Paper 4:

Ashfaq Farooqui, Kristofer Bengtsson, Petter Falkman, and Martin Fabian. Real-time Visualization of Robot Operation Sequences. *2018 IFAC Symposium on Information Control Problems in Manufacturing (INCOM)*, 2018, Bergamo, Italy.

RQ3

Is it feasible to automatically learn formal models of manufacturing and systems? If so, what would be required to make it a reality?

- Active and Passive model learning techniques were studied
- A proof of concept study was done to evaluate L^* on manufacturing systems
- L^+ was presented by integrating active and passive modes of learning

Paper 3:

Ashfaq Farooqui, Petter Falkman, and Martin Fabian. Towards Automatic Learning of Discrete-Event Models using Queries and Observations. *Submitted for possible journal publication*, 2018

Paper 5:

Ashfaq Farooqui, Petter Falkman, and Martin Fabian. Towards Automatic Learning of Discrete-Event Models from Simulations. *14th IEEE Conference on Automation Science and Engineering (CASE)*, 2018, Munich, Germany.

Directions for Future Work

- Virtual Device for PLC like devices
- Improved data structures for active learning
- Learn richer formalism's – Extended Finite Automata
- Incorporating `restart` during the learning process
- Apply active learning on real world practical systems

Thank You!